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Impact of seed coating with superabsorbent polymers on morphological, physiological and production traits of maize (*Zea mays* L.)

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Abstract: Due to ongoing climate change, the need for the application of adaptive strategies in agriculture is increasing, particularly in areas with insufficient rainfall, high temperatures and weather fluctuations during the vegetation period. Therefore, an experiment was conducted in 2020 and 2021 to determine the influence of superabsorbent polymers (SAPs) on morphological, physiological and production traits of maize. SAPs were applied using a method of seed coating, which is considered cost-effective and environmentally friendly. Due to the impact of SAPs, significantly larger weights of leaves and roots, as well as the length of roots in the initial growth stage, were found. Furthermore, the SAP treatment condition found significantly larger values of leaf relative water content and spectral indexes PRI (photochemical reflectance index) and NDVI (normalised difference vegetation index). Applying SAPs also led to a significant increase in spikes per plot and grain yield of maize. Moreover, the results significantly impact the interaction between year and treatment. The correlation analysis indicates a higher correlation between the observed traits in the SAPs treatment condition, which subsequently impacted the final maize production. These results confirm that applying SAPs can be considered a suitable strategy for mitigating the impacts of adverse weather conditions, especially in terms of sustainability and maintaining maize production.

Keywords: spectral indices; WinRhizo; adaptability; field conditions

Maize (*Zea mays* L.) is considered one of the most important grains in nutrition and a notable bioenergetic crop (Bassu et al. 2014), although as reported by Perera and Weerasinghe (2014), the most significant part of production is used as feed for farm animals, part for human nutrition, various industrial processing, and export. Data from the Food and Agriculture Organisation (FAO) show that global maize production in 2020 was 1 162 million tons (FAO 2022). However, with the increasing trend of global climatic changes, it is expected that the grain yield and maize quality will decrease as a result of biotic and abiotic stresses (Sabagh et al. 2018). Among abiotic factors, drought is one of the most significant factors limiting field crop productivity (Hassan et al. 2016).

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Furthermore, developing maize adaptation strategies is important for agricultural production and food security (Ahmad et al. 2020). One strategy to effectively counteract the negative impact of drought on field crops (De Barros et al. 2017) and to increase the soil water status and growth of crops in areas with a limited water supply is the application of multifunctional superabsorbent polymers (Yang et al. 2018). Other advantages of the application of these substances include improvement in plant germination and plant growth and an increase in yield (Yazdani et al. 2007), as well as improvement of the physical properties of the soil and a decrease in watering requirements (Blodgett et al. 1993). Superabsorbent polymers, a new class of polymer materials with a strong hydrophilic group, can absorb 100–1 000 times their weight in water. Due to these characteristics, their use in agriculture has been intensifying (Cheng et al. 2015) as they dramatically increase the effectiveness of water use (Chang et al. 2021). Although in practice, the application method of superabsorbent polymers as soil conditioners is more common (Saha et al. 2020), another option is the application using the seed coating method (Pathak and Kingsly Ambrose 2019). This application method can aid in increasing the water availability for seeds by providing a water supply nearby (Mangold and Sheley 2007) and supplying water directly to seed during germination and the initial growth phase (Gubišová et al. 2021); thus, coating seeds with water-absorbent materials can improve their survival, especially with plants planted in dry and low-fertility areas (Su et al. 2017). As Finch-Savage and Bassel (2016) reported, seed germination and early development of healthy juvenile plants are limiting factors for crop production. Seed coating can also influence the proportional division of plant organs during early growth, especially in favour of strengthening the root system (Gorim and Asch 2012). This is particularly important with maize, the production of which is increasingly influenced by suboptimal water supply (Rosenzweig and Hillel 2012) and by dry periods at the beginning of vegetation, which increase the risk of low yield (Hlavinka et al. 2009).

Therefore, this study focuses on the influence of seed coating with superabsorbent polymers on the morphological, physiological, and production parameters of maize grown in field conditions. As a result, this maize production strategy can be considered environmentally friendly, economically effective, and sustainable.

MATERIAL AND METHODS

Experimental site and design. The experiment was conducted in 2020 and 2021 at the experimental station of the Slovak University of Agriculture (SUA) in Nitra (18°09’E, 48°19’N). The location is part of the Danubian Lowland, near the Zobor mountains and in the catchment area of the Nitra River. From the perspective of long-term climatic characteristics, the area can be considered warm and dry, with a yearly rainfall of 539 mm and an average temperature of +10.2 °C. The rainfall and average monthly temperatures during the vegetation period during the experimental years were measured at the weather station of SUA and are listed in Table 1. The soil was classified as Haplic Luvisol, and the soil texture was classified as silt loam.

Common wheat (*Triticum aestivum* L.) was selected as the pre-crop of the maize. After its harvest in the fall, stubble ploughing was conducted, followed by mid-depth tillage and doses of PK fertilisers were

Table 1. Precipitation and temperature during the maize vegetation

	April	May	June	July	August	September	October	November	
Precipitation (mm)									sum
2020	6.6	54.4	66.8	38.4	74.0	96.0	151.8	17.8	505.8
2021	36.4	113.2	17.9	42.3	128.2	36.1	17.6	35.2	426.9
Normal	36	59	59	65	55	58	46	45	423
Temperature (°C)									mean
2020	7.8	10.1	18.1	19.5	20.9	15.4	9.3	2.6	13.0
2021	7.2	11.9	20.4	22.4	18.4	14.9	9.3	4.6	13.6
Normal	11.4	16.0	19.6	21.7	21.1	15.9	10.4	5.6	15.2

Normal – representing climatic normal of experimental location from 1991–2020

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applied. In the spring, the property was levelled using disks, and a dose of nitrogen, calculated based on the soil supply and estimated plant requirements, was applied (Sainju 2017). Nitrogen was applied in the form of urea (80 and 100 kg N/ha in 2020 and 2021, respectively), phosphorus in dose 30 kg P/ha for both years in superphosphate and potassium in dose 80 kg K/ha for both years in K_2SO_4. Soil samples were collected at a depth of 0.3 m, and laboratory tests for macronutrient content, soil reaction, and humus content were subsequently performed (Table 2). Based on these analyses, it can be concluded that the supply of NPK nutrients in the soil is at medium values.

The content of inorganic nitrogen was determined using the calorimetric method, the ammonia form of nitrogen using Nessler's reagent (Koch and McMeekin 1924), and nitrate nitrogen using phenol 2.4-disulfonic acid (Panáková et al. 2016). The phosphorus and potassium contents were determined using the Mehlich III test (Mehlich 1984). The soil reaction was determined using a 1 mol/L KCl solution, as described by Kabala et al. (2016). Finally, the carbon content in the soil sample was established based on the Tjurin method (Kononova 1975).

The sowing of the maize was performed on 28 April 2020 and 27 April 2021 using a 4-row sowing machine. The randomised complete block design in three replications was utilised. Control (without superabsorbent polymers (SAPs) treatment) and SAPs treatment were sown in 8 rows, the distance between rows was 0.75 m, with the length of each plot of 20 m. The total area of each experimental plot was 105 m^2 (5.25 × 20 m). Protection against diseases and pests and weed control were performed based on the occurrence of these factors and their growth status at that time.

Superabsorbent polymers and plant material. Maize seeds were treated using the seed coating technology Aquaholder®Seed (PeWaS s.r.o., Bratislava, Slovak Republic). This technology is based on superabsorbent polymers, which can absorb water up to 100 times its weight and subsequently release it to roots during the dry period.

A moderately tall maize Kerala (FAO 350) cultivar was selected for the experiment. This cultivar belongs to a new genetic group with excellent heterosis and particularly high and stable yield in various soil-climatic conditions.

Measurements and harvesting. In each experimental year, the growth of individual treatments in two rows of 10 m length (7.5 m^2) was evaluated to determine the number of sprouted plants. In 2020, this was performed 29 days after sowing (DAS), and in 2021, 35 DAS was in phase BBCH 16 (Biologische Bundesanstalt, Bundessortenamt and Chemical Industry). On these dates, samples of 10 plants of each treatment were collected to determine the leaf and root weight. The soil remnants were removed from them manually under running lukewarm water, and subsequently, the leaf and root system of each plant was weighted.

The same area was used for collecting spikes per plot in the maize's full maturity phase. Subsequently, the sample was used in a laboratory analysis to determine the parameters of the weight of 1 000 grains using the instrument Numirex (Mezos, s.r.o, Hradec Králové, Czech Republic) and the specific weight of maize using the hectoliter weight apparatus.

The experimental plots were harvested using a combine harvester John Deere t670i (Deere & Company, Moline, USA) on 27 November 2020 and 16 November 2021 in the full maturity phase; subsequently, the total yield per 1 hectare was calculated. Each plot was harvested separately, and the grain yield value was weighed on portable scales.

Additionally, in 2021, further analyses of the root system (root length, root volume, and surface area) were conducted using an image analysis system WinRHIZO™ (Regent Instruments Inc., Quebec, Canada), which is specially designed for root measurement in different forms. At 40 DAS, five representative maize plants were manually collected (to 0.30 m depth) at each treatment and transferred to

Table 2. Soil properties in experimental plots

Year	Macronutrient content (mg/kg)			pH	Carbon content (%)
	N_{in}	P	K		
2019/2020	17.52	78.22	292	6.51	1.04
2020/2021	12.03	85.10	303	6.13	0.89

N_{in} – sum of the nitrate and ammoniac forms of nitrogen

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the laboratory in a portable refrigerator. The soil remnants were removed from them manually under running lukewarm water, and subsequently, their root system was separated with a scalpel. Afterwards, each plant was scanned and analysed separately.

Normalised difference vegetation index (NDVI) and photochemical reflectance index (PRI) were measured during the vegetation year 2021 at 45 and 64 days, respectively. The measurements were recorded between 10 a.m. and 1 p.m. CET (Central European Time) at full light without cloud cover. Five representative maize plants were selected from each treatment, and five measurements were conducted on the flag leaf of each plant. The measurements were made using the instrument PolyPen RP 410 (PSI spol. s.r.o., Drásov, Czech Republic), which incorporates the formulas of commonly used reflectance indices:

$$NDVI = (RNIR - RRED)/(RNIR + RRED) \quad (1)$$
(Carlson and Ripley 1997)

$$PRI = PRI = (R531 - R570)/(R531 + R570) \quad (2)$$
(Gamon et al. 1992).

Leaf relative water content (RWC) was determined in 2021. From a single treatment, five topmost fully expanded leaves were collected; these were immediately inserted in hermetically sealed packaging and placed in a cooled portable refrigerator. Subsequently, the samples were transported to the laboratory, where they were immediately weighted to obtain leaf sample weight (FW); immediately after, the sample was hydrated to full turgidity for 3–4 h under normal room light and temperature. After the time required for hydration, the samples were removed from the water, and the remnants of the surface moisture were removed using filtering paper; immediately after, the samples were weighed to obtain a fully turgid weight (TW). Subsequently, the samples were inserted in Petri dishes and dried in an electrically controlled dryer (MEMMERT GmbH + Co. KG, Schwabach, Germany) at a temperature of 80 °C for 24 h. After being cooled down in a desiccator, the samples were weighed to determine dry weight (DW). RWC was calculated using the following equation:

$$RWC (\%) = [(FW - DW)/(TW - DW)] \times 100 \quad (3)$$
(González and González-Vilar 2001).

Statistical analysis. The statistical analysis was conducted in the program Statistica 12 (StatSoft, Inc., Tulsa, USA), using a factorial and one-way ANOVA (Statsoft 2016). Tukey's multiple range test was used with the significance level $\alpha = 0.05$. In addition, the Pearson coefficient was used to determine correlation relationships among the analysed maize traits.

RESULTS

The course of weather conditions during the two experimental years was very different (Table 1), which significantly impacted the observed parameters of maize. It can be assumed that especially the extraordinary drought (Kožnarová and Klabzuba 2002) during the sowing in 2020 significantly affected the sprouting and emergence of maize. Moreover, the extraordinarily cold months of April and May in both years moderately delayed the development of the young plants; however, this negative factor was compensated in 2021 with higher rainfall during sowing. The different course of weather conditions was also in the following vegetation phases. The cold months of June and July in 2020 they probably caused a decrease in the values for selected maize traits compared to the 2021 year.

Impact of superabsorbent polymers on root length, volume, and surface area. The analysis of morphological characteristics of maize roots showed that seed coating using SAPs had a positive effect on the outcomes, although statistical significance was shown only in the case of root length. As shown in Figure 1, the root length with the SAPs treatment was longer by 33.40 cm (17.59%) than in the control. Further, root volume also increased due to SAP application; however, the difference between the treatment and control was insignificant (0.17 cm^3; 9.24%). A similar trend was found in comparing the surface areas of both treatments: the maize with SAPs treatment had a surface area larger by 8.47 cm^2 (12.92%) than the untreated ones.

Effect of superabsorbent polymers on leaf relative water content, photochemical reflectance index, and normalised difference vegetation index. The fact that SAPs have a positive effect on root system and soil characteristics is relatively well documented; however, little information exists about the influence of these materials on the above-ground plant parts. This experiment found a significant effect of SAPs on leaf relative water content and maize spectral indexes. Furthermore, it is clear from Figure 2 that in the case of RWC, as well as that of PRI and NDVI, the differences between the SAPs treatment and control were significant.

The impact of superabsorbent polymers on grain yield, plants per plot, spikes per plot, specific weight, weight of 1 000 grains, leaf weight and root weight. The seed treatment significantly affected the grain yield and spikes per plot. Furthermore, significance was shown for the two traits investigated

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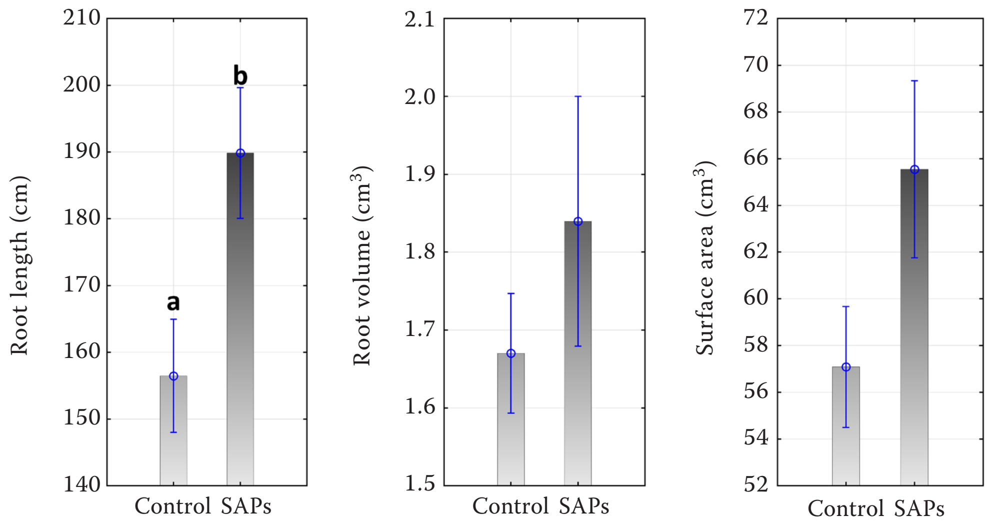

Figure 1. Root length, root volume, and surface area of maize depend on the treatment. Different small letters indicate the significance of the difference at probability level α = 0.05. Vertical bars denote ± standard errors. SAPs – superabsorbent polymers

during vegetation, leaf weight and root weight. In the comparison of the results of the individual treatments, it was shown that the SAPs treatment had significantly higher values of leaf weight and root weight (Figure 3), on average by 0.86 g (24.29%) and 0.46 g (21.00%), respectively. Although a significant difference was not found in plants per plot in the experimental treatments, it was found with the spikes per plot trait (Figure 4). The treatment with SAP application significantly increased this trait compared with the control. It can be assumed that primarily, this, in combination with the abovementioned, caused the maize treated with SAP to have a significantly higher grain yield than the control (Figure 4), on average by 1.13 t/ha (10.74%).

Effect of year × treatment interactions on maize traits. The overall effect of the year × treatment interaction was statistically significant for the weight of 1 000 grains and leaf and root weights. As shown in Table 3, in most traits, the highest values were found in the 2021 × SAPs interaction, with varying significance levels compared to the other combinations. By contrast, combining 2020 with unfavourable weather conditions and uncoated maize seeds resulted in the lowest values of most traits.

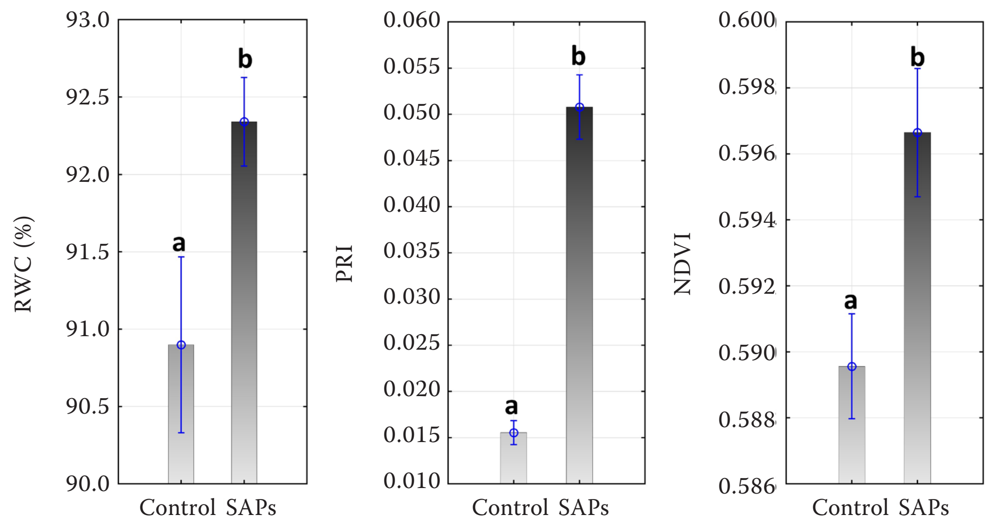

Figure 2. Relative water content (RWC), photochemical reflectance index (PRI) and normalised vegetation index (NDVI) of maize leaves depending on the treatment. Different small letters indicate the significance of the difference at probability level α = 0.05. Vertical bars denote ± standard errors. SAPs – superabsorbent polymers

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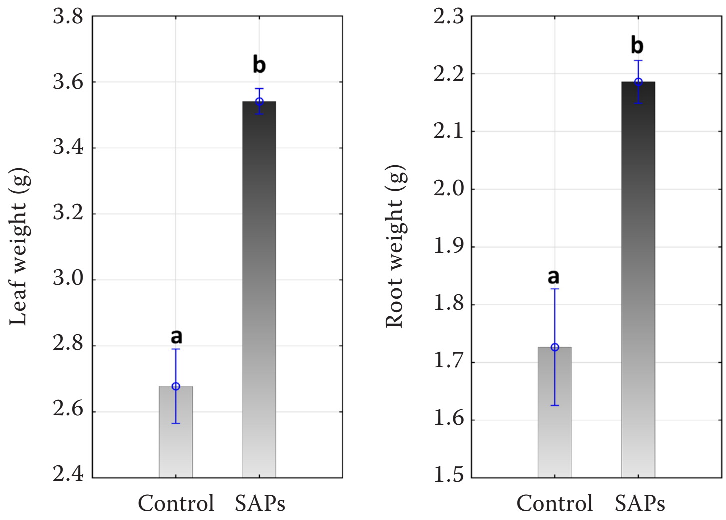

Figure 3. The leaf weight and root weight of maize depend on the treatment. Different small letters indicate the significance of the difference at probability level α = 0.05. Vertical bars denote ± standard errors. SAPs – superabsorbent polymers

Correlation analysis. A correlation analysis was performed for each treatment individually to emphasise the positive effect of superabsorbent polymers on mutual relationships between maize traits. This is particularly important given that the positive relationship between the individual elements of yield formation primarily determines the production of crops as can be seen from the figures, high or very high positive correlations were found in all cases in the maize with SAP-coated seeds (Figure 5). By contrast, slight correlations were found in many cases of the control, and a negative correlation was found between specific weight and spikes per plot. Thus, it can definitely be confirmed that SAP's application in maize production is of considerable importance.

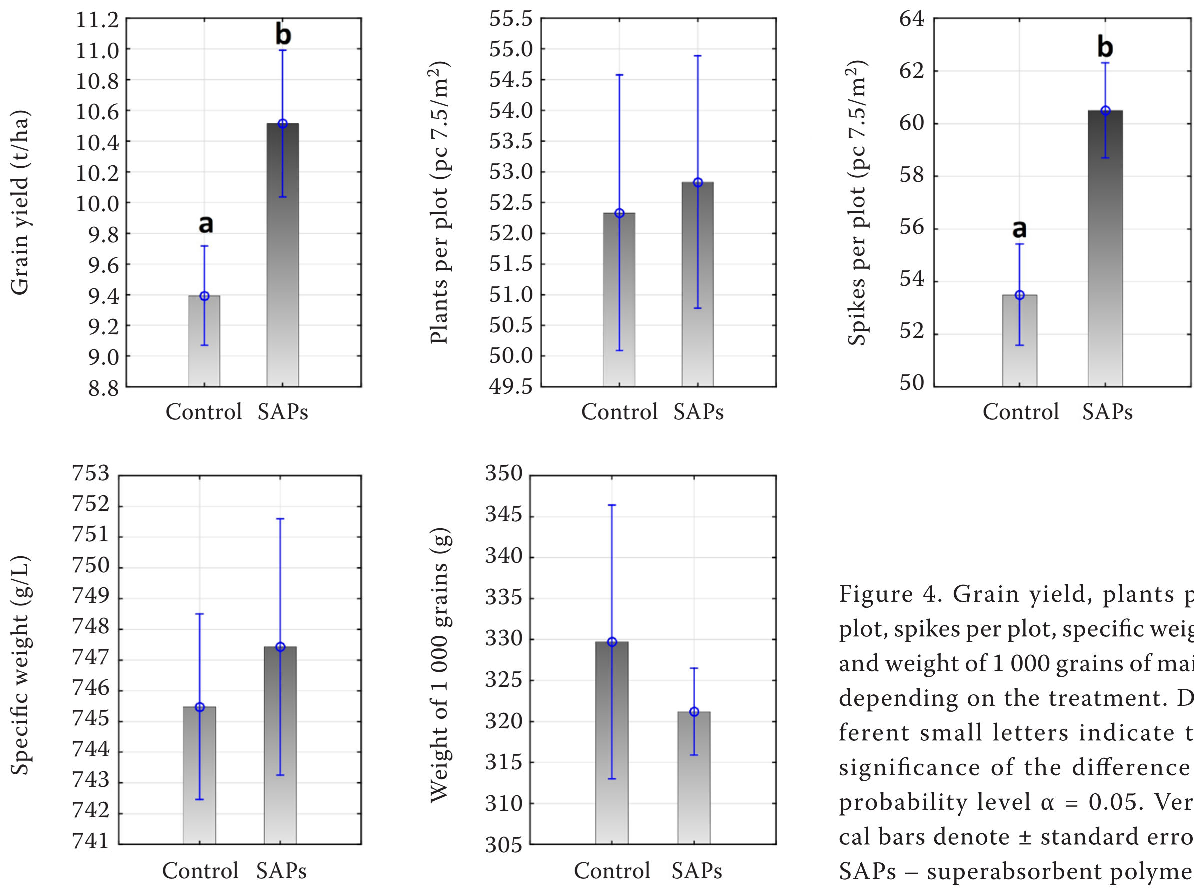

Figure 4. Grain yield, plants per plot, spikes per plot, specific weight and weight of 1 000 grains of maize depending on the treatment. Different small letters indicate the significance of the difference at probability level α = 0.05. Vertical bars denote ± standard errors. SAPs – superabsorbent polymers

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Table 3. Interactions between the year and the treatment

Year × treatment interaction	Grain yield (t/ha)	Plants per plot	Spikes per plot	Weight of 1 000 grains (g)	Specific weight (g/L)	Leaf weight	Root weight
		(pc 7.5/m²)				(g)	
2020 × C	8.92[a]	48.00[a]	51.33[a]	295.34[a]	742.41[ab]	2.20[a]	1.30[a]
2020 × S	9.58[a]	49.67[a]	58.00[ab]	310.72[ab]	738.63[a]	3.47[c]	2.08[b]
2021 × C	9.87[ab]	56.67[a]	55.67[ab]	364.10[c]	748.55[ab]	3.15[b]	2.16[bc]
2021 × S	11.45[b]	56.00[a]	63.00[b]	331.70[bc]	756.24[b]	3.61[c]	2.29[c]

Different small letters indicate the significance of the difference at probability level α = 0.05. C – indicate control treatment (without superabsorbent polymers); S – indicate superabsorbent polymers treatment

DISCUSSION

Maize is one of the most produced cereals globally. It is especially used in human and animal nutrition and is a crop suitable for biofuel production. As a direct consequence of global climate change, higher abiotic and biotic stress, which has threatened world maize production, has been observed in various regions (Chávez-Arias et al. 2021). Due to climatic changes, weather events will be increasingly frequent in the future, which will make implementing adaptive strategies necessary (Sheoran et al. 2022). The objective of this experiment was to determine whether one such adaptive strategy, the application of superabsorbent polymers using seed coating, will positively mitigate the effects of drought in maize cultivation. The weather conditions of the experimental years were different, which had an impact on the results. This is consistent with the findings in a study in which a large dependence between crop productivity and weather conditions was confirmed (Omoyo et al. 2015). Drought, in particular, is considered key environmental stress; it results from temperature dynamics, light intensity, and low rainfall (Seleiman et al. 2021). The growth phase, in combination with the severity and duration of the drought, are factors that influence the reaction of plants to the drought (Gray and Brady 2016). It is also well known that the germination of seeds and healthy development of juvenile plants are key factors for the formation of the crop yield (Finch-Savage and Bassel 2016), and water stress during these phases is the largest cause of yield loss (Zvinavashe et al. 2021). This study found a significant influence of SAPs on the weight of leaves and roots of

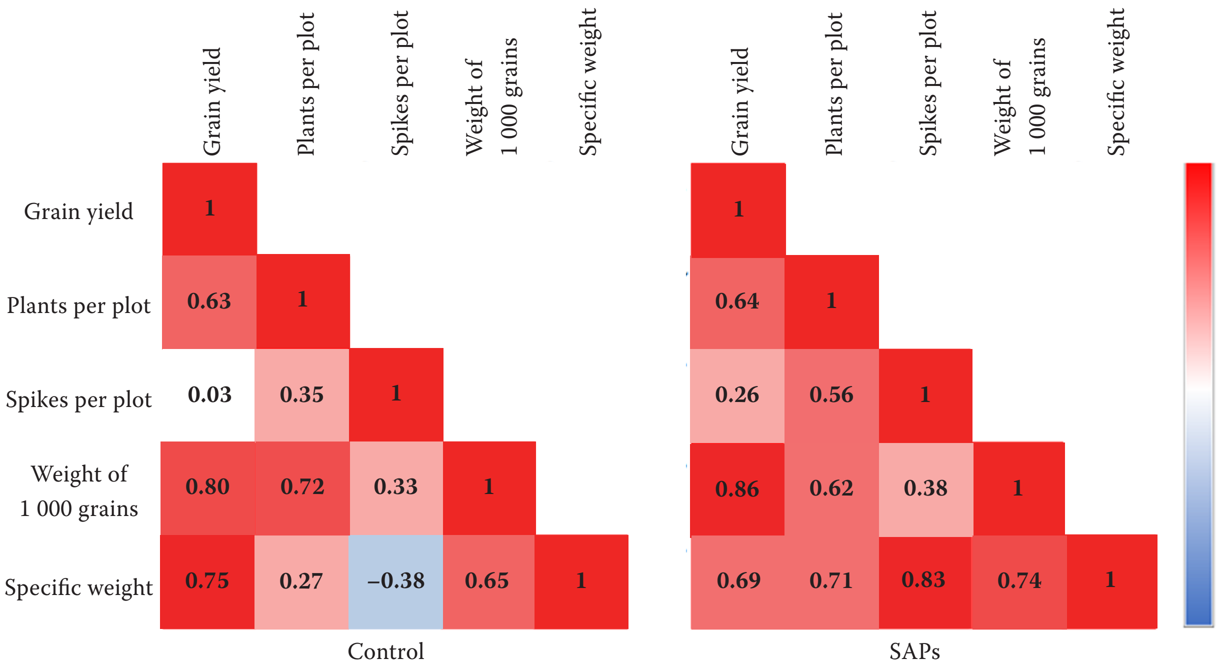

Figure 5. Correlation analysis between maize yield components depending on the treatment. SAPs – superabsorbent polymers

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young plants, with significantly higher values of these traits in the SAP treatment condition. This is consistent with the findings of Pačuta et al. (2021) that plants treated with SAPs could cope with drought stress better than those growing in the control condition. However, drought conditions during growth phases reduce the plant and leaf size due to decreased transpiration and photosynthesis (Devi et al. 2022). Root length and diameter distribution are important characteristics to consider when describing and comparing root systems. Root length and diameter distribution can be obtained by two methods: microscopic measurements, which are labour intensive, or computer analysis, which is rapid but sensitive to the scanning protocol (Bouma et al. 2000). Our findings obtained using WinRHIZO software confirmed significantly higher values of root length with SAP treatment, and a similarly positive trend was found in root volume and surface area, although without statistical significance. Furthermore, in the interaction with the year, it was confirmed that SAPs have a positive effect, in some cases significant, on the weight of maize leaves and roots in the early stages of growth. This could have been caused by higher water availability to seeds due to treating the seeds with SAPs (Gubišová et al. 2021). In the later growth phases, drought can decrease the green leaf duration as a consequence of accelerated ageing Dwyer et al. (1992), which can directly influence the yield components through induced infertility, kernel abortion, or shrivelled grain, which will be subsequently reflected in the reduction of the harvest index (Araus et al. 2012). This is supported by the results of this experiment, where lower values of spikes per plot and weight of 1 000 grains were found in the interaction of 2020, a year with unfavourable weather conditions, and the control compared with the SAP treatment. Particularly, this finding led to the hypothesis that although SAPs primarily influence soil characteristics and plant root systems, other physiological processes, which affect yield component formation as well as the final maize yield, can be a part of this. Malik et al. (2023) also highlight the need to understand that the influence of SAP application must be considered in the relationship to soil variables as well as plant parameters. Therefore, in 2021, spectral index analysis using a non-destructive method and evaluation of leaf relative water content was performed in this experiment. The PRI measurement can be used to indicate water stress in early growth phases; however, its use cannot be independent of light conditions (Sarlikioti et al. 2010). The structure of leaves and pigments is changed with induced stress, which leads to changes in reflectance, thus altering PRI (Alonso et al. 2017). A few studies show that the photochemical reflectance index is influenced by the structure of the growth (Gamon 2015) or growth variables such as the phenological phase and leaf area index (LAI) (Cheng et al. 2013). This study found a significantly higher value of PRI with SAPs treatment than with the control treatment, which confirms the above statements. Furthermore, significantly higher values were found for NDVI on the SAP treatment. The value of the normalised difference vegetation index is directly proportional to the photosynthetic activity of the observed growth (Tucker et al. 2005). It positively correlates to the chlorophyll content of the leaves (Zhou et al. 2020). Values of NDVI can also be considerably influenced by the size of the leaf area of the crops and the nitrogen, chlorophyll, and water content in tissue (Din et al. 2017). This was supported by the evaluation results of leaf relative water content, as significantly higher RWC content was found in the SAPs' treatment condition leaves. Moreover, relative water content (RWC) is greatly used in the ecophysiological field to describe the water saturation level in plant leaves. RWC is a suitable measure of plant hydration and is generally accepted as a proxy for the physiological consequences of cell deficit of water (Farinas et al. 2019). As is well known, the production of field crops results from the positive relationships between yield components; thus, a correlation analysis was performed. Statistically, correlation is a simple measure which defines the strength of mutual dependence between the observed variables. A higher correlation between two traits can be caused by the influence of a third variable (Devasree et al. 2020). Therefore, to emphasise the effect of the seed treatment with SAPs on yield components, the correlation analysis was performed individually for each treatment. As shown in Figure 5, mutual relationships were considerably stronger in the SAPs treatment condition compared to the control. This probably affected the SAPs treatment condition, reaching a significantly higher maize grain yield. The relationships between yield components concerning the overall production have been well documented (Mahesh et al. 2022).

Finally, the influence of SAPs on maize growth was already visible in the first phenological phases, even significant in the case of root length. In addition, significantly higher values of spectral indices associated with photosynthetic activity and chlorophyll content (PRI, NDVI) and significantly higher RWC values were measured on SAPs treatment.

This indicates that seed coating with SAPs has a stimulating effect on maize already in the first and riskiest growth stages, eventually resulting in increased production.

The use of this form of plant protection against weather fluctuations is particularly suitable in areas with prolonged drought and high temperatures.

However, there is still plenty of room for further research, especially in relation to the impact of SAPs on the quality of production or plant metabolic processes.

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