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Effect of seed coating on the yield of soybean *Glycine max* (L.) Merr.

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Abstract: Enhanced seeds, e.g. dressed, encrusted or pelleted seeds, are often sown in agricultural practice. These treatments play a different role depending on the type and chemical composition of the preparation. The aim of the experiment was to compare the effectiveness of three coatings (B – chitosan, C – chitosan + alginate/jojoba oil/E and D – chitosan + alginate/PEG) applied to soybean seeds in comparison to control (A). The study was carried out in three cultivars: Annushka, Mavka and Smuglyanka. The coatings did not differentiate seed yield in 2018 due to favourable weather conditions. The use of coating D in the following years increased seed yield by 0.46 t/ha in 2019 and by 0.51 t/ha in 2020 compared to control. The obtained results allow concluding that coating D was the most effective in soybean cultivation. The field emergence capacity, plant density as well as the SPAD (soil plant analysis development) and LAI (leaf area index) indices were significantly increased compared to control as a result of this coating application. The g_s index (stomatal leaf conductance) was significantly reduced. The cv. Smuglyanka yields were significantly higher compared to cvs. Mavka and Annushka, by 0.32 t/ha and 0.85 t/ha, respectively. The difference in seed yield between 2018 and 2019 was 0.81 t/ha.

Keywords: abiotic stress; sowing seeds; active ingredient; seed germination; plant condition; yield components

Soybean is one of the most important crops in the world. This is due to the versatile use of its seeds. In the European Union, the increasing interest in soybean cultivation results from the high demand for vegetable protein in the feed industry (Watson et al. 2017). Soybean is a thermophilic plant and therefore requires sowing seeds in warmed soil to avoid low temperature stress (Madias et al. 2021). The best quality seeds should be sown in order to obtain fast and proper soybean emergence. For this purpose, seeds are cleaned after harvest, sorted, dried and enhanced with various substances (Korbecka-Glinka et al. 2021). Coating is one of the advanced treatments, which consists in applying a tightly adhering coatings of different chemical composition to seeds. The most commonly reported active ingredients in coatings include fungicides, insecticides, nematicides, predator deterrents and herbicides (Pedrini et al. 2017). Coatings may also contain nutrients or microorganisms (Afzal et al. 2020). Avelar et al. (2015) showed that a liquid polymer most effectively coated soybean seeds. However, the best results were obtained with a polymer powder in combination with a fungicide. As a result, these authors achieved a fast and even soybean emergence. Polymers applied alone were less effective. Zeng et al. (2012) showed that chitosan coating is effective in controlling pests and increases soybean yield. Pedrini et al. (2020) argued that the composition of seed coating should be adapted to local conditions, it should be ecological

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and applied in justified cases. In this aspect, Poliserpi et al. (2021) pointed out that some components of coated seeds could pose a risk to birds. Gesch et al. (2012) and Bandera et al. (2021) reported that in the case of early sowing, properly prepared coatings could increase soybean cold tolerance. Ma (2019) argued that coated seeds were an effective means of reducing various biotic and abiotic stresses in precision agriculture. As a result, the plants grew better, were healthier and produced higher yields. Zeng and Zhang (2010) applied a coating to soybean seeds and achieved a yield increase by 17.95% at a lower costs compared to a commercial preparation.

The aim of the study was to determine the reaction of soybean to the application of protective coatings to seeds. The research hypothesis assumed that the coatings would contribute to the uniform plant density, which in turn would increase seed yield.

MATERIAL AND METHODS

The field experiment was conducted in the years 2018–2020. It was located on a private farm in Makowisko (50°3'N, 22°47'E), Podkarpackie province, Poland. The first factor tested was the different coating variants applied to soybean seeds compared to control (seeds without coating).

The following abbreviations are used in the remainder of the article: A – control (seeds without coating); B – seeds coated once with chitosan; C – seeds coated twice: chitosan + alginate/jojoba oil/E and D – seeds coated twice: chitosan + alginate/PEG.

As a result of laboratory work (Łukasiewicz Research Network – Institute of Biopolymers and Chemical Fibers, Poland), three coatings with different chemical compositions were prepared. In principle, they were to play a protective role for soybean seeds, mainly against low temperature after sowing. The first prepared variant (B) was a monolayer coating, i.e. chitosan with an average molecular weight: M_v = 235 kDa, and deacetylation degree: SD = 87%, in the form of a lactate salt with pH = 6.2. The second and third variants were two-layer coatings, in which chitosan was the first layer and sodium alginate was the second layer. Generation of the chitosan/alginate complex is possible due to the formation of $\sim NH_3^+ \ldots\text{-}O(O)C\sim$ ionic bonds between the functional groups of positively charged chitosan (polycation) and negatively charged alginate (polyanion). The thus obtained coating does not dissolve quickly after contact with water. Functional substances with melting points guaranteeing different behavior at 4 °C and 18 °C were introduced into the coatings. In the second variant (C), jojoba oil was introduced in the form of an olive oil-based emulsion with the addition of a detergent, and in the third variant (D), the coating consisted of a mixture of polyethylene glycol PEG 400 and PEG 600.

The individual layers of coatings were prepared in the form of solutions or emulsions and sprayed on the seeds using a laboratory device. The seeds moved in a stream of warm air introduced from below. The air temperature did not exceed 40 °C, so as not to reduce seed germination energy, and the rate of ingredient application was adjusted so not to inflict any mechanical damage or seed swelling due to moisture.

The second experimental factor was the soybean cultivar: Annushka, Mavka and Smuglyanka were used in the study. The breeder of the cultivars was the Scientific Research Center of Soya Development "AgeSoya" Sp. z o.o., Poland. The experiment was conducted in four replicates in a split-plot design.

Weather conditions were given according to the readings of the Experimental Station for Variety Testing in Skołoszów. The experiment was established on sandy loam soil, Haplic Luvisol (IUSS Working Group WRB 2015). The soil was slightly acidic from 5.8 to 6.1 mol/L KCl. The content of available phosphorus (P from 98.1 to 145.6 mg/kg DM (dry matter) of soil), potassium (K from 186.8 to 231.2 mg/kg DM of soil) and magnesium (Mg from 25 to 54 mg/kg DM of soil) was very high or high. Soil sample analyses (Fotyma et al. 2015) were carried out at the District Chemical-Agricultural Station in Rzeszów. The seeds were sown in the second decade of April. In individual years, it was on 12/04/2018, 16/04/2019 and 15/04/2020. In 2018, soil temperature in the second decade of April was 10.3 °C. In 2019 and 2020, soil temperature at the same time was significantly lower, 6.1 °C and 7.6 °C, respectively (Table 1).

Sixty germinating seeds were sown per 1 m^2. Row spacing was 45 cm and sowing depth was 4 cm. Before

Table 1. Soil temperature (°C) in April at a depth of 5 cm

Year	Monthly decades		
	I	II	III
2018	5.7	10.3	11.5
2019	6.0	6.1	10.3
2020	5.5	7.6	10.1

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sowing, the seeds were inoculated with HiStick® Soy (BASF), containing *Bradyrhizobium japonicum*. The plot area was 15 m^2. Winter wheat was the forecrop. Soybean has not been previously grown in the experimental field. NPK fertilisation (kg/ha) was: 30 N, 17.44 P and 49.8 K. Afalon Dyspersacyjny 450 S.C. (linuron) at a dose of 1.5 L/ha was used for weed control. Plant development stages were given according to the BBCH scale – Biologische Bundesanstalt, Bundessortenamtund Chemische Industrie (Meier 2001).

Plant density after emergence and before harvest was calculated per 1 m^2. The measurement of stomatal conductance of leaves (g_s) was performed with a Meter Porometr SC-1 apparatus (Pullman, USA). Plant nutritional status (SPAD – soil plant analysis development) was measured with a SPAD 502P chlorophyll meter (Konica Minolta, Inc. Tokyo, Japan). The leaf area index (LAI) measurement was performed using a LP-80 AccuPAR Meter (Pullman, USA). The SPAD and g_s measurements were performed at the BBCH 13 phase, while the LAI at the BBCH 65 phase.

At the stage of technological maturity, 20 plants were collected from each plot to measure the number of pods per plant, number of seeds per pod and TSW (thousand seed weight). Soybean was harvested at full maturity. Seed yield from the plots was calculated per 1 ha taking into account 15% moisture.

The obtained results were subjected to statistical analysis. An analysis of variance was made. The significance of differences between the characteristic values was found based on the Tukey's half-confidence intervals, with the significance level $\alpha = 0.05$. Calculations were performed using the Statistica 10 PL software (Stat Soft, Inc., Tulsa, USA).

RESULTS AND DISCUSSION

Air temperature in April and May 2018 was higher and rainfall was lower than the multi-annual average. April and May in 2019 and 2020 were cooler months compared to the multi-annual data. During these years, heavy rainfall occurred in May. June was warm in each of the analysed years, but in 2019, it was distinguished by low rainfall. In July 2020, rainfall was also low, but with moderate air temperatures. The following months were warm. Each year, precipitation was lower in September compared to the multi-annual sum (Figure 1). Kuchlan et al. (2019) reported that soybean plants were very sensitive to various weather conditions. This had an impact on yield variability in years and the intensification of disease or pest pressure.

The applied coatings exerted a different effect on plant density after emergence and before harvest. The use of coating D effectively increased the field emergence capacity compared to coating C and control. The cv. Annushka had the highest plant density per 1 m^2, cv. Mavka had a significantly lower density and cv. Smuglyanka the lowest. In 2018, the field emergence capacity was significantly higher compared to 2019 and 2020. Pre-harvest plant density was the highest in 2018, and the lowest in 2019 (Table 2). Gesch et al. (2012) obtained a higher plant density after sowing coated soybean seeds at a very early date compared to the control. However, this varied over the years. When

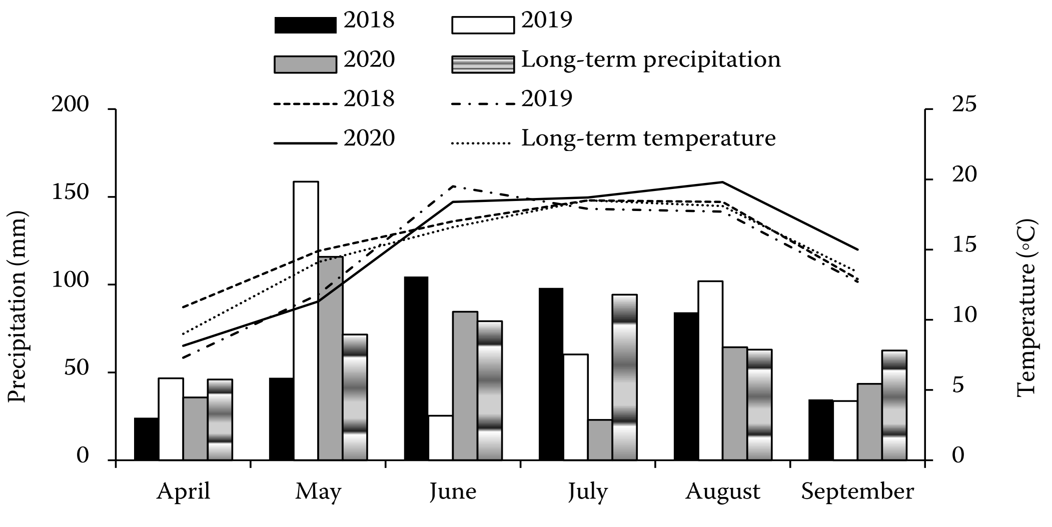

Figure 1. Weather conditions in the study years

https://doi.org/10.17221/246/2021-PSE

Table 2. Plant density after emergence and before harvest was calculated per 1 m^2

Specification	Planting density after emergence (pcs/m^2)	Field emergence capacity (%)	Planting density before harvest (pcs/m^2)
Seed coating (SC)			
A	38^{a}	63^{a}	35^{a}
B	43^{bc}	72^{bc}	40^{bc}
C	40^{ab}	68^{ab}	38^{ab}
D	46^{c}	77^{c}	44^{c}
Cultivar (C)			
Annushka	45^{c}	75^{c}	43^{c}
Mavka	42^{b}	70^{b}	39^{b}
Smuglyanka	39^{a}	65^{a}	36^{a}
Year (Y)			
2018	47^{b}	78^{b}	41^{b}
2019	39^{a}	65^{a}	37^{a}
2020	40^{a}	67^{a}	39^{ab}
ANOVA			
SC × C	ns	ns	ns
SC × Y	***	***	***
C × Y	**	**	***
SC × C × Y	ns	ns	ns

***$P < 0.001$; **$P < 0.01$, *$P < 0.05$; ns – non-significant, according to the Tukey's honestly significant difference (*HSD*) test. Mean values with different letters in columns are statistically different. A – control (seeds without coating); B – seeds coated once with chitosan; C – seeds coated twice: chitosan + alginate/jojoba oil/E; D – seeds coated twice: chitosan + alginate/PEG

pelleted seeds were sown at the normal or late date, deterioration in emergence was observed compared to control, especially during drought.

After applying coating D, the SPAD index measurements increased significantly compared to coating C and control. The g_s measurement was the highest in control. It follows that the coatings exerted stress on the plants in their early developmental stages. The LAI was the highest after the application of coating D, significantly lower LAI was obtained after the application of coating B and control. It was shown that the cv. Smuglyanka had higher g_s and LAI, but lower SPAD compared to the cv. Annushka. The lowest values of the examined indices were obtained in 2019 (Table 3). Wiatrak (2013) showed that the result of sowing coated seeds was an increase in the NDVI (normalized difference vegetation index) and LAI measurements. Hence, the coating with a polymer improved the growth and development parameters of soybean plants in the study of the above author.

Seed coating had no significant effect on the number of pods per plant and TSW. It was shown that the number of seeds in the pod was higher after applying coating D. The average seed yield after coating D application was the highest. A significantly lower number was obtained in control and after applying coating C. The tested cultivars differed significantly in yield components and seed yield. The cv. Smuglyanka yielded the highest, cv. Mavka significantly lower and cv. Annushka had the lowest yield. Soybean yielding was variable over the study years. The lowest yield was collected in 2019, and the highest in 2018. The difference amounted to 0.81 t/ha (Table 4). Soybean yield in the study of Wiatrak (2013) increased from 8.1% to 14.0% after sowing seeds with a polymer containing microelements compared to control. Gesch et al. (2012) also obtained a beneficial effect of sowing coated seeds on soybean yield, but only in one studied year and at a very early sowing date. They showed that the difference in seed yield between 2005 and 2006 was on average 1.0 t/ha.

The effectiveness of coated seeds varied in the study years (Figure 2). In 2018, favourable weather conditions occurred on the sowing date. As a result, the application of coated seeds did not bring the expected

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Table 3. Plant field measurements

Specification	SPAD	g_s	LAI
Seed coating (SC)			
A	38.5[a]	385.5[d]	3.04[a]
B	38.8[ab]	375.4[c]	3.35[b]
C	38.5[a]	365.3[b]	3.41[bc]
D	39.1[b]	355.6[a]	3.53[c]
Cultivar (C)			
Annushka	40.4[b]	360.5[a]	2.59[a]
Mavka	38.5[ab]	368.3[ab]	3.45[b]
Smuglyanka	37.3[a]	382.6[b]	3.95[c]
Year (Y)			
2018	39.8[b]	386.3[c]	3.52[c]
2019	37.3[a]	356.7[a]	3.09[a]
2020	39.1[b]	368.4[b]	3.37[b]
ANOVA			
SC × C	*	ns	ns
SC × Y	**	*	*
C × Y	***	*	**
SC × C × Y	ns	ns	ns

See Table 2. SPAD – soil plant analysis development; LAI – leaf area index; g_s – stomatal leaf conductance

results compared to control. In the following years, weather conditions were less favourable during the sowing period. The effect was that coating D significantly increased soybean yield compared to control and coating C. Rocha et al. (2019) concluded that the effects of using coated seeds depended on many factors, including: plant species or growing conditions. Nevertheless, seed coating is gaining popularity and requires further research.

In conclusion, weather conditions were variable over the study years and modified the effectiveness of the applied coatings on soybean seeds. The coatings did not differentiate seed yield in 2018 due to favourable weather conditions. The use of coating D in the following years increased seed yield by 0.46 t/ha in 2019 and by 0.51 t/ha in 2020 compared to control. On average, the application of coating D during the study period resulted in the higher field emergence capacity, plant density, number of seeds in a pod and the SPAD and LAI indices. The g_s measurement was the highest in control. The cv. Smuglyanka yielded the highest, cv. Mavka significantly lower and cv. Annushka gave the lowest yield. The lowest yield was harvested in 2019, and the highest in 2018. The difference amounted to 0.81 t/ha.

Table 4. Yield components and seed yield

Specification	The number of pods per plant	The number of seeds in the pod	Thousand seed weight (g)	Seed yield (t/ha)
Seed coating (SC)				
A	33.3[a]	2.15[a]	150.4[a]	3.77[a]
B	29.6[a]	2.16[a]	153.7[a]	3.93[ab]
C	31.1[a]	2.16[a]	151.3[a]	3.86[a]
D	27.5[a]	2.25[b]	152.9[a]	4.16[b]
Cultivar (C)				
Annushka	27.3[a]	2.14[a]	138.2[a]	3.48[a]
Mavka	31.2[b]	2.16[a]	152.4[b]	4.01[b]
Smuglyanka	32.6[b]	2.23[b]	165.6[c]	4.33[c]
Year (Y)				
2018	33.4[b]	2.11[a]	148.3[a]	4.29[c]
2019	28.3[a]	2.18[a]	152.3[b]	3.48[a]
2020	29.5[a]	2.24[b]	155.8[c]	4.02[b]
ANOVA				
SC × C	ns	*	ns	ns
SC × Y	**	***	**	**
C × Y	***	*	**	***
SC × C × Y	ns	*	ns	ns

See Table 2

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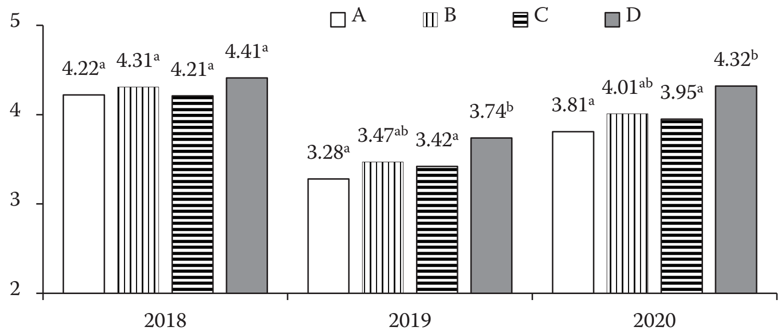

Figure 2. Effect of seed coating on soybean yield (t/ha). A – control (seeds without coating); B – seeds coated once with chitosan; C – seeds coated twice: chitosan + alginate/jojoba oil/E; D – seeds coated twice: chitosan + alginate/PEG

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