

**Theses of doctoral (PhD) dissertation**

**FLORAL RESPONSES TO THE INCREASING CARBON-DIOXIDE  
CONCENTRATION OF THE AIR**

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## 1. PRELIMINARIES AND OBJECTIVES OF THE DOCTORAL THESIS

Recently, it has become a fact that the image and living communities of the Earth have changed. Due to the use fossil fuels and the declining area of tropical rainforests, humankind has already intervened into natural processes to the extent that it already endangers its very existence. Recognizing the potential impacts of global climate change, the Stockholm Conference of the United Nations in 1972 has already called for the research of the relationship between greenhouse gas emissions and climate change.

The effects of energy production, industry, agriculture and transport on the composition of the atmosphere are currently evident; for example, in the increase of the proportion of greenhouse gases and in the increase of various solid and aerosol particles with various size and chemical composition and dust in the atmosphere. Any quantitative change in the atmospheric components might unbalance the energy distribution of the Earth-atmosphere system and might result in a global change in temperature (*Friedlingstein et al.*, 2006).

A stock of plants is an open ecological system that has a continuous, constant and dynamic interaction with abiotic and biotic environmental factors. The extent of photosynthesis is influenced by a number of external (environmental) factors such as light intensity, CO<sub>2</sub> concentration, temperature, water and nutrient supply, while internal factors include, for example age and physiology of the plant, especially its leaves. There are very important interactions amongst the various factors: environmental factors affect the growth and development of plants, size and composition of the leaf surface, duration of the photosynthesis apparatus and the length of the growing season.

As a preliminary of the research, it was necessary to set up a null hypothesis. The following hypotheses have been raised:

- Changes in CO<sub>2</sub> concentration influence the photosynthetic activity of different plants.
- Changes in CO<sub>2</sub> concentration have a different effect on the photosynthetic activity of different plants.
- Changes in CO<sub>2</sub> concentration have an impact on the morphological characteristics of different plants.

There are important and significant differences between C<sub>3</sub> and C<sub>4</sub> plants in terms of photosynthesis. To examine and analyse the increase of CO<sub>2</sub> concentration, climate chamber experiments are necessary, which are able to model the above.

Most important objectives of the research:

- Elaboration of a cost-effective simulation toolset for the modelling of different climatic conditions.
- Analysis of the effects of CO<sub>2</sub> concentration on the photosynthetic activity of pea, winter wheat and soy plants by means of SPAD measurements.
- Analysis of the effect of CO<sub>2</sub> treatments in different phenological phases on the SPAD values of pea, winter wheat and soy plants.
- Analysis of the CO<sub>2</sub> concentration on the chlorophyll fluorescence parameters of pea, winter wheat and soy plants by means of light- and dark-adapted measurements.
- Analysis of the effect of CO<sub>2</sub> treatments in different phenological phases on the chlorophyll fluorescence parameters of pea, winter wheat and soy plants by means of light- and dark-adapted measurements.
- Quantification of the effect of CO<sub>2</sub> treatments on the morphologic characteristics of pea, winter wheat and soy plants.
- Analysis of the results by means of novel statistical methods.

## **2. MATERIAL AND METHOD**

### **2.1. INTRODUCTION OF THE MEASUREMENT LOCATION**

The measurements were carried out at the Research Institute of Nyíregyháza of DE-AKIT and in the plant growth chamber of the Faculty of Agricultural and Food Sciences and Environmental Management of the University of Debrecen between 2015 and 2018.

### **2.2. VARIETIES ANALYSED IN THE SCOPE OF THE RESEARCH**

The effects of increased CO<sub>2</sub> concentrations on plant development, SPAD and chlorophyll fluorescence parameters were analysed in my experiments. In the scope of the examinations, pea, winter wheat and soy plants were included. The study began with the cultivation of the *Irina* pea variety, followed by the sowing of the autumn wheat variety *KWS Farinelli*. As a third plant, the soybean variety *Pannónia Kincse* (Treasure of Pannonia) was grown. I also planned the examination of maize, but the conditions of plant cultivation in the climatic chambers, light intensity and stress factors made the appropriate analysis of maize impossible, plant development stopped at 7-8 leaf stage.

The *Irina* dry pea variety requires intensive cultivation conditions it has a moderate level of resistance. *KWS Farinelli* is an early maturity variety, which is able to achieve stable quality under intensive circumstances. *Pannónia Kincse* is treasure is the most popular soybean variety of the past years and its production year stability stands out from other varieties.

### **2.3. TREATMENTS OF THE EXPERIMENTS**

In the case of the experiments performed in the climatic chambers, the desired CO<sub>2</sub> concentration in the control chamber was 400 ppm, while the elevated concentration was 600 ppm. Currently the atmospheric CO<sub>2</sub> concentration is slowly reaching 400 ppm. Taking into account the degree of climate change, I considered the effects of the increased 600 ppm CO<sub>2</sub> concentration to be optimal, which could be reached by the actual atmosphere in 50-100 years. CO<sub>2</sub> concentration in the chamber was raised from the CO<sub>2</sub> cylinder to the desired range and it was checked on a daily basis. At the desired target concentration, a difference of  $\pm 5\%$  difference could be kept; when CO<sub>2</sub> concentration decreased or increased, I intervened.

## **2.4. MEASURING EQUIPMENT AND ANALYTICAL METHODS**

### ***CI-340 handheld photosynthesis system and TESTO 535 CO<sub>2</sub> concentration measuring tool***

The CI-340 portable photosynthesis system is a handheld device, which is able to measure plant respiration evaporation, stomatal conductance and the amount and gross difference of incoming and outgoing CO<sub>2</sub>. In the scope of the experiments, it was used for the measurement of CO<sub>2</sub> concentration, which is determined with a decimal accuracy.

The TESTO 535 is a precise CO<sub>2</sub> measurement device, which is suitable for the measurement of the air quality of a room. Maximum and minimum mean values can be measured with its help. The device operated at high accuracy, it does not require constant configuration.

### ***SPAD-502 chlorophyll meter***

The SPAD-502 is manufactured by Minolta (*Minolta Camera Co., Osaka, Japan*); it measures the “greenness” of leaves (*Minolta, 1990*). This “greenness” and the correlation of the differences amongst acetone-extracted chlorophyll contents measured in spectrophotometers was examined by *Marquard and Tipton (1987)* and they found that there were significant correlations amongst the values. Its operating principle was elaborated by *Inada (1963)*, it is based on the determination of the penetration of light through the leaf at 650 and 940 nm wavelength. It measures the proportion of the red and near infrared spectrum penetrating the 2x3 mm area of the leaf (*Schröder et al., 2000*). The device calculates relative chlorophyll content (SPAD value) from the intensity of the emitted and incoming light, which varies between 1 and 100.

### ***OS5p+ chlorophyll fluorescence meter***

The OS5p+ is a portable system, which includes the latest developments for various chlorophyll fluorescence measurements. The OS5p+ is able to measure most of the changes caused by plant stress and it elaborates an automated, wide-range and up-to-date measurement log based on the measured data, which is stored in its memory (*OS5p user's guide*).

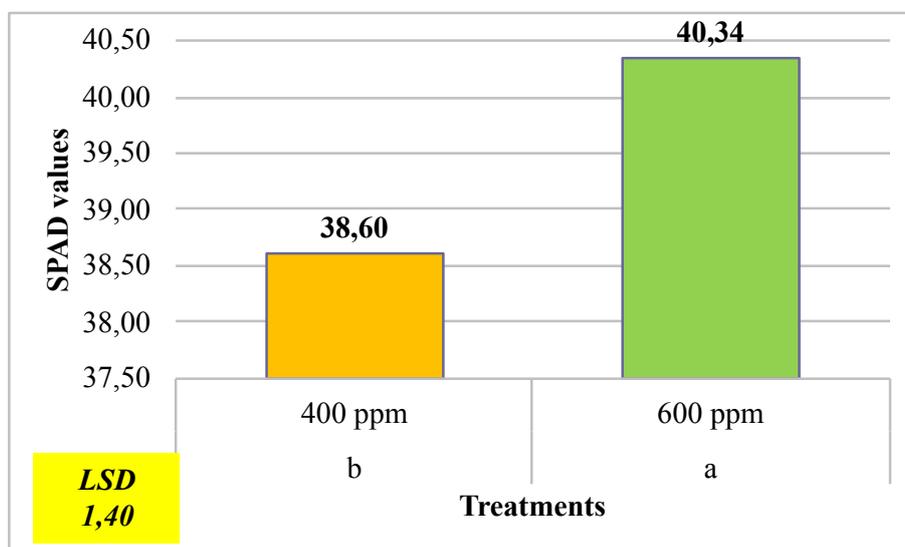
### ***Statistical evaluation of the experiment data***

The statistical analysis was carried out in R 1.1.383 statistical environment (*R Core Team, 2016*) with RStudio (*RStudio Team, 2016*) graphic interface, and the use of *gplots (Warnes et al., 2015)*, *car (Fox és Weisberg, 2011)* and *agricolae (de Mendiburu, 2016)* packages. The diagrams were prepared with the Mac Ms Excel 15.40 software. Type I error was set at 5% ( $\alpha = 0.05$ ).

### 3. RESULTS

#### 3.1. Results of the chlorophyll content analyses

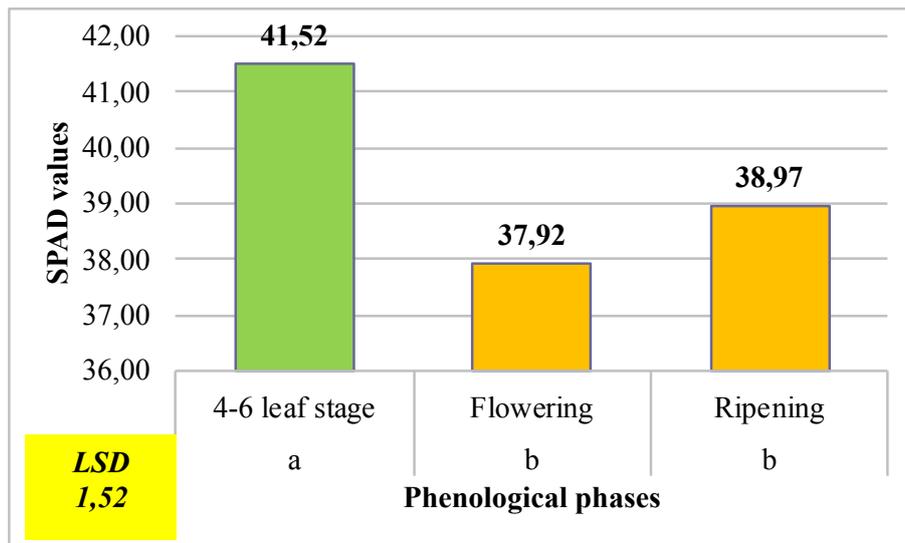
The effect of CO<sub>2</sub> treatments on SPAD values in pea experiments was analysed by means of a post hoc test, which resulted in two homogenous groups, where there were significant differences. The highest SPAD value was measured at 600 ppm CO<sub>2</sub> concentration, the mean SPAD value was 40.34. Higher CO<sub>2</sub> concentration resulted in 1.74 higher SPAD values, than the lower, 400 ppm concentration. It can be established, that in comparison with the atmospheric concentration, the elevated CO<sub>2</sub> concentration significantly increased SPAD values (Figure 1).



*Data indicated in different colours are different based on the LSD test*

**Figure 1:** Effect of CO<sub>2</sub> concentration on the SPAD values of pea

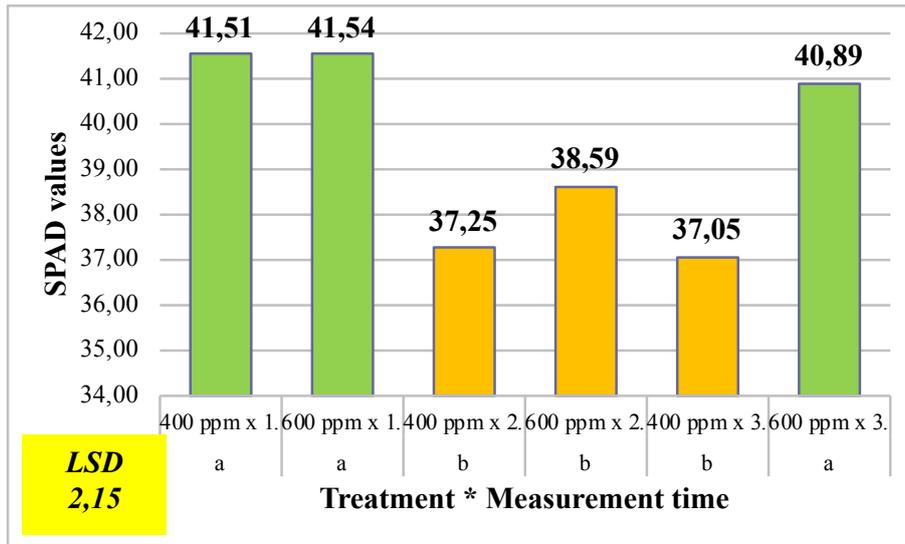
Correlation was found in terms of the chlorophyll content by phenological phase, the effect of which is shown in Figure 11. On the basis of the post hoc test, two homogenous groups are distinguished, which are significantly ( $P < 0.001$ ) different from each other. The highest values (mean: 41.52 SPAD value) were measured at 4-6 leaf stage. 3.6 lower SPAD values were measured during flowering and 2.55 lower SPAD values during the phenological phase of ripening. The lowest values were measured during flowering: 37.92 SPAD value (Figure 2).



*Data indicated in different colours are different based on the LSD test*

**Figure 2:** Effect of the CO<sub>2</sub> treatment on SPAD values of pea by phenological phase

The difference amongst SPAD values was significant in the case of the interaction of CO<sub>2</sub> concentration and phenological phases as well. Higher CO<sub>2</sub> concentration resulted in increased SPAD values measured at the given moment. The highest SPAD values were measured at 4-6 leaf stage in both treatments; there was no real difference: 0.03 SPAD value. The lowest SPAD value (37.05) was measured at 400 ppm concentration, during ripening; it significantly ( $P < 0.05$ ) differed from the values measured at the elevated CO<sub>2</sub> concentration (40.89). During the phenological phase of flowering, the mean SPAD value of 38.59 was caused by the higher CO<sub>2</sub> concentration, which although surpassed the value of the 400 ppm CO<sub>2</sub> treatment measured at the same moment by 1.34, but the difference is not significant (Figure 3).



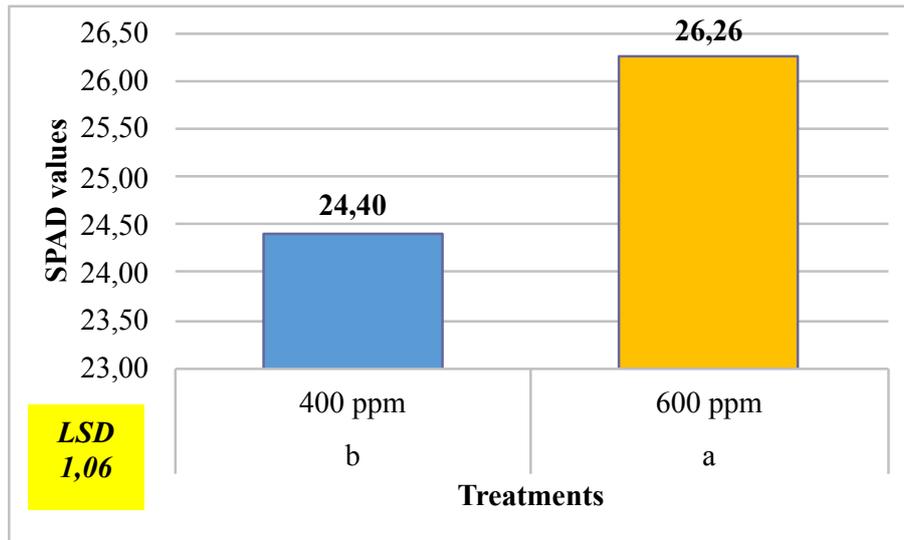
Data indicated in different colours are different based on the LSD test

1: 4-6 leaf phase; 2: flowering phase; 3: ripening phase

**Figure 3:** Interaction of the treatment and phenological phases on the SPAD values of pea

The effect of CO<sub>2</sub> on the SPAD values of pea was examined. In the average of the measurements and based on the results of the repeated measurement model, the increase of CO<sub>2</sub> concentration at a 0.05% level of significance has an effect on the measured SPAD values. Besides, phenological phase (P<0.001), and their interaction (P<0.05) significantly affected the development of SPAD values.

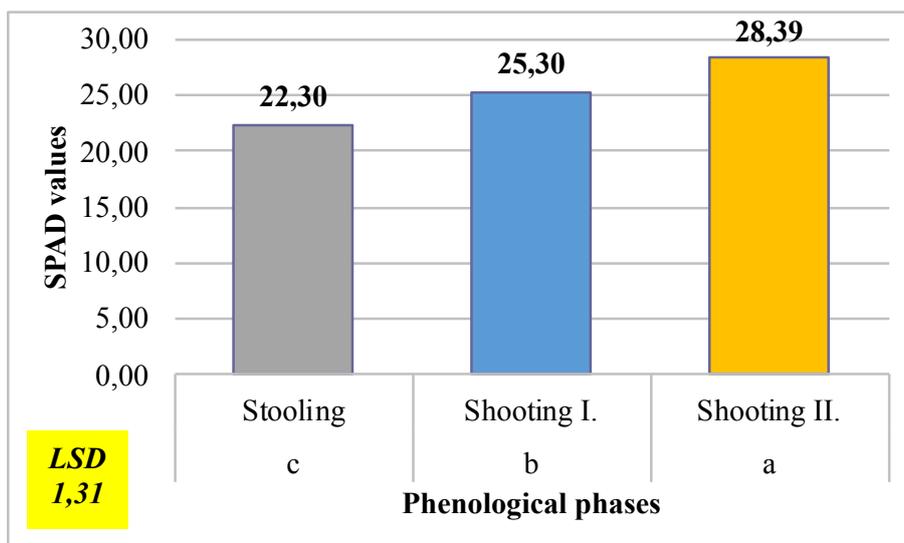
In the winter wheat experiment, the effect of CO<sub>2</sub> treatments on SPAD values were analysed again via a post hoc test, in the course of which two homogenous groups are distinguished, differing significantly from each other (P<0.05). The highest SPAD value was measured at 600 ppm CO<sub>2</sub> concentration, its mean value is 26.26. Higher CO<sub>2</sub> concentration resulted in 1.86 higher SPAD value in average, than the lower 400 ppm concentration. It can be established that in comparison with the atmospheric concentration, the elevated CO<sub>2</sub> concentration significantly increased SPAD values (Figure 4).



Data indicated in different colours are different based on the LSD test

**Figure 4:** Effect of CO<sub>2</sub> concentration on the SPAD values of winter wheat

SPAD values were affected by phenological phases as well, which shown in Figure 5. According to the post hoc test, three homogenous groups are distinguished, which have a significant ( $P < 0.001$ ) difference. The highest values (mean value: 28.39) were measured in the shooting II phenological phase. A 3.09 lower SPAD value was measured in the shooting I phase and 6.09 lower in the stooling phenological phase. The lowest mean value was measured during stooling (22.30) (Figure 5).



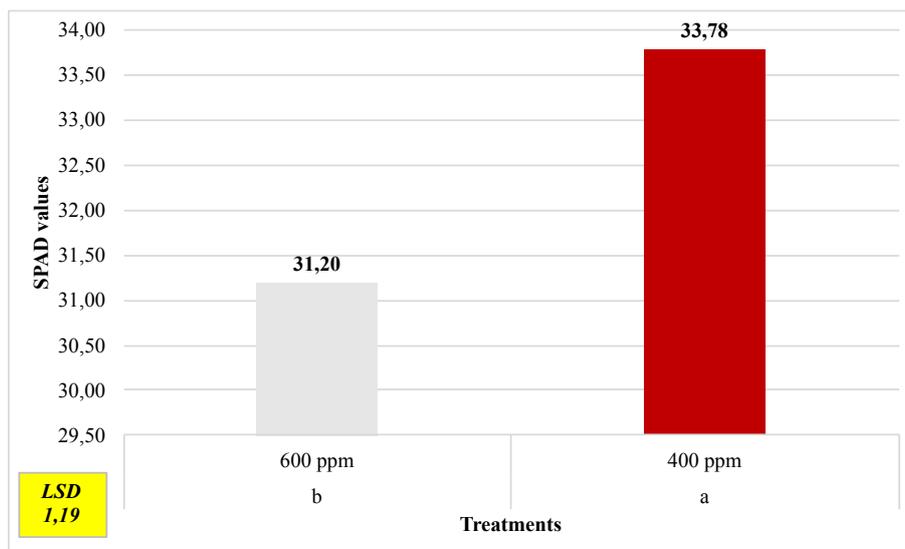
Data indicated in different colours are different based on the LSD test

**Figure 5:** Effect of the CO<sub>2</sub> treatment on the development of SPAD values of winter wheat by phenological phase

Interaction of CO<sub>2</sub> concentration and phenological phases did not affect SPAD values significantly. Higher CO<sub>2</sub> concentration resulted in increased SPAD values measured at the given moment. The highest SPAD values were measured in shooting II phenological phase, where the difference is 2.12 SPAD value. The lowest SPAD value (21.75) was measured at 400 ppm concentration, during stooling. During the shooting I phenological phase, the mean SPAD value of 26.47 was caused by the higher CO<sub>2</sub> concentration, which although surpassed the value of the 400 ppm CO<sub>2</sub> treatment measured at the same moment by 2.34, but the difference is not significant.

In the course of the research, soybean was used as crop under laboratory circumstances. The experiment sought the answer to the question how carbon-dioxide concentration and the concentration in different phenological phases influences SPAD values measured at different development stages of soybean.

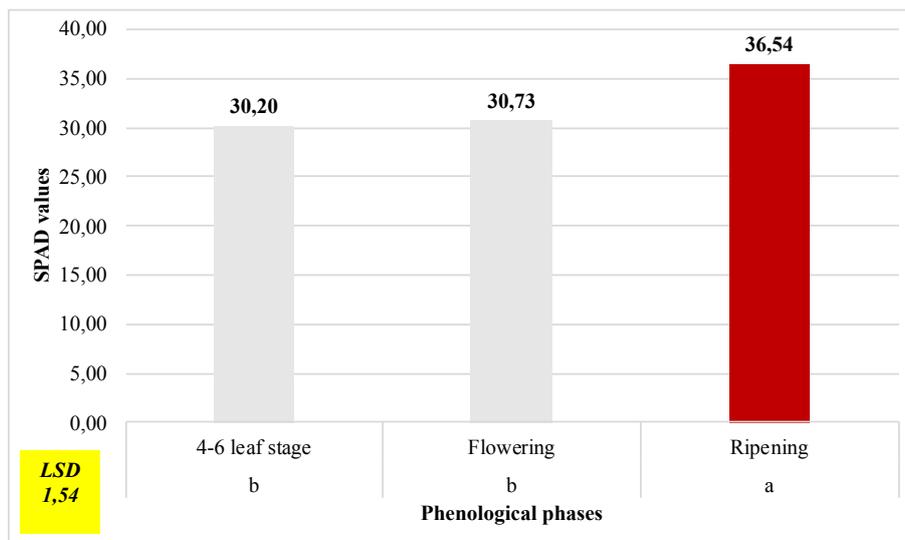
The effect of CO<sub>2</sub> treatments on SPAD values were analysed again via a post hoc test, in the course of which two homogenous groups are distinguished, differing significantly from each other ( $P < 0.001$ ). The higher mean SPAD value was measured at 400 ppm CO<sub>2</sub> concentration, its mean value is 33.78. Atmospheric CO<sub>2</sub> concentration resulted in 2.58 higher SPAD value in average, than the elevated 600 ppm concentration. It can be established that SPAD values measured at atmospheric concentration significantly differed from those measured at elevated CO<sub>2</sub> concentration (Figure 6).



*Data indicated in different colours are different based on the LSD test*

**Figure 6:** Effect of CO<sub>2</sub> concentration on the SPAD values of soybean

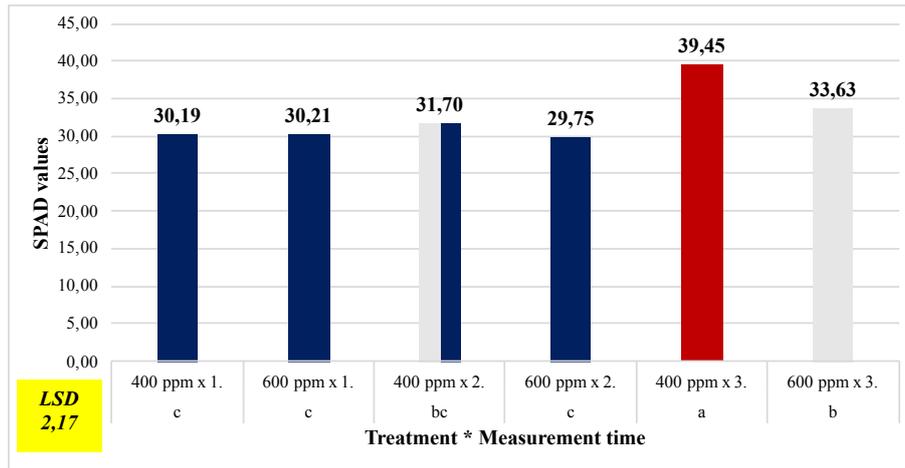
SPAD values of soybean are affected by CO<sub>2</sub> concentration in each phenological phase; the effect is shown in Figure 17. According to the post hoc test, two homogenous groups are distinguished, which are significantly ( $P < 0.001$ ) different from each other. The highest mean SPAD value (36.54) was measured during the phase of ripening. 5.81 lower SPAD values were measured during flowering and 6.34 lower SPAD values during the 4-6 leaf stage. The lowest values were measured in the 4-6 leaf stage: 30.2 SPAD value (Figure 7).



*Data indicated in different colours are different based on the LSD test*

**Figure 7:** Effect of CO<sub>2</sub> treatment on the development of SPAD values of soybean by phenological phase

Interaction of CO<sub>2</sub> concentration and phenological phases significantly differed based on the measured SPAD value. Usually, atmospheric CO<sub>2</sub> concentration resulted in increased SPAD values. The highest SPAD value was measured in the ripening phase in both treatments, but the mean values measured at atmospheric concentration significantly surpassed (by 5.82 SPAD value) the values measured at 600 ppm concentration. The lowest mean SPAD values (30.19 and 30.21) were measured in the 4-6 leaf stage; they significantly ( $P < 0.001$ ) differed from the mean values measured during ripening. During the phenological phase of flowering, higher mean SPAD values were caused by the 400 ppm CO<sub>2</sub> concentration, which significantly ( $P < 0.05$ ) differed from the values measured at ripening, but the difference was not significant in the given phase (Figure 8).



Data indicated in different colours are different based on the LSD test

1: 4-6 leaf stage; 2: flowering phase; 3: ripening phase

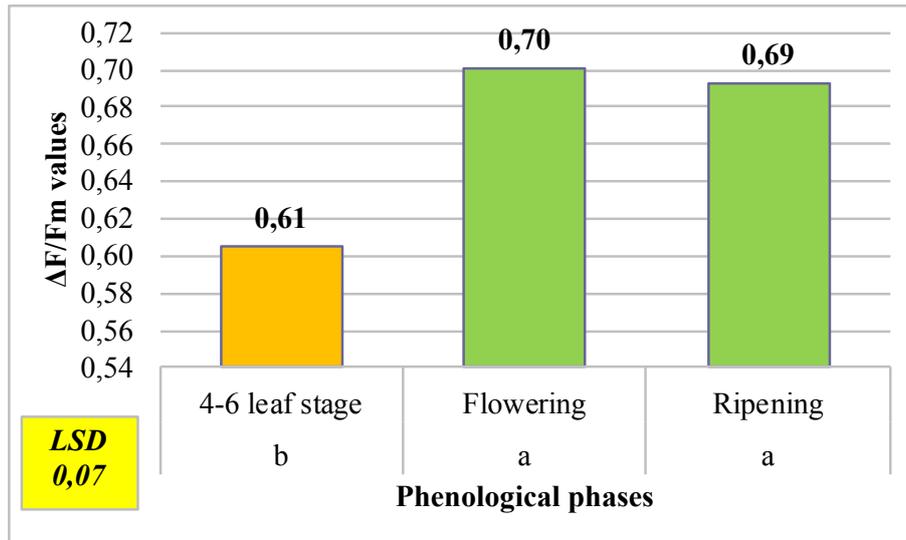
**Figure 8:** Effect of the interaction of the treatment and phenological phases on the SPAD values of soybean

The effect of CO<sub>2</sub> concentration on the mean SPAD values of soybean was examined. According to the average of the measurements and the results of the repeated measurement model, CO<sub>2</sub> concentration at a 0.05% level of significance has an effect on the measured SPAD values. Besides, phenological phase (P<0.001), and their interaction with the measurement times (P<0.01) significantly differed from each other.

### 3.2. Actual quantum efficiency of light-adapted reaction centres ( $\Delta F/F_m$ )

In the case of pea, the analysis of the effect of CO<sub>2</sub> treatments on  $\Delta F/F_m$  values resulted in a homogenous group, which significantly differed from each other. In the case of 600 ppm concentration 0.667, while at 400 ppm, 0.664 were measured.

CO<sub>2</sub> concentration affects  $\Delta F/F_m$  values in the case of pea, the effect of which is shown in Figure 9. Based on the post hoc test, two homogenous groups are distinguished, which are significantly (P<0.05) different from each other. The highest values (mean value: 0.7) were measured during the flowering phase. 0.9 lower SPAD values were measured during the 4-6 leaf stage, which was significantly different. Additionally, 0.01 lower value was measured during the phenological phase of ripening, but in this case, the different is not verifiable (Figure 9).

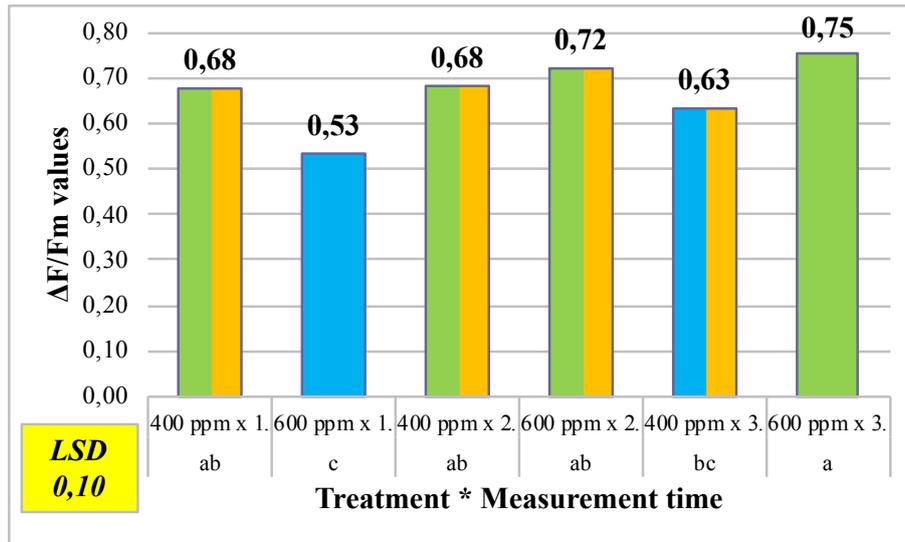


*Data indicated in different colours are different based on the LSD test*

**Figure 9:** Effect of the CO<sub>2</sub> treatment on  $\Delta F/F_m$  values of pea by phenological phase

In the interaction of CO<sub>2</sub> concentration and phenological phases, the difference was significant for the measured  $\Delta F/F_m$  values. With the increase of the CO<sub>2</sub> concentration, values were increased during flowering and ripening, but a decline was recorded during the 4-6 leaf stage. The highest values were measured at 600 ppm CO<sub>2</sub> concentration, during flowering (0.72) and ripening (0.75), while the lowest value (0.53) was measured at 600 ppm concentration, in the 4-6 leaf stage, which significantly ( $P < 0.01$ ) differed from the values measured at lower CO<sub>2</sub> concentration. In the case of atmospheric concentration, no extreme values were measured.

In the phenological phase of flowering, there was no significant difference between the two concentrations. During ripening, elevated CO<sub>2</sub> concentration resulted in higher  $\Delta F/F_m$  values, which surpassed the values measured at 400 ppm CO<sub>2</sub> concentration by 0.12 and differed significantly ( $P < 0.01$ ) (Figure 10).



Data indicated in different colours are different on the basis of the LSD test

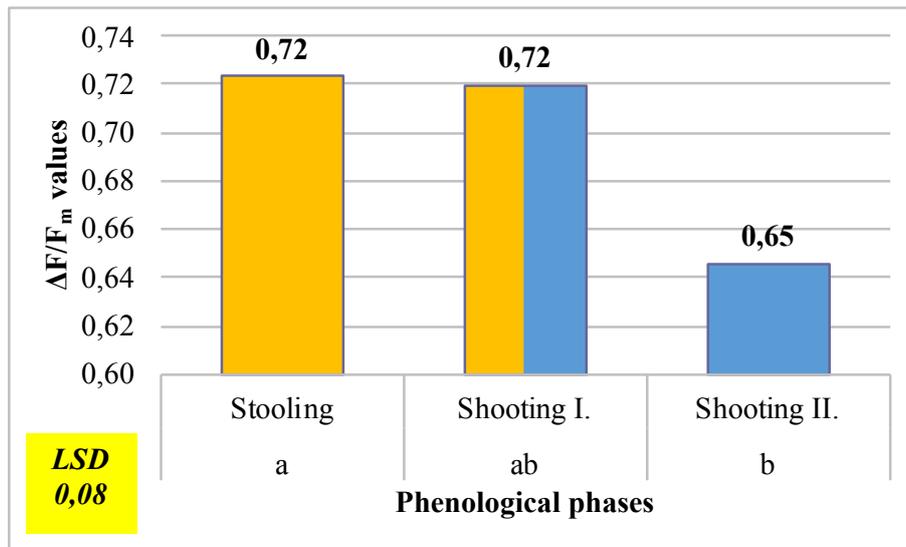
1: 4-6 leaf stage; 2: flowering phase; 3: ripening phase

**Figure 10:** Effect of the interaction of the treatment and phenological phases in the  $\Delta F/F_m$  values of pea

The effect of CO<sub>2</sub> on  $\Delta F/F_m$  values was examined. In the average of the measurements and based on the results of the repeated measurement model, the increase of CO<sub>2</sub> concentration at a 0.05% level of significance has an effect on the  $\Delta F/F_m$  values. However, phenological phases and their interaction with CO<sub>2</sub> ( $P < 0.05$ ) significantly affected  $\Delta F/F_m$  values.

Analysis of the effect of winter wheat CO<sub>2</sub> treatments on  $\Delta F/F_m$  resulted in a homogenous group that do not differ significantly from each other. In the case of 600 ppm concentration 0.70, at 400 ppm 0.69 mean values were measured.

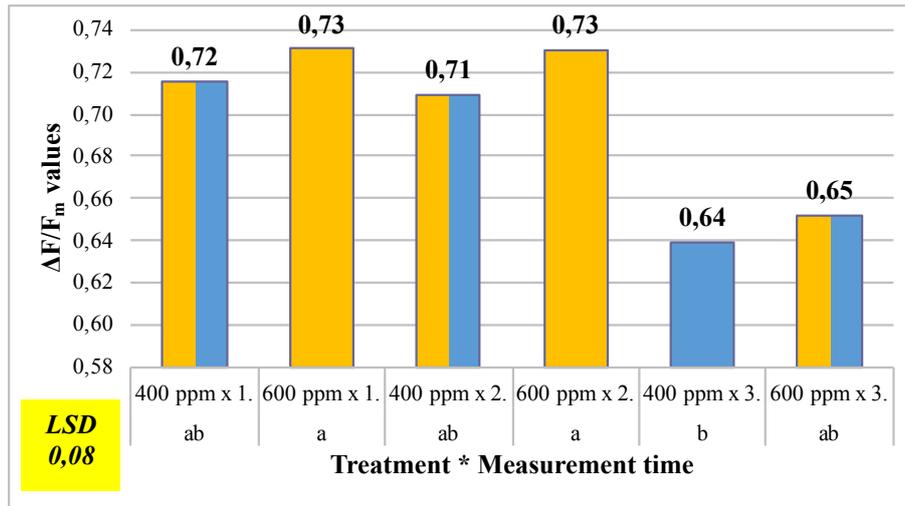
CO<sub>2</sub> concentration affected the  $\Delta F/F_m$  values of winter wheat by in each phenological phase, the effect of which is shown in Figure 11. Based on the post hoc test, two homogenous groups are distinguished, which are significantly ( $P < 0.05$ ) different from each other. The highest value (mean value: 0.72) was measured during the stouling phase. Identical values were measured during the shooting I phase, which did not differ significantly. Additionally, 0.07 lower value was measured during the shooting II phenological phase, where the difference was significant ( $P < 0.05$ ) (Figure 11).



*Data indicated in different colours are different based on the LSD test*

**Figure 11:** Effect of the CO<sub>2</sub> treatment on ΔF/F<sub>m</sub> values of winter wheat by phenological phase

The interaction of CO<sub>2</sub> concentration and phenological phases there was no detectable effect on ΔF/F<sub>m</sub> values in the case of winter wheat. With the increase of CO<sub>2</sub> concentration, higher values were measured in all three phenological phases. The highest values were measured at 600 ppm CO<sub>2</sub> concentration, during stooling (0.73) and shooting I phase (0.73), the lowest value (0.64) at 400 ppm concentration, in the shooting II phase. It can be established, that in the case of 600 ppm concentration, mean values were higher in all three phenological phases, but no significant results was recorded (Figure 12).



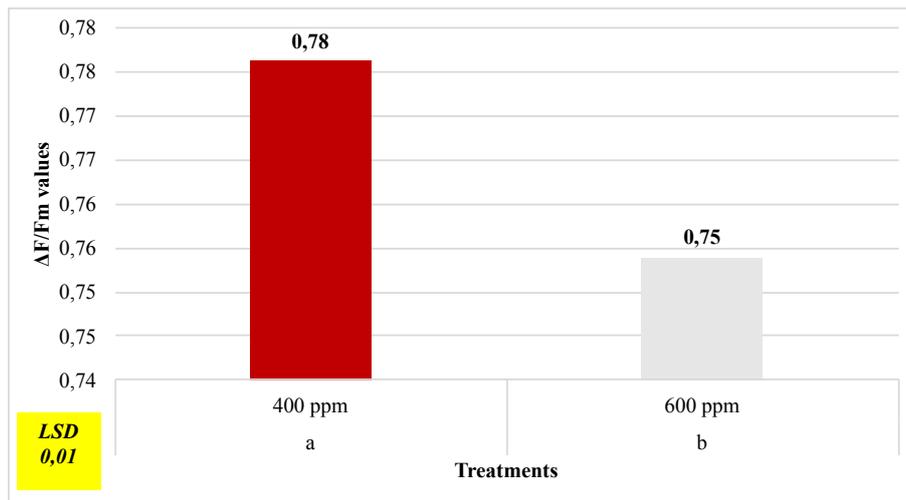
Data indicated in different colours are different on the basis of the LSD test

1: stooling phase; 2: shooting I phase; 3: shooting II phase

**Figure 12:** Effect of the interaction of treatments and phenological phases on the  $\Delta F/F_m$  values of winter wheat

The effect of CO<sub>2</sub> on the mean  $\Delta F/F_m$  values of winter wheat was examined. In the average of the measurements and based on the results of the repeated measurement model, the increase of CO<sub>2</sub> concentration at a 0.05% level of significance had no effect on the  $\Delta F/F_m$  values. Significant result was recorded in terms of phenological phases, but there was no significant difference amongst  $\Delta F/F_m$  values in the case of the interaction of the phenological phase and CO<sub>2</sub> concentration.

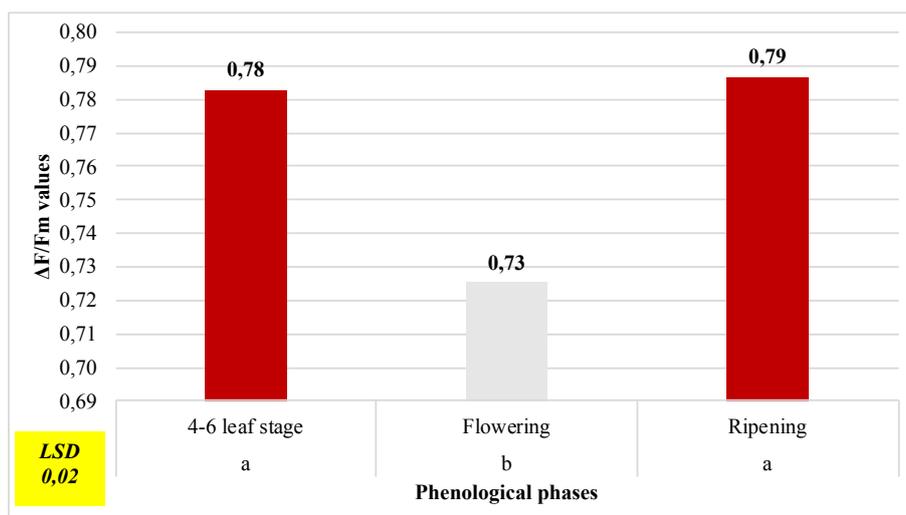
Analysis of the effect of CO<sub>2</sub> treatments on  $\Delta F/F_m$  values of soybean was carried out by means of a post hoc test; two homogenous groups are distinguished and a significant ( $P < 0.01$ ) difference was recorded. Higher mean  $\Delta F/F_m$  values were measured at atmospheric concentration, which had a mean value of 0.78. This value surpassed the mean value measured at the elevated CO<sub>2</sub> concentration by 0.03. It can be established, that there is a significant difference in the average of  $\Delta F/F_m$  values measured at atmospheric concentration, in comparison with the elevated CO<sub>2</sub> concentration (Figure 13).



Data indicated in different colours are different based on the LSD test

**Figure 13:** Effect of CO<sub>2</sub> concentration on the ΔF/F<sub>m</sub> values of soybean

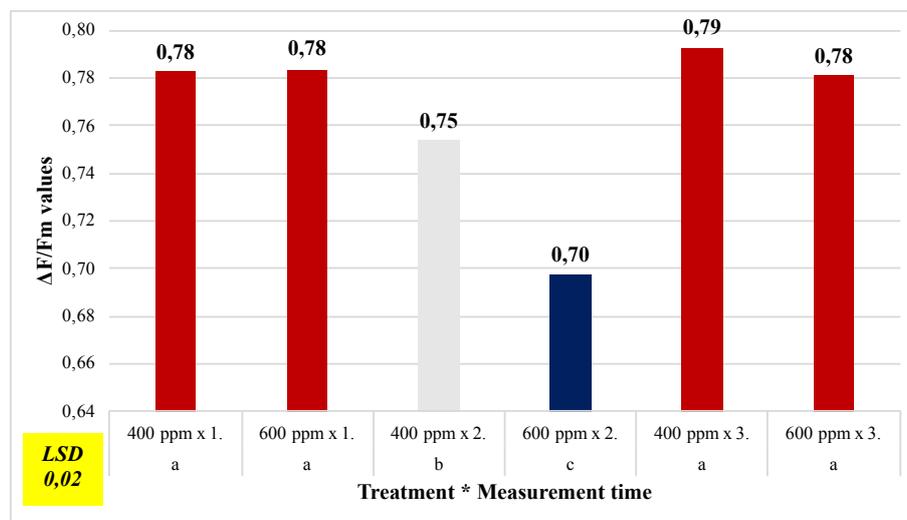
Different effect was recorded on the ΔF/F<sub>m</sub> values in each phenological phase; this is shown in the effect of which is shown in Figure 14. Based on the post hoc test, two homogenous groups are distinguished, which are significantly (P<0.001) different from each other. The highest value (mean value: 0.79) was measured during the ripening phase. A mean value of 0.78 was recorded on the 4-6 leaf stage. There was no difference between these two groups, however during in the flowering phase, the 0.73 mean value significantly differs from the other group (Figure 14).



Data indicated in different colours are different based on the LSD test

**Figure 14:** Effect of the CO<sub>2</sub> treatment on ΔF/F<sub>m</sub> values of soybean by phenological phase

When examining soybean, significant values can be observed in the case of the interaction of CO<sub>2</sub> concentration and phenological phase. Mean values measured in the 4-6 leaf stage did not differ. During flowering, a considerable reduction was measurable in both CO<sub>2</sub> concentrations, at atmospheric CO<sub>2</sub> it was 0.03, while in the case of the elevated CO<sub>2</sub> concentration it was 0.08 compared to the first measurements, which was significant in both cases. In the phase of ripening, the 400 ppm CO<sub>2</sub> concentration resulted in a higher  $\Delta F/F_m$  mean value, but it was only 0.01 higher compared to the 600 ppm CO<sub>2</sub> concentration, therefore the difference was not significant in this phase (Figure 15).



Data indicated in different colours are different based on the LSD test

1: 4-6 leaf stage; 2: flowering phase; 3: ripening phase

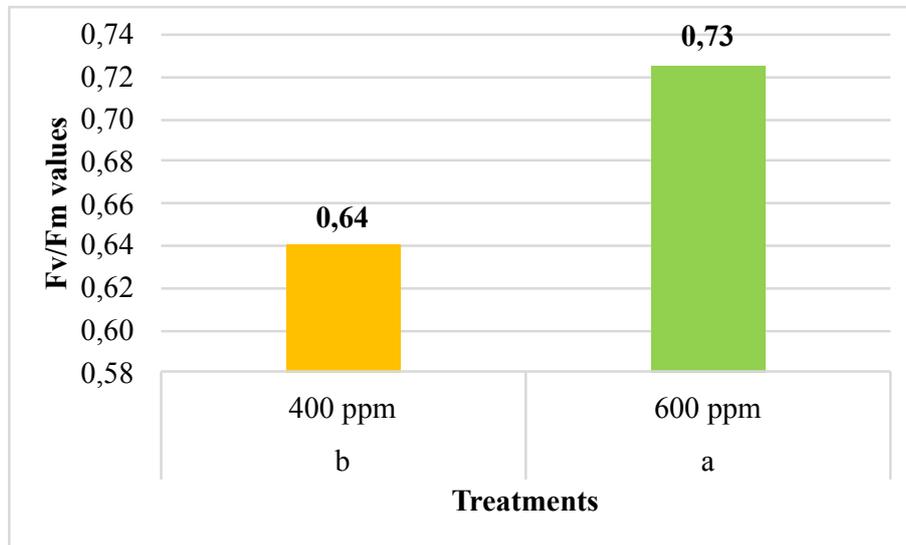
**Figure 15:** Effect of the interaction of the treatment and phenological phases on the  $\Delta F/F_m$  values of soybean

The effect of CO<sub>2</sub> on  $\Delta F/F_m$  values was examined. In the average of the measurements and based on the results of the repeated measurement model, the increase of CO<sub>2</sub> concentration at a 0.05% level of significance has an effect on the  $\Delta F/F_m$  values. In the case of phenological phases ( $P < 0.001$ ) and their interaction with CO<sub>2</sub> ( $P < 0.01$ ) significantly results were found.

### 3.3. Maximum quantum efficiency of PSII reaction centres ( $F_v/F_m$ )

Analysis of the effect of CO<sub>2</sub> treatments in the case of pea by means of a post hoc test resulted in two homogenous groups, which are significantly ( $P < 0.01$ ) different from each other. The highest  $F_v/F_m$  values were measured at 600 ppm CO<sub>2</sub> concentration, their mean

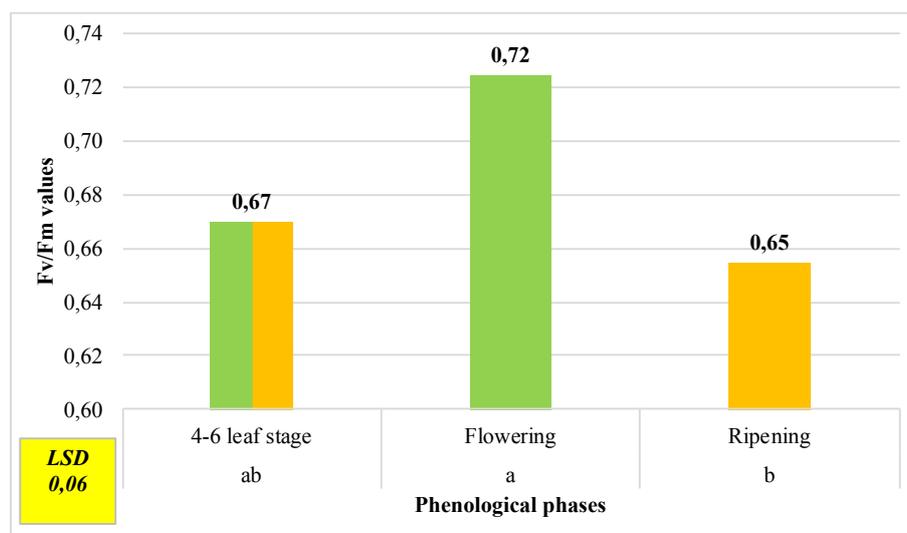
value was 0.73. Higher CO<sub>2</sub> concentration resulted in 0.09 higher values, than the lower, 400 ppm concentration. It can be established, 600 ppm CO<sub>2</sub> concentration significantly (P<0.01) increased the value of F<sub>v</sub>/F<sub>m</sub> in comparison with the 400 ppm concentration (Figure 16).



Data indicated in different colours are different based on the LSD test

**Figure 16:** Effect of CO<sub>2</sub> concentration on the F<sub>v</sub>/F<sub>m</sub> values of pea

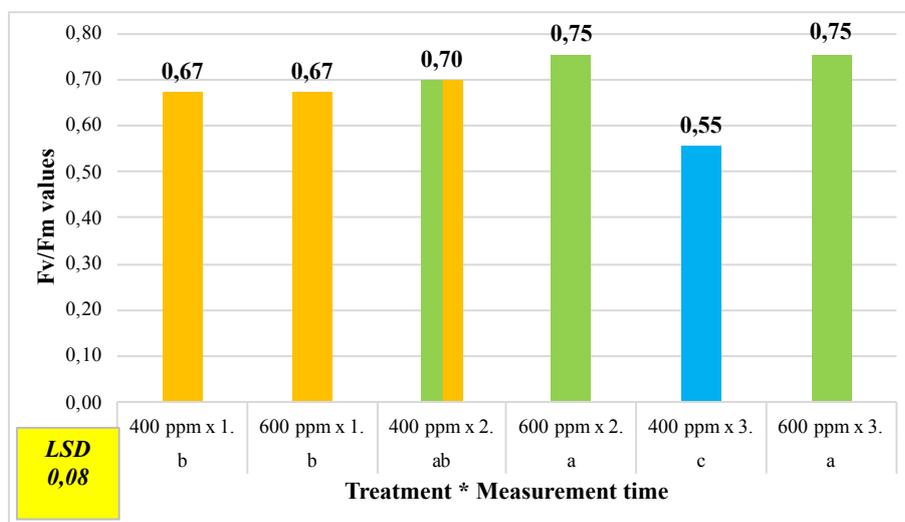
The F<sub>v</sub>/F<sub>m</sub> value was not significantly affected by the CO<sub>2</sub> concentration in the phenological phases on P<0.05 level of significance. The highest value was measured during flowering (0.72). The lowest mean value was recorded during ripening (0.65) (Figure 17).



Data indicated in different colours are different based on the LSD test

**Figure 17:** Effect of the CO<sub>2</sub> treatment on the F<sub>v</sub>/F<sub>m</sub> values of pea by phenological phase

Interaction of the CO<sub>2</sub> concentration and the phenological phases had a significant effect (P<0.01) on the measured F<sub>v</sub>/F<sub>m</sub> values. With the increase of the CO<sub>2</sub> concentration – except for the 4-6 leaf stage where identical mean values were recorded (0.67) - F<sub>v</sub>/F<sub>m</sub> values have increased. The highest value (0.75) was measured in during the phenological phases of flowering and ripening. The lowest value was recorded at 400 ppm CO<sub>2</sub> concentration; it was 0.2 lower than in the case of 600 ppm CO<sub>2</sub> concentration, thus it shows a P<0.01 significant difference. During flowering, the higher CO<sub>2</sub> concentration resulted in a higher value as well; it surpassed the mean F<sub>v</sub>/F<sub>m</sub> value measured at the same time at 400 ppm CO<sub>2</sub> concentration by 0.05, but in this phenological phase, the difference was not significant (Figure 18).



Data indicated in different colours are different based on the LSD test

1: 4-6 leaf stage; 2: flowering phase; 3: ripening phase

**Figure 18:** Effect of the interaction of the treatment and phenological phases on the F<sub>v</sub>/F<sub>m</sub> values of pea

The effect of CO<sub>2</sub> on the mean F<sub>v</sub>/F<sub>m</sub> values of pea was examined. In the average of the measurements and based on the results of the repeated measurement model, the increase of CO<sub>2</sub> concentration at a 0.05% level of significance affected F<sub>v</sub>/F<sub>m</sub> values. No significant result was recorded in terms of phenological phases at 0.05% level of significance. However, the interaction of phenological phases and CO<sub>2</sub> concentration had a significant effect on F<sub>v</sub>/F<sub>m</sub> values.

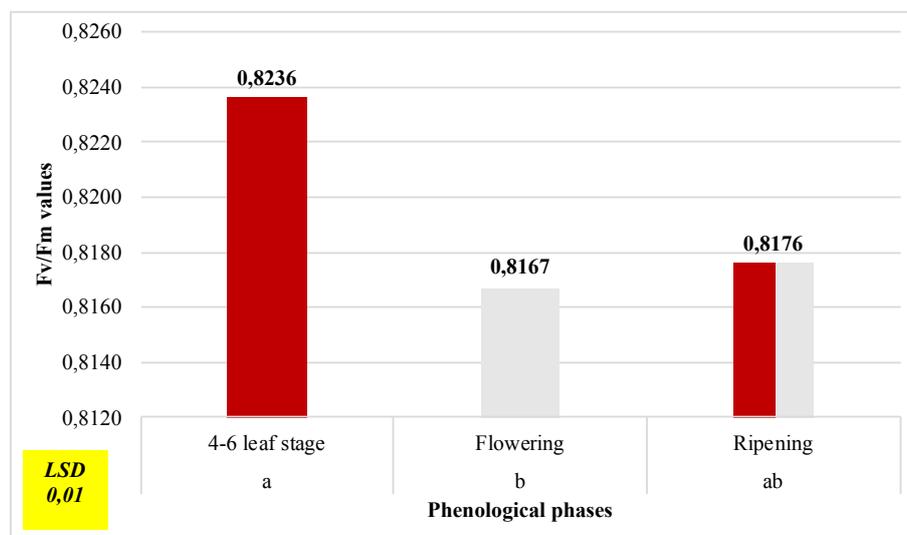
The effect of CO<sub>2</sub> on the F<sub>v</sub>/F<sub>m</sub> values of winter wheat was examined. The value of F<sub>v</sub>/F<sub>m</sub>, if the circumstances of development are optimal, is around 0.832 ± 0.004 in the case of

living plants (Björkmann and Demmig- Adams, 1987). In the average of the measurements and based on the results of the repeated measurement model, the increase of CO<sub>2</sub> concentration at a 0.05% level of significance did not influence F<sub>v</sub>/F<sub>m</sub> values. However, based on the individual measurements, a considerable variability was observed in terms of the F<sub>v</sub>/F<sub>m</sub> value, as it was established by Veres *et al.* (2011).

There was no close correlation among phenological phases on 0.05% probability level and the interaction of the phenological phase and CO<sub>2</sub> concentration did not affect significantly the F<sub>v</sub>/F<sub>m</sub> values.

Analysis of the effect of CO<sub>2</sub> treatments via a post hoc test in the case of soybean resulted in a homogenous group that do not differ significantly from each other. In the case of 400 ppm concentration 0.82, at 600 ppm 0.81 mean values were measured.

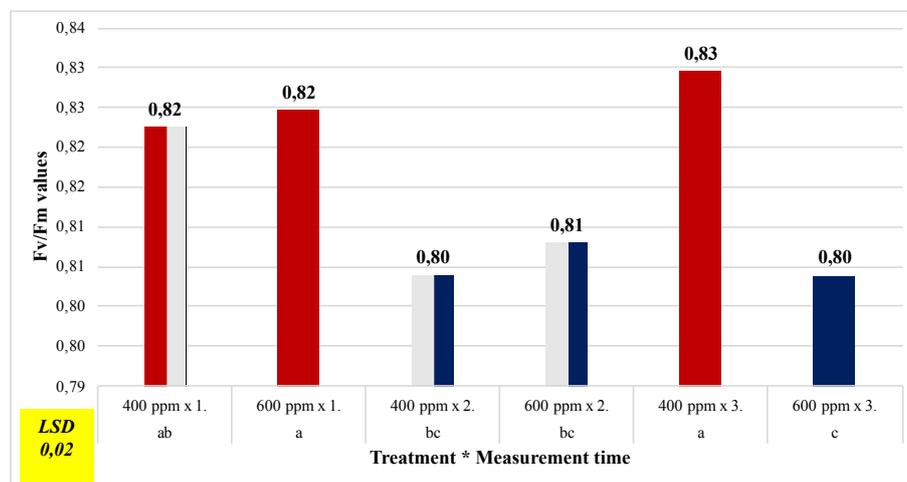
However, the treatment influenced F<sub>v</sub>/F<sub>m</sub> values in each phenological phase, which is shown in Figure 19. According to the post hoc test, two homogenous groups are distinguished, where there is a significant (P<0.05) difference. The highest mean F<sub>v</sub>/F<sub>m</sub> value was measured in the 4-6 leaf stage (0.8236). During flowering, the mean value was 0.8167, which differed significantly. During ripening, the measured mean value (0.8176) was not significantly different as compared to the mean values measured during the other two growth phases. (Figure 19).



Data indicated in different colours are different based on the LSD test

**Figure 19:** Effect of the CO<sub>2</sub> treatment on F<sub>v</sub>/F<sub>m</sub> values of soybean by phenological phase

Interaction of CO<sub>2</sub> concentration and phenological phases had a significant (P<0.05) effect on the measured F<sub>v</sub>/F<sub>m</sub> values. The elevated CO<sub>2</sub> concentration resulted in higher mean values in the 4-6 leaf stage and during flowering, while a considerable change was measured during ripening. There was no significant difference between the two CO<sub>2</sub> concentrations during the 4-6 leaf stage. The same was found during flowering in terms of the two concentrations. However, during the ripening phase, a significant (P<0.05) difference was measured between the two CO<sub>2</sub> concentrations. Examining measurement times, it can be established that the mean values measured during flowering significantly differ from the ones measured in other periods. The lowest mean value was measured at 600 ppm CO<sub>2</sub> concentration during the ripening phase (Figure 20).



Data indicated in different colours are different based on the LSD test

1: 4-6 leaf stage; 2: flowering phase; 3: ripening phase

**Figure 20:** Effect of the interaction of the treatment and phenological phases on the F<sub>v</sub>/F<sub>m</sub> values of soybean

The effect of CO<sub>2</sub> on F<sub>v</sub>/F<sub>m</sub> values was examined as well. In the average of the measurements and based on the results of the repeated measurement model, it was found that the increase of CO<sub>2</sub> concentration at a 0.05% level of significance did not have an effect on the F<sub>v</sub>/F<sub>m</sub> values. However, mean values measured in different growth phases and the interaction of the treatment and the measurement time had significant (P<0.05) effects.

### **3.4. Effect of CO<sub>2</sub> concentration on the morphologic characteristics of the analysed plants**

Elevated CO<sub>2</sub> concentration affects the morphologic characteristics of plants as well. In the scope of the experiments concerning peas, 6-6 plants were randomly analysed for both concentration. It was found, that the average root weight was 0.06 g higher in the case of the elevated CO<sub>2</sub> concentration, however root length showed a 1.43 decline. Plant weight was 0.27 g higher at 600 ppm CO<sub>2</sub> concentration, but in the case of sprout length 1.5 cm lower values were measured. The weight of pods was also higher at 600 ppm CO<sub>2</sub> concentration by 0.9 g.

The effect of higher CO<sub>2</sub> concentration on morphologic properties was examined in the case of wheat. Similarly to the pea experiment, 6-6 plants were analysed randomly. It was found that root weight was 0.051 g higher in the case of 600 ppm CO<sub>2</sub> concentration, and root length also showed higher values in this case by 1.86 cm. Plant weight was 1.43 g higher at 600 ppm CO<sub>2</sub> concentration. In the case of the mean values of root length, inverse proportionality was found, as 2.2 cm lower values were measured at higher CO<sub>2</sub> concentration.

Higher CO<sub>2</sub> concentration affects the morphologic properties of soy plants as well. In the case of the soybean experiments 4-4 plants were analysed randomly for both concentrations. It was found that the mean root weight was 0.6 g higher at 600 ppm CO<sub>2</sub> concentration and mean root length also shows higher values (17 cm). Plant weight was 5.7 g higher at 600 ppm CO<sub>2</sub> concentration and sprout length was also 35 cm higher. The weight of pods also increased as a result of the treatment. Weight and size of the pods was higher at the elevated CO<sub>2</sub> concentration (2.02 g). At atmospheric CO<sub>2</sub> concentration, the mean weight of pods was 1.51. g. It can be established that the increase of atmospheric CO<sub>2</sub> concentration had a positive effect on morphologic properties; plants usually use additional CO<sub>2</sub> for weight increase. From a generative aspect, the CO<sub>2</sub> treatment had positive effects.

#### 4. NEW SCIENTIFIC RESULTS

1. A cost-effective toolset was elaborated, which is capable of the modelling of different climatic scenarios in a simple, constantly controlled manner and it is reliable in use of practice.
2. It was found that photosynthetic activity increases for pea and winter wheat crops as a result of CO<sub>2</sub> treatments, while it declines in the case of soybean. In case of pea, I was statistically verified on 5% probability level, based on the measured dark-matched  $F_v/F_m$  values. The average values of light-adapted measurements increased by the effect of CO<sub>2</sub> treatments for pea and winter wheat plants. In case of soybean, the photosynthetic activity decreased, which was confirmed by light- and dark-adapted measurements, but statistically significant difference between the  $\Delta F/F_m$  values could be detected.
3. It was confirmed, that CO<sub>2</sub> concentration has a different effect in different phenological phases on the SPAD values of the C3 pea, winter wheat and soybean, near 5% level of significance. The *Irina* pea varieties were in 4-6 leaf stage, while the *KWS Farinelli* winter wheat and *Pannónia Kincse* soybean in stage of before harvesting reached the average highest SPAD values.
4. I was found that the 600 ppm CO<sub>2</sub> concentration near 5% probability level, significantly increased the SPAD values of the examined plants, which were average two SPAD values higher.
5. It was confirmed that the operation of photosynthetic reaction centres is plant specific at different CO<sub>2</sub> concentrations.

## **5. PRACTICAL USEFULNESS OF THE RESULTS**

1. A cost effective and reliable system was elaborated for the modelling of climatic conditions, which is able to simulate the effects of various climatic scenarios. The climate chambers can be used to control CO<sub>2</sub> treatments between 600 and 1500 ppm CO<sub>2</sub> concentrations.
2. By modifying the humidity system, it is possible to examine the effect of atmospheric drought in the climate chamber. The humidity in the chambers can be reduced to between 20% and 40%.
3. By modifying the number of light sources and fluorescent lamps, it is possible to perform light-stress tests. The intensity of the light emitted can easily be measured with a suitable device.
4. In addition, based on the information that did not form an integral part of the dissertation, I found that irrigation increases the effects of increased atmospheric CO<sub>2</sub> concentration. In drier conditions, the CO<sub>2</sub> effect was reduced. The sprouting started sooner, the development of the species was accelerated, which was mainly measured in the morphological characteristics of the plants.

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