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Radiation use efficiency by tomato transplants grown under extended photoperiod

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Abstract. The study focused on the effect of an extended photoperiod on the radiation use efficiency (*RUE*) by the tomato transplants *(Solanum lycopersicum* L.*)* in the pre–reproductive period. In two consecutive series of experiments, the photoperiod was 16 and 22 hours. The photon irradiance at the plant tops was maintained at low, medium and high levels: 100, 170 and 240 µmol m^{-2} s^{-1}, respectively. The plants were grown under two lighting systems with different light quality. The difference was 7% higher blue flux share in Spectrum II. The use of an extended photoperiod, especially in combination with high irradiance level, resulted in the plant leaf chlorosis. When varying the radiation dose components, the deviation from the reciprocity law was recorded. By the analysis results, the chlorophyll degradation was a response to the extended photoperiod rather than the radiation dose. Without additional blue flux, under a regular photoperiod, *RUE* reduced by 8% at the high irradiance level. Under extended photoperiod, the shift from the low to high irradiance level reduced *RUE* by 20–37%, with bigger reduction values being observed at higher irradiance levels. Seven percent addition of blue flux made it possible to increase *RUE* by 5–8% at the same and lower irradiance levels and under the regular photoperiod. With the extended photoperiod under these conditions, *RUE* decreased by 8–21%. The study results verify a great influence of an extended photoperiod on *RUE*, while the degree of influence depends on other parameters of light environment – light quality and irradiance level.

Key words: photoperiod, irradiance, light quality, doze, biometry, radiation use efficiency, chlorophyll, chlorosis.

INTRODUCTION

The greatest global challenge existing beyond national boundaries is to maintain a balance between the growing production and environmental sustainability. The way to achieve such a balance is the maximal use of energy and material resourcesin the production of goods without compromising the agroecosystems. The photosynthetically active radiation (PAR) is an essential environmental factor when growing plants. The radiation affects them in many ways – from the variation in their productivity to such reasonably subtle implications as the influence on their developmental stability (Rakutko et al., 2018).

Numerous studies focused on plant cultivation under the artificial irradiation with different photoperiods (Sysoeva & Markovskaya, 2008). A promising trend is the use of an extended photoperiod, up to continuous lighting, in order to maximize the plant productivity and to minimize the costs of indoor plant lighting (Adams & Langton, 2005). In this case, the energy saving is achieved by the extended service life of light sources as there is no transient mode in the on/off switching (Ohyama & Kozai, 1998; Sysoeva et al., 2010).

Various plant species respond to an extended photoperiod differently. Tomato demonstrates the accelerated development in the early ontogenesis stages with the subsequent slowdown (Demers & Gosselin, 2002). For this reason, the low–intensity continuous lighting with alternating air temperature is used for growing tomato transplants (Ohyama et al., 2005).

There is evidence, however, of the negative effects of this method, the photo–damage of leaves, in particular. The possible causes are hyper–accumulation of starch, continuous photo–oxidative pressure, continuous light signalling, a mismatch between the frequency of internal (circadian) biorhythms and the external light / dark cycle (circadian asynchrony), and suppressed light–dependent chlorophyll deficiency (Velez-Ramirez et al., 2011; Shibaeva & Titov, 2017).

The study aimed to explore the effect of an extended photoperiod on the radiation use efficiency (RUE) by tomato transplants in the pre–reproductive period.

MATERIALS AND METHODS

The study object was tomato transplants (*Solanum lycopersicum* L.) of Blagovest F_1 variety. The seeds were sown in a tray filled with the mix of peat and soil substrate in the proportion of 1:2. After the second true leaf had appeared, the seedlings were pricked out into containers of 1,000 cm^3 each and placed in the room with an artificial climate, where they were grown to 39 days after emergence.

The air temperature was automatically maintained at $+21 \pm 1.0$ °C with the humidity of 65–70%. The air velocity in the plant growing zone was 0.2–0.3 $m\ s^{-1}$. Two lighting systems were used in the experiment. The light sources were OSRAM L58W/840 LUMILUX Cool White and OSRAM L58W/77 FLUORA fluorescent lamps. The first lighting system (reference) had only fluorescent lamps with the overall spectral ratio blue:green:red = 32 %:34 %:34 % (Spectrum I). The second lighting system had the same number and type of fluorescent lamps as the first lighting system but the LEDs with 440 nm wavelength were added. They redistributed the energy in PAR range towards the shorter wavelengths. The spectral ratio of the second lighting system was blue:green:red = 39 %:31 %:30 % (Spectrum II). Thus, the difference in the light quality was rather a small increase (7%) in the blue band in Spectrum II.

The radiation use efficiency (RUE) was evaluated by the amount of dry matter (g mol^{-1}) synthesised in the plant leaves under the influence of the radiation dose. It was calculated by the formula

$$RUE = SLW/H. \tag{1}$$

The specific leaf weight (SLW), g m^{-2}, was calculated by the formula

$$SLW = M_L \cdot v_L / S_L, \quad (2)$$

where S_L is the leaf area, m^2; M_L is the wet fresh leaf mass, g; v_L is the leaf dry matter content, rel. units.

The radiation dose H, mol m^{-2}, is the energy generated by the light sources for the entire growing period T, day, calculated as

$$H = DLI \cdot T. \quad (3)$$

The energy generated by light sources per day (*DLI*, day light integral, mol m^{-2} day^{-1}) was calculated by the formula

$$DLI = 0.0036 \cdot E \cdot PP, \quad (4)$$

where E is the photon irradiance created by the light sources, μmol m^{-2} s^{-1}; PP – photoperiod, h.

Two consecutive series of experiments with different photoperiods – 16 hours (regular) and 22 hours (extended) were conducted. The photon irradiance of tomato transplant tops was maintained at low, medium and high levels: 100, 170 and 240 μmol m^{-2} s^{-1}, respectively. The transplants were watered and fertilized as required.

The chlorophyll content was determined by CCM–200 meter (Opti–Science, USA) in relative units. The leaf dry matter content was determined by drying the leaves to the constant mass at a temperature of +105 °C. The experiments had three replications, with the mean values being calculated per six transplants per replication. The data were processed with *Statistica* 7.0 and *Excel 2003* software packages. Statistical differences were analyzed using one–way analysis of variance (*ANOVA*). The least significant difference (*LSD*) at the 0.95 level ($p \leq 0.05$) was used to compare the mean values by Fisher's test.

RESULTS AND DISCUSSION

The application of extended photoperiod could increase the growth and yields of plants. At the same time, it leads to leaf chlorosis and necrosis. In our experiment with the extended photoperiod, the leaf variegation was observed already on the sixth day at all irradiance levels and both spectra.

Fig. 1 shows the typical tomato transplants grown under different irradiation levels. Fig. 2 shows the tomato leaves under different photoperiods at the end of the experiment. In our experiment, the difference in leaf appearance under different spectra was not recorded.

Figure 1. Tomato transplants grown under different photoperiods (16 h – left and 22 h right) and different irradiation levels (100, 170, and 240 μmol m^{-2} s^{-1}).

The experiment demonstrated that the longer photoperiod resulted in the significant decrease in the chlorophyll content and the development of heavy inter–vein chlorosis in tomato leaves. Table 1 presents the resulting experimental data.

DLI is the initial energy factor affecting the plants. It is not influences by the spectrum type and increases with the increasing irradiance and photoperiod. In the experiment, its values were almost the same, with the differences being 2.2%, in the combination of 240 µmol m^{-2} s^{-1} irradiance and 16–h photoperiod compared to the combination of 170 µmol m^{-2} s^{-1} irradiance and 22–h photoperiod (13.8 and 13.5 mol m^{-2} day^{-1}, respectively, as shown in bold in Table 1). This gives reason to expect compliance with the reciprocity law, according to which the plant response under these irradiation conditions should be the same.

However, the analysis of the data in the rest of Table 1 showed the significant deviations of some indicators from this law under such a variation range of light environment parameters. The above comments are equally applicable to the next parameter – the radiation dose H. Numerically, it is defined as the number of moles of photons of the radiation flux generated by the light sources and incident on a surface unit, including the plant leaves. From the photometric point of view, only this particular flux part is useful; the rest should be regarded as waste.

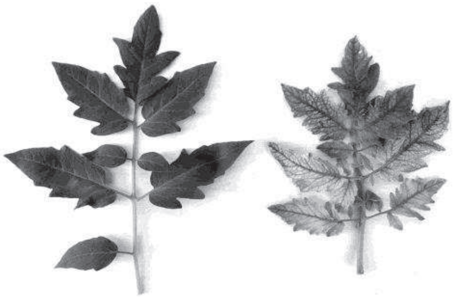

Figure 2. Tomato leaves under the16 h (left) and 22 h (right) photoperiod.

The decrease of leaf chlorophyll content, observed under the extended photoperiod, resulted in the reduced radiation absorption that was a protective response to the excess flux energy. Under the higher irradiance, the chlorophyll content at *PP* = 16 h increased under both spectra. However, its increment rate was lower under the radiation with a bigger share of blue flux (Spectrum II).

DLI values recommended for commercial tomato cultivation are known to be 20–30 mol m^{-2} day^{-1} (Moe et al., 2006). Under our conditions, these values in the variants with *PP* = 22 h under photon irradiance of 100 and 170 µmol m^{-2} s^{-1}, with *DLI* being 7.9 and 13.5 mol m^{-2} day^{-1}, respectively, were even lower than in the variant with *PP* = 16 h and photon irradiance of 240 µmol m^{-2} s^{-1} and *DLI* 13.8 mol m^{-2} day^{-1}, in which the leaf chlorosis was not observed. This suggests that chlorophyll degradation in this case was a response to an extended photoperiod rather than to *DLI* .

The leaf surface area S_L determines the amount of captured flux emitted by the light sources and its further use in photosynthesis. The studies show that an increase in the leaf surface area is more important than an increase in the chlorophyll content (Solhaug, 1991). Moreover, under higher photon irradiance level, the photosynthetic activity may be higher under a lower level of chlorophyll content (Leverenz, 1987). The experiment demonstrated significant (several times) reduction in the leaf surface area of transplants grown under the extended photoperiod. The blue radiation (Spectrum II) reduced the area further.

Table 1. Lighting regimes and values of tomato plant growth indicators under the different light quality, photoperiods, and irradiance at the end of the experiment

Indicator	Spectrum Type	*PP*, h	Irradiance *E*, umol·m^{-2}·s^{-1}		
			100	170	240
Daily lighting integral *DLI*, mol m^{-2} day^{-1}	I, II	16	5.8	9.8	**13.8**
		22	7.9	**13.5**	19.0
Radiation dose H, Mol m^{-2}	I, II	16	224.6	381.9	539.1
		22	308.9	525.1	741.3
Chlorophyll Content Index, rel.units	I	16	24.3 ± 1.8^{a}	43.7 ± 3.5^{b}	56.8 ± 3.8^{c}
		22	4.1 ± 0.3^{d}	4.6 ± 0.4^{e}	4.9 ± 0.4^{e}
	II	16	22.3 ± 1.9^{a}	43.4 ± 3.5^{b}	48.0 ± 4.5^{f}
		22	3.9 ± 0.3^{d}	4.9 ± 0.4^{e}	5.0 ± 0.4^{e}
Leaf area S_L, cm^{2}	I	16	981 ± 24^{a}	1123 ± 25^{b}	1029 ± 25^{c}
		22	164 ± 3^{d}	221 ± 5^{e}	229 ± 5^{e}
	II	16	926 ± 23^{f}	1018 ± 21^{c}	993 ± 19^{a}
		22	121 ± 3^{g}	184 ± 4^{h}	199 ± 4^{i}
Leaf fresh mass M_L, g plant^{-1}	I	16	29.77 ± 1.21^{a}	46.7 ± 1.84^{b}	47.77 ± 1.92^{b}
		22	4.78 ± 0.22^{c}	9.21 ± 0.38^{d}	11.13 ± 0.41^{e}
	II	16	29.85 ± 1.28^{a}	45.83 ± 1.94^{b}	48.18 ± 1.95^{b}
		22	3.97 ± 0.24^{f}	8.34 ± 0.41^{d}	10.76 ± 0.42^{e}
Leaf dry matter content v_L, %	I	16	9.6 ± 0.6^{a}	11.9 ± 0.7^{b}	13.8 ± 0.8^{c}
		22	11.0 ± 0.8^{b}	11.5 ± 0.9^{b}	12.4 ± 1.0^{b}
	II	16	9.5 ± 0.6^{a}	11.9 ± 0.7^{b}	12.6 ± 0.8^{b}
		22	11.2 ± 0.8^{b}	12.5 ± 0.8^{b}	14.1 ± 0.9^{c}
Specific leaf weight (*SLW*), g m^{-2}	I	16	29.1 ± 1.8^{a}	49.5 ± 3.2^{b}	64.1 ± 3.7^{c}
		22	32.1 ± 2.1^{a}	47.9 ± 2.7^{b}	60.3 ± 3.2^{c}
	II	16	30.6 ± 1.7^{a}	53.6 ± 2.3^{d}	61.1 ± 3.3^{c}
		22	36.7 ± 2.2^{a}	56.7 ± 2.1^{d}	76.2 ± 3.4^{e}
RUE, g mol^{-1}	I	16	0.130 ± 0.008^{a}	0.130 ± 0.009^{a}	0.119 ± 0.007^{b}
		22	0.104 ± 0.005^{c}	0.091 ± 0.005^{d}	0.081 ± 0.004^{e}
	II	16	0.136 ± 0.006^{a}	0.140 ± 0.007^{a}	0.113 ± 0.005^{b}
		22	0.119 ± 0.005^{b}	0.108 ± 0.003^{c}	0.103 ± 0.003^{c}

Means followed by the same letter do not differ significantly at $\alpha = 0.05$.

The similar pattern was observed for the fresh mass of leaves M_L. The lengthening of the photoperiod is reported to affect not only the accumulation of total biomass, but also its distribution over the plant organs. In tomato plants, the starch accumulation in the leaves is observed that can lead to lower photosynthesis rate (Doraiset al., 1996). In the experiment, the fresh mass increased with higher irradiance for both spectra. In absolute values, under the extended photoperiod, the wet mass yield was significantly lower.

The dry matter content v_L negatively correlates with the relative leaf growth rate and positively – with the leaf age. Leaves with high dry matter content are harder and less subject to physical damage. According to available data, bigger dry mass of plants under the extended photoperiod can be associated either with an increase in the photosynthetic plant area, or with the improved photosynthetic efficiency per leaf surface unit owing to higher chlorophyll content (Langton et al., 2003). However, the maximum chlorophyll content is not always correlated with the maximum fresh mass (Lefsrud et al., 2006).

In the experiment, a monotonic increase in the dry matter content was observed under the increasing photon irradiance with the higher share of blue (Spectrum II). At the same time, under the extended photoperiod, the dry matter content was higher at all irradiance levels. Under Spectrum I, the dry matter content for an extended photoperiod was lower than that under Spectrum II with higher irradiance levels.

The ratio of leaf area to dry leaf mass, i.e. specific leaf weight, *SLW*, is widely used in environmental studies. In the experiment, *SLW* increased with the growing irradiance for both spectra and photoperiods. Blue radiation additionally increased this index. Under Spectrum II, *SLW* values under *PP* = 16 h were smaller than those under *PP* = 22 h at any irradiance levels. Under Spectrum I, *SLW* value was smaller at higher irradiance levels when *PP* = 22 h than when *PP* = 16 h. That means the extended photoperiod contributed to an increase in *SLW* for both types of spectrum and any irradiation level, with the exception of medium and high levels with Spectrum I, where *SLW* values reduced.

Fig. 3 shows the deviation of ΔRUE, %, depending on the irradiance level for different light quality and photoperiods. ΔRUE calculation basis was the experimental conditions with the regular photoperiod (*P P*= 16 h), medium irradiance (E = 170 μmol $m^{-2}s^{-1}$, and no additional blue flux (Spectrum I).

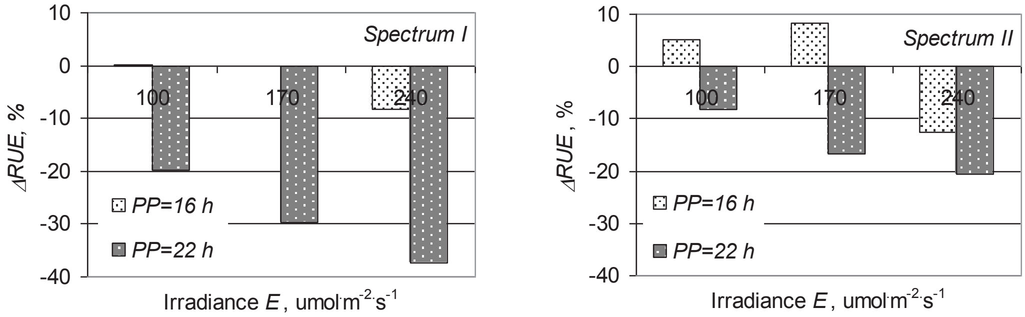

Figure 3. Deviation in *RUE* under varied light environment parameters.

Without additional blue flux, under a regular photoperiod, *RUE* reduced by 8% at high irradiance levels. With the extended photoperiod, under these conditions, the change in the irradiance level reduced *RUE* by 20–37%, with bigger reduction values being observed at higher irradiance levels. Seven percent addition of blue flux made it possible to increase *RUE* by 5–8% at the same and lower irradiance levels and under *PP* = 16 h. Under *PP* = 22 h and these conditions, *RUE* decreased by 8–21%.

CONCLUSIONS

In a series of experiments, tomato transplants in the pre–reproductive period were exposed to PAR with different photoperiods, photon irradiance, and light quality. An extended photoperiod was found to result in the development of leaf chlorosis. When varying the radiation dose components, the deviation from the reciprocity law was recorded. The analysis showed that the chlorophyll degradation was a response to the extended photoperiod rather than to the radiation dose. The chlorophyll content at

PP = 16 h increased with higher irradiance, while its increment rate decreased under radiation with a bigger share of blue flux.

The study results verify a great influence of an extended photoperiod on *RUE*, while the degree of influence depends on other parameters of light environment – light quality and irradiance level.

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