Thesis of Doctoral (PhD) Dissertation

THE EFFECTS OF DROUGHT STRESS ON SOYBEAN (GLYCINE MAX (L.) MERRILL) GROWTH, PHYSIOLOGY AND QUALITY

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1. INTRODUCTION AND OBJECTIVES

Soybean (*Glicyne max* (L.) Merrill) is one of the most important food legumes. The current global climatic changes have put this crop under certain periods of drought stress during different stages of its vegetative growth, and soybean is reported to be sensitive to several abiotic stresses as compared to other legumes and crops (Silveira et al., 2003; Fan et al., 2013; Talebi et al., 2013). Moreover, soybean is currently sown as a rainfed crop in many regions, that's why drought is continuously affecting soybean production and quality (Liu et al., 2004; Manavalan et al., 2009), especially with the fact that drought intensively increased over the past decades, altering precipitation amounts and distribution (De Paola et al., 2014), and is predicted to further increase in frequencies and intensities (Zhao and Running, 2010; Turner et al., 2011), putting the production of soybean, and other sensitive crops, under serious challenges and raising the concern about the world's food security (Oh and Komatsu 2015; Vurukonda et al., 2016), especially with the fact that global population is continuously increasing and expected to reach 9.1 billions in 2050 (Sto, 2011). Understanding the influence of drought stress on crops becomes vital, as such understanding can be exploited in irrigation-scheduling practices which, in part, reduces drought-related fluctuations in food production (Wei et al., 2018). However, the response to drought stress is a very complex process that involves multiple mechanisms on different morphological, physiological and metabolic levels (Seki et al., 2003; Mattana et al., 2005; Yamaguchi-Shinozaki and Shinozaki, 2006; Reynolds and Tuberosa, 2008; Rahdari and Hoseini, 2012).

Nitrogen (N) is one of the most important macronutrients for plant vegetative growth and development, affecting several functions and components such as enzymes, proteins and cell walls to name a few (Fageria and Baligar, 2005). Because of its high protein concentration in the seeds, soybean plants have high N requirements (Bellaloui et al., 2015). N is particularly important under drought stress conditions (Caliskan et al., 2008; Salvagiotti et al., 2008) for improving shoot nitrogen and shoot biomass accumulation (Purcell and King, 1996).

Phosphorus (P), after nitrogen, is also one of the most important mineral nutrients for plant development and energy conservation and transfer (Abel et al., 2002; Elser et al., 2007). Although soil might have high concentrations of P, yet most of it can be unavailable for plants due to its poor solubility and fixation (Smith et al., 2011; Mahanta et al., 2014). Like N, soybean has high requirements of available P (10-15 mg kg^{-1} soil) (Aune and Lal, 1995), and low soil-P availability limits soybean yields (Qingping et al., 2003). However, excessive amounts of P resulted in growth inhibition in soybean (Cai et al., 2004), in addition to the fact that only 10%–45% of P- fertilizer added to the soil is readily usable (Adesemoye and Kloepper, 2009), so it's of high importance to determine the best P-rate application that can be optimally used by plants. P application was reported to enhance drought stress tolerance (Gutiérrez-Boem and Thomas, 1998; Singh and Sale, 2000).

Our research aimed at revealing the sole effect of on-field drought stress on 7 soybean genotypes, with evaluating the sole and combined influence of drought stress and nitrogen fertilizer application on 2 soybean genotypes; *'Pannonia Kincse'*, where only mineral nitrogen fertilizer was applied, and *'Boglár',* where nitrogen was applied from 2 different sources; fixed-N_2 through inoculation with *Bradyrhizobium japonicum* bacterium, and mineral nitrogen fertilizer. In addition, we aimed at revealing the effects of applying different N-fertilizer rates under natural drought on some physiological traits, namely; relative chlorophyll content (SPAD), leaf area index (LAI) and normalized difference vegetative index (NDVI) of the 2 soybean genotypes.

Separetely, we also monitored the sole and combined effects of P fertilization and drought stress on the 2 soybean genotypes, in addition to revealing the probable positive effects of exogenously spraying H_2O_2 at early bloom (R1) stage on the physiology and the seed yield of the 2 soybean genotypes.

Besides the on-field experiments, we illustrated the influence of PEG-induced drought stress on the germination parameters and the physiology of 2 soybean genotypes; *'ES Mentor'* and *'Pedro'* under controlled environment (climate chamber) conditions.

2. MATERIALS AND METHODS

2.1. FIELD EXPERIMENTS

2.1.1. Location of Field Experiments

All field experiments were carried out in the experimental station of the University of Debrecen (Látókép) (N. latitude 47^{o} 33', E. longitude 21^{o} 27') during 2017, 2018 and 2019 growing seasons. Soil type of the site is calcareous chernozem.

2.1.2. Weather Conditions of Field Experiments

The mean temperature during the period before sowing was characterized by colder levels in January during 2017 and 2019 compared to the average of the past 10 years before the experiment (2007 – 2016), followed by very close levels from February to April, whereas it followed an ooposite trend in 2018 (Fig. 1).

During the vegetative period of soybean (from May till September), the mean temperature during 2017 and 2019 was very close to average, whereas 2018 had higher levels during the early vegetative stages in May, and also during the late reproductive stages in July and August (Fig. 1).

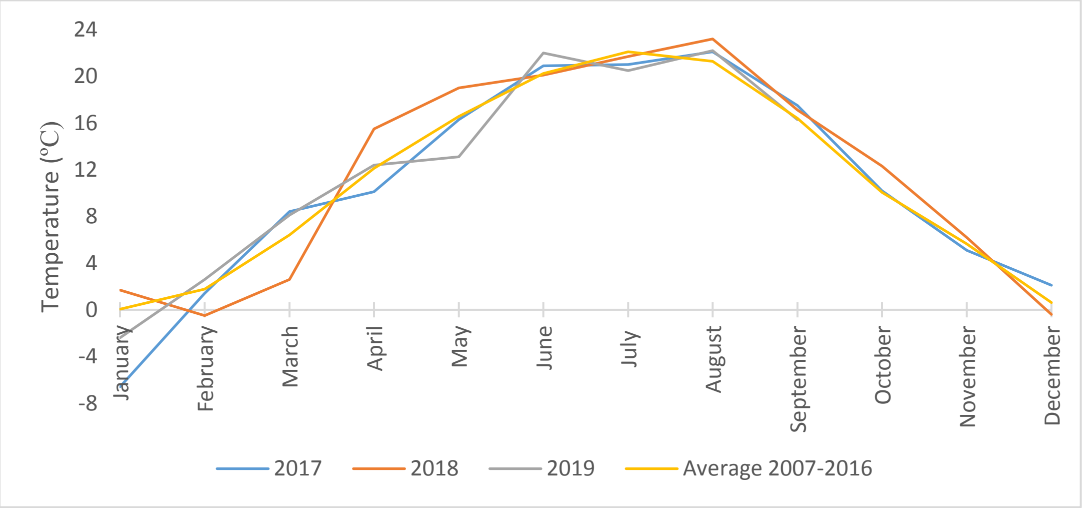

Fig. 1. Mean temperature in 2017, 2018 and 2019 compared to the average 2007-2016 in Látókép, Debrecen, Hungary. Source: meteorological station in the experimental site.

As for precipitation distribution and amounts, the early months of the year before sowing (from January till March) experienced relatively less precipitation amounts in 2017 compared to 2007-2016 average, whereas April had above-average precipitation. In 2018, the precipitation in both February and March was measurably higher than the average, whereas April received an equivalent amount. 2019, on the other hand, followed an opposite trend compared to 2018 as February and March were the months where significant low precipitation was recorded, whereas April was slightly above the average (Fig. 2).

During the vegetative period of soybean plants, precipitation in May was less than the average in 2017, close to the average in 2018 and higher than the average in 2019. The two years of 2017 and 2018 were close to the 10-year average precipitation amount in June, whereas 2019 was the year where precipitation was noticeably less than the average. In July, precipitation amount in 2017 was close to the average, whereas 2018 had lower, and 2019 had higher precipitation amount compared to the average. On the contrary in August, 2017 was also close to average, whereas 2018 was higher, and 2019 was lower than the average (Fig. 2).

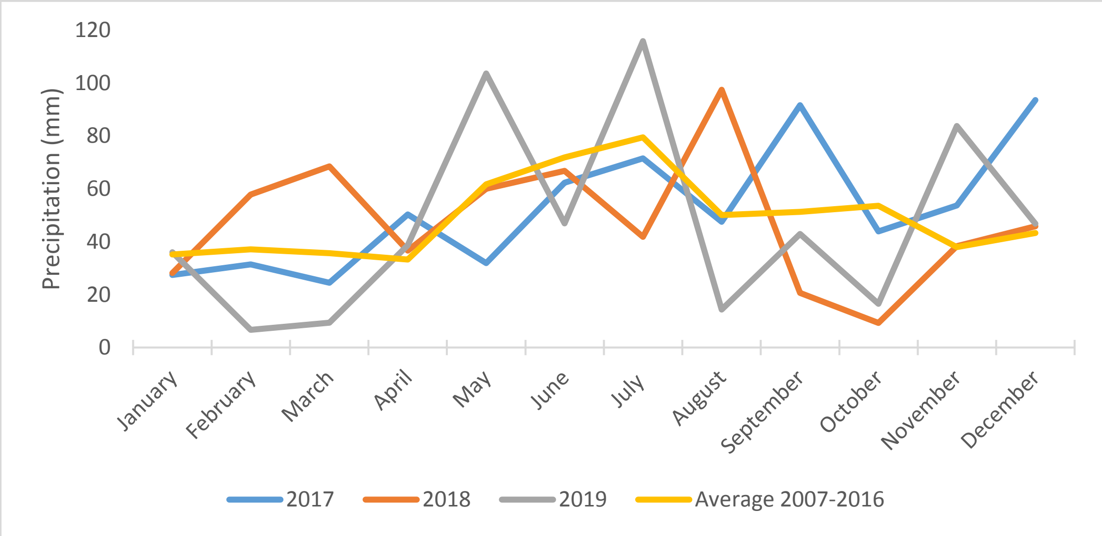

Fig. 2. Precipitation amounts in 2017, 2018 and 2019 compared to the average 2007-2016 in Látókép, Debrecen, Hungary. Source: meteorological station in the experimental site.

2.1.3. The Effect of Drought Stress on The Morpho-physiology, Yield Components and Seed Quality of 7 Soybean Genotypes

A field experiment was carried out on 7 soybean genotypes; Bokréta, Bólyi 612, ES Pallador, ES Mentor, Pannonia Kincse, Coraline and Ananda. Sowing dates were April 26th in 2017, April 23rd in 2018 and April 24th in 2019, and harvest dates were September 15th in 2017, September 16th in 2018 and September 23rd in 2019.

The experimental design was split-plot design, with 2 irrigation regimes; drought-stressed regime (DS) and fully-irrigated regime (FI) being the main plots and the 7 genotypes being the sub-plots with 4 replications. The final plot number was 56 (7 genotypes * 2 irrigation regimes * 4 replications). The plot area was 23.4 m^2, with 6 rows in each plot.

DS treatment received only precipitation as water irrigation amount, whereas FI treatment received, in addition to precipitation, a total of 80mm of irrigation water in 2017 and 100 mm in 2018 and 2019.

2.1.4. The Effects of Drought Stress and Nitrogen Fertilization on The Morpho-physiology, Yield Components and Seed Quality of 2 Soybean Genotypes

2 field experiments were carried out on 2 soybean genotypes; *'Pannonia Kincse'* and *'Boglár'* during 2017, 2018 and 2019 growing seasons.

In the first experiment, *'Pannonia Kincse'* genotype was sown in a split-plot design; 3 irrigation regimes; non-irrigated, half-irrigated and fully irrigated (NI, HI and FI, respectively) represented the main plots, and 3 N-fertilizer rates (applied with sowing as a single application in the form of NH_4NO_3); 0, 35 and 105 kg ha^{-1} N (0N, 35N and 105N, respectively) represented the sub-plots with 4 replications each. Phosphorus (P) and Potassium (K) fertilizers were applied adequately at the time of sowing. Final plot number for this experiment was 36 (3 irrigation regimes * 3 fertilization rates * 4 replications). The plot area was 27 m² with 12 rows in each plot.

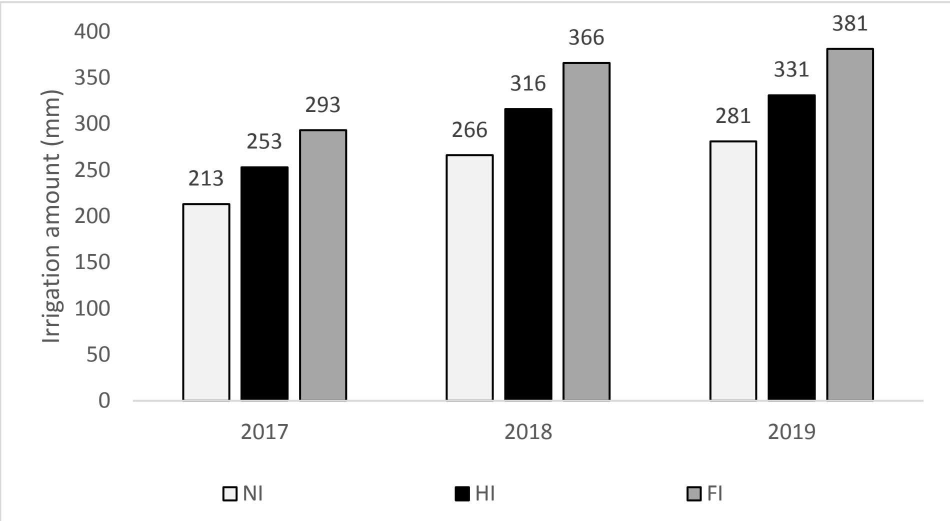

Fig. 3. Irrigation amounts during the vegetative period of soybean genotypes in 2017, 2018 and 2019 in Látókép, Debrecen. NI: non-irrigated, HI: half-irrigated, FI: fully-irrigated.

In the second experiment, *'Boglár'* genotype was sown in a split-split-plot design; the same 3 irrigation regimes represented the main plots, and 2 inoculation treatments; inoculated with *Bradyrhizobium japonicum* inoculant (+) and non-inoculated (-) represented the sub-plots, and the same 3 N-fertilizer rates represented the sub-sub-plots. Phosphorus (P) and Potassium (K) fertilizers were applied adequately at the time of sowing. Final plot number for this experiment was 72 (3 irrigation regimes * 2 inoculation treatments * 3 fertilization rates * 4 replications). The plot area was 27 m² with 12 rows in each plot.

In both experiments, NI treatment received only precipitation as water irrigation amount, whereas HI treatment received, in addition to precipitation, a total of 40 mm of irrigation water in 2017 and 50 mm in 2018 and 2019. FI treatment, on the other hand, received, in addition to precipitation, a total of 80 mm of irrigation water in 2017 and 100 mm in 2018 and 2019 (Fig. 3).

2.1.5. The Effects of Drought Stress and Phosphorus Fertilization on The Morpho-physiology, Yield Components and Seed Quality of 2 Soybean Genotypes

Two soybean genotypes; *'Pannonia Kincse'* and *'Boglár'* were sown on April 23rd and 24th, and were harvested on September 15th and 23rd in 2018 and 2019, respectively. The experimental design was split-split plot design, with genotypes being the main plots, irrigation regimes being the sub-plots and P fertilization rates being the sub-sub-plots. Three P-fertilizer rates; 0, 45 and 90 kg ha^{-1} P_2O_5 (0P, 45P and 90P, respectively) were applied under two irrigation regimes; drought stress regime (accounting only on the precipitation as the only source of water supply) and fully-irrigated regime (where, in addition to precipitation, a total of 100 mm of irrigation water was applied). Each treatment consisted of three replications. Final plot number was 36 (2 genotypes * 2 irrigation regimes * 3 fertilization rates * 3 replications). The plot area was 10 m^2 with 6 rows in each plot.

2.1.6. The Effects of Drought Stress and Exogenous Application of Hydrogen Piroxide (H_2O_2) on The Physiology and The Yield of 2 Soybean Genotypes

Two soybean genotypes; *'Pannonia Kincse'* and *'Boglár'* were sown on April 23rd and 24th and were harvested on September 15th and 23rd in 2018 and 2019, respectively. The experimental design was split-plot design, with genotypes representing the main plots and irrigation treatments being the sub-plots. Three irrigation treatments were applied, each of which in three replications; fully-irrigated (FI) treatment where, in addition to precipitation, a total of 100 mm of irrigation water was applied, drought-stressed treatment (counting only on precipitation) with the application of 1mM of Hydrogen Peroxide (H_2O_2) as a foliar spray at R1 stage (Fehr and Caviness, 1977) (HP) and drought-stressed treatment with distilled-water foliar spray at R1 stage (DW). The final number of plots was 18 (2 genotypes * 3 irrigation treatments * 3 replications), with a plot area of 10 m^2. Each plot had 6 rows.

All traits were measured at R2 stage (1-2 weeks after H_2O_2 application).

2.1.7. Measurements of Field Experiments

To calculate the relative water content, ten fully-matured leaves were collected and fresh weight (FW) of each leaf was measured immediately. Dry weight (DW) was determined via drying the sample leaves at 80 °C to constant weight, and turgid weight (TW) was obtained after floating the leaves in distilled water at 4 °C for 48 h. RWC was calculated as $RWC(\%) = (FW - DW)/(TW - DW) \times 100\%$ (Weatherley, 1950).

Stomatal conductance (g_s) was measured using AP4 porometer (Delta-t devices, UK).

Leaf Area Index (LAI) values were recorded using SS1 – SunScan canopy analysis system (Delta- T Devices, UK). Relative chlorophyll content (in the form of Soil Plant Analysis

Development; SPAD) was measured using SPAD-502Plus (Konica Minolta, Japan). Normalized Difference Vegetation Index (NDVI) values were recorded using Trimble Greenseeker Handheld (AS Communications Ltd, UK). 10 randomly-selected plants from the middle rows of each plot were used for the mentioned traits, and 3 measurements from the second most developed trifoliate (1 measurement for each leaflet) were taken and then averaged. All traits were measured at four different stages of soybean's life cycle (Fehr and Caviness, 1977); fourth node (V4), full bloom (R_2), full pod (R4) and full seed (R6).

Flower number per plant was determined at R2 stage. Pod number per plant was determined at R4 stage. Plant height was measured at R6 stage using a standard ruler. 10 randomly-selected plants from the middle rows of each plot were used for these traits.

Seed yield was calculated by harvesting the middle 4 meters of each plot and adjusting the yield to 13% moisture content. 100-seed weight was determined after oven-drying the seeds at 65 C until constant weight. Both protein and oil concentrations were determined using NIR analyser Granolyser (Pfeuffer, Germany).

2.2. CLIMATE CHAMBER EXPERIMENTS

2.2.1. The Effects of PEG-induced Drought Stress on The Germination Parameters of 2 Soybean Genotypes

The experiment was conducted on a two-stage basis at the Institute of Crop Sciences, University of Debrecen in 2018.

In a preliminary field experiment, 20 soybean genotypes were subjected to continuous drought stress conditions by withholding irrigation water throughout the vegetative period of soybean plants. After the harvest, a cluster analysis was conducted to group the genotypes based on their reactions to drought. Based on the results of the cluster analysis, two genotypes; ES Mentor (100-seed weight = 201 g) and *'Pedro'* (100-seed weight = 161 g) were chosen for this experiment.

In both stages, the 2 soybean genotypes were surface-sterilized using 6% (v/v) H_2O_2 for 20 minutes, rinsed extensively with deionized water and germinated geotropically between moisten filter papers at 22 °C. Each roll contained 30 seeds. PEG 6000 (VWR International bvba Geldenaaksebaan, Leuven, Belgium) was used in both stages to induce drought stress.

In the first stage, PEG concentrations of 0, 10, 15, 20, 25 and 30% were applied, whereas in the second stage, and based on the results of the first stage, 0, 2.5, 5, 7.5, 10, 12.5 and 15% concentrations were applied. Each treatment (concentration) had 3 replications in both stages.

Germinated seeds were counted every day, and the daily-associated root elongation was measured. Each stage was considered finished when the average hypocotyl of the control treatment reached 3 cm long.

Germination energy (GE) was expressed as the percentage of germinated seeds after five days from the beginning of each stage of the experiment.

From the germination counts the following germination parameters were determined (Saxena et al., 1996);

(1) Ultimate Germination (UG): The maximum number of seeds that germinated during the experiment.

(2) Mean Period of Ultimate Germination (MPUG) $= \frac{\sum_{i=1}^{d} Ni\ Di}{UG}$

(3) Percentage Inhibition or Stimulation $= \frac{UG\ in\ aqueous\ extracts\ (\%)}{UG\ in\ distilled\ water\ (\%)}$

where,

N is the daily increase in seedling number, and D is the number of days from seed placement.

2.2.2. The Effects of PEG-induced Drought Stress on The Physiology of 2 Soybean Genotypes

Seedlings of the two soybean genotypes were germinated following the above-mentioned method under no-stress conditions (0% PEG) for using them in this experiment. Seedlings with good vigor were then planted in 5-liter pots. Each pot contained 10 seedlings. Each pot received 50 ml of dicot nutrient solution. Nutrient solution of each pot was replaced with fresh alternative every 3 days. PEG 6000 (VWR International bvba Geldenaaksebaan, Leuven, Belgium) was used to induce drought stress. PEG concentrations were as follows; 0, 2.5, 5, 7.5 and 10% (0%PEG, 2.5%PEG, 5%PEG, 7.5%PEG and 10%PEG, respectively).

Relative chlorophyll content (SPAD values) was recorded using SPAD-502Plus (Konica Minolta, Japan). Stomatal conductance (g_s) was measured using AP4 porometer (Delta-t devices, UK). Both SPAD and (g_s) were calculated by averaging 10 values per leaf of the second most recently developed trifoliate.

Chl-fluorescence was determined on dark-adapted leaves (20 min of dark adaptation) by attaching light exclusion clips to the central region of each leaf. Chl-fluorescence parameters were measured using a portable chlorophyll fluorometer-PAM-2100 (WALZ, Germany) as described by Schreiber et al. (1986). The fluorescence parameters included the minimal fluorescence (F_0) when PS II centres are open (open state) and increases the maximum fluorescence (F_m) when PS II centres are closed (closed state), the variable fluorescence (F_v), the potential photosynthetic capacity (F_v/F_o) which reflects the efficiency of electron donation to PS II and the ratio $(F_m–F_0)/F_m$, also known as F_v/F_m (potential/maximum photochemical efficiency of PS II) which is calculated from fluorescence values F_0 and F_m. The F_v/F_m ratio is one of the most common parameters used in fluorescence that reflects the capacity to trap electron by the PS II reaction centre. The actual photochemical efficiency of PS II (Yield) was also recorded. All of the fluorescence parameters were recorded from the second last fully-developed trifoliate of one seedling in every pot (replication).

Chlorophylls $_a$ and $_b$ and total carotenoids concentrations were calculated using the method described by Wellburn (1994). The following equations were used for quantifying chl_a and $_b$ and total carotenoids contents (Wellburn, 1994):

Chl_a (µg ml^{-1}) = (11.65 A_{664}-2.69 A_{647})

Chl_b (µg ml^{-1}) = (20.81 A_{647}-4.53 A_{664}).

Chl_{x+c} (µg ml^{-1}) = (1000 A_{480} – 0.89 Chl_a – 52.02 Chl_b)/245

Each treatment had 3 replications in a split-plot design where the genotype represented the main plots and PEG concentrations represented the sub-plots. The total number of pots was 30 (2 genotypes x 5 PEG treatments x 3 replicates).

All measurements were made at 4 different stages of each genotype (Fehr and Caviness, 1977); second node (V2), fourth node (V4), full bloom (R2) and full pod (R4).

2.3. STATISTICAL ANALYSIS

For germination parameters experiment, the statistical analysis was conducted using “Repeated Measurement” method (IBM SPSS ver.26, USA software) software. For all other experiments, SPSS software was run to analyze and compare the means (ANOVA) and to indicate the effect size (by means of Partial Eta Squared), followed by Tukey post-hoc test to indicate the statistically-different means, and Pearson’s correlation to indicate correlation coefficient (IBM SPSS ver.26, USA software). All data presented and analyzed in all field experiments are means of the three years of experiment.

3. RESULTS AND DISCUSSION

3.1. FIELD EXPERIMENTS

3.1.1. The Effect of Drought Stress on The Morpho-physiology, Yield Components and Seed Quality of 7 Soybean Genotypes

3.1.1.1. The Effect of Drought Stress on The Normalized Difference Vegetation Index (NDVI) of 7 Soybean Genotypes

Although its effect was not significant, yet drought decreased NDVI in all genotypes at all studied stages.

The effect of the stage was highly significant; NDVI values were at their maximum at R2 stage, regardless of irrigation regime and genotype. On the other hand, some genotypes had the minimum NDVI at the earlier studied stage (V4) where the plants were still developing their vegetative growth, whereas others had its minimum value at the late season (R6) stage when plant were getting ready for converting into maturity stages.

Genotype's effect on NDVI values was also significant, with Ananda having the highest average NDVI (80.8) and Bokréta with the lowest (75.2).

3.1.1.2. The Effect of Drought Stress on The Leaf Area Index (LAI) of 7 Soybean Genotypes

In all genotypes, drought decreased the average LAI. In certain genotypes, LAI was lower in the drought-stressed treatments throughout the season (i.e. at all stages), whereas in other genotypes, LAI of drought-stressed treatment could maintain slightly higher value at the late R6 stage but without affecting the average seasonal decrease caused by drought.

Regardless of irrigation and genotype, LAI gradually increased through stages, starting with a minimum value at R4 stage and reaching its peak at R4 stage.

Highly significant effect of genotype factor on LAI trait was found out and estimated at 19.6%. The highest LAI throughout the experiment period was recorded in Bólyi 612 (5.8), and the lowest was in ES Mentor (3.9).

All the three factors; irrigation, stage and genotype had highly significant effect on LAI trait, which might suggest this trait to be the most reliable physiological trait to count on in evaluating soybean's performance in the study area.

3.1.1.3. The Effect of Drought Stress on The Plant height of 7 Soybean Genotypes

In all genotypes, drought decreased plant height; the average reduction of all genotypes was calculated as 6.2%. Moreover, the decrease was significant in Bokréta, Coraline, Bólyi 612 and ES Pallador, whereas it was not significant in the other genotypes.

There were also significant differences among genotypes under both irrigation regimes. Under fully-irrigated treatment, ES Pallador plants showed the highest value of this trait, whereas Bólyi 612 plants showed the lowest value. Under drought-stressed treatment, Ananda had the tallest plants, whereas ES Mentor was significantly shorter than all other genotypes.

3.1.1.4. The Effect of Drought Stress on The Flower number per plant of 7 Soybean Genotypes

Drought decreased the flower number per plant in all genotypes; the decrease was, on average, 13.9%, being significant in Bokréta, Coraline, Bólyi 612 and ES Pallador.

Regardless of irrigation regime, significant differences in this trait were recorded among genotypes, with Bólyi 612 having the highest flower number and Bokréta having the lowest flower number under both irrigation regimes compared to the other genotypes.

3.1.1.5. The Effect of Drought Stress on The Pod number per plant of 7 Soybean Genotypes

Both irrigation and genotype factors followed the same trend of the previous trait (flower number per plant), as Bólyi 612 and Bokréta, under both irrigation treatments, had the highest and the lowest pod number, respectively.

3.1.1.6. The Effect of Drought Stress on The 100-seed weight of 7 Soybean Genotypes

Except for ES Mentor and Ananda, the 100-seed weight decreased under drought stress conditions; the decrease was significant in both Bokréta and *'Pannonia Kincse'*. Interestingly, the 100-seed weight of Ananda did not change under both irrigation regimes, and that of ES Mentor was higher under drought stress conditions, which might draw a conclusion that these two genotypes could be adopted under drought stress conditions in the study area.

As for comparing among genotypes, Bokréta had the lowest value of this trait, whereas ES Mentor had the highest value under both irrigation regimes, supporting the initial conclusion of the suitability of ES Mentor for cultivation in the study area even under drought stress conditions in case the 100-seed weight (i.e. seed size) was the target.

3.1.1.7. The Effect of Drought Stress on The Seed Yield of 7 Soybean Genotypes

Drought stress resulted in less seed yield in all genotype; however, only in ES Mentor and Coraline were the reductions significant. Averaged over all genotypes, 5.9% less seed yield was recorded under drought stress conditions.

Under both irrigation regimes, Ananda, ES Pallador and *'Pannonia Kincse'* genotypes had significantly higher seed yield compared to the other genotypes, with ES Pallador resulting in the highest seed yield under drought (4372 kg ha^{-1}), whereas Ananda resulted in the best seed yield under fully-irrigated regime (4511 kg ha^{-1}). These results suggest that Ananda, ES Pallador and *'Pannonia Kincse'* genotypes might be more suitable for cultivation in the study area, especially under drought conditions (Fig. 4).

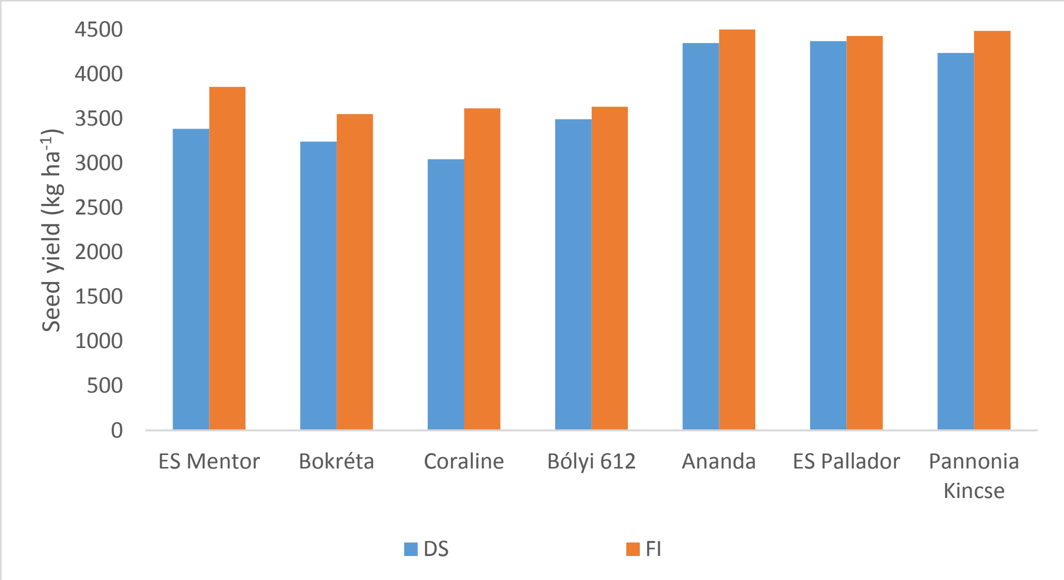

Fig. 4. Seed yield (kg ha^{-1}) of 7 soybean genotypes under drought-stressed (DS) and fully-irrigated (FI) treatments in Látókép, Debrecen averaged over 2017, 2018 and 2019.

3.1.1.8. The Effect of Drought Stress on The Protein Concentration of 7 Soybean Genotypes

Drought differently affected the protein concentration in the produced seeds; it resulted in increasing this concentration in ES Mentor, Bokréta and ES Pallador genotypes, whereas it decreased it in Coraline, Ananda and *'Pannonia Kincse'* and did not affect it in Bólyi 612 genotype. All differences were insignificant. This alteration resulted in very similar average protein concentration among genotypes under both irrigation regimes.

Significant differences among genotypes were recorded for this trait under both irrigation regimes, with ES Mentor resulting in the highest protein concentration and Bólyi 612 resulting in the lowest.

3.1.1.9. The Effect of Drought Stress on The Oil Concentration of 7 Soybean Genotypes

Also for this trait, drought had different effects among genotypes; it increased the oil concentration in the produced seeds of ES Mentor, Coraline, Ananda and *'Pannonia Kincse'*, whereas reduced it in Bokréta, Bólyi 612 and ES Pallador; however, all increases and reductions were insignificant, and the average oil concentration among all genotypes was very similar under both irrigation regimes.

The genotype Coraline resulted in the highest oil concentration in the produced seeds under both irrigation regimes (23.9 and 23.7% under DS and FI regimes, respectively), whereas Ananda had the lowest oil concentration under both regimes (21.5 and 21.1% under DS and FI regimes, respectively) as well.

3.1.2. The Effects of Drought Stress and Nitrogen Fertilization on The Morpho-physiology, Yield Components and Seed Quality of 2 Soybean Genotypes

3.1.2.1. The Effect of Chemical N-fertilizer on The Morpho-physiology, Yield Components and Seed Quality of Soybean Genotype 'Pannonia Kincse' under Different Irrigation Regimes

3.1.2.1.1. The Effect of Chemical N-fertilizer on The Relative Chlorophyll Content (SPAD) of Soybean Genotype 'Pannonia Kincse' under Different Irrigation Regimes

Except for an insignificant decrease in 105N treatment compared to 35N counterpart, increasing fertilization rate was accompanied by increases in SPAD values in all fertilization treatments; the increase was significant in 105N treatment at both V4 and R6 stages as compared to 0N counterparts. However, no significances were estimated when fertilization rate was increased from 35 to 105 kg ha^{-1}. On average, 35N and 105N resulted in 1.4 and 2.4% increase in SPAD values, respectively compared to 0N counterpart. Fertilization was positively correlated with SPAD trait at all stages, but more obviously at V4 and R6 stages where the correlation was significant.

Regardless of fertilization treatment, SPAD values increased with plants reached early reproductive stage (R2), then a relatively-slight decrease was recorded at R4 stage, followed by rapid increase at R6 stage.

Drought at both vegetative (V4) and early reproductive (R2 and R4) stages enhanced SPAD trait; the enhancement was even significant at R4 stage; however, drought resulted in significantly less SPAD values at late reproductive stage (R6).

Under all irrigation regimes, SPAD values increased along with plants' life stage development (except for a reduction at R4 stage under fully-irrigated system). The correlation coefficient, with irrigation treatments, was negative at both V4 and R4 stages, but positive at both R2 and R6 stages.

3.1.2.1.2. The Effect of Chemical N-fertilizer on The Normalized Difference Vegetation Index (NDVI) of Soybean Genotype 'Pannonia Kincse' under Different Irrigation Regimes

Fertilization relatively enhanced NDVI values at all studied stages; however, all enhancements were insignificant. On average, NDVI was 0.5 and 1.2% higher in 35N and 105N treatments, respectively compared to 0N treatment. NDVI was positively correlated with fertilization treatments at all stages, being significant only at V4 stage.

Regardless of fertilization treatment, NDVI was measurably increased when plants entered early reproductive stage (R2), followed by gradual, slight reductions at the next reproductive stages.

At both V4 and R2 stages, drought enhanced NDVI values, whereas it resulted in lower NDVI values at the later stages (R4 and R6). Fully-irrigated regime could increase NDVI values while plants were developing from stage to stage, whereas NDVI peaked at R2 stage under both non- and half-irrigated regimes and started degrading after that stage. Correlation with irrigation was negative at the first-two studied stages (V4 and R2), but positive at later stages (R4 and R6).

3.1.2.1.3. The Effect of Chemical N-fertilizer on The Leaf Area Index (LAI) of Soybean Genotype 'Pannonia Kincse' under Different Irrigation Regimes

Compared to 0N counterpart, 105N treatment significantly increased LAI value at all stages except the late reproductive stage R6 where the LAI values were very close in all fertilization treatments. LAI values rapidly increased with plants' development in life cycle, peaking at R4 stage, followed by reducing LAI values in all fertilization treatments. The correlation coefficient decreased with the development of plants through stages, being significant and positive at all stages except for the late R6 stage.

Drought significantly-positively affected LAI at V4 stage; however, it resulted in reducing LAI values at all reproductive stages, especially at R4 stage where the reduction was significant. Regardless of irrigation regime, gradual enhancements in LAI values with plants' development were recorded until the peak at R4 stage, where LAI started degrading after. The correlation coefficient gradually increased from stage to another until R4 stage; after that it started decreasing with staying positive.

3.1.2.1.4. The Effect of Chemical N-fertilizer on The Plant Height (cm) of Soybean Genotype 'Pannonia Kincse' under Different Irrigation Regimes

Both irrigation and fertilization had highly significant effect on the plant height, whereas their interaction had no significant effect. However, slightly-positive correlation coefficient was estimated with both irrigation and fertilization.

Regardless of irrigation regime, increasing fertilization rate was accompanied by insignificant enhancement in plant height; 35N and 105N treatments resulted in 2.4 and 3.9% taller plants, respectively (averaged among all three irrigation regimes). Fertilization's effect on this trait was 16.4%.

Plant height was positively affected by irrigation; however, the ratios of enhancement differed between half- and fully-irrigated regimes. Half-irrigated regimes resulted in 2.8, 4.6 and 5.1% taller plants, whereas fully-irrigated regime resulted in 4.7, 7.1 and 5.3% taller plants in 0N, 35N and 105N treatments, respectively. Moreover, the difference was significant in both 35N and 105N treatments under fully-irrigated regime as compared to non-irrigated counterparts but only for 105N treatment under half-irrigated regime. 28.6% of the differences in this trait were caused by the different irrigation regimes applied.

3.1.2.1.5. The Effect of Chemical N-fertilizer on The Flower Number per Plant of Soybean Genotype 'Pannonia Kincse' under Different Irrigation Regimes

Both irrigation and fertilization highly-significantly influenced this trait, and their interaction had significant effect as well. This trait was significantly correlated with fertilization and highly-significantly correlated with irrigation.

Under all irrigation regimes, increasing fertilization rate resulted in higher flower number per plant (except 105N under fully-irrigated regime as compared to 35N counterpart). On average, 35N treatment enhanced this trait by 6.5% compared to 0N, and 105N had a slight, additional enhancement by 1.4%. The effect size of fertilization on this trait was estimated as 9.3%.

Half-irrigated regime significantly increased flower number per plant in all fertilization treatments compared to non-irrigated counterparts; the average increase was 18.1%. However, further water irrigation amounts (fully-irrigated regime) did not further enhance this trait except in 35N treatment, yet still average increase, compared to non-irrigated counterpart, was 16.7%. Irrigation explained 34.2% of differences in flower number per plant.

3.1.2.1.6. The Effect of Chemical N-fertilizer on the 100-seed Weight (g) of Soybean Genotype 'Pannonia Kincse' under Different Irrigation Regimes

Only fertilization had a highly-significant effect on this trait, whereas irrigation, solely and in interaction with fertilization, had no significant effect. Moreover, the correlation with fertilization was highly significant, whereas no correlation with irrigation could be estimated.

Fertilization enhanced the 100-seed trait, regardless of irrigation regime. The average enhancement was 10.6 and 11.2% in 35N and 105N, respectively compared to 0N counterpart.

Both half- and fully-irrigated regimes could insignificantly enhance this trait, compared to non-irrigated counterpart, in both 0N and 35N treatments, but not 105N.

3.1.2.1.7. The Effect of Chemical N-fertilizer on The Seed Yield (kg ha^{-1}) of Soybean Genotype 'Pannonia Kincse' under Different Irrigation Regimes

Only fertilization had significant effect on yield, whereas both sole irrigation and its interaction with fertilization had no significant effects on this trait. Yield correlation with irrigation and, to a higher extent, with fertilization was positive.

Fertilization increased the yield under all three irrigation regimes, again except 105N treatment under fully-irrigated regime, introducing a conclusion that moderate fertilization is an advisable practice under all irrigation regimes, whereas high rates of N are only recommended under relative drought conditions. On average, 35N treatment resulted in a 6.3% increase (4813 kg ha^{-1}), whereas 105N had 6.9% higher yield (4839 kg ha^{-1}) as compared to non-fertilized (0N) counterpart (4527 kg ha^{-1}) (Fig. 5).

Although it was not statistically significant, yet irrigation could enhance the yield under all fertilization rates except for fully-irrigated treatment in 105N rate where a reduction in the yield was recorded compared to non-and half-irrigated counterparts. Averaged among the three fertilization rates, half-irrigation regime increased the yield by 4.6% (4781 kg ha^{-1}), whereas fully-irrigated regime had increased it by 5.6% (to 4827 kg ha^{-1}) compared to non-irrigated counterpart (4571 kg ha^{-1}) (Fig. 5).

100-seed weight, pod number per plant, flower number per plant and NDVI were highly-significantly correlated with the final seed yield. Yield was also correlated with both fertilization and irrigation, whereas it was negatively correlated with protein concentration, SPAD, LAI and oil concentration.

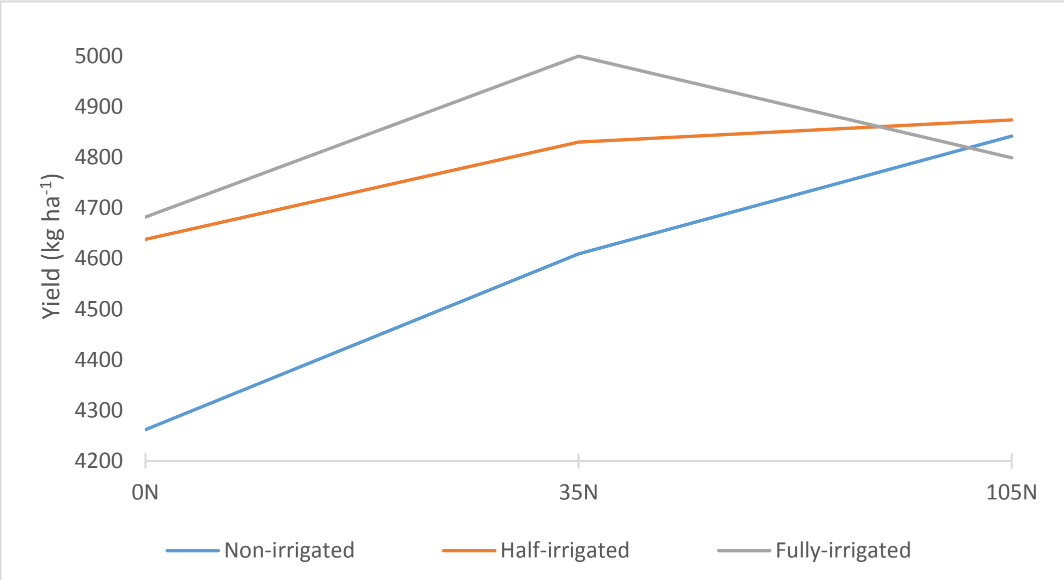

Fig. 5. The effect of different fertilization rates (0, 35 and 105 kg ha^{-1}) on the yield (kg ha^{-1}) of soybean genotype *'Pannonia Kincse'* under different irrigation regimes (non-irrigated, half-irrigated and fully-irrigated) in Látókép, Debrecen averaged over 2017, 2018 and 2019.

3.1.2.1.8. The Effect of Chemical N-fertilizer on The Protein Concentration (%) of Soybean Genotype 'Pannonia Kincse' under Different Irrigation Regimes

Irrigation and fertilization solely and also their interaction (irrigation*fertilization) had highly significant ($p<0.01$) effects on protein concentration. Moreover, the correlation between this trait and the fertilization rate was highly significant, and the correlation with irrigation regimes was significant as well.

Fertilization, regardless of irrigation regime, could enhance protein concentration only when applied in a high rate (105N). Protein concentration was 1.9 and 1.1% higher in 105N treatment in half- and fully-irrigated, respectively; moreover, it was significantly higher (by 7.3%) under non-irrigated regime, and this high fertilization rate, under non-irrigated regime, resulted in the best protein concentration compared to all other N rates and irrigation regimes, which implies the importance of N application in relatively high rates under drought stress conditions as it could alleviate the effect of drought in reducing protein concentration recorded in both 0N and 35N treatments, and even resulting in the highest protein concentration. The effects size (calculated as partial Eta squared) of fertilization (28.4%) was higher than that of irrigation (15.4%); i.e. 28.4% of the differences among protein concentration values can be explained by the changes in fertilization rates, whereas 15.4% can be explained by different irrigation regimes.

Irrigation increased protein concentration in both 0N and 35N; moreover, the increase in fully-irrigated treatment (by 5.3 and 4.5% in 0N and 35N, respectively) was significant compared to non-irrigated counterpart. On the other hand, non-irrigated treatment resulted in relatively higher protein concentration in 105N treatment as compared to the other two irrigation regimes, however, the difference was slight and insignificant.

3.1.2.1.9. The Effect of Chemical N-fertilizer on The Oil Concentration (%) of Soybean Genotype 'Pannonia Kincse' under Different Irrigation Regimes

Oil concentration was highly-significantly affected ($p<0.01$) by irrigation, significantly affected ($p<0.05$) by fertilization whereas their interaction had no significant effect. However, the correlation coefficient was negative in relation with fertilization and, to a higher level, with irrigation; i.e. increasing fertilization or irrigation water amount resulted, in most cases, in reducing oil concentration.

Fertilization, especially applied in higher (105N) rate decreased oil concentration, regardless of irrigation regime; however, all reductions were slight and insignificant. Overall fertilization effect on oil concentration was 7.5%.

oil concentration was reversely affected by increasing irrigation water amounts. The reduction ratios in fully-irrigated, compared to non-irrigated, regime (by 4.0 and 4.4%) were significant in both 0N and 35N treatments, respectively but not in 105N treatment (where the reduction ratio was 2.3%). The effect size of irrigation on this trait was 36.1%.

3.1.2.2. The Effect of Nitrogen and Inoculation on The Morpho-physiology, Yield Components and Seed Quality of Soybean Genotype 'Boglár' under Different Irrigation Regimes

3.1.2.2.1. The Effect of Nitrogen and Inoculation on The Relative Chlorophyll content (SPAD) of Soybean Genotype 'Boglár' under Different Irrigation Regimes

In inoculated plants at all studied stages, increased SPAD values could be recorded with increasing fertilization rates, with the high fertilization rate being significantly higher at late reproductive stages (R4 and R6) compared to 0N counterpart. On average, SPAD value was 3.5 and 6.4% in 35N and 105N treatments, respectively compared to 0N treatment. Significant correlation between fertilization and SPAD trait at all stages was estimated. A very similar conclusion was recorded in non-inoculated plants, and the enhancement rate was 2.6 and 6.6%

for 35N and 105N treatments, respectively compared to 0N treatment. Correlation coefficient with fertilization was positive and significant at all stages except for R2 stage.

Drought had vulnerable and insignificant effect on SPAD values at the studied stages in inoculated plants, but had significant negative effect at R6 stage, where 7.7 and 11.8% reduction in SPAD value was recorded compared to half- and fully-irrigated treatments, respectively. On average, irrigation increased SPAD values by 1.0 and 2.9% under half- and fully-irrigated regimes, respectively compared to non-irrigated counterpart. Only at R6 stage was the correlation between irrigation and SPAD significant. In non-inoculated plants also, drought decreased SPAD value by 5.4 and 10.8% compared to half- and fully-drought regimes, respectively. Similar conclusion was recorded regarding correlation.

Interestingly, non-inoculated plants had higher SPAD values than inoculated counterparts in all fertilization treatments and under all irrigation regimes.

3.1.2.2.2. The Effect of Nitrogen and Inoculation on The Normalized Difference Vegetation Index (NDVI) of Soybean Genotype 'Boglár' under Different Irrigation Regimes

Except for a slight, insignificant decrease in 105N compared to 35N counterpart, increased fertilization rate in inoculated plants was accompanied by increased NDVI values, with 105N treatment being significantly higher than 0N treatment at V4 stage, and significantly higher than both 0N and 35N treatments at R2 stage. Averaged over all stages, 1.3 and 2.2% higher NDVI values were recorded in 35N and 105N treatments, respectively compared to 0N counterpart. In all fertilization treatments, a rapid increase in NDVI was recorded between V4 and R2 stages, followed by gradual reduction through later stages. The correlation coefficient was highly-significant at both V4 and R2 stages, but started decreasing after to become slightly negative at R6 stage. Non-inoculated plants responded positively to fertilization; however, no significance was recorded. Similar trend was recorded among stages for non-inoculated plants, and correlation coefficient was insignificantly positive throughout all stages.

In general, irrigation enhanced this trait in inoculated plants (except at R2 stage, where also both irrigation regimes had higher NDVI value than non-irrigated counterpart, but half-irrigated regime had higher NDVI than did fully-irrigated regime). Moreover, drought significantly reduced (by 5.3% compared to fully-irrigated counterpart) NDVI value at R6 stage. On average, drought reduced NDVI value by 1.5 and 2.0% compared to half- and fully-irrigated regimes, respectively. The effect of irrigation on NDVI values through stages was similar to that of fertilization. The correlation with irrigation was positive at all stages except for R2 stage. Irrigation's effect on non-inoculated plants was more measurable at late reproductive stages (R4 and R6), but only half-irrigated regime, on average, resulted in better NDVI than drought-stressed counterpart. NDVI values reached their maximum at R2 stage under both non- and half-irrigated regimes, whereas it reached the maximum at R4 stage under fully-irrigated regime, but without reaching the maximum value of the other two regimes. Correlation with irrigation was negative at both V4 and R2 stages, but positive later at R4 and R6 stages.

A very close average value of NDVI was recorded for both inoculated and non-inoculated plants.

3.1.2.2.3. The Effect of Nitrogen and Inoculation on The Leaf Area Index (LAI) of Soybean Genotype 'Boglár' under Different Irrigation Regimes

Enhanced LAI values could be recorded at all stages with increasing fertilization rate in both inoculated and non-inoculated plants, with the high rate (105N treatment) having significantly higher values at both V4 and R2 stages and an average 18.8 and 14% higher LAI values compared to 0N and 35N treatments, respectively in inoculated plants, and 14.9 and 8.0% in non-inoculated plants. Regardless of inoculation, gradual increases in LAI values through plants' development were recorded, with a peak at R4 stage in all fertilization treatments. Significant correlation at all studied stages, except for the late R6 stage, was estimated, regardless of inoculation.

In inoculated plants, half-irrigated regime did not result in better LAI values at both V4 and R2 stages, but did at later stages. Fully-irrigated regime, on the other hand, had higher LAI values at all stages compared to both other regimes. Irrigation increased LAI by 8.3 and 14.9% under half- and fully-irrigated regimes, respectively compared to non-irrigated counterpart. Similar conclusion could be recorded in non-inoculated plants in all stages except for V4 stage, where fully-irrigated regime, in addition to half-irrigated regime, couldn't enhance LAI. In this trait as well, irrigation followed similar trend to fertilization effect throughout plants' development, regardless of inoculation. The correlation coefficient gradually increased through stages to reach a highly-significant peak at R4 stage, followed by a reduction at R6 stage that, however, kept it significant in inoculated plants, but not in non-inoculated counterparts.

Inoculated plants were, on average, 4% higher in LAI compared to non-inoculated counterparts, but the difference was insignificant.

3.1.2.2.4. The Effect of Nitrogen and Inoculation on The Plant Height (cm) of Soybean Genotype 'Boglár' under Different Irrigation Regimes

Both irrigation and fertilization, but not their interaction, had highly significant effect on the plant height of inoculated plants, whereas both treatments, in addition to their interaction, had no significant effect on non-inoculated plants. Correlation coefficient was positive, yet not significant, with both treatments, regardless of inoculation treatment.

In inoculated plants, both half- and fully-irrigated regimes resulted in significantly taller plants compared to non-irrigated counterpart, regardless of fertilization treatment. Compared to half-irrigated, however, fully-irrigated regime could enhance this trait only in 0N treatment, resulting in similar enhancement average of 7.5% as compared to non-irrigated regime. 46.0% of differences in plant height were resulted from the different irrigation regimes. In non-inoculated plants, similar enhancement, as a result of irrigation application, was recorded; however, no significant differences were recorded. Moreover, half-irrigated regime resulted in taller plants than did fully-irrigated regime, regardless of fertilization treatment.

Although not statistically significant, yet measurable enhancements in this trait were accompanied with increasing fertilization rate in inoculated plants. On average, 4.1 and 7.3% taller plants were resulted from 35N and 105N treatments, respectively as compared to 0N treatment. Fertilization was responsible for 38.7% of differences in plant height. Similar enhancements by fertilization treatments were recorded in non-inoculated plants.

Inoculation had no significant effect on this trait; however, inoculated plants were, on average, 1.8% taller than non-inoculated plants.

3.1.2.2.5. The Effect of Nitrogen and Inoculation on The Flower Number per Plant of Soybean Genotype 'Boglár' under Different Irrigation Regimes

Flower number per plant was differently affected in terms of inoculation; in inoculated plants, Irrigation had highly significant effect on this trait, whereas fertilization had no significant effect. In non-inoculated plants, irrigation had significant, and fertilization had highly-significant effects. However, the interaction between fertilization and irrigation had no significant effect, regardless of inoculation, whereas the correlation was positive, and in most cases significant, with both fertilization and irrigation.

Compared to non-irrigated regime, both half-and fully-irrigated regimes in inoculated plants significantly increased flower number per plant in all fertilization treatments (23.7 and 22.5% on average, respectively). Similar conclusion could be made in non-inoculated plants, where the differences were not significant, yet drought stress decreased flower number per plant by 13.5 and 12.6% compared to half- and fully-irrigated regimes, respectively. The effect size of irrigation on this trait was estimated as 36.3% and 8.7% in inoculated and non-inoculated plants, respectively.

Increasing fertilization rate in inoculated plants was accompanied by relevant increases in flower number per plant under all irrigation regimes; average increase was 1.7 and 6.8% in 35N and 105N, respectively compared to 0N counterpart. All increases were insignificant. Similarly, 5.2 and 22.3% increased flower number per plant, on average, were obtained from 35N and 105N treatments, respectively compared to 0N counterpart, with an effect size of 15.1%.

2.8% higher flower number (47.2 flower per plant) was achieved in inoculated plants compared to non-inoculated counterparts (45.9 flower per plant).

3.1.2.2.6. The Effect of Nitrogen and Inoculation on The Pod Number Per plant of Soybean Genotype 'Boglár' under Different Irrigation Regimes

Similar effects of fertilization and irrigation were estimated on soybean plants compared to flower number per plant trait, with similar correlation trend as well.

Apart from a slight decrease under fully-irrigated regime in 105N treatment, compared to half-irrigated regime, increasing irrigation water amount in inoculated plants resulted in increasing pod number per plant. Moreover, the increase was significant under half-irrigated regime with an average increase of 22.0%. Non-inoculated plants, on the other hand, followed the same trend as of flower number per plant. The differences in pod number per plant were 33.8% in inoculated plants, and 7.9% in non-inoculated plants, caused by irrigation regimes.

On average, pod number per plant in inoculated plants was enhanced by increasing fertilization rate; this trait was 0.5 and 4.9% higher in 35N and 105N treatments, respectively compared to 0N counterpart. This conclusion could also be reported in non-inoculated plants with higher differences among fertilization treatments; 9.6 and 19.7% average increase in this trait was recorded in 35N and 105N treatments, respectively compared to 0N counterpart. The effect size of fertilization on this trait was estimated as 12.8%.

Inoculation did not result in changing the average pod number per plant (37.8 pod per plant).

3.1.2.2.7. The Effect of Nitrogen and Inoculation on The Seed Yield (kg ha^{-1}) of Soybean Genotype 'Boglár' under Different Irrigation Regimes

In inoculated plants, only irrigation had highly significant effect on the yield, whereas both irrigation and fertilization had significant effect on the final yield. However, interaction between irrigation and fertilization had no significant effect on this trait, regardless of inoculation. Moreover, highly-significant correlation coefficient in relation with irrigation was estimated for inoculated plants, whereas both correlation coefficients with irrigation and fertilization were significant in non-inoculated plants.

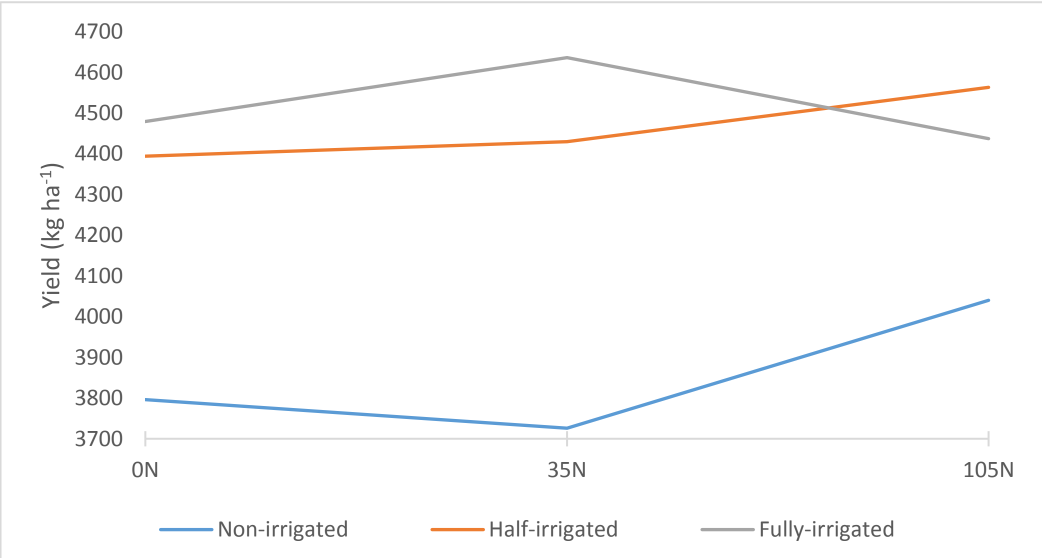

Fig. 6. The effect of different fertilization treatments (0, 35 and 105 kg ha^{-1}) on seed yield (kg ha^{-1}) of inoculated soybean genotype *'Boglár'* under different irrigation regimes (non-irrigated, half-irrigated and fully-irrigated) in Látókép, Debrecen averaged over 2017, 2018 and 2019.

In inoculated plants, measurable increases were recorded in all fertilization treatments under half-irrigated regime as compared to non-irrigated counterpart; the increase ratio was, on average, 15.8% (being significant in both 0N and 35N treatments). Under fully-irrigated regime, however, further enhancements (by 1.9 and 4.6%) were recorded in 0N and 35N treatments, respectively, whereas yield was reduced by 2.8% in 105N treatment under this regime (Fig. 6). Overall irrigation effect on yield was calculated as 35.6%. In non-inoculated plants, on the other hand, average yield was reduced by drought. However, increasing the fertilization rate was accompanied with reducing the yield gap between drought-stressed treatments and the other two irrigated treatments (Fig. 7), leading to a conclusion of the importance of N fertilizer application under drought stress conditions in case the plants are not inoculated. 7.0% of changes in yield were caused by different irrigation regimes.

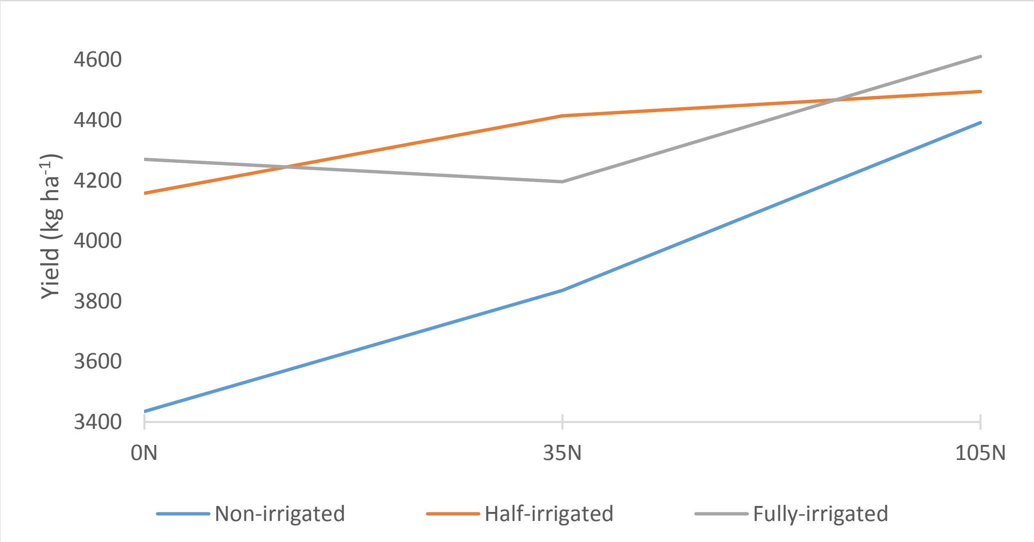

Fig. 7. The effect of different fertilization treatments (0, 35 and 105 kg ha^{-1}) on seed yield (kg ha^{-1}) of non-inoculated soybean genotype *'Boglár'* under different irrigation regimes (non-irrigated, half-irrigated and fully-irrigated) in Látókép, Debrecen averaged over 2017, 2018 and 2019.

In the presence of drought, whether severe (non-irrigated regime) or moderate (half-irrigated regime), 35N treatment did not have a measurable role on the yield in the case of inoculated plants, whereas 105N increased the yield by 6.4 and 3.8% under non- and half-irrigated regimes, respectively (Fig. 6), emphasizing the importance of N fertilization application in inoculated soybean under drought stress conditions. However, under fully-irrigated regime, 105N treatment resulted in the lowest yield compared to both 0N and 35N treatments, whereas 35N treatment increased the yield by 3.5 and 4.5% compared to 0N and 105N, respectively (Fig. 6). In total, the effect size of fertilization was much lower than that of irrigation and was estimated as only 1.6%. In non-inoculated plants, fertilization, in general, enhanced the final yield; 4.9 and 13.8% increased yield was achieved under half- and fully-irrigated regimes, respectively compared to drought-stressed counterpart (Fig. 7). The estimated effect size on the yield was 7.2%.

On average, the inoculated plants resulted in 1.8% higher yield than the non-inoculated counterparts. However, the application of fertilization (35N and 105N treatments) under drought stress conditions (non-irrigated regime) resulted in higher yields in the non-inoculated plants, most probably because of the negative influence of mineral N fertilizer on the symbiotic process. Moreover, relatively-high fertilization rate (105N) resulted in better yield in non-inoculated plants, compared to inoculated counterparts, when drought was waived off.

3.1.2.2.8. The Effect of Nitrogen and Inoculation on The Protein Concentration (%) of Soybean Genotype 'Boglár' under Different Irrigation Regimes

Irrigation, fertilization and their interaction had highly significant effect on Protein concentration in both inoculated and non-inoculated plants. Moreover, highly-significant correlation with both treatments was estimated.

In inoculated plants, protein concentration significantly increased with increasing irrigation water amount in both 0N and 35N treatments, whereas only fully-irrigated regime resulted in better protein concentration in 105N treatment. Drought resulted, on average, in 2.5 and 5.7% reduction in protein concentration compared to half- and fully-irrigated regimes, respectively. Irrigation was responsible for 58.9% of changes in this trait. Drought significantly reduced protein concentration of non-inoculated plants in both 0N and 35N treatments, whereas it slightly enhanced this trait in 105N treatment. On average, 3.0 and 4.8% reductions were resulted from drought-stressed regime compared to half- and fully-irrigated regimes, respectively. 34.1% of changes in this trait could be explained by changes in irrigation regimes.

Regardless of inoculation, and apart from a slight, insignificant reduction in 35N under non-irrigated regime compared to 0N counterpart, fertilization enhanced protein concentration under all three irrigation regimes. Moreover, this increase was significant in 105N treatment under non-irrigated regime in inoculated plants, and under both non- and half-irrigated regimes in non-inoculated plants. The effect size of fertilization treatments on protein concentration was 55.3 and 37.5% in inoculated and non-inoculated plants, respectively.

Interestingly, non-inoculated plants had higher protein concentration than inoculated counterparts under all irrigation regimes and in all fertilization treatments (except in 105N treatment under fully-irrigated regime), with an average increase of 1.1%.

3.1.2.2.9. The Effect of Nitrogen and Inoculation on The Oil Concentration (%) of Soybean Genotype 'Boglár' under Different Irrigation Regimes

Both irrigation and fertilization had highly significant effect on this trait in inoculated plants, and significant effect in non-inoculated plants, whereas their interaction did not. The correlation was negative with both treatments, regardless of inoculation.

In inoculated plants, on the contrary to protein concentration, irrigation resulted in reduced oil concentration, regardless of fertilization treatment. Applied half-irrigated regime resulted in significantly reduced oil concentration in both 0N and 35N treatments, whereas the reduction was insignificant in 105N treatment. Increasing the irrigation water amount (fully-irrigated regime) further reduced oil concentration in all three fertilization treatments but in a much lower ratio. Similarly in non-inoculated plants, drought, on average, resulted in 2.3 and 2.8% increase in oil concentration compared to half- and fully-irrigated regimes, respectively. 48.7% of changes in this trait were resulted from the different irrigation regimes applied in inoculated plants, and 8.1% in the case of non-inoculated plants.

On average, Oil concentration was reduced with increasing fertilization rate, regardless of inoculation. The average reduction resulted from higher fertilization rate (105N) was 2.7 and 2.2% compared to 0N and 35N treatments, respectively in inoculated plants, and 2.7 and 1.8%, respectively in non-inoculated plants. The effect size of fertilization was calculated as 27.6% for inoculated, and 8.5% for non-inoculated plants.

Inoculated plants had, on average, 1.8% higher oil concentration than non-inoculated counterparts.

3.1.3 The Effects of Drought Stress and Phosphorus Fertilization on The Morpho-physiology, Yield Components and Seed Quality of 2 Soybean Genotypes

3.1.3.1 The Effects of Drought Stress and Phosphorus Fertilization on The Stomatal Conductance (g_s) (mmol m^{-2} s^{-1}) of 2 Soybean Genotypes

In the two studied genotypes, both irrigation and fertilization treatments had highly-significant effect on g_s, whereas their interaction did not.

In both genotypes, and regardless of irrigation regime, 45P treatment increased g_s (by 9.0 and 6.0% for *'Pannonia Kincse'* and *'Boglár'*, respectively) compared to 0P. 90P treatment, on the other hand, had higher g_s than 0P, but not 45P. The effect size of fertilization on g_s in *'Pannonia Kincse'* genotype was estimated as 34.1; i.e. 34.1% of changes in g_s are the result of the different fertilization rates. In *'Boglár'* genotype, on the other hand, the effect size was estimated as 29.9%. However, the correlation between g_s and fertilization was slight and insignificant.

Drought significantly decreased g_s in all fertilization treatments of both genotypes. The average reduction was 45.9 and 50.7% for *'Pannonia Kincse'* and *'Boglár'*, respectively. Irrigation was responsible for 97.2 and 98.7% of changes in g_s in *'Pannonia Kincse'* and *'Boglár'*, respectively. In addition, the correlation coefficient between g_s and irrigation was highly significant in both genotypes.

3.1.3.2 The Effects of Drought Stress and Phosphorus Fertilization on The Relative Chlorophyll Content (SPAD) of 2 Soybean Genotypes

The effect of fertilization was highly-significant on *'Pannonia Kincse'* and significant on *'Boglár'* genotype, whereas the effect of irrigation was only highly-significant on *'Pannonia Kincse'*. The interaction of fertilization and irrigation had no significant effect on both genotypes.

45P enhanced SPAD values in both genotypes compared to 0P, regardless of irrigation regime; however, the differences were insignificant. 90P did not further enhance SPAD values compared to 45P counterparts for both genotypes and under both irrigation regimes. 29.6 and 21.4% of differences in SPAD were attributed to fertilization effect in *'Pannonia Kincse'* and *'Boglár'*, respectively. The correlation with fertilization was significant in both genotypes.

Drought stress decreased SPAD values by an average of 2.5 and 1.3% for *'Pannonia Kincse'* and *'Boglár'*, respectively; however, the reductions were insignificant. 28.0% of differences in this trait were a result of drought stress in *'Pannonia Kincse'*, but only 4.0% in the case of *'Boglár'* genotype.

3.1.3.3. The Effects of Drought Stress and Phosphorus Fertilization on The Plant Height (cm) of 2 Soybean Genotypes

Highly significant effects of both fertilization and irrigation were estimated in both genotypes, whereas the fertilization*irrigation effect was significant in *'Boglár'* only.

P-fertilizer application, under both irrigation regimes, significantly increased plant height in both genotypes compared to non-fertilized counterpart. However, increasing the fertilization rate (90P) had no significant effect on this trait compared to the lower rate (45P); it slightly increased the plant height of *'Boglár'* genotype, but decreased it in *'Pannonia Kincse'* genotype. 88.3 and 79.3% of differences in plant height in *'Pannonia Kincse'* and *'Boglár'*, respectively were attributed to different fertilization rates, with a highly significant correlation coefficient.

Regardless of fertilization treatment, drought stress significantly decreased the plant height of both genotypes; the average reduction was 15.4 and 12.4% in *'Pannonia Kincse'* and *'Boglár'*, respectively. Drought stress was responsible for 91.4 and 87.2% changes in the plant height of *'Pannonia Kincse'* and *'Boglár'*, respectively. In addition, the plant height of both genotypes was highly-significantly correlated with irrigation treatments.

3.1.3.4. The Effects of Drought Stress and Phosphorus Fertilization on The Pod Number Per plant of 2 Soybean Genotypes

The effect of fertilization on this trait was highly significant in both genotypes, whereas irrigation's effect was highly significant in the case of *'Pannonia Kincse'*, and significant in the case of *'Boglár'*. However, the interaction of irrigation and fertilization did not have any significance, regardless of genotype.

Under both irrigation regimes, pod number per plant in both genotypes was lower in non-fertilized plots compared to fertilized counterparts; however, the reduction was insignificant (except for drought-stressed, non-fertilized treatment of *'Boglár'*, where the reduction was significant). Fertilization rates had an effect percentage of 48.2 and 59.4% of the pod number per plant of *'Pannonia Kincse'* and *'Boglár'*, respectively. The correlation coefficient of this trait with fertilization was significant, and higher for *'Boglár'* compared to *'Pannonia Kincse'*.

Although drought reduced pod number per plant in both genotypes, yet its effect was more measurable on *'Pannonia Kincse'*, where the reduction was significant, regardless of fertilization treatment. In *'Boglár'*, however, pod number per plant was significantly lower in 0P treatment, whereas the difference was slight and insignificant in both 45P and 90P treatments, leading to a conclusion that P-fertilizer application could partly ameliorate the negative effect of drought stress on this trait by decreasing the reduction level of pods resulting from exposure to drought. 83.4 of differences in this trait were attributed to drought stress application on *'Pannonia Kincse'* genotype, which was considerably higher that the effect of drought stress application on *'Boglár'* genotype where the effect size was estimated as 12.9%. This conclusion was supported by the higher correlation coefficient of this trait with irrigation treatments in the case of *'Pannonia Kincse'* compared to *'Boglár'* genotype.

3.1.3.5. The Effects of Drought Stress and Phosphorus Fertilization on The Seed Yield (kg ha-1) of 2 Soybean Genotypes

Regardless of genotype, both irrigation and fertilization treatments, but not their interaction, had highly significant effects on the final seed yield. The correlation of both treatments with the yield was also highly significant in both genotypes.

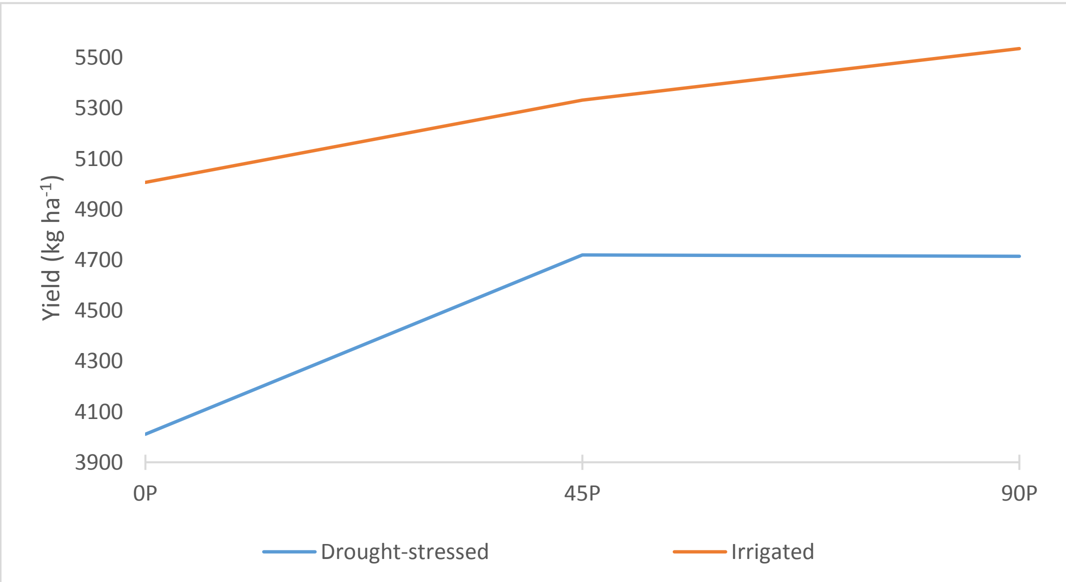

Fig. 8. The effect of drought stress on the seed yield (kg ha^{-1}) of soybean genotype *'Pannonia Kincse'* under different P-fertilizer rates (0, 45 and 90 kg ha^{-1}) in Látókép, Debrecen averaged over 2017 and 2018 years.

Fertilization, regardless of rate, significantly increased the final seed yield of both genotypes and under both irrigation regimes. However, 90P did not result in any further yield increase compared to 45P counterpart under drought stress conditions, whereas it slightly increased the yield under irrigated regime in both genotypes (Fig. 8 and 9). 73.3 and 67.6% of changes in the final seed yield were attributed to the different rate of fertilization in *'Pannonia Kincse'* and *'Boglár'*, respectively.

The final seed yield was significantly decreased by drought, regardless of genotype and fertilization treatment. On average, *'Pannonia Kincse'* and *'Boglár'* had 13.5 and 12.5% less yield, respectively as a result of drought stress. Drought stress was estimated to be responsible for 83.6 and 68.0% of the differences of the final seed yield of *'Pannonia Kincse'* and *'Boglár'*, respectively.

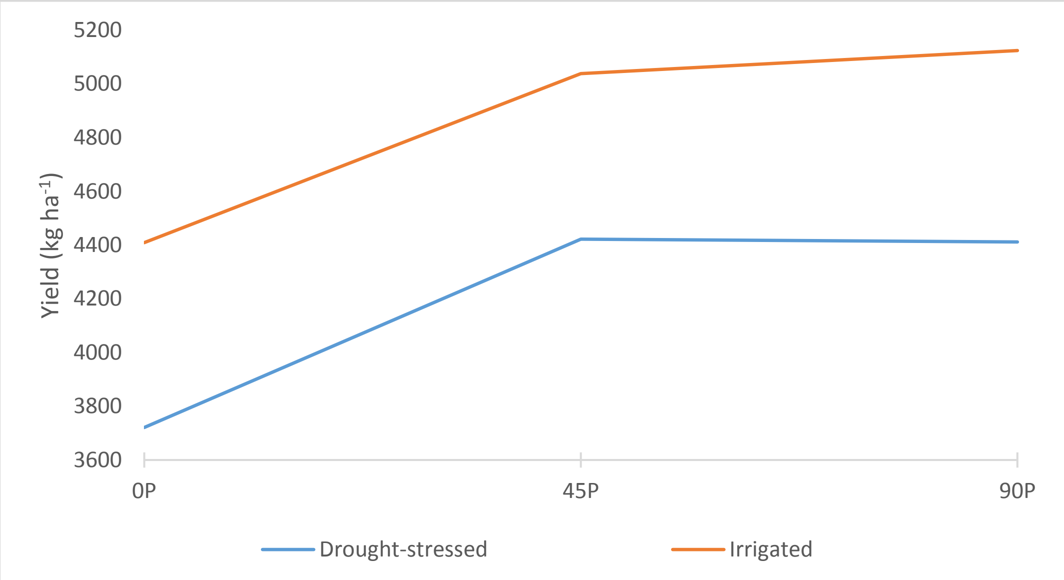

Fig. 9. The effect of drought stress on the yield (kg ha^{-1}) of soybean genotype *'Boglár'* under different P-fertilizer rates (0, 45 and 90 kg ha^{-1}) in Látókép, Debrecen averaged over 2017 and 2018 years.

3.1.3.6. The Effects of Drought Stress and Phosphorus Fertilization on The Protein Concentration (%) of 2 Soybean Genotypes

Irrigation had highly significant effect on protein concentration in both genotypes; moreover, the correlation between protein concentration and irrigation treatments was significantly negative, i.e. increasing irrigation water amount was accompanied by decreasing protein concentration. In other words; drought stress increased protein concentration. Fertilization, on the other hand, had relatively low effect on this trait, with a non-significant correlation.

Compared to 0P treatment, 45P treatment resulted in relatively higher protein concentration, regardless of genotype and irrigation regime. 90P treatment, on the other hand, resulted in higher protein concentration only under drought stress conditions, but not under irrigated conditions. However, all differences were insignificant.

Drought stress resulted in significantly higher protein concentration in both genotypes, regardless of fertilization treatment. The average protein concentration was 4.8 and 16.9% higher of drought-stressed *'Pannonia Kincse'* and *'Boglár'* plants, respectively compared to their irrigated counterparts. 31.2% of increased protein concentrations were attributed to drought stress in *'Pannonia Kincse'*, and drought had even higher (84.7%) attribution in the case of *'Boglár'* genotype.

3.1.3.7. The Effects of Drought Stress and Phosphorus Fertilization on The Oil Concentration (%) of 2 Soybean Genotypes

Fertilization had highly significant effect on the oil concentration in both genotypes, and irrigation had significant effect on this trait in *'Pannonia Kincse'* genotype, and even highly significant effect in the case of *'Boglár'* genotype.

Both fertilization treatments (45P and 90P) significantly increased oil concentration in both genotypes and under both irrigation regimes. Moreover, 90P treatment had significantly higher oil concentration than 45P treatment in both genotypes under drought stress conditions, but not under irrigated conditions. Compared to 0P treatment, 45P and 90P treatments resulted, on average, in 5.8 and 10.1% higher oil concentration, respectively in *'Pannonia Kincse'*, and 5.9 and 10.0%, respectively in *'Boglár'*. Fertilization rates were responsible for 74.8 and 69.3% of differences in this trait in *'Pannonia Kincse'* and *'Boglár'*, respectively, with a highly significant correlation of this trait with fertilization treatments.

Drought, on average, resulted in reducing the oil concentration in both genotypes, with more measurable effect in *'Boglár'*, where the difference was significant, regardless of fertilization treatment (with and average reduction of 6.6%). Similar to its effect on the protein concentration, drought affected *'Boglár'* genotype by a higher ratio (62.2%) than did on *'Pannonia Kincse'* genotype (13.6), which is further supported by the correlation coefficient, as it was highly significant in *'Boglár'*, but not in *'Pannonia Kincse'*.

3.1.4. The Effects of Drought Stress and Exogenous Application of Hydrogen Piroxide (H_2O_2) on The Physiology and The Yield of 2 Soybean Genotypes

3.1.4.1. The Effects of Drought Stress and Exogenous Application of Hydrogen Piroxide (H_2O_2) on The Stomatal Conductance (g_s) (mmol m^{-2} s^{-1}) of 2 Soybean Genotypes

In both genotypes, g_s was significantly higher when irrigation (FI) was applied; however, H_2O_2-sprayed plots were significantly higher than drought-stressed counterparts in terms of g_s value. Drought application reduced g_s by 51.6 and 47.7% compared to irrigated counterparts, whereas H_2O_2 spraying decreased the reduction ratio to 21.6 and 19.5% in *'Boglár'* and *'Pannonia*

Kincse', respectively. Correlation between g_s and irrigation treatment was highly significant (<.01), and the effect size of H_2O_2 application (calculated as partial Eta squared) was 81.6 and 90.5% in *'Boglár'* and *'Pannonia Kincse'*, respectively; in other words, H_2O_2 application was responsible for 81.6 and 90.5% of g_s changes in *'Boglár'* and *'Pannonia Kincse'*, respectively.

3.1.4.2. The Effects of Drought Stress and Exogenous Application of Hydrogen Piroxide (H_2O_2) on The Relative Chlorophyll Content (SPAD) of 2 Soybean Genotypes

In *'Boglár'*, drought significantly decreased SPAD trait by 26.7% (to 26.4) compared to the irrigated counterpart (36.0), whereas H_2O_2 spraying resulted in better SPAD (37.2) than both (FI) and (DW) counterparts. In *'Pannonia Kincse'*, on the other hand, irrigation resulted in the highest SPAD value (43.3); it was significantly higher (by 22.4%) than drought-stressed counterpart (33.6). However, (HP) treatment enhanced this trait (by 13.1%) compared to (DW), without reaching the same level of (FI) treatment as in *'Boglár'*. The correlation with irrigation was significant (<.05) and highly significant (<.01) in *'Boglár'* and *'Pannonia Kincse'* genotypes, respectively, and the effect size of H_2O_2 application was noticeably higher (85.7%) in *'Boglár'* compared to *'Pannonia Kincse'* (59.1%).

3.1.4.3. The Effects of Drought Stress and Exogenous Application of Hydrogen Piroxide (H_2O_2) on The Relative Water Content (RWC) (%) of 2 Soybean Genotypes

In *'Boglár'*, drought significantly decreased RWC (to 57.3%) compared to the irrigated counterpart (72.7%). H_2O_2-sprayed treatment, however, significantly increased RWC (to 69.3%) compared to drought-stressed treatment and had very close value to (FI) treatment. In *'Pannonia Kincse'*, applying H_2O_2 significantly increased RWC (to 79.7%) compared to the drought-stressed treatment (61.7%); however, irrigation treatment had significantly higher RWC (68.3%) compared to (HP) and (DW) treatments.

H_2O_2 application had a significant effect size on RWC (by 95.9 and 97.3% in *'Boglár'* and *'Pannonia Kincse'*, respectively) with a highly significant correlation coefficient.

3.1.4.4. The Effects of Drought Stress and Exogenous Application of Hydrogen Piroxide (H_2O_2) on The Leaf Area Index (LAI) of 2 Soybean Genotypes

Both genotypes followed the same trend; LAI was significantly lower in (DW) treatment (by 13.0 and 17.5% in *'Boglár'* and *'Pannonia Kincse'*, respectively) compared to (FI) counterpart. (HP) treatment resulted in the highest LAI in both genotypes; LAI was 21.3 and 28.8% higher compared to (DW) counterparts in *'Boglár'* and *'Pannonia Kincse'*, respectively.

Significant correlation was recorded between irrigation and LAI; the effect size of H_2O_2 application was also significant in both genotypes (with ratios of 92.8 and 95.1% in *'Boglár'* and *'Pannonia Kincse'*, respectively) as well.

3.1.4.5. The Effects of Drought Stress and Exogenous Application of Hydrogen Piroxide (H_2O_2) on The Plant Height (cm) of 2 Soybean Genotypes

Drought significantly reduced plant height in both genotypes compared to irrigated counterpart; the reduction ratio was 13.2 and 7.1% in *'Boglár'* and *'Pannonia Kincse'*, respectively. Applying H_2O_2 significantly increased plant height in both genotypes; plant height was 3.6% less in *'Boglár'*, whereas it was only 0.2% less in *'Pannonia Kincse'* compared to irrigated counterparts. H_2O_2 application had an effect size of 84.2 and 82.8% in *'Boglár'* and *'Pannonia Kincse'*, respectively.

3.1.4.6. The Effects of Drought Stress and Exogenous Application of Hydrogen Piroxide (H_2O_2) on The Seed Yield (kg ha-1) of 2 Soybean Genotypes

Irrigation resulted in the best yield in both genotypes; the yield significantly increased by 27.3 and 24.3% in irrigated treatment compared to drought-stressed counterpart in *'Boglár'* and *'Pannonia Kincse'*, respectively. H_2O_2 spraying also increased the yield of both genotypes compared to drought-stressed treatment; the increase ratio was 21.2 and 13.5% in *'Boglár'* and *'Pannonia Kincse'*, respectively (Fig. 10). The effect size of H_2O_2 application was bigger (78.9%) in *'Pannonia Kincse'* compared to *'Boglár'* (72.1%). Correlation of irrigation with yield was highly significant in both genotypes.

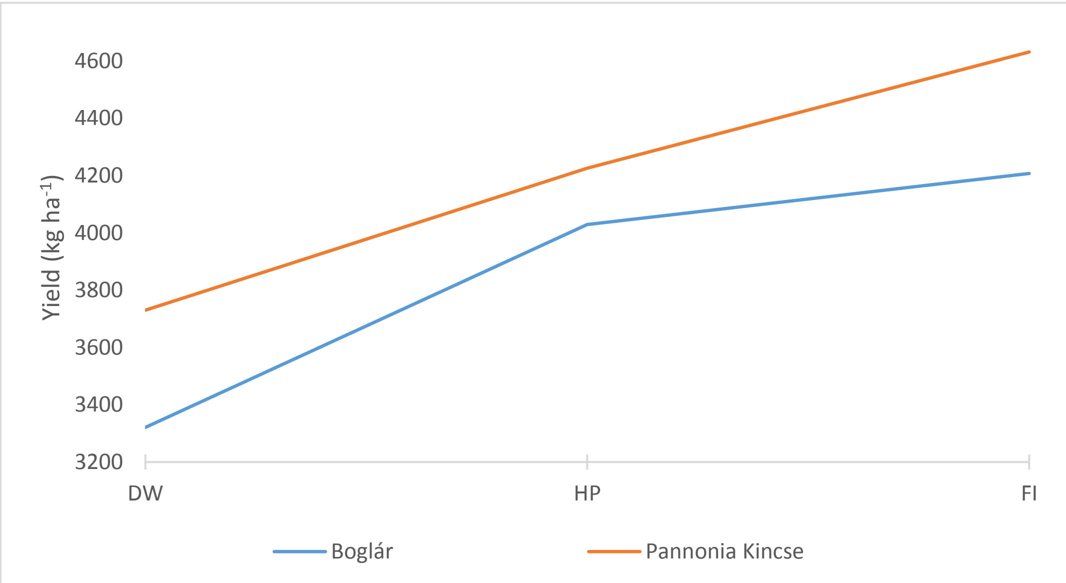

Fig. 10. The seed yield (kg ha^{-1}) of soybean genotypes *'Boglár'* and *'Pannonia Kincse'* under three irrigation treatments; fully-irrigated (FI), drought-stressed with H_2O_2 foliar spray (HP) and drought-stressed (DW) in Látókép, Debrecen averaged over 2017 and 2018 years.

3.2. CLIMATE CHAMBER EXPERIMENTS

3.2.1. The Effects of PEG-induced Drought Stress on The Germination Parameters of 2 Soybean Genotypes

3.2.1.1. First-stage Experiment

3.2.1.1.1. The Effects of PEG-induced Drought Stress on The Germination Ratio (%) of 2 Soybean Genotypes

Significant differences were recorded among PEG concentrations of both genotypes.

For genotype *'ES Mentor'*, germination started at the second day after seeding for both 0 (control) and 10% of PEG concentration with significant differences between the two ratios (82.5 and 15.4%, respectively). After that, the control kept a very similar ratio of germinated seeds, whereas (10%) treatment gradually increased until peaking at the fifth day after seeding, where the germination ratio (72.6%) was very close to the peak of the control (83.6%), then a degradation in the germinated seeds was recorded at the sixth day after seeding, followed by continuous increasing without reaching the same peak.

(15%) treatment started germination at the fifth day after seeding with a low ratio (8.8%) compared to both control and (10%) treatment, and gradually increased till the eighth day after seeding, reaching (22%), thereafter a very little decrease was recorded.

(20%) treatment could not germinate until the last day of the experiment, with a very low ratio (7.7%) compared to both control and (10%) treatment.

For genotype *'Pedro'*, only the control could germinate in the second day after seeding with a relatively-high ratio (46%), then further increase (to 81%) at the third day, but after that, a peak with a very small increase (to 83%) was recorded in the fourth day, then in the following days, a fluctuation in germination was recorded; however, it was not extreme. The germination ratio of the control was significantly higher than all of the other concentrations' ratios, regardless of the day-after-seeding.

(10%) treatment started to germinate in the third day (7.7%), and increased gradually till reaching the peak (37.4%) at the fifth day, then a slight reduction (to 31.9%) was recorded at the next day, followed by an increase (to 33.0%) and then a peak (of 41.8%) at the eighth day.

Both (15%) and (20%) treatments had very low germination ratios compared to both control and (10%) treatments.

3.2.1.1.2. The Effects of PEG-induced Drought Stress on The Root elongation (RE) (cm) of 2 Soybean Genotypes

For genotype *'ES Mentor'*, root elongation of control treatment increased rapidly starting from the first day of germination (second day after seeding) (1.7 cm) till the seventh day (16.1 cm), followed by another rapid increase between the eighth and the ninth days (15.5 and 21.6 cm, respectively). The average root elongation was significantly higher than those of the other concentrations starting from the third day.

The root elongation of (10%) concentration slowly increased day after day, with slight decreases at days 5 and 8 after seeding, reaching the peak (8.0 cm) at day 9 with a noticeable increase compared to the previous days. Similarly, (15%) treatment slowly increased during the days after germination, peaking at day 8 (2.6 cm), and slightly decreasing at day 9 (2.0 cm).

(20%) treatment did not give noticeable values, as it started root elongation only at the final day of the experiment.

For genotype *'Pedro'*, the root elongation of the control treatment rapidly (and significantly compared to the other concentrations) increased till day 7 (reaching 13.7 cm), and then slightly increased, until peaking (14.4 cm) at day 9.

The root elongation of (10%) treatment slowly increased during the first few days after germination till day 5 (reaching 2.1 cm), thereafter, a relatively rapid increase was recorded at day 6 (to 4.4 cm), followed by alterations during the next days.

Both (15%) and (20%) concentration treatments acted very similar to genotype *'ES Mentor'*, indicating that under severe drought stress conditions, both genotypes responded similarly to drought stress by means of root elongation.

3.2.1.1.3. The Effects of PEG-induced Drought Stress on The Ultimate germination (UG) of 2 Soybean Genotypes

Both genotypes followed the same trend; increasing PEG concentration was accompanied by significant decrease in (UG). Moreover, *'ES Mentor'* was significantly higher, compared to *'Pedro'*, in UG under both 0 and 10%, whereas it was insignificantly higher under both 15 and 20% PEG concentrations.

3.2.1.1.4. The Effects of PEG-induced Drought Stress on The Mean period of ultimate germination (MPUG) of 2 Soybean Genotypes

For both genotypes, MPUG increased with increasing PEG concentration. Compared to control, MPUG insignificantly increased in (10%) treatment, whereas it was significantly higher in both (15 and 20%) treatments. MPUG was insignificantly lower for *'ES Mentor'* in both control and (10%) treatments, whereas it was higher under the higher concentrations, reflecting the ability of *'Pedro'* to reach the ultimate germination in relatively shorter period of time under drought conditions which, in turn, provides another evidence of *'Pedro'* to tolerate higher water stress levels compared to *'ES Mentor'*; this conclusion is supported by the results of root elongation, which lead to the conclusion that the germinated seeds of *'Pedro'* were able to better tolerate water stress.

3.2.1.1.5. The Effects of PEG-induced Drought Stress on The Percentage inhibition or stimulation (%) of 2 Soybean Genotypes

For both genotypes, the germination inhibition increased with increasing PEG concentration, however, the differences were insignificant. Under each PEG concentration, the inhibition was insignificantly higher for *'Pedro'* compared to *'ES Mentor'*, which is consistent with the results of germination ratio, as *'Pedro'* showed less germination ratio than did *'ES Mentor'* under water stress conditions.

There was significant negative correlation between PEG concentration and root elongation, germination ratio, germination energy and ultimate germination; i.e. increasing drought severity (by increasing PEG concentration) significantly decreases these traits, whereas both mean period of ultimate germination and inhibition percentage were positively correlated with increasing drought severity.

3.2.1.2. Second-stage Experiment

3.2.1.2.1. The Effects of PEG-induced Drought Stress on The Germination Ratio (%) of 2 Soybean Genotypes

For both genotypes, the higher PEG concentrations significantly affected both germination ratio and root length; however, the effects were relatively different on each genotype.

For genotype *'ES Mentor'*, PEG treatments of (0, 2.5 and 5%) started germinating at the second day after seeding; the germination ratio was lower as PEG concentration (drought stress) was higher (74.8, 44.0 and 14.3% for 0, 2.5 and 5%, respectively). However, (2.5%) treatment resulted in very close ratios compared to control after day 2, whereas (5%) treatment reached that only after day 4.

Both (7.5 and 10%) treatments started germination at day 3; however, (10%) treatment could reach a higher final germination ratio (90%) than did (7.5%) treatment (83.6%). (12.5%) treatment started germination at day 4 with a very low ratio (7.7%), and gradually increased till day 8 where a rapid increase (to 73%) was achieved, followed by a final ratio of (77.3%). 15% treatment started germination at day 4 with the same ratio as (12.5%) treatment, however, the daily increase was noticeably less, reaching a final ratio of (23.7%).

For *'Pedro'*, control, (2.5 and 5%) treatments started germination at the second day, but both control and (2.5%) treatments reached the same final ratio of (85.1%), whereas (5%) could reach a slightly higher ratio (87.3%); the difference, however, was insignificant. (7.5%) treatment, although it started germinating at day 3, could reach very close ratios after day 3 compared to (5%) treatment, and after day 5 compared to control and (2.5%) treatments. (10%) treatment could be considered as the middle trend; it started germinating at day 3 with a very low ratio

(5.5%), then rapidly increased till day 6 (76.3%), after that, a measurable decrease was recorded at day 7 (to 47.1%), followed by rapid (to 81.4%), at day 8, and slight (to 82.7%) increase at day 9.

(12.5%) and (15%) treatments followed a very similar trend at most days of the experiment; they started germinating at day 4 (11.0 and 8.8%, respectively), then increased gradually till day 9; however, (12.5%) treatment resulted in much better germination ratios starting from day 8.

From a seed-size standpoint, and in both stages, *'ES Mentor'* (100-seed weight = 201 g) could achieve higher germination ratio compared to *'Pedro'* (100-seed weight = 161 g) (except for 15% at the second-stage experiment); this could lead to a conclusion that seed size plays a role in seed germination ratio under both no-drought and relatively moderate drought stress conditions.

3.2.1.2.2. The Effects of PEG-induced Drought Stress on The Root elongation (RE) (cm) of 2 Soybean Genotypes

For *'Pedro'*, control treatment was significantly higher than the other PEG-concentration treatments starting from the third day after seeding, peaking at day 6 (16.8 cm), whereas all other concentrations gradually increased root elongation day after day (peaking at day 9).

Both (2.5%) and (5%) treatments had very close root elongation values all days long, whereas (7.5%) and (10%) could be considered as the middle trend, though the root elongation was significantly higher for (7.5%) treatment starting from day 6 compared to counterpart values of (10%) treatment.

Both (12.5%) and (15%) treatments had very close values till day 7, where (12.5%) treatment had measurably higher values.

For *'ES Mentor'*, relatively similar results were obtained as compared to *'Pedro'*, except that the differences between (2.5%) and (5%) treatments were relatively less. In addition, (10%), (12.5%) and (15%) treatments had very close values all days long.

3.2.1.2.3. The Effects of PEG-induced Drought Stress on The Ultimate germination (UG) of 2 Soybean Genotypes

For *'ES Mentor'*, (UG) was similar in control, (2.5 and 5%) treatments; however, it significantly decreased in both (12.5 and 15%) treatments. For *'Pedro'* also, same UG (with a value of 26) was recorded for control, (2.5 and 5%) treatments. However, UG decreased under higher PEG concentrations; the reduction was significant in both (12.5 and 15%) treatments.

3.2.1.2.4. The Effects of PEG-induced Drought Stress on The Mean period of ultimate germination (MPUG) of 2 Soybean Genotypes

Both genotypes tended to increase MPUG with increasing PEG concentration, moreover, the increase was significant under the high concentrations (12.5 and 15%) compared to the control and the low concentrations (2.5 and 5%).

3.2.1.2.5. The Effects of PEG-induced Drought Stress on The Percentage inhibition or stimulation (%) of 2 Soybean Genotypes

Similarly for both genotypes, increasing PEG concentration was accompanied by an increase in inhibition percentage; however, it was insignificant for both genotypes.

Same correlation trends were recorded for both genotypes as compared to the first-stage experiment.

3.2.2. The Effects of PEG-induced Drought Stress on The Physiology of 2 Soybean Genotypes

Both genotypes could not survive after V2 stage in 10% PEG treatment, moreover, both 7.5% PEG and 5% PEG treatments caused *'ES Mentor'* plants to die starting from the stage after V4, whereas only 7.5% PEG treatment had a similar effect on Pedro plants.

3.2.2.1. The Effects of PEG-induced Drought Stress on The Total Chlorophyll Content ($Chl_{a,b}$) (µg ml^{-1}) of 2 Soybean Genotypes

For genotype *'ES Mentor'*, both Chl_a and Chl_b decreased as PEG concentration increased at all 4 studied stages; the reduction was insignificant at both vegetative stages (V2 and V4 stages), however, the reduction was significant at reproductive stages (R2 and R4).

For *'Pedro'*, 2.5% PEG treatment had the best Chl_a content at V2 stage, and 5% PEG treatment was also better than control treatment. However at the following stages, control treatment could maintain the best Chl_a content, and the increase in PEG concentration was accompanied by a decrease in Chl_a content. All differences were insignificant. Chl_b, on the other hand, was significantly higher for 5% PEG treatment than control at V2 stage; it was also higher for 2.5 PEG treatment, whereas 7.5% PEG and 10% PEG treatments resulted in the least Chl_b content at this stage. At V4 stage, 2.5% PEG resulted in higher Chl_b content as compared to control treatment, and both 5% PEG and 7.5 PEG treatments were significantly lower. In the following stages (R2 and R4), Chl_b content insignificantly decreased with increasing PEG concentration.

3.2.2.2. The Effects of PEG-induced Drought Stress on The Total Carotenoids (Chl_{x+c}) (µg ml^{-1}) of 2 Soybean Genotypes

For *'ES Mentor'*, control treatment had the highest Chl_{x+c} content at all studied stages compared to PEG treatments; the higher PEG concentration, the lower Chl_{x+c} was, however, the differences were insignificant at all stages except for at R4 stage where control treatment was significantly higher than 2.5% PEG treatment.

For *'Pedro'*, both 2.5% PEG and 5% PEG treatments had higher Chl_{x+c} than control treatment (4.28 ±1.4) at V2 stage, whereas Chl_{x+c} of both 7.5% PEG and 10% PEG treatments were lower. At the following stages, Chl_{x+c} content decreased as PEG concentration increased, but the differences were insignificant.

3.2.2.3. The Effects of PEG-induced Drought Stress on The Maximum Photochemical Efficiency of PS Ⅱ (F_v/F_m) of 2 Soybean Genotypes

For both genotypes, F_v/F_m followed one trend throughout the studied stages; it decreased with increasing PEG concentration. Moreover, for *'ES Mentor'*, control and 2.5% PEG treatments were not significantly different in all stages, however, 5% PEG and 7.5% PEG treatments were significantly less at V4 stage compared to control, whereas the difference was significant only in 7.5% PEG treatment for *'Pedro'*.

3.2.2.4. The Effects of PEG-induced Drought Stress on The Actual photochemical efficiency of PS Ⅱ (ΦPS Ⅱ) of 2 Soybean Genotypes

Increasing PEG concentration was accompanied by a non-significant decrease in (ΦPS Ⅱ) of *'ES Mentor'* in all stages. For *'Pedro'* on the other hand, 2.5% PEG treatment resulted in better, yet not significant, (ΦPS Ⅱ) compared to control treatment at both vegetative stages (V2 and V4), however, control was the highest at later stages and (ΦPS Ⅱ) decreased with increasing PEG concentration.

3.2.2.5. The Effects of PEG-induced Drought Stress on The Stomatal Conductance (g_s) (mmol m^{-2} s^{-1}) of 2 Soybean Genotypes

Significant differences were recorded for both genotypes in response of stomatal conductance to PEG application; increasing PEG concentration resulted in lower stomatal conductance in all stages (except for a slight increase in 5% PEG treatment compared to 2.5% PEG treatment at V2 stage for *'Pedro'*). Control treatment was significantly higher than all other PEG treatments, and 2.5% PEG treatment was significantly better than higher PEG-concentration treatments for *'ES Mentor'*.

Stomatal conductance showed significant negative correlation with drought application at all stages in both genotypes. SPAD value was also negatively affected by drought in both genotypes; the effect was more measurable at R4 stage. In additions, both genotypes showed reduced F_v/F_m value with increasing drought stress at all stages. However, both F_v and F_m were positively correlated with drought stress except at V4 stage in *'ES Mentor'*, whereas both traits were negatively affected by drought in *'Pedro'*, and the most negative effect occurred at R2 stage.

In *'ES Mentor'* all chlorophylls were more affected by drought at reproductive as compared to vegetative stages, whereas in *'Pedro'* Chl_a was most-negatively affected by drought at R2 stage, whereas both Chl_b and Chl_{x+c} were most affected at V4 stage.

Calculating the effect size also reflected the effect of PEG concentration on the different traits studied; except Chl_b at V4 stage and Fv/Fm at R2 stage, PEG concentration was higher and more significant compared to genotype effect.

4. NEW SCIENTIFIC RESULTS

1- SPAD is not a reliable trait when evaluating the effect of drought stress on soybean in the study area, whereas LAI presented a steady trend through stages and genotypes, suggesting that it can be a reliable physiological trait to count on in evaluating soybean's performance in the study area.

2- Ananda and ES Mentor genotypes can be adopted under drought stress conditions in the study area in case optimum seed size is the target of cultivating soybean, whereas Ananda, ES Pallador and Pannonia Kincse genotypes are more suitable for cultivation in the study area, especially under drought conditions, in case the aim of cultivation is the maximum seed yield.

3- Regardless of fertilizer application (N, P) and rate, drought resulted in shorter plants in all field experiments, leading to a conclusion that this physio-morphological trait can be counted as an early-season indicator of the expected yield, taking into consideration that plant height had a positive correlation coefficient in all field experiments. As for yield component traits, both flower and pod number^{-1} showed measurable reductions under drought stress conditions, which can also be taken into consideration for estimating the probable reductions in the final yield caused by this abiotic stress.

4- High protein concentration in the seeds can be achieved by applying high nitrogen fertilizer rates (regardless of its source whether from inoculation or chemical fertilizer); in our experiment, Pannonia Kincse had 3.5% and Boglár had 4.8 and 4.7% seed protein concentration (inoculated and non-inoculated, respectively) when 105 kg ha^{-1} of mineral fertilizer was applied as compared to control treatment with no N fertilizer applied.

5- High oil concentration in the seeds can be achieved by the application of P fertilizer, regardless of water availability for the plants; in our experiment, 45 and 90 kg ha^{-1} of P increased the oil concentration by 5.8 and 10.1% respectively in Pannonia Kincse, and by 5.9 and 10.0% respectively in Boglár as compared to the non-fertilized control.

6- Exogenously-sprayed plants with 1 mM H_2O_2 under drought stress conditions had 21.3% higher seed yield in the case of Pannonia Kincse genotype and 13.3% in the case of Boglár genotype, confirming that this treatment can be extremely beneficial under drought stress conditions.

7- Chl *a* consistently decreased under all drought stress severities and at all studied stages, whereas Chl *b* showed relatively higher levels under mild and moderate drought stress levels at early stages (V2 and V4); however, it followed the similar trend of Chl *a* at later stages (R2 and R4). This conclusion suggests counting on Chl *a* concentration measurement, rather than Chl *b*, to evaluate drought susceptibility when plants are subjected to drought stress early in the season.

8- Stomatal conductance trait showed significant reductions in both studied genotypes, even with mild drought stress application (2.5% PEG concentration) at all stages, suggesting that this trait could also be a suitable early alert of drought occurrence.

5. PRACTICAL UTILIZATION OF RESULTS

1- Low-rate N fertilization of soybean in the study area is recommended under all irrigation regimes, whereas high rates of N are only recommended under relative drought conditions.
2- Relatively-high mineral N-fertilizer rates under drought stress conditions in the study area are of much importance whether the seeds were pre-inoculated or not.
3- The final seed yield was noticeably affected by the application of P-fertilizer, however, the high rate (90P) did not significantly increase the yield compared to the lower rate (45P).
4- P application significantly increased the oil concentration in the produced seeds, with more significant effect under drought stress conditions, whereas it did not affect the protein concentration trait.
5- Treating drought-stressed soybean plants with 1 mM of H_2O_2 could alleviate the negative influence of drought and enhance both the morpho-physiology and the yield of soybean plants.

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7. PUBLICATION LIST

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List of publications related to the dissertation

Hungarian scientific articles in Hungarian journals (1)

1. Ábrahám, É. B., **Basal, O.**: Különböző éréscsoportú szójafajták tesztelése a Hajdúságban. *Agrárunió. 3*, 22-23, 2018. ISSN: 1589-6846.

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