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Agro-biological traits of soybean cultivars, their yield quantity and quality under Central European conditions

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Abstract

Information on genotype testing on yield and grain quality could be also essential to soybean breeders and agronomists in achieving higher biological and economic efficiency of inputs in Central Europe. This study aimed to evaluate eleven selected soybean (*Glycine max* (L.) Merrill) cultivars in Hungary. From 2017 to 2019, a field experiment on chernozem soil was set up. The experimental site has a temperate continental climate with a 30-year average temperature of 10.3°C and rainfall of 560.1 mm. During the vegetation period (April–September), these data are 17.5°C and 346 mm, respectively. There were significant differences among the cultivars in the measured parameters. During the three years of the experiment, there were significant differences ($p < 0.001$) in the leaf area index (LAI) among the cultivars. The highest LAI (15.03 m^2 m^{-2}) was measured in 'Isidor' in 2018. There were significant differences among the cultivars in the normalised difference vegetation index (NDVI) value during the three experimental years. The correlation between seed yield and the maximum LAI and NDVI values was moderate ($r = 0.362$ and 0.353, respectively). There were significant differences in seed yield and protein yield among the cultivars because they responded differently to the given environmental conditions. Protein yield was determined by seed yield ($r = 0.978$) rather than the protein content ($r = 0.364$). On average of the three years, 'Isidor' produced the highest protein yield (1659.3 kg ha^{-1}). The differences in protein yield among the cultivars were high in 2017, 2018, and 2019: the range was 1215.5, 676.3, and 824.2 kg ha^{-1}, respectively. Among cultivars, large annual differences in oil yield were also found.

The investigation of the present study is intended as a contribution to the more efficient and successful soybean cultivation in the region.

Keywords: *Glycine max*, legumes, pulses, leaf area index, normalised difference vegetation index, protein content, oil content.

Introduction

Soybean (*Glycine max* (L.) Merill) is an important leguminous oilseed crop cultivated throughout the world with multiple uses as a source of bio-diesel, food, and feed (Zhao et al., 2017). In the USA, studies have found that soybean seeds contain about 41.3% protein and 19.9% oil (Shi et al., 2010), 5% minerals and 35% carbohydrates in average (Wilson, 2004). Also, they have a content of high crude protein and balanced amino acid, most of which are deficient in cereal crops (Nahashon, Kilonzo-Nthenge, 2011). Toleikienė et al. (2019) reported that using soybeans in crop rotation is beneficial for the next crop, among others.

Hungary lies on the northern border of the soybean production area of Europe, and this causes several problems for the farmers. One of them is the relatively short vegetation period for soybeans. The very low air humidity in the flowering stage or the erratic rainfall often reduce the yield (Nagy, Pepó, 2019).

According to extensive physiological research, the yield of soybean is positively related to the leaf area index (LAI) at the R5 growth stage (Wells et al., 1982; Johnson, 1987; Kumudini, 2002). The assimilation capacity of soybean during the reproductive stages (R1 to R7) and pod numbers have a stronger effect on the yield than in the vegetative period (emergence to V5) (Board, Tan, 1995). The results of Liu et al. (2005) show that the numbers of pod and seed per plant are still very important among the yield components: high-yielding cultivars tend to have a significantly higher number of pods and seeds than medium- and low-yielding cultivars. The results showed significant differences between the LAI and leaf area duration (LAD) values within each maturity group. In the reproductive stages, higher LAI and LAD values were in close relation with high yield of cultivars in each group. According to Morrison et al. (1999), modern soybean cultivars are more efficient at producing and allocating carbon resources to seeds compared with their predecessors. After testing cultivars with different genetic backgrounds, they reported that there was a significant decrease in LAI, while the yield of the modern soybean cultivars was significantly higher than that of the older cultivars.

Many experimental studies have found that when soybean is subjected to drought stress at the growth stage,

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morphological traits, disease resistance, protein content, oil content, and seed yield are inhibited (Mengistu et al., 2010; Dong et al., 2019; Basal, Szabó, 2020; Du et al., 2020). Impaired LAI (Tagliapietra et al., 2018) and low chlorophyll content can limit the photosynthetic capacity and associated reduction in seed production (Houborg et al., 2015). If the LAI is below the standard values, the percentage of absorbed to irradiated photosynthetically active radiation (PAR) is below the maximum potential (Gonzalez-Dugo et al., 2010).

As the seed oil content and protein content are other critical traits in soybean, testing the seed quality reaction of soybean cultivars is required (Matoša Kočar et al., 2018). A higher protein content under irrigated conditions could be associated with higher LAI and canopy closure, which, in turn, improves the PAR interception and nitrogen metabolism, respectively (Pinnamaneni et al., 2021). In addition, the significant varietal divergence has been reported for soybean seed protein content and oil content (Prysiazhniuk et al., 2019; Sobko et al., 2020). Information on the variability of yield and seed composition of cultivars could be vital to soybean breeders and agronomists for high seed nutritional composition and the development of cultivar-specific agro-technological package (Kristó et al., 2020; Miladinov et al., 2020).

This study was aimed to test the selected soybean cultivars under Central European conditions in order to characterise them according to their physiological traits, seed yield and quality, and select the cultivars best suited for the given conditions.

Materials and methods

The experiment was conducted from 2017 to 2019 at the Látókép experimental site (47°33′42″ N; 21°27′02″ E) of the University of Debrecen, Hungary.

The soil of the experimental area was *Calcic Endofluvic Chernozem* (Endosceletic) (WRB, 2014) with an average humus content (Hu% = 2.7–2.8) of the upper 25 cm layer; the thickness of the humus layer around 80 cm. The upper (0–75 cm) soil layers were almost neutral (pH_{KCl} = 6.46–6.6). The calcareous soil had average phosphorus supply (AL-soluble P_2O_5 133 mg kg^{-1}) and average-good potassium supply (AL-soluble K_2O 240 mg kg^{-1}). The bulk density of the cultivated (0–40 cm) soil layer was relatively high, from 1.40 to 1.46 g cm^{-3}, and 1.23–1.28 g cm^{-3} at the 40–200 cm layer. It had a favourable water regime: in the 0–200 cm layer, the field water storing capacity was 808 mm; in the upper 200 cm layer, the unavailable water content was 295 mm. In the 0–200 cm layer, the amount of available water in the saturated state was 513 mm, of which 342 mm was readily available. Depending on the weather conditions, the water table was at the depth of 3–5 m.

The research was carried out in a small plot (2.7 × 10.0 m = 27 m^2) experiment with four replicates; the total area was 1188 m^2. There were six rows in each plot, the row space was 0.45 m. Before sowing, 70 kg ha^{-1} N fertiliser was applied. Planting was on 26 April in 2017, 23 April in 2018, and 24 April in 2019, with 500,000 seeds per ha seed rate and at the depth of 5 cm. The average 1000 kernel weight of seeds was 190 g. In 2017, the forecrop was maize, and in 2018 and 2019, it was winter wheat. Eleven selected cultivars, their maturity group, and the originating country were (NÉBIH, 2017): 'ES Navigator' (000; France), 'Bokréta' (00; Hungary), 'Boglár' (00; Hungary), 'Coraline' (00/0; Germany), 'Bólyi 612' (0; Hungary), 'ES Mentor' (0; France), 'Ananda' (0/I; Germany), 'ES Pallador' (I; France), 'Isidor' (I; France), 'Pannónia kincse' (I; Hungary), and 'Bóbita' (I/II; Hungary). All cultivars were GMO-free. The principle of the selection was choosing cultivars that were grown in large area in Europe and Hungary, to enable their comparison under Hungarian ecological conditions. The seeds for sowing were purchased from the seed market.

In 2017, cultivars 'Coraline', 'ES Navigator', and 'ES Mentor' were harvested on 1 September, and 'Ananda', 'Boglár', 'Bokréta', 'Bóbita', 'Bólyi 612', 'ES Pallador', 'Isidor', and 'Pannónia Kincse' – on 15 September. In 2018, all cultivars were harvested on 19 September. In 2019, 'Boglár', 'Bokréta', 'Coraline', 'ES Navigator', and 'ES Mentor' were harvested on 23 September, and 'Ananda', 'Bóbita', 'Bólyi 612', 'ES Pallador', 'Isidor', and 'Pannónia Kincse' – on 2 October. The yield of each plot was measured by a plot combine harvester Sampo Rosenlew SR 2010 (Sampo Rosenlew, Finland) equipped with a Coleman weighing system. The seed moisture, protein content, and oil content were measured using equipment of Pfeuffer Granolyser NIR (Pfeuffer, Germany). It uses NIR (near-infrared) spectroscopy making 1500 individual scans per sample. The built-in spectrometer scans the sample seeds within the range of 950 to 1540 nm. The yield was standardised to 12% moisture content.

The leaf area index (LAI) and normalised difference vegetation index (NDVI) were measured five times a year. The growth stages are presented in Table 1. Also, the maximum plant height, the number of nodes, the lowest pod height, seed yield, seed moisture, oil content, and protein content were recorded.

For NDVI measurements, a handheld crop sensor Trimble GreenSeeker (Trimble Inc., USA) was used. The head of this sensor utilises active illumination with light-emitting diodes (LED) at two steady wavelengths, 656 and 774 nm. The optical reflectance sensor measures the amount of each type of light that is reflected from the plants and records the intensity of the reflected light (red and NIR); then the equipment calculates the index using that data. The sensor was used to do multiple readings on the plot. The sensor consistently 60 cm above the canopy for optimal reading was held.

LAI was measured using portable plant canopy analyser system Delta-T SunScan SS1 COM-R4 (Delta-T Devices Ltd., UK) with a radio link. It measures light transmission and analyses the incident and transmitted photosynthetically active radiation (PAR) within crop canopies. The 100 cm long probe has 64 PAR sensors with a spectral range of 400–700 nm. Readings are in units of PAR quantum flux (µmol m^{-2} s^{-1}) and units of LAI (m^2 m^{-2}). The number of nodes and the height of the lowest pod were observed on five plants per plot.

Protein yield was calculated by the formula:

Protein yield (kg ha^{-1}) = grain yield (kg ha^{-1}) × protein content (%) / 100.

The meteorological data of the experimental site proved that the average temperature of the experimental years and growing seasons was higher than the 30-year average (10.3°C and 17.5°C, respectively) in all three years (Table 2). From 2017 to 2019, the annual precipitation was higher than the 30-year average, but the distribution was uneven, and this had an adverse effect on the development of the plants. During the vegetation period (April–September), the amount and distribution of the rainfall were more favourable in 2019 compared with the 2018 and 2017; the rainfall was 355.4 mm in 2017, 323.4 mm in 2018, and 365.3 mm in 2019, while the 30-year average was 346.0 mm.

To analyse and evaluate the experimental data, statistical software package IBM SPSS, version 22.0 (IBM Corp., USA) was used. A GLM model was used to compare means with descriptive statistics and LSD post hoc test options included, and Pearson's correlation analysis (two-tailed) was used to test for linear relationships. For a complex evaluation of cultivar traits, radar charts were used (Figures 5–8). For drawing these diagrams, marks were given to the traits involved in the analysis: the best value got mark 1 and the worst mark 11.

Results and discussion

To test the agro-biological traits, yield quantity, and quality under the experimental conditions, eleven cultivars were used. Analysis of the LAI allows to state that there were significant differences among the cultivars ($p <$ 0.001) at all five measurement times during the three years (Figure 1). Since weather conditions were different in the course of three years, the development rate of the soybean was also different. The flowering stages (BBCH 60 600–65 605) were delayed by ten days in 2019 compared to

Table 1. Growth stages of soybean cultivars at the five measurements in 2017–2019

Cultivar	Measurement 1			Measurement 2			Measurement 3			Measurement 4			Measurement 5		
	2017	2018	2019	2017	2018	2019	2017	2018	2019	2017	2018	2019	2017	2018	2019
ES Navigator	V4	R1	R1	R2	R3	R3	R4	R5	R5	R6	R7	R6	R8	R8	R8
Boglár	V4	R1	R1	R2	R3	R3	R4	R4	R5	R6	R6	R6	R8	R8	R8
ES Mentor	V4	V4	R1	R2	R2	R3	R4	R4	R5	R6	R6	R6	R8	R8	R8
Bokréta	V4	V4	R1	R2	R2	R3	R4	R4	R5	R6	R6	R6	R8	R8	R8
Coraline	V4	V4	V4	R2	R2	R2	R4	R4	R4	R6	R6	R6	R8	R8	R8
Bólyi 612	V4	V4	V4	R2	R2	R2	R4	R4	R4	R6	R6	R6	R8	R8	R8
Ananda	V4	V4	V4	R2	R2	R2	R4	R4	R4	R6	R6	R5	R7	R7	R8
Isidor	V4	V4	V4	R1	R2	R2	R3	R4	R4	R5	R6	R5	R7	R7	R8
ES Pallador	V4	V4	V4	R2	R2	R2	R4	R4	R4	R6	R6	R5	R7	R7	R8
Pannónia kincse	V4	V4	V4	R2	R2	R2	R4	R4	R4	R6	R6	R5	R7	R7	R8
Bóbita	V4	V4	V4	R1	R2	R2	R3	R4	R4	R5	R6	R5	R7	R7	R8

V4 – fourth trifoliolate, BBCH 15 105; R1 – beginning flowering, BBCH 60 600; R2 – full flowering, BBCH 65 605; R3 – beginning pod, BBCH 71 701; R4 – full pod, BBCH 75 705; R5 – beginning seed, BBCH 76 706; R6 – full seed, BBCH 77 707; R7 – beginning maturity, BBCH 79 709; R8 – full maturity, BBCH 89 809 (Fehr et al., 1971; Meier, 2018)

Table 2. Climatic data of the experimental site in 2017–2019

	Temperature °C			Precipitation mm			Number of rainy days		
	2017	2018	2019	2017	2018	2019	2017	2018	2019
January	−6.6	1.7	−2.4	27.5	28.2	36.1			
February	1.4	−0.5	2.6	31.4	57.9	6.7			
March	8.4	2.6	8.1	24.5	68.5	9.4			
April	10.1	15.5	12.4	50.4	36.6	38.7	8	8	9
May	16.3	19.0	13.0	31.9	60.0	103.7	7	7	18
June	20.9	20.1	22.0	62.3	66.8	46.9	7	13	7
July	21.0	21.7	20.4	71.6	41.9	115.9	6	8	8
August	22.2	23.2	22.2	47.5	97.5	14.4	4	6	4
September	15.5	17.1	16.3	91.7	20.6	45.7	10	4	7
October	10.2	12.3	11.6	43.9	10.1	23.3			
November	5.1	6.2	7.2	53.7	52.0	84.3			
December	2.1	−0.4	0.6	93.6	50.9	53.6			
Growing season	17.7	19.4	17.7	355.4	323.4	365.3	42	46	53
Year	10.6	11.5	11.2	630.0	591.0	578.7			
30-year (1981–2010) average	10.3	10.3	10.3	560.1	560.1	560.1			

Number of rainy days – number of days with >0.1 mm rainfall

2017 and 2018. The studied cultivars belonged to different maturity groups, and their growth stages were not uniform at the measurement times, but the difference was only 1–3 days (Table 1). Although the difference among the cultivars was narrow in the length of the flowering time, the result universally implies a substantial genetic variability in the flowering stage among the soybean cultivars. In fact, soybean cultivars have different flowering times, and this variation is often more pronounced due to the variations in the genetic makeup, agrotechnical measures, and climatic factors (Singh, 2011).

A significant year and soybean cultivar interaction on LAI was also observed.

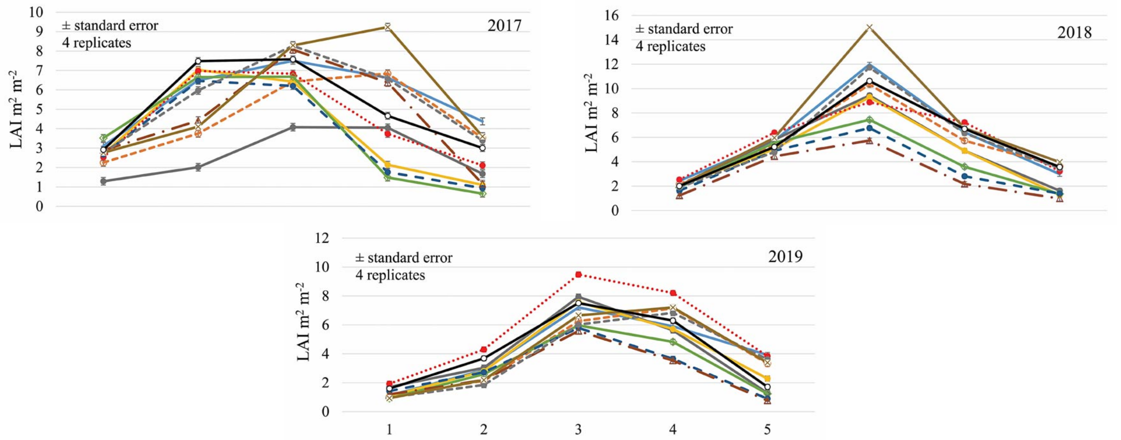
In 2017, 'Isidor' developed the largest (9.23 $m^2 m^{-2}$) and 'Boglár' the lowest (4.05 $m^2 m^{-2}$) LAI. Among the cultivars, the maximum LAI average was 7.15 $m^2 m^{-2}$. That year, the large LAI remained for a relatively long period in the growing season.

In 2018, the LAI developed slowly at the beginning of the season. Then, due to favourable weather conditions in June and July, it increased rapidly and reached the large area of 9.75 $m^2 m^{-2}$ on average of the cultivars. This means that LAI was under genetic control but was also influenced by the weather conditions of the growing season. With the changes in the genetic characteristics of soybean cultivars, the LAI ranged from 5.74 for 'ES Navigator' (the lowest) to 15.03 $m^2 m^{-2}$ for 'Isidor' (the highest). This caused a very high (261.8%) deviation between the studied cultivars. After the highest values, the LAI of each cultivar decreased rapidly. This deviation could be due to the sensitive influence of pedoclimatic conditions, as the season had a very high temperature and low relative air humidity that forced the sensitive cultivars for early senescence.

In 2019, under the conditions of a colder growing season, the early-stage LAI slowly increased. On average, the maximum LAI of the cultivars was 7.11 $m^2 m^{-2}$, i.e., similar to that of 2017. 'Bólyi 612' developed the largest (9.48 $m^2 m^{-2}$) and 'ES Navigator' the lowest (5.58 $m^2 m^{-2}$) LAI. After reaching its maximum, the LAI decreased relatively slowly in 2019, in consequence of favourable weather conditions. Due to high amount of rainfall in July, 'Isidor', 'ES Pallador', and 'Pannónia kincse' were lodged, and a lower LAI was observed.

As an eco-physiological trait that influences light capture, a lower LAI could limit the attainable grain yield. An average yield loss of 769 ± 319 kg ha^{-1} for every unit decrease in the LAI below the optimum has been estimated in soybean (Malone et al., 2002). Hence, improvement programmes should consider the LAI as a fundamental trait in the development of soybean cultivars. Although there has been a wider genetic and seasonal variation that caused a significant fluctuation of LAI, the early-stage LAI for most cultivars studied was above the optimum (6.0–6.5 $m^2 m^{-2}$) LAI required for potential soybean grain yield (Tagliapietra et al., 2018). This suggests that optimisation of LAI under such a scenario could have important practical implications in agronomic management practices such as seeding rate, pest, and disease management (Zhang et al., 2002).

The growth rate and the maximum LAI were also influenced by the maturity group, but weather conditions could modify the effect. In 2018 and 2019, 'ES Navigator', the super early (000) maturity group cultivar, developed the lowest LAI, but in 2017, it was 'Boglár' (00) that had the lowest LAI, which could be due to the low temperature in May. The variation in LAI due to the maturity group has been reported in various studies (Zanon et al., 2015; Santachiara et al., 2017; Tagliapietra et al., 2018; Basal, Szabó, 2020). This variation could be explained by the fact that the cultivars of long and moderate maturity groups have a lower optimum photoperiod and are not often stimulated to flower early in the season. Lengthening of the vegetative stage increases the LAI (Zanon et al., 2015). Therefore, it is more useful to study allometric relationships between dynamics in LAI and maturity group of soybean cultivars to improve LAI as a yield-attributed trait. This result universally indicated that the maturity group, weather conditions, and seasonal variation were found an important restrictive factor that could determine the successful role of LAI in the grain yield in soybean.



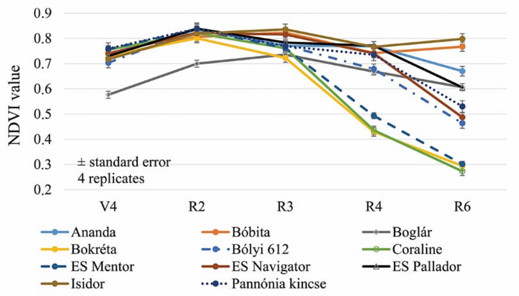
Note. Standard error of means; the differences among the cultivars were significant at $p < 0.001$; the growth stages of soybeans are presented under Table 1.

Figure 1. Leaf area index (LAI) values for soybean cultivars during the growing season in 2017–2019

The result of the ANOVA showed significant differences ($p < 0.001$) in NDVI value among the cultivars in all measurements during three experimental years; the standard deviations were very low. In 2017, the NDVI value decreased rapidly after the R3 (BBCH 71 701) growth stage in 'Bokréta', 'ES Mentor', and 'Coraline' (Figure 2). 'Isidor' had the highest value (0.84), and it remained high (0.80) even at the R6 (BBCH 77 707) growth stage. NDVI had a quadratic response to developmental plasticity, even though the degree of plasticity varied depending on the genetic landscape of the soybean cultivars. It could be attributed to the fact that leaves are fully green during the early growing season, and in the later stages, the leaf colour becomes a mixture of green, yellow, and brown, which later deteriorates the numerical values of the NDVI traits. In 2017, the lowest range in the season (difference between the lowest and highest values) had 'Bóbita' (0.09), and the largest range had 'Coraline' (0.55).

In 2018, the maximum values were higher compared to 2017: the highest value (0.87) was measured in 'ES Pallador' in the R2 (BBCH 65 605) growth stage. In 2018, the largest range was measured in 'ES Navigator' (0.60). In 2019, the NDVI values were lower than in 2017 or in 2018. The highest value (0.89) was in 'ES Pallador' at the R4 (BBCH 75 705) growth stage. In 2019, the largest range had 'ES Navigator' (0.67), which was confirmed by Zhang et al. (2014). Crusciol et al. (2017) also referred varietal differences in NDVI values in soybean. This deviation in NDVI profiles could be due to differences in varietal response to seasonal pedoclimatic variability during the growing season indicating that NDVI can be applicable to predict grain yield under marginal environmental conditions. It has been estimated in the case of other crops that every 0.1 unit of increment in the NDVI value enhances the grain yield by about 1.1–2.6 t ha^{-1} (Panek, Gozdowski, 2021). Hence, evaluating NDVI and associated eco-physiological traits could serve as a foundation for precision breeding and agronomic based grain yield enhancement in future soybean cultivation. There have been numerous studies that reported a strong association between NDVI and grain yield prediction, at which the vegetation reaches the maximum level of greenness (Ferencz et al., 2004; Xu, Katchova, 2019).

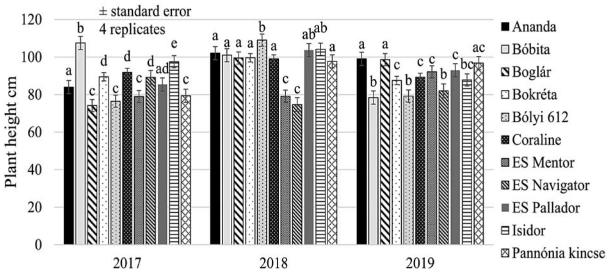
The combined ANOVA revealed that the plant height was significantly regulated by seasonal variability, to the extent that it varied with the genetic potential of soybean cultivars. A high variation was found in plant height between growing seasons or years, the average being 23.5%, but the reaction of the cultivars was different (Figure 3). The most stable cultivar was 'Coraline': its height changed only by 10.9% over the year of the experiment; the biggest change was in 'Bólyi 612' (42.5%). Kato et al. (2019) also reported similar results, but the cultivars were different. A plant height of 70–90 cm has been reported as optimal for soybean cultivars with both the tallest and shortest height possibly causing yield reduction through the influence on the shoot architecture (Chen, Nelson, 2006; Huang et al., 2011; Yang et al., 2021). This indicates that optimising plant height is important and should be addressed in the soybean breeding programme. This cultivar selection trait can have a double benefit, as it is a key component of the shoot architecture. Variation in plant height due to seasonal variability and cultivar differences has been frequently reported with a primary aim of improving soybean grain yield through enhancing shoot architecture (Yang et al., 2021).



Note. The growth stages of soybeans are presented under Table 1.

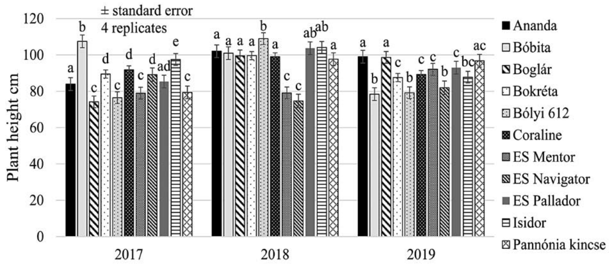
Figure 2. Normalised difference vegetation index (NDVI) values for soybean cultivars during the growing season of 2017

In 2019, the highest yield was harvested in each cultivar, except 'ES Mentor', which had the maximum yield in 2017 (Figure 4). The difference between the highest and lowest yield was 2426.78 kg ha^{-1} in 2017 ('Ananda' and 'Boglár'), 1759.82 kg ha^{-1} in 2018 ('ES Pallador' and 'ES Navigator'), and 1991.46 kg ha^{-1} in 2019 ('Isidor' and 'ES Navigator'). This variation may be attributed to a difference in root development, which may influence the ability of the soybean cultivars to exploit growth resources during the season. This result further suggests a substantial genetic variability for grain yield within the soybean cultivars, which will provide ample scope for selecting superior cultivars, particularly in the framework of current climate change scenarios. A wider genetic variation in soybean cultivars for grain yield has been reported previously (Sobko et al., 2020). These observations could reinforce the idea that screening large numbers of soybean cultivars for grain yield and for wider environmental adaptability could significantly contribute to breeding programmes as well as soybean demand in the country. Although the average maximum grain yield (2426.78 kg ha^{-1}) in 2017 was about 10.38% higher than the yield in Poland and 18.93% in Ukraine, it was 30.14% lower than the yield in Germany and lagged about 25.49%



Note. Standard error of means; the differences among the cultivars were significant at $p < 0.001$; the different letters mean significant difference at $p < 0.05$ among the cultivars in the given year.

Figure 3. Plant height of soybean cultivars in 2017–2019



Note. Standard error of means; the differences among the cultivars were significant at $p < 0.001$; the different letters mean significant difference at $p < 0.05$ among the cultivars in the given year.

Figure 4. Seed yield of soybean cultivars in 2017–2019

behind the USA (FAO; https://www.fao.org/faostat/en/#data/QCL). This result substantiates that there still is a need to improve potential soybean grain yield with a specific set of agronomic management practices.

The differences among the cultivars were significant ($p < 0.001$) in all three years. As revealed by the Pearson's correlation analysis, the grain yield showed a medium positive relationship with the maximum LAI and NDVI values (r = 0.362 and 0.353, respectively). The main inference drawn is that relating the LAI and NDVI values to the grain yield of soybean cultivars gives a better and universal relationship, which could be a potential yield improvement avenue in the framework of the current climate change scenarios.

The variation in the seed protein content of the cultivars was different in the course of the three years. The highest variation was observed in 2017, with a 53.8% difference between the lowest (27.09%) and highest (41.67%) protein content; in 2018 and 2019, it was 16.0% and 10.5%, respectively. It was affected by the climatic conditions. Other researchers (Wang et al., 2008; Rotundo, Westgate, 2009) reported that the protein content of the soybean seed ranged between 30% and 50%, and the cultivar, location, and climate had an effect on the variation of the seed quality of soybean.

The protein yield of the eleven soybean cultivars was calculated using protein yield and content data (Table 3). The results of the ANOVA showed that there were significant differences ($p < 0.001$) in the protein yield of the cultivars in all the three years. The variation was much higher in the yield than in the protein content among the cultivars. In 2017, the difference was extensive and amounted to 1215.5 kg ha^{-1}: the highest protein yield (1748.4 kg ha^{-1}) had 'Isidor', while the lowest (532.9 kg ha^{-1}) had 'Boglár'. A higher protein yield could be associated with higher efficiency of nitrogen use by the cultivars, as nitrogen is the building block of proteins. In 2018, the difference was lower (676.3 kg ha^{-1}): the highest protein yield (1528.2 kg ha^{-1}) gave 'ES Pallador', while the lowest (851.9 kg ha^{-1}) had 'ES Navigator'. In 2019, the difference was also low (824.2 kg ha^{-1}): the highest protein yield (2225.8 kg ha^{-1}) had 'Isidor', while the lowest (1401.6 kg ha^{-1}) had 'ES Navigator'.

Summarising the results of three experimental years, it can be stated that the best was 'Isidor': it had 26.2% higher protein yield than the average, and the lowest had 'Boglár' – 24.6% lower than the average. Overall, there was a 2201.2 kg ha^{-1} difference in protein yield between the cultivars across three years of the experiment. The correlation between the protein yield and the seed yield was very strong and significant (p = 0.01) in 2017, 2018, and 2019 (r = 0.995, 0.969, and 0.970, respectively). The correlation between the protein yield and the protein content varied and was not significant (r = 0.671, 0.242, and 0.178, respectively).

To analyse and show the complex assessment of soybean cultivars, radar charts were used. Five traits were involved: seed yield, the protein content, the oil content, the lowest pod height, and the number of nodes. In 2017, the highest seed yield (4394.1 kg ha^{-1}) was in 'Ananda': its protein content (39.58%), the lowest pod height (15.7 cm) and the number of nodes (13.5) were medium, but the oil content (22.06%) was the lowest among the cultivars. The seeds of 'Isidor' contained the highest protein content (41.66%), its lowest pod height was the best, but other parameters were medium. The highest oil content was in 'Boglár', but it was the last in seed yield and protein content. In 'Bokréta', the highest number of nodes was paired with a very low seed yield, the protein content, and the lowest pod height. 'Coraline' had both high protein and oil content, but low seed yield and the lowest pod height (Figure 5).

In 2018, very large LAI caused a high level of fungal disease infections in consequence of the closed, humid conditions in the stand. Despite the high maximum LAI values, the seed yield was lower in 2018 than in 2017 or 2019, except for 'Boglár' and 'Bóbita'. In 2018, the highest seed yield was harvested in 'ES Pallador' (4160.47 kg ha^{-1}), the protein content was medium (34.63%), the oil content (22.90%), and the number of nodes (14.9) were very low (Figure 6). In 2018, 'Coraline' had the highest protein content (38.35%), and it had the second highest oil content (24.48%), but a low seed yield (3209.47 kg ha^{-1}). 'ES Navigator' had the highest oil content (24.93%) but the

Table 3. Protein yield (kg ha^{-1}) of soybean cultivars in 2017–2019

Cultivar	2017	2018	2019	Average of three years	Experiment mean difference[1] %
Ananda	1731.8 a	1377.2 a	1938.9 a	1682.6 a	16.4
Bóbita	1302.9 b	1180.4 a	1907.3 a	1463.5 b	1.2
Boglár	532.9 c	1264.1 a	1475.2 b	1090.7 c	−24.6
Bokréta	906.4 d	1017.7 b	1944.3 a	1289.5 d	−10.8
Bólyi 612	1185.3 e	1233.2 a	1455.0 b	1291.2 d	−10.7
Coraline	1297.2 b	1224.9 a	1420.0 b	1314.0 d	−9.1
ES Mentor	1746.1 a	1078.2 b	1572.9 b	1465.7 b	1.4
ES Navigator	1124.5 e	851.9 c	1401.6 b	1126.0 c	−22.1
ES Pallador	1626.0 f	1528.2 d	1946.7 a	1700.3 a	17.6
Isidor	1748.4 a	1499.2 d	2225.8 c	1824.5 e	26.2
Pannónia kincse	1567.2 f	1471.5 d	1939.2 a	1659.3 f	14.7

Note. [1] – per cent differences from the three years main average of the experiment (1446.1 kg ha^{-1}); in the columns, the different letters mean significant difference at p = 0.05 among the cultivars in the given year.

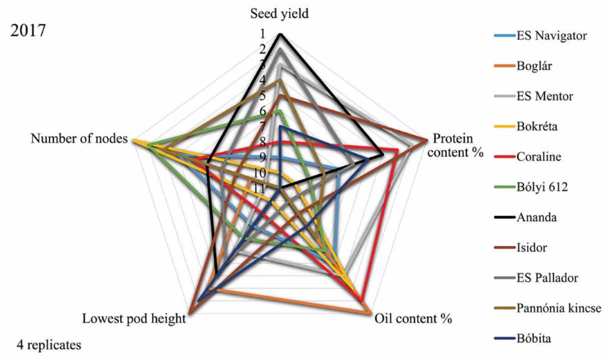


Figure 5. Evaluation of soybean cultivar traits in 2017

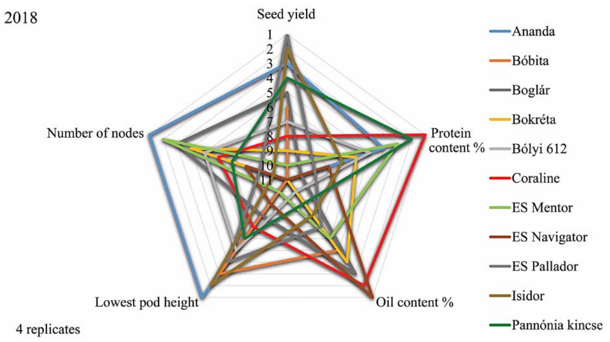


Figure 6. Evaluation of soybean cultivar traits in 2018

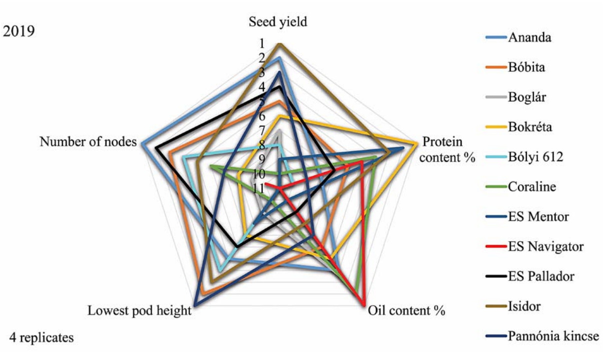


Figure 7. Evaluation of soybean cultivar traits in 2019

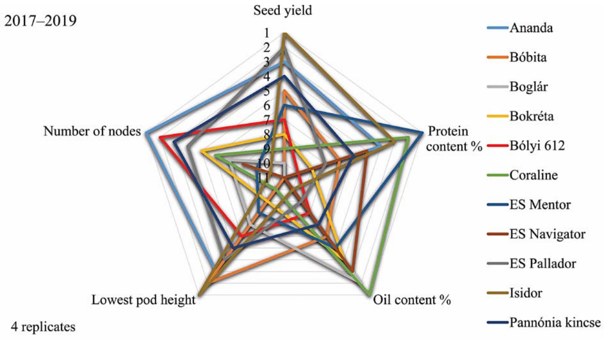


Figure 8. Evaluation of soybean cultivar traits, average of 2017–2019

lowest seed yield (2400.65 kg ha^{-1}) and medium protein content (35.00%). 'Ananda' had the highest number of nodes (16.7) and the best pod height (14.3 cm); it produced a good seed yield (3809.3 kg ha^{-1}) and had a good protein content (37.60%).

The highest seed yield was harvested in 2019: the average seed yield among the eleven cultivars was 4378.58 kg ha^{-1}, and the protein content was also high (39.51%). In 2019, 'Isidor' produced the highest seed yield (5328.79 kg ha^{-1}) with a good protein content (40.53%), best pod height, but relatively low oil content (19.42%). The highest protein content was in 'Bokréta' (41.42%), but its other parameters were medium. 'ES Navigator' had the highest oil content (20.95%), but the lowest seed yield; its protein content was medium (40.43%) among the cultivars. The number of nodes was the highest (16.23) in 'Ananda', and its seed yield also was high (5088.85 kg ha^{-1}), but the protein content was low (38.42%). 'Bólyi 612' had a medium seed yield (3894.26 kg ha^{-1}), but a very low content of protein (37.70%) and oil (19.15%) compared to other cultivars (Figure 7).

As the overall results of three years were analysed, it can be concluded that the three-year average of the seed yield was 3789.98 kg ha^{-1}. The difference between the lowest and highest values (range) was 1597.31 kg ha^{-1}, the average protein content was 37.42% with a range of 7.22%, and the average oil content was 22.45% with 2.52% range (Figure 8). The effect of cultivars was very significant ($p < 0.001$) on the seed yield, protein content, and oil content and significant ($p < 0.05$) on the number of nodes and the lowest pod height. These results support the findings of Toleikiene et al. (2021). 'Isidor' produced the highest seed yield, 4518.92 kg ha^{-1} on average with third best protein content (39.30%) and tenth oil content (21.57%); its lowest pod was at the height of 15.7 cm. 'ES Mentor' had the highest protein content (39.86%) with medium seed yield (3624.11 kg ha^{-1}) and medium oil content (22.47%), but the number of nodes and the lowest pod height were in the lower field among the cultivars.

On average, 'Coraline' had the highest oil content (23.81%) and second highest protein content (39.54%), but the seed yield was low (3332.86 kg ha^{-1}), and the lowest pod height was at 9.8 cm only. 'Ananda' had the third highest seed yield (4430.75 kg ha^{-1}), a good protein content (38.53%), but the lowest oil content (21.29%) and medium number of nodes (15.5). The three-year average shows that 'ES Navigator' produced the lowest seed yield (2921.61 kg ha^{-1}) with medium protein (37.51%) and good oil (23.62%) content.

In our experiment, the cultivars with high protein content had medium seed yield capacity; genetic improvement in seed yield resulted in a decrease in protein content, similarly to the results of Wilson et al. (2014) and de Felipe et al. (2016).

According to the research reports (Board, Tan; 1995; Egli, 2013; He et al., 2020), the number of nodes per plant is in close connection with the number of pods per plant or pods per hectare and seed yield. The results of current experiment showed that the cultivars reacted differently to the weather conditions of the years. A medium but significant correlation ($p = 0.01$) was found between the number of nodes and seed yield during the years of the experiment (r = 0.378, 0.475, and 0.487, respectively). Based on the three-year data, the results of ANOVA showed a significant interaction ($p < 0.001$) between the cultivars and the years by the seed yield, the oil content, the number of nodes, and the plant height. The interaction was not significant ($p = 0.993$) in the case of the protein content.

In the course of three years, soybean cultivars from maturity group I ('Isidor', 'ES Pallador', and 'Pannónia kincse') had a larger seed yield than earlier cultivars. According to Van Roekel et al. (2015) and Santachiara et al. (2017), later cultivars develop larger biomass and produce higher seed yield than the earlier ones. The response of the cultivars to the weather conditions differed. In most of the cultivars, the lowest seed yield was observed in 2018, a dry year, but 'Boglár', 'Bokréta', and 'Bólyi 612' produced the lowest seed yield in 2017. There were differences among the cultivars in drought tolerance: 'Coraline', 'Isidor', and 'Bólyi 612' had better drought tolerance, while 'Boglár' was more sensitive.

Conclusions

1. A positive correlation was found between the maximum leaf area index (LAI) and the seed yield of soybean, but its strength and significance varied between the years 2017–2019 (r = 0.675, 0.856, and

0.277, respectively). A positive correlation was found between the maximum LAI and the protein content (*r* = 0.680, 0.605, and 0.658, respectively), but the correlation between the maximum LAI and oil content (*r* = −0.713, −0.657, and −0.388, respectively) was negative.

2. The three-year average protein content of the cultivars ranged between 32.6% and 39.9%, and the oil content from 21.3% to 23.8%; the differences were significant. The pairwise relationship between the seed yield and other observed parameters was medium or weak. The protein yield was determined more by seed yield (*r* = 0.978) than protein content (*r* = 0.364) on average of the years.

3. On average of the three years, 'Isidor' produced the highest seed yield and the highest protein yield. During the three years of the experiment, it yielded 5473 kg ha^{-1} protein, i.e., 2201 kg ha^{-1} more than the protein yield of 'Boglár', which was 3272 kg ha^{-1}. On average, 'ES Mentor' had the highest protein content (39.86%) but a low seed yield.

4. 'Coraline' had the highest oil content (23.81%), and its protein content was high as well (39.54%).

5. In similar agroecological conditions, 'Isidor' is the recommended cultivar for protein production, 'Coraline' for oil production, and 'Isidor' for seed yield. The best cultivar depends on the purpose of cultivation.

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Gauruotosios sojos veislių agrobiologinės savybės, derliaus kiekis ir kokybė Vidurio Europos sąlygomis

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Santrauka

Siekiant efektyvesnių biologinių ir ekonominių sąnaudų, Vidurio Europos selekcininkams bei agronomams būtų svarbios žinios apie sojos genotipų kiekybinius ir kokybinius derliaus skirtumus. Tyrimo tikslas – įvertinti 11 Vengrijoje auginamų gauruotosios sojos (*Glycine max* (L.) Merrill) veislių. Lauko eksperimentai buvo atlikti 2017–2019 m., sojas auginant juodžemyje žemyninio klimato sąlygomis, esant vidutinei metinei 10,3 °C temperatūrai ir 560,1 mm metinių kritulių kiekiui (pagal 30 metų vidurkį); vegetacijos laikotarpiu (balandžio–rugsėjo mėn.) šie duomenys buvo atitinkamai 17,5 °C ir 346 mm. Per trejus eksperimento metus veislės reikšmingai skyrėsi lapų ploto indeksu (LPI, angl. *leaf area index*) ($p < 0{,}001$) – didžiausias LPI (15,03 m^2 m^{-2}) buvo 2018 m. veislės ‘Isidor’ sojų. Per trejus metus veislės reikšmingai skyrėsi pagal normalizuoto skirtumo augalijos indeksą (NDVI, angl. *normalised difference vegetation index*). Sėklų derlius koreliavo su didžiausiomis LPI ir NDVI vertėmis (atitinkamai $r = 0{,}362$ ir $r = 0{,}353$). Sėklų ir baltymų derlius tarp veislių labai skyrėsi – baltymų derlius labiau priklausė nuo sėklų derliaus ($r = 0{,}978$) nei nuo baltymų kiekio sėklose ($r = 0{,}364$). 2017, 2018 ir 2019 m. auginant sojas baltymų kiekio metiniai skirtumai tarp veislių buvo dideli: atitinkamai 1215,5, 676,3 ir 824,2 kg ha^{-1}; didžiausiu baltymų derliumi (1659,3 kg ha^{-1}) pasižymėjo veislė ‘Isidor’. Trejus metus augintų veislių sėklos pasižymėjo ir dideliais aliejaus kiekio skirtumais.
Šis tyrimas suteikė žinių apie gauruotosios sojos veislių našumą regione.

Reikšminiai žodžiai: *Glycine max*, pupiniai augalai, lapų ploto indeksas, normalizuoto skirtumo vegetacijos indeksas, baltymų kiekis, aliejaus kiekis.