DOI: 10.21005/AAPZ2023.68.4.4

FOLIA POMERANAE UNIVERSITATIS TECHNOLOGIAE STETINENSIS
Folia Pomer. Univ. Technol. Stetin., Agric., Aliment., Pisc., Zootech. 2023, 369(68)4, 30–42

Received 29 Aug 2023
Revised 7 Oct 2023
Accepted 9 Oct 2023

Renata MATUSZAK-SLAMANI, Maciej ULAN

INTERACTIONS BETWEEN LIGHT INTENSITY AND DROUGHT STRESS AND THEIR INFLUENCE ON THE GROWTH OF WHEAT SEEDLINGS

Department of Bioengineering, West Pomeranian University of Technology in Szczecin, Poland

Abstract. In this paper, wheat seedlings were exposed to different levels of photon flux density (PFD) and drought stress. Seedlings of the wheat cv. Goplana were cultivated in controlled conditions in a miniphytotrone and exposed to three different photosynthetic photon flux densities (400, 800, and 1200 $\mu mol \cdot m^{-2} \cdot s^{-1}$) and drought stress (a water potential of −0.6 MPa). The Hoagland's solution-treated seedlings served as a control. The fresh and dry matter of the overground parts and roots, relative chlorophyll concentration, electrical conductivity and chlorophyll fluorescence parameters were measured. Drought stress decreased the biomass of wheat seedlings, cv. Goplana. Higher intensities of photosynthetically active irradiation stimulated biomass growth both under control conditions and under drought stress. Drought and higher PFD intensity resulted in a decrease in chlorophyll content. Only the highest light intensity, together with drought stress, negatively affected the structure of cell membranes, increasing their permeability. Both of the applied stress factors did not cause significant changes in the values of the determined parameters of chlorophyll fluorescence in the leaves of wheat seedlings. These results suggest that the increase in light intensity has a mobilising effect on the plant, stimulating the development of biomass both under control conditions and under drought stress. No changes in the values of chlorophyll fluorescence parameters under the influence of different light intensities and drought stress may indicate that there were no significant disturbances in the course of the light phase of photosynthesis in the leaves of the tested seedlings.

Key words: drought stress, photosynthetic photon flux density, spring wheat, hydroponics; plant growth.

INTRODUCTION

Plants are exposed to various environmental stresses during growth and development under natural and agricultural conditions (Ahluwalia et al. 2021; Seleiman et al. 2021). Under natural growing conditions, plants are rarely exposed to a single stress; most often, we encounter the interaction of several interdependent stresses, e.g., high temperature, water deficit, salinity, and too much irradiation in the photosynthetically active range (PAR: 400–700 nm). Plants are therefore exposed to multi-stress conditions. The interaction of several unfavorable factors causes a specific reaction in the plant, which is expressed primarily in the inhibition of growth and a lower,

---

Corresponding author: Renata Matuszak-Slamani, Department of Bioengineering, West Pomeranian University of Technology in Szczecin, Papieża Pawła VI 3, 71-459 Szczecin, Poland, e-mail: renata.matuszak@zut.edu.pl.

often worse-quality, yield. Stress is generally described as one of the extracellular factors that adversely affect plant growth and development, including crop quality and yield (Chhaya et al. 2021; Seleiman et al. 2021).

Drought is one of the most severe environmental stresses affecting plant productivity. This abiotic stress limits the worldwide utilisation of arable lands and negatively affects crop productivity (Zhang et. al. 2022). It is a natural phenomenon, recurring in nature, complex, and difficult to define (Ahluwalia et al. 2021). According to the United Nations World Water Development report, an estimated 55 million people worldwide are affected by drought, and about 700 million are at risk of being displaced by 2030 because of it (WWAP 2018).

In general, the effect of drought stress mainly depends upon species, genotype, size, and age, as well as the time and intensity of stress (Le Gall et al. 2015). The drought stress induces various physiological and biochemical reactions at the cellular and entire plant organism levels: inhibits sprouting, growth, and development, and interrupts appropriate physiological processes. In response, plants undergo several physiological and morphological modifications like reduced transpiration and photosynthesis rate, osmotic adjustments, decreases in chlorophyll contents, repressed root and shoot growth, spike length, plant height, root and shoot dry biomasses, grain yield, overproduction of reactive oxygen species (ROS), modified stress signaling pathways, and senescence (Le Gall et al. 2015; Hasanuzzaman et al. 2018; Ahluwalia et al. 2021; Chhaya et al. 2021; Ilyas et al. 2021; Seleiman et al. 2021). This makes drought stress a complex phenomenon (Farooq et al. 2009; Fang and Xiong 2015).

Light, being one of the key environmental factors, has a crucial role in plant development (Berenschot and Quecini 2014; Wang et al. 2017; Sharma et al. 2020; Lu 2021). Light quantity (intensity and photoperiod) and quality (spectral composition) affect plant growth and physiology and interact with other environmental parameters and cultivation factors in determining plant behavior (Lu 2021; Paradiso and Proietti 2022). Light availability can be highly variable and unpredictable in nature. However, at high or low levels, light is also considered a stress factor. The condition of light as stress occurs when photosynthetic dyes absorb too much PAR energy in relation to the possibility of converting it into chemical energy in the photosynthesis process. Then they will arise oxygen radicals, which may result in the process of photo-inhibition and ultimately cause a great reduction in the primary productivity of plants (Gururani et al. 2015; Sharma et al. 2020). Fluctuations in light intensity also have an impact on the various physiological and biochemical processes of plants. Stress can also occur in low light because of insufficient energy. Low light stress has many negative impacts on plants like: a reduction in photosynthetic efficiency, restricted carbon and nitrogen metabolism, and enhanced oxidative stress (Apel and Hirt 2004; Wang et al. 2013; Sharma et al. 2020).

Rather well recognized is the reaction of plants to a single stress factor such as drought stress (Fang and Xiong 2015; Dutta et al. 2018; Wach and Skowron 2022; Zhang et al. 2023) or light stress (Schumann et al. 2017; Monostori et al. 2018; Ksas et al. 2022). More complicated is the response of cultivated plants to stress caused by a number of stress factors, as it is in natural conditions.

Research into the plant response to water stress is becoming increasingly important because drought, in conjunction with coincident high temperatures and radiation, poses the most important environmental constraints to plant survival and crop productivity.

Knowledge of the reactions of plants to various stresses and of their responses to stress, particularly multi-stresses, is of great scientific and practical value.

Therefore, the aim of the present study was to assess the interactions between different photosynthetic photon flux densities and drought stress and their influence on the growth of Goplana cv. wheat seedlings. The study aimed also at an analysis of the scope of these effects assuming that a exposure to different photosynthetic photon flux densities can enhance tolerance to environmental stresses such as drought.

MATERIALS AND METHODS

The experiments were conducted in controlled conditions, using Hoagland's solution as the growth medium for spring wheat (*Triticum asetivum* L.) cv. Goplana.

Wheat seeds were washed three times with distilled water and placed in a petri dish for 24 hours. Kernels of the tested cereal were put into "Szmal" germination apparatus (Kospin, Poddębice, Poland), 100 kernels per one, and then into containers with Hoagland's solution. Wheat seedlings were grown in a miniphytotrone under controlled conditions: a temperature of 20°C (the temperature was lowered by 2°C per day to achieve 12°C), a 12 h day/12 h dark photoperiod at a photosynthetic photon flux density (PPFD) of approximately 400, 800, and 1200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ provided by LEDs. After 11 days of growth, plants were subjected to drought stress. Polyethylene glycol 6000 (PEG 6000) was added to the nutrient solution to make the water potential −0.6 MPa (Michel and Kaufmann 1973), which simulated drought stress treatment (DS). The Hoagland's solution-treated seedlings served as a control (C). In such conditions, wheat seedlings were grown for another 14 days.

Biometric and physiological measurements on wheat seedlings were carried out after 14 days of growth under drought-induced stress. Fresh and dry matter from the overground parts and roots of wheat seedlings cv. Goplana were also collected. To determine dry matter, samples were divided into roots and overground parts, oven dried at 105°C for 12 h, and then weighed. Overground parts and roots dry matter were expressed as $g \cdot plant^{-1}$. Biometric and physiological measurements were carried out on 10 randomly selected plants from each experimental variant.

The relative chlorophyll concentration was determined using a non-destructive method. The SPAD value of the leaf was determined using a chlorophyll meter, SPAD-502 (Minolta CO. Ltd., Japan). Results were given in SPAD, the value is proportional to the content of chlorophyll in the examined leaf area (6 mm^2) (Monje and Bugbee 1992). SPAD measurements were carried out on 10 randomly selected plants from each experimental variant.

Measurements of chlorophyll fluorescence were performed using a pulsed fluorometer PAM-200 (Heinz Walz GmbH, Germany) controlled by a computer. Intact leaves attached to the plants were dark-adapted for 15 minutes. After dark adaptation, intact plants were immediately used to measure the F_V/F_M parameter (indicating the maximum photochemical efficiency of photosystem II), $Y = (F'_M - F_T) / F'_M$ – maximum efficiency of photon energy in term of the photosynthetically active range (PAR) into chemical energy in given light conditions, $Rfd = (F_P - F_T) / F_T$ was calculated – vitality index informing about the interaction of light phase reactions with dark phase reactions, a gauge of potential photosynthetic activity in given light conditions. Chlorophyll fluorescence measurements were carried out on 6 randomly selected plants from each experimental variant.

Leaf membrane damage was determined by a recording of electrolyte leakage (EL) described by Dexter et al. (1932) with modifications (Matuszak-Slamani and Mila 2017). To assess damage to the cell membrane structure and the loss of controlled and selective permeability of water solutions, were used a modified conductometric method. Parts of the second leaf (7 cm long) were taken at a distance of 2 cm from the tip (10 randomly selected plants from each experimental variant). The parts of the leaf were rinsed in redistilled water and placed in test tubes. Each test tube was filled with 7 cm^3 of redistilled water up to 1.6 $\mu S \cdot cm^{-1}$. Pieces of leaves were completely immersed in water (room temperature, 20°C). After 3 hours at the shaker, the electric conductivity of solutions was measured (W_1) using a conductometer CPC-551 (Elmetron, Poland). After measurement, the solution was poured back into the test tube with a piece of plant. Then, to cause extreme damage, pieces of plants immersed in water were placed in a freezer (−30°C, 24 h). After defrosting and reaching room temperature for several hours after they were taken out of the freezer (2 hours in the shaker), conductivity was measured again (W_2). The permeability of cytoplasmic membranes was measured to assess the impact of electrolytes from plant tissues based on the changes in conductivity of solutions. The electrolyte leakage (EL) was calculated as a relative value of electrical conductivity (EC):

$$EC = \frac{(W_1 - W_0)}{(W_2 - W_0)} \cdot 100\%$$

where:
W_0 – conductivity of redistilled water ($W_0 < 1.6\ \mu S \cdot cm^{-1}$),
W_1 – value of electrical conductivity of leakage from leaves tissues,
W_2 – value of electrical conductivity of leakage from broke leaves tissues (freezer –30°C, 24 h).

Values were expressed in the percentage of maximum leakage of electrolyte from leaves' tissues (EC).

Statistical analysis was performed using Statistica 12.0. Prior to the analysis, the data for normal distribution (Shapiro-Wilk's test) and homogeneity of variances (Levene's test) were checked. The variation analysis was used to compare mean values. Using two-factor analysis of variance and Tukey's test, homogeneous groups were separated at the significance level $\alpha < 0.05$.

RESULTS AND DISCUSSION

In this research, the influence of three different light intensities was examined on the growth and development of wheat seedlings of the Goplana cultivar under drought stress.

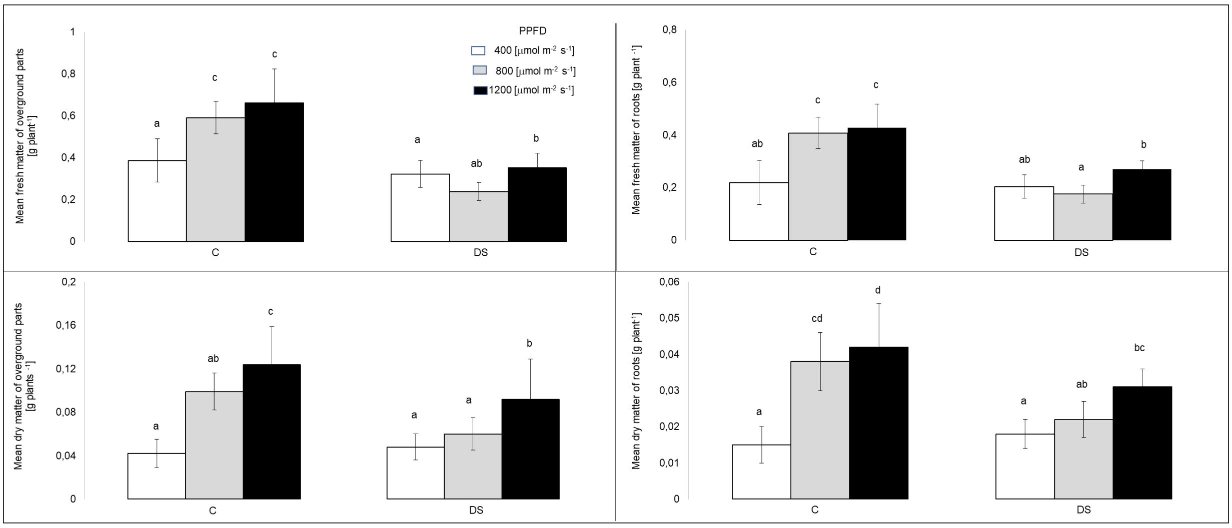
The influence of different photosynthetic photon flux densities (PPFD) on the average content of fresh and dry masses of overground parts and roots of wheat seedlings growing under drought stress is presented in Figure 1. The biomass of overground parts and roots of seedlings growing on Hoagland solution (C) was higher at higher light intensity values. The fresh mass of the overground part and roots of seedlings growing at PPFD 800 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and 1200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ was on average higher by about 60% and 90%, respectively, compared to seedlings growing at irradiance of 400 $\mu mol \cdot m^{-2} \cdot s^{-1}$. On the other hand, the dry matter increased by about 160% on average. Similarly, when effects of light intensity and spectral distribution were studied in ryegrass, the number of tillers was significantly higher in plants grown at high light intensities than those at low intensities, regardless of the red/far-red ratio (Gautier et al. 1999). Elevated light intensities made possible with LEDs increased photosynthetic activity, the number of tillers, biomass, and yield (Monostori et al. 2018). Lu (2021) in their research stated that light intensity affects plant growth in the case of lettuce. In this experiment, the lettuce was grown at different light intensities (high level: 187 $mol \cdot m^{-2} \cdot s^{-1,}$ middle: 125 $mol \cdot m^{-2} \cdot s^{-1}$, and low level: 85 $mol \cdot m^{-2} \cdot s^{-1}$). After one month that the lettuce sizes were different, the shoot fresh and root fresh matter increased in the higher intensity and decreased in the low-light intensity compared to the middle-light intensity.

The results presented in Figure 1 also show that drought stress caused a significant reduction in the average fresh and dry matter of the overground part and roots compared to seedlings growing on the Hoagland solution at the same PPFD values (800 and 1200 $\mu mol \cdot m^{-2} \cdot s^{-1}$). Only in the case of seedlings growing at PPFD 400 $\mu mol \cdot m^{-2} \cdot s^{-1}$, no significant differences in fresh matter were observed between plants growing under control conditions and those under drought stress. Roots are possibly the first organ to perceive drought stress, and the root system has a critical role in responding to drought stress (Ilyas et al. 2021). A common response to water deficits that protects the plants from extensive water loss, which might result in cell dehydration, runaway xylem cavitation, and death, is dental closure, together with leaf growth inhibition (Chaves et al. 2003). The study on wheat (Qayyum et al. 2011) showed that drought limits not only germination but also early seedling growth.

Under drought stress, a statistically significant increase in biomass compared to seedlings growing at PPFD 400 μmol·m^{-2}·s^{-1} was found only at an irradiance of 1200 μmol·m^{-2}·s^{-1}. The fresh mass of the overground part increased by about 10% and the roots by 30%, respectively. On the other hand, the dry matter of the overground part and roots increased by 80% on average. The increase in root biomass at higher irradiance values under control conditions and at 1200 μmol·m^{-2}·s^{-1} under drought stress conditions suggests that higher light intensity stimulates the development of the root system. A well-developed root system increases water absorption efficiency from soil (Hossain et al. 2016) and allows productivity under water scarcity to be maintained (Ilyas et al. 2021).

With the increase in photosynthetically active irradiation, the biomass of wheat seedlings of the Goplana cultivar is higher, both under control conditions and under drought stress. It appears that an increase in light intensity mobilises the plant and encourages the growth of biomass.

Ahmadi et al. (2020) analyzed the role of various LED lights (red, blue, red + blue, and white) as well as normal greenhouse light (as a control) to stimulate defense mechanisms against drought stress in two genotypes of Melissa officinalis L. The authors demonstrate that pre-treatment with LEDs with high-intensity output for 4 weeks alleviated the harmful effects of drought stress in the two genotypes. Under drought stress, LED red + blue pre-treated plantlets of the two genotypes exhibited the highest relative growth index of shoot and root and total phenolic and anthocyanin content compared to those irradiated with other LEDs and greenhouse lights. Monostori et al. (2018) found in their research that the elevated light intensity provided by the LEDs resulted in increased biomass and yield, mainly due to the elevated photosynthetic activity of plants. They stated increases of 40% in biomass and 60% in yield.

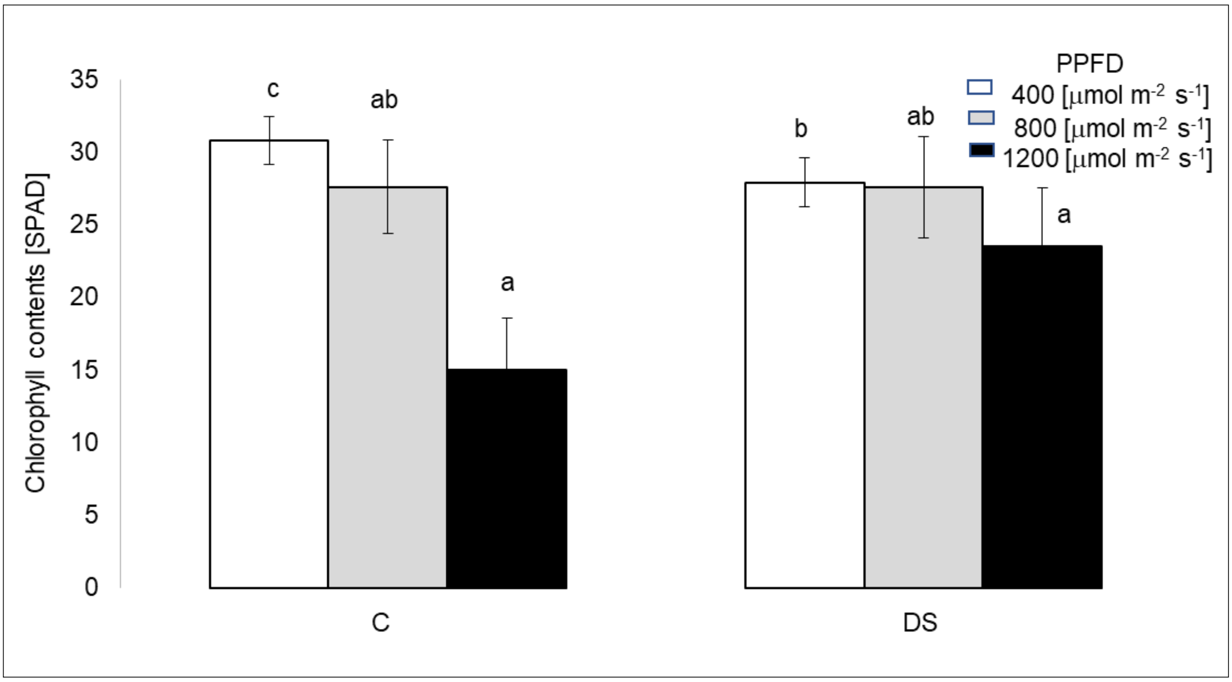


C – control; DS – drought stress. Average values marked with the same letters do not differ at the significance level of p = 0.05; Tukey's test. Standard deviation is marked.

Fig. 1. Influence of different photosynthetic photon flux densities (PPFD) on biometric parameters of Goplana wheat seedlings growing under drought stress

Figure 2 shows the effect of water deficiency and different intensities of photosynthetically active irradiation on the content of chlorophyll in the leaves of wheat seedlings of the Goplana cultivar. Photosynthetic pigments play an important role in photosynthesis as they can assimilate and transfer light energy. Chlorophylls are one of the most important pigments and represent a significant index of photosynthetic capacity (Yang 2007). In general, chlorophyll content will decrease after exposure to low-light stress. The results of Zhu et al. (2017) indicated that the chlorophyll a content under low light stress (750, 500, and 250 $\mu mol \cdot m^{-2} \cdot s^{-1}$) was decreased in purple pak-choi, resulting in photosynthetic damage, but the chlorophyll b content was increased to resist low light stress. Ma et al. (2010) found that the chlorophyll a content did not change under low light, while the chlorophyll b content increased.

In our research, it was found that with the increase in light intensity, the chlorophyll content significantly decreased in the leaves of wheat seedlings growing both under control conditions and under drought stress. Chlorophyll content in the leaves of seedlings growing under control conditions at PPFD 1200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and 800 $\mu mol \cdot m^{-2} \cdot s^{-1}$ was significantly lower by 51% and 10%, respectively, compared to 400 $\mu mol \cdot m^{-2} \cdot s^{-1}$. The main responses to low and high irradiance levels are to increase light capture and energy dissipation, respectively, which are reflected by changes in chlorophyll content and chlorophyll fluorescence (Xu et al. 2009). Wang et al. (2020) in their studies found that the chlorophyll contents of all plants decreased in response to increasing irradiance levels. This implies greater fractional nitrogen investments in chlorophyll and light-harvesting pigment-binding complexes under low irradiance (Hikosaka and Terashima 1995). In addition, studies by Wittmann et al. (2001) and Griffin et al. (2004) have suggested that strong irradiance may destroy chlorophyll and that plants can optimize the efficiency of light absorption by decreasing chlorophyll content per unit leaf area. The reduction of chlorophyll content may decrease photosynthetic capacity (Dai et al. 2009).

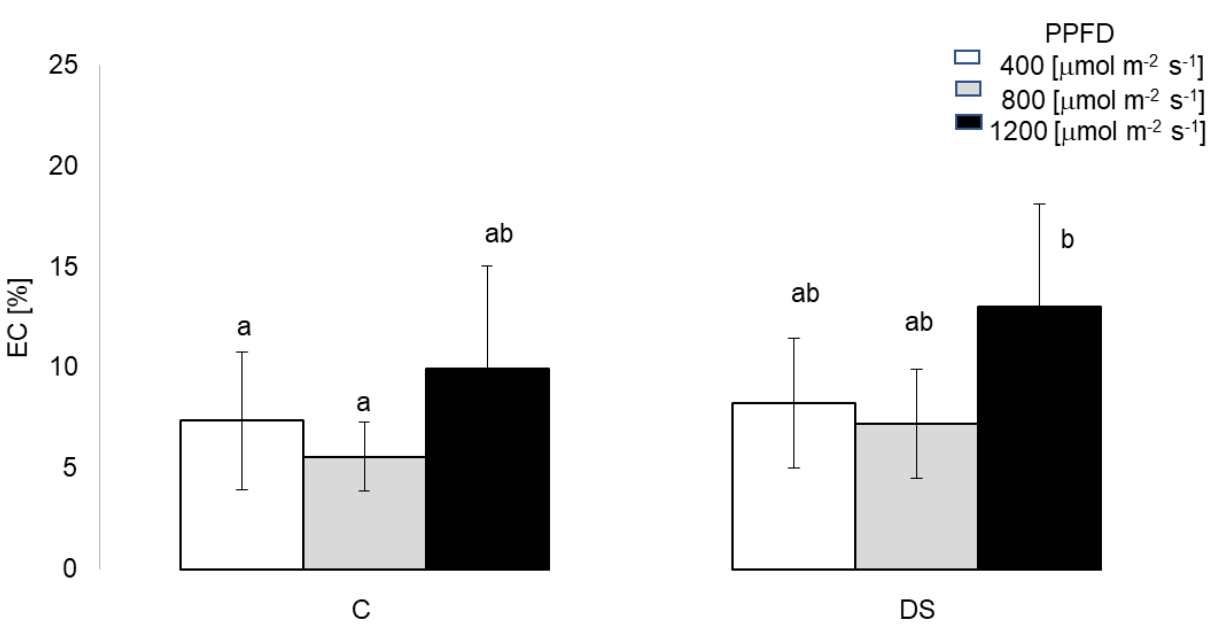


C – control; DS – drought stress. Average values marked with the same letters do not differ at the significance level of p = 0.05; Tukey's test. Standard deviation is marked.

Fig. 2. Chlorophyll content in leaves of Goplana seedlings growing under different light intensities ($\mu mol \cdot m^{-2} \cdot s^{-1}$) and drought stress

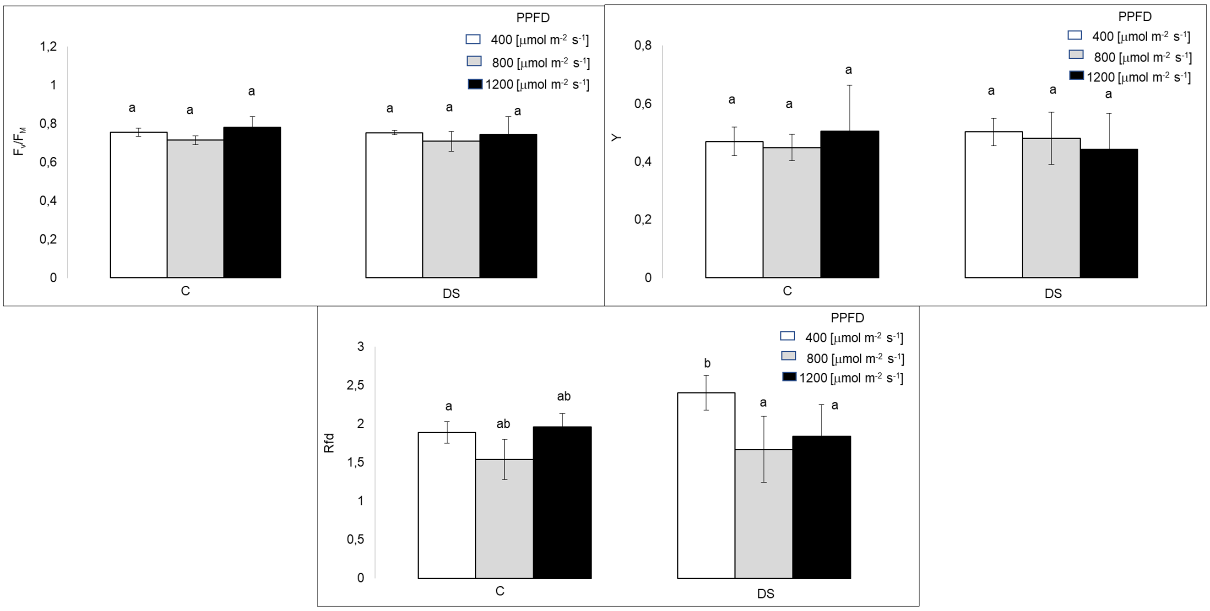
Under drought stress, only at a PPFD of 1200 μmol·m^{-2}·s^{-1}, significantly lower (by 16%) chlorophyll content was found in leaves compared to seedlings growing at 400 μmol·m^{-2}·s^{-1}. Drought stress caused a significant decrease in chlorophyll content only in the leaves of seedlings growing at PPFD 400 μmol·m^{-2}·s^{-1} compared to seedlings growing on Hoagland's solution at the same light intensity. At higher PPFD values, no significant differences were observed in the content of chlorophyll in the leaves of plants growing under control conditions compared to drought stress. Under well-hydrated conditions, C3 plants use a large fraction of absorbed light through photosynthesis and photorespiration. This fraction decreases as photosynthetic photon flux density increases, even more so when drought is superimposed (Chaves et al. 2003). To get rid of excess light, plants can either prevent its absorption, for example, by losing chlorophyll (Havaux and Tardy 1999).

The assessment of damage to cell membrane structure and the loss of controlled and selective permeability of water solutions was made using a modified conductometric method (Fig. 3). In normal conditions, the cell membrane is selectively permeable, but stress factors cause damage to the membrane. The larger the damage, the more of the cell content flows outside, causing an increase in electric conductivity (Matuszak-Slamani and Mila 2017). Drought stress causes excessive production of reactive oxygen species (ROS), which leads to damage, to the cell membrane. Also, peroxidation of membrane lipids changes the permeability of membranes, systems, and their structures. This leads to increased permeability and loss of cell membrane integrity (Zlatev and Lidon 2012; Dutta et al. 2018). In our study, we did not observe statistically significant differences in the amount of electrolyte leakage in wheat seedlings grown under control and drought stress conditions at the same PPFD levels. It was found that a greater outflow of electrolytes occurs in seedlings growing under drought stress conditions at various levels of irradiation compared to seedlings grown under control conditions. However, these differences were not statistically significant.



C – control; DS – drought stress. Average values marked with the same letters do not differ at the significance level of $p = 0.05$; Tukey's test. Standard deviation is marked.

Fig. 3. Influence of different photosynthetic photon flux densities (PPFD) on the electric conductivity (EC) of Goplana wheat seedlings growing under drought stress



C – control; DS – drought stress. Average values marked with the same letters do not differ at the significance level of $p = 0.05$; Tukey's test. Standard deviation is marked

Fig. 4. Influence of different photosynthetic photon flux densities (PPFD) on changes in chlorophyll fluorescence parameters for leaves of Goplana wheat seedlings subjected to drought stress

The influence of different photosynthetic photon flux densities (PPFD) on changes in chlorophyll fluorescence parameters for leaves of wheat seedlings growing under drought stress is presented in Figure 4.

The data a presented in Figure 4 shows that under the influence of different values of irradiation and drought stress, there are no significant changes in the values of the determined parameters of chlorophyll fluorescence (F_V/F_M and Y) in the leaves of wheat seedlings. This may indicate that in the tested leaves' seedlings, there were no disruptions in the course of the light phase of photosynthesis (Murkowski 2002).

The value of the F_V/F_M ratio in stress-free conditions for most plants is close to 0.83. The values of the F_V/F_M ratio obtained by us do not show statistically significant differences; however, they are lower than 0.8. According to some authors (Basu et al. 1998; Seppanen 2000), lower values indicate that the plants grew under stress and the reaction centres of photosystem II (PSII) were damaged, which resulted in a decrease in the efficiency of electron transport. Kalaji and Łoboda (2010) do not fully confirm these observations. According to their studies, the F_V/F_M ratio in barley seedlings growing under stress caused by too low or high PAR intensity did not show significant changes after 24 hours of stress; changes were noticed only after 7 days of stress. In various studies (Souza et al. 2004; Zlatev and Yordanov 2004; Živčák et al. 2008), the quantum efficiency of open PSII reaction centres in the dark-adapted state (F_V/F_M) showed a small and mostly non-significant reduction under drought conditions. It confirms that plant primary processes in PSII are quite resistant to water deficits (Oukarroum et al. 2007). According to some authors (Lauriano et al. 2006; Kalaji and Łoboda 2010), changes in the values of many fluorescence parameters intensify with increasing drought stress. A permanent decrease in the value of the F_V/F_M parameter and a decrease in the value of the Y parameter are used as indicators of photoinhibition in stressed plants (Yin et al. 2006; Kalaji and Łoboda 2010). In sunflower plants exposed to high light intensity and drought, there was a decline in numerous parameters, including water potential, parameter *Y*, and maximal photochemical efficiency PSII (F_V/F_M). When the irradiation level was reduced, the potential of water and F_V/F_M increased (Correia et al. 2006).

The stress caused by different levels of irradiation did not cause significant changes in the value of the Rfd parameter (vitality index PSII) in the leaves of seedlings growing under control conditions. This parameter provides information about the interaction of the PAR-dependent phase reaction with the dark phase reactions. The value of the Rfd parameter in control conditions at PPDF 400 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$ was statistically significantly lower than in the drought at the same irradiance. Under the influence of drought stress, the highest value of the Rfd parameter was found in the seedlings growing at 400 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$. Higher PAR intensities caused a significant decrease in the Rfd parameter value (about 30% in relation to PPFD 400 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$). The decrease in the Rfd value may indicate that, most likely, under the influence of applied stress (drought and light stress), the enzymes responsible for CO_2 assimilation in the dark phase of photosynthesis were inactivated.

CONCLUSIONS

The light intensity and drought stress interact and their effects on wheat seedlings can be complex. Under drought stress, light intensity can have both positive and negative effects on plants.

Our research indicates that drought stress caused the negative effects on the biomass of Goplana cv. wheat seedlings. The photosynthetically active irradiation intensities higher than 400 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$ stimulated biomass growth both under control conditions and under drought stress. Both of the applied stress factors resulted in a decrease in chlorophyll content, however did not cause significant changes in the values of the determined parameters of chlorophyll fluorescence (F_V/F_M and *Y*) in the leaves of wheat seedlings. It may indicate that there were no significant disturbances in the light phase of photosynthesis in the leaves of the tested seedlings. The highest light intensity, together with drought stress increased their permeability of cell membranes.

Overall, the interaction between light intensity and drought stress in wheat seedlings is highly dependent on the specific conditions and severity of both factors. It is crucial for farmers and researchers to carefully manage these interactions to optimize wheat growth and minimize yield losses in the face of drought stress.

REFERENCES

Ahluwalia O., Singh P.C., Bhatia R. 2021. A review on drought stress in plants: Implications, mitigation and the role of plant growth promoting rhizobacteria. Resour. Environ. Sustain. 5, 100032. DOI: 10.1016/j.resenv.2021.100032.

Ahmadi T., Shabani L., Sabzalian M.R. 2020. LED light mediates phenolic accumulation and enhances antioxidant activity in *Melissa officinalis* L. under drought stress condition. Protoplasma 257, 1231–1242. DOI: 10.1007/s00709-020-01501-4.

Apel K., Hirt H. 2004. Reactive oxygen species: Metabolism, oxidative stress, and signal transduction. Annu. Rev. Plant Biol. 55, 373–399. DOI: 10.1146/annurev.arplant.55.031903.141701.

Basu P.S., Sharma A., Sukumaran N.P. 1998. Changes in net photosynthesis rate and chlorophyll fluorescence in potato leaves induced by water stress. Photosynthetica 35, 13–19. DOI: 10.1023/A:1006801311105.

Berenschot A.S., Quecini V. 2014. A reverse genetics approach identifies novel mutants in light responses and anthocyanin metabolism in petunia. Physiol. Mol. Biol. Plants 20(1), 1–13. DOI: 10.1007/s12298-013-0212-4.

Chaves M.M., Maroco J.P., Pereira J.S. 2003. Understanding plant responses to drought – from genes to the whole plant. Funct. Plant Biol. 30(3), 239–264. DOI: 10.1071/FP02076.

Chhaya C., Yadav B., Jogawat A., Gnanasekaran P., Kumari P., Lakra N., Krishan Lal S., Pawar J., Prakash Narayan O. 2021. An overview of recent advancement in phytohormones-mediated stress management and drought tolerance in crop plants. Plant Gene 25, 100264. DOI: 10.1016/j.plgene.2020.100264.

Correia M.J., Osorio M.L., Osorio J., Barrote I., Martins M., David M.M. 2006. Influence of transient shade periods on the effects of drought on photosynthesis, carbohydrate accumulation and lipid peroxidation in sunflower leaves. Environ. Exp. Bot. 58, 75–84. DOI: 10.1016/j.envexpbot.2005.06.015.

Dai Y., Shen Z., Liu Y., Wang L., Hannaway D., Liu H. 2009. Effects of shade treatments on the photosynthetic capacity, chlorophyll fluorescence, and chlorophyll content of *Tetrastigma hemsleyanum* Diels et Gilg. Environ. Exp. Bot. 65(2-3), 177–182. DOI: 10.1016/j.envexpbot.2008.12.008.

Dexter S.T., Tottingham W.E., Graber L.F. 1932. Investigation of the hardiness of plants by measurement of electrical conductivity. Plant Physiol. *7*(1), 63–78. DOI: 10.1104/pp.7.1.63.

Dutta T., Neelapu N.R., Wani S.H., Challa S. 2018. Response of pulses to drought and salinity stress response. A physiological perspective, in: Pulse improvement. Physiological, molecular and genetic perspectives. Eds. S.H. Wani, M. Jain. Cham, Springer Nature Switzerland, 77–98.

Fang Y., Xiong L. 2015. General mechanisms of drought response and their application in drought resistance improvement in plants. Cell. Mol. Life Sci. 72, 673–689. DOI: 10.1007/s00018-014-1767-0.

Farooq M., Wahid A., Kobayashi N., Fujita D., Basra S.M. 2009. Plant drought stress. Effects, mechanisms and management, in: Sustainable agriculture. Eds. E. Lichtfouse, M. Navarrete, P. Debaeke, S. Véronique, C. Alberola. Dordrecht, Springer, 153–188.

Gautier H., Varlet-Grancher C., Hazard L. 1999. Tillering responses to the light environment and to defoliation in populations of perennial ryegrass (*Lolium perenne* L.) selected for contrasting leaf length. Ann. Bot. 83, 423–429. DOI: 10.1006/anbo.1998.0840.

Griffin J.J., Ranney T.G., Pharr D.M. 2004. Photosynthesis, chlorophyll fluorescence, and carbohydrate content of illicium taxa grown under varied irradiance. J. Am. Soc. Horti. Sci. 129(1), 46–53. DOI: 10.21273/JASHS.129.1.0046.

Gururani M.A., Venkatesh J., Tran L.S. 2015. Regulation of photosynthesis during abiotic stress-induced photoinhibition. Mol. Plant. 8(9), 1304–1320. DOI: 10.1016/j.molp.2015.05.005.

Hasanuzzaman M., Al Mahmud J., Anee T.I., Islam M.T., Nahar K. 2018. Drought stress tolerance in wheat. Omics approaches in understanding and enhancing antioxidant defense, in: Abiotic stress-mediated sensing and signaling in plants. An omics perspective. Eds. S. Zargar, M. Zargar. Singapore, Springer, 267–307.

Havaux M., Tardy F. 1999. Loss of chlorophyll with limited reduction of photosynthesis as an adaptive response of Syrian barley landraces to high-light and heat stress. Funct. Plant Biol. 26, 569–578. DOI: 10.1071/PP99046.

Hikosaka K., Terashima I. 1995. A model of the acclimation of photosynthesis in the leaves of C3 plants to sun and shade with respect to nitrogen use. Plant Cell Environ. 18, 605–618. DOI: 10.1111/j.1365-3040.1995.tb00562.x.

Hossain M.A., Wani S.H., Bhattacharjee S., Burritt D., Tran L. 2016. Drought stress tolerance in plants, vol 1. Eds. Cham, Springer International Publishing.

Ilyas M., Nisar M., Khan N., Hazrat A., Khan A.H., Hayat K., Fahad S., Khan A., Ullah A. 2021. Drought tolerance strategies in plants. A mechanistic approach. J. Plant Growth Regul. 40, 926–944. DOI: 10.1007/s00344-020-10174-5.

Kalaji M.H., Łoboda T. 2010. Fluorescencja chlorofilu w badaniach stanu fizjologicznego roślin. Warszawa, Wydaw. SGGW [in Polish].

Ksas B., Alric J., Caffarri S., Havaux M. 2022. Plastoquinone homeostasis in plant acclimation to light intensity. Photosynth. Res. 152(1), 43–54. DOI: 10.1007/s11120-021-00889-1.

Lauriano J.A., Ramalho J.C., Lindon F.C., Do Ceumatos M. 2006. Mechanisms of energy dissipation in peanut under water stress. Photosynthetica 44, 404–410. DOI: 10.1007/s11099-006-0043-4.

Le Gall H.L., Philippe F., Domon J.M., Gillet F., Pelloux J., Rayon C. 2015. Cell wall metabolism in response to abiotic stress. Plants 4(1), 112–166. DOI: 10.3390/plants4010112.

Lu N. 2021. Light environment and plant growth in plant factories. IOP Conf. Ser. Earth Environ. Sci. 686, 012002. DOI: 10.1088/1755-1315/686/1/012002.

Ma Z.Q, Li S.S., Zhang M.J., Jiang S.H., Xiao Y.L. 2010. Light intensity affects growth, photosynthetic capability, and total flavonoid accumulation of *Anoectochilus* plants. Hortscience 45(6), 863–867. DOI: 10.21273/HORTSCI.45.6.863.

Matuszak-Slamani R., Mila A. 2017. Ocena przepuszczalności błon komórkowych siewek jęczmienia w warunkach niedoboru wody [Evaluation of cell membrane permeablity of barley seedlings in conditions of water deficit]. Acta Agroph. 24(3), 465–473 [in Polish].

Michel B.E., Kaufmann M.R. 1973. The osmotic potential of polyethylene glycol 6000. Plant Physiol. 51(5), 914–916. DOI: 10.1104/pp.51.5.914.

Monje O.S., Bugbee B. 1992. Inherent limitations of nondestructive chlorophyll meters: A comparison of two types pf meters. Sci. Hortic. 27(1), 69–71. DOI: 10.21273/HORTSCI.27.1.69.

Monostori I., Heilmann M., Kocsy G., Rakszegi M., Ahres M., Altenbach S.B., Szalai G., Pál M., Toldi D., Simon-Sarkadi L., Harnos N., Galiba G., Darko É. 2018. LED lighting – modification of growth, metabolism, yield and flour composition in wheat by spectral quality and intensity. Front. Plant Sci. 4(9), 605. DOI: 10.3389/fpls.2018.00605.

Murkowski A. 2002. Oddziaływanie czynników stresowych na luminescencje chlorofilu w aparacie fotosyntetycznym roślin uprawnych [Effects of some stress factors on chlorophyll luminescence in the photosynthetic apparatus crop plants]. Acta Agrophy. 61, 1–158 [in Polish].

Oukarroum A., Madidi S.E., Schansker G., Strasser R.J. 2007. Probing the response of barley cultivars (*Hordeum vulgare* L.) by chlorophyll a fluorescence OLKJIP under drought stress and re-watering. Environ. Exp. Bot. 60, 438–446. DOI: 10.1016/j.envexpbot.2007.01.002.

Paradiso R., Proietti S. 2022. Light-quality manipulation to control plant growth and photomorphogenesis in greenhouse horticulture: The state of the art and the opportunities of modern LED systems. J. Plant Growth Regul. 41, 742–780. DOI: 10.1007/s00344-021-10337-y.

Qayyum A., Razzaq A., Ahmad M., Jenks M.A. 2011. Water stress causes differential effects on germination indices, total soluble sugar and proline content in wheat (*Triticum aestivum* L.) genotypes. Afr. J. Biotechnol. 10, 14038–14045. DOI: 10.5897/AJB11.2220

Schumann T., Paul S., Melzer M., Dörmann P., Jahns P. 2017. Plant growth under natural light conditions provides highly flexible short-term acclimation properties toward high light stress. Front. Plant Sci. 8, 681. DOI: 10.3389/fpls.2017.00681.

Seleiman M.F., Al-Suhaibani N., Ali N., Akmal M., Alotaibi M., Refay Y., Dindaroglu T., Abdul-Wajid H.H., Battaglia M.L. 2021. Drought stress impacts on plants and different approaches to alleviate its adverse effects. Plants 10(2), 259. DOI: 10.3390/plants10020259.

Seppanen M.M. 2000. Characterization of freezing tolerance in *Solanum commersionii* (dun.) with special reference to the relationship between freezing and oxidative stress. Helsinki, University of Helsinki.

Sharma A., Kumar V., Shahzad B., Ramakrishnan M., Singh Sidhu G.P., Bali A.S., Handa N., Kapoor D., Yadav P., Khanna K., Bakshi P., Rehman A., Kohli S.K., Khan E.A., Parihar R.D., Yuan H., Thukral A.K., Bhardwaj R., Zheng B. 2020. Photosynthetic response of plants under different abiotic stresses: A review. J. Plant Growth Regul. 39(2), 509–531. DOI: 10.1007/s00344-019-10018-x.

Souza R.P., Machado E.C., Silva J.A., Lagôa A.M., Silveira J.A. 2004. Photosynthetic gas exchange, chlorophyll fluorescence and some associated metabolic changes in cowpea (*Vigna unguiculata*) during water stress and recovery. Environ. Exp. Bot. 51, 45–56. DOI: 10.1016/S0098-8472(03)00059-5.

Wach D., Skowron P. 2022. An overview of plant responses to the drought stress at morphological, physiological and biochemical levels. Pol. J. Agron. 50, 25–34. DOI: 10.26114/pja.iung.435.2022.04.

Wang J.H., Cai Y.F., Li S.F., Zhang S.B. 2020. Photosynthetic acclimation of rhododendrons to light intensity in relation to leaf water-related traits. Plant Ecol. 221, 407–420. DOI: 10.1007/s11258-020-01019-y.

Wang L., Deng F., Ren W.J., Yang W.Y. 2013. Effects of shading on starch pasting characteristics of indica hybrid rice (*Oryza sativa* L.). PLoS ONE 8(7), e68220. DOI: 10.1371/journal.pone.0068220.

Wang Y., Tong Y., Chu H., Chen X., Guo H., Yuan H., Yan D., Zheng B. 2017. Effects of different light qualities on seedling growth and chlorophyll fluorescence parameters of *Dendrobium officinale*. Biologia 72(7), 735–744. DOI: 10.1515/biolog-2017-0081

Wittmann C., Aschan G., Pfanz H. 2001. Leaf and twig photosynthesis of young beech (*Fagus sylvatica*) and aspen (*Populus tremula*) trees grown under different light regime. Basic Appl. Ecol. 2(2), 145–154. DOI: 10.1078/1439-1791-00047.

WWAP. 2018. The United Nations World water development report 2018: Nature based solutions. UNESCO, Paris.

Xu F., Guo W., Wang R., Xu W., Du N., Wang Y. 2009. Leaf movement and photosynthetic plasticity of black locust (*Robinia pseudoacacia*) alleviate stress under different light and water conditions. Acta Physiol. Plant. 31, 553–563. DOI: 10.1007/s11738-008-0265-0.

Yang F.J. 2007. Effect of light stresson the content of chloroplast pigment and taxolin the leaves of *Taxus chinensis* var. mairei. Bull. Bot. Res. 27(5), 556–558.

Yin C.Y., Berninger F., Li C.Y. 2006. Photosynthetic responses of *Populus przewalski* subjected to drought stress. Photosynthetica 44, 62–68. DOI: 10.1007/s11099-005-0159-y.

Zhang H., Zhu J., Gong Z., Zhu J.K. 2022. Abiotic stress responses in plants. Nat. Rev. Genet. 23, 104–119. DOI: 10.1038/s41576-021-00413-0.

Zhang Y., Xu J., Li R., Ge Y., Li Y., Li R. 2023. Plants' response to abiotic stress: Mechanisms and strategies. Int. J. Mol. Sci. 24(13), 10915. DOI: 10.3390/ijms241310915.

Zhu H., Li X., Zhai W., Liu Y., Gao Q., Liu J., Ren L., Chen H., Zhu Y. 2017. Effects of low light on photosynthetic properties, antioxidant enzyme activity, and anthocyanin accumulation in purple pak-choi (*Brassica campestris* ssp. *Chinensis* Makino). PLoS ONE 12(6), e0179305. DOI: 10.1371/journal.pone.0179305.

Zlatev Z., Lidon F.C. 2012. An overview on drought induced changes in plant growth, water relations and photosynthesis. Emir. J. Food Agric. 24, 57–72. DOI: 10.9755/ejfa.v24i1.10599.

Zlatev Z., Yordanov I. 2004. Effects of soil drought on photosynthesis and chlorophyll fluorescence in common bean plants. Bulg. J. Plant Physiol. 30(3-4), 3–18.

Živčák M., Brestič M., Olšovská K., Slamka P. 2008. Performance index as a sensitive indicator of water stress in *Triticum aestivum* L. Plant Soil Environ. 54(4), 133–139. DOI: 10.17221/392-PSE.

INTERAKCJA POMIĘDZY INTENSYWNOŚCIĄ ŚWIATŁA A STRESEM SUSZY I ICH WPŁYW NA WZROST SIEWEK PSZENICY

Streszczenie. W badaniach siewki pszenicy poddano działaniu różnych poziomów gęstości strumienia fotonów (PFD) i stresu suszy. Siewki pszenicy odmiany Goplana były uprawiane w kontrolowanych warunkach w minifitotronie i poddane działaniu trzech różnych poziomów gęstości strumienia fotonów promieniowania fotosyntetycznie czynnego (400, 800 i 1200 μmol·m^{-2}·s^{-1}) oraz stresu suszy (potencjał wody −0,6 MPa). Kontrolę stanowiły siewki podlewane roztworem pożywki Hoaglanda. Zmierzono świeżą i suchą masę części nadziemnych i korzeni, względną zawartość chlorofilu, przewodność elektryczną i parametry fluorescencji chlorofilu. Stres suszy zmniejszył biomasę siewek pszenicy odmiany Goplana. Wyższe natężenie napromieniowania fotosyntetycznie czynnego stymulowało wzrost biomasy zarówno w warunkach kontrolnych, jak i stresu suszy. Susza oraz wyższe natężenie PFD wpłynęły na obniżenie zawartości chlorofilu. Tylko najwyższa intensywność światła wraz ze stresem suszy wpłynęły negatywnie na strukturę błon komórkowych, zwiększając ich przepuszczalność. Obydwa z zastosowanych czynników stresowych nie wywołały istotnych zmian w wartościach wyznaczanych parametrów fluorescencji chlorofilu w liściach siewek pszenicy. Otrzymane wyniki sugerują, że wzrost intensywności światła działa mobilizująco na roślinę, stymulując rozwój biomasy, zarówno w warunkach kontrolnych, jak i stresu suszy. Brak zmian w wartościach parametrów fluorescencji chlorofilu pod wpływem różnej intensywności światła i stresu suszy może świadczyć o tym, że w liściach badanych siewek nie wystąpiły znaczące zakłócenia w przebiegu fazy świetlnej fotosyntezy.

Słowa kluczowe: susza, fotosyntetyczna gęstość strumienia fotonów, pszenica jara, hydroponika, wzrost roślin.