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New assessment tool for artificial plant lighting: case of tomato (*Lycopersicon Esculentum* Mill.)

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Abstract. Growing crops under artificial conditions need a very favourable environment, especially the spectral composition of radiation influencing the plant biometry greatly. The study objective was to find how to assess the closeness of real growing conditions to the optimal ones using a single coefficient, which would reflect several time dependencies of individual growth indicators. The plant growth friendliness factor (K_G) was proposed for this purpose. Tomato transplants (*Lycopersicon Esculentum* Mill., 'Polonaise F_1') were grown in a peat substrate under two lighting systems with different light quality.One system consisted of eight fluorescent lamps OSRAM L58W / 840 LUMILUX Cool White and eight lamps L58W / 77 FLUORA mounted on the standard frame, alternating the lamp types (Type I spectrum).In theother lighting system, the PCB Star LEDs with wavelengths of red 630 nm and far-red 735 nm were added (Type II spectrum). The irradiance level was maintained at 140 µmol m^{-2} s^{-1}, the photoperiod was 16 h. The ratio of long-wave flux to the total flux K_L was calculated for these lighting systems (0.37 rel.units for Type I spectrum and 0.50 rel.units for Type II spectrum) and K_G factor was determined by the proposed formula. The value of K_G was found to be twice as small for Type I spectrum than for Type II spectrum. The significant difference in biometric parameters of tomato transplants grown under Type I and Type II spectra was revealed. The plants grown in the environment characterized by higher K_G, were higher; they had more significant wet mass and stem neck diameter.

Key words: greenhouse, plant lighting, *Lycopersicon esculentum,* light quality.

INTRODUCTION

Tomato (*Lycopersicon Esculentum* Mill.) is a fruit of great commercial importance. It is considered one of the most widely spread vegetables in the world cultivated under various production systems - from field plantations to modern plant factories. In industrial greenhouses, certain crops are grown throughout the year, with all environmental factors being under control. Therefore, these facilities are essential for food supply and food security in many parts of the globe, especially in the high latitude countries. In addition to natural sunlight, artificial radiation sources are used. In some cases, plants are grown under artificial lighting only (city farms, grow boxes, green walls, etc.). The plants require an optimal combination of environmental factors, with the light taking a special place among them. Variation in lighting conditions (intensity, duration, periodicity, and, particularly, the light quality) has a different effect on the growth and development of plants (Baeza et al., 2018).

The light quality is usually characterised by the share of energy in certain bands of photosynthetically active radiation (PAR) in blue (B) 400–500 nm, green (G) 500–600 nm, and red (R) 600–700 nm spectrum range. The far-red (FR) 700–800 nm energy plays an essential role in plant lighting. The general pattern is the intense light absorption by the plant leaves in B and R bands, and the reflection in G band. In FR band, both reflection and transmission are observed (Larcher, 2000). In several experiments, the effects of wavebands on plants were established. The B band radiation was found to be of critical importance. It affected the morphology of pepper stem and leaves and caused variations in the chloroplast composition (higher ratio of Chl a / Chl b) that improved the photosynthesis efficiency (Hoffmann et al., 2015). G radiation has a positive effect on the development of tomato and sweet pepper plants (Samuolienė et al., 2012). The FR radiation was revealed to increase the height of sweet pepper plants and the stem mass (Dale & Blom, 2004). The energy ratio in the above bands was found necessary for the normal photomorphogenesis of various plants as well (Kim et al., 2006).

The investigation results, available to date, prove an increased share of B radiation to contribute to the cell division and the emergence of first sprouts, and to prevent the seedling elongation. R radiation stimulates the root system development, influences the formation of fruits and seed germination, and promotes the flowering (Park & Runkle, 2018). The G wavelength has a minimal effect, although it is essential in the plant lighting, especially in the case of inter-lighting (Kim et al., 2004).

Advanced technical solutions associated with protected agriculture practices must focus on energy saving, in the first place, and provide the favourable environment for plants. In this context, the researchers need to take into account the recent fundamental scientific achievements. It is known that the low degree of optical energy conversion into the dry matter of plant tissues causes significant energy inputs in the lighting. Therefore, the use of artificial lighting sources brings forward the issues of energy efficiency and inside environment assessment (Rakutko & Patsukov, 2013).

The most important indicator of the plant lighting effectiveness is the plant growth dynamics, which is characterised by several biometric parameters. To create the mathematical models of their behavior is an important step towards the development of the theory and practice of plant lighting control. The obtained data can be used to develop the algorithms for plant performance control (Rakutko, 2018).

The mathematical relationship between the environmental factors and the productional process in plants will allow optimizing the plant growth and development by selecting the necessary combinations of parameters of these factors while achieving the maximum plant productivity. For this purpose, a dynamic model of a plant is required, which would consider the changes in its mass or the assimilating surface area in the growing process.

The study objective was to find how to assess the closeness of real growing conditions to the optimal ones using a single coefficient, which would reflect several dependencies of individual growth indicators on time.

MATERIALS AND METHODS

The study object was tomato plants (*Lycopersicon Esculentum* Mill., 'Polonaise F_1'). Tomato seeds were sown in one container with the peat substrate. The container was covered with film and placed in the room with the air temperature of +26 to 28 °C and the humidity of 70 to 75%. The first single sprouts appeared on the 3rd day. After the mass emergence of sprouts, when about 80% of their total number appeared, the plants were exposed to the round-a-clock lighting with the HPS lamp DNaz 400 (with irradiation 100 µmol m^{-2} s^{-1}). From this moment, the age of plants was recorded (DAE – the day after seedling emergence). On the 3rd DAE, the photoperiod was set at 16 hours. On the 10thDAE at the second true leaf phase, the plants were picked out in pots with the volume of one-litre filled with the 2:1 mix of peat and garden soil. The acidity of peat was neutralised with dolomite meal to pH of 6.0. One kilogramme of peat included the following mineral nutrients: K_2O – 330.2 mg, P_2O_5 – 42.8 mg, CaO – 151.6 mg, MgO – 102.8 mg, and N_2O_5 – 63.1 mg. On the 14th DAE, the pots were placed under the lighting facilities. The plants were watered and fertilized as required. On the 20thDAE, the third true leaf appeared. The first measurements were carried out on the 22ndDAE, the second measurements – on the 30th DAE, the third measurements – on the 38th DAE, and the fourth measurements – on the 46th DAE.

A comparative experiment was carried out in a laboratory room (6×6×3.5 m), with the specialized equipment being installed to provide the required plant growing conditions: an air conditioning system, electric fans, a water evaporator, a combined sensor for microclimate parameters, a control panel, and irradiation facilities. The room was divided into two zones by the light tight screens made of white plastic film, protecting the plants from being irradiated by the unit in the adjacent section and from the natural light, but not impeding the airflow inside the sections. During the experiment, the same level of total photon flux density (PAR+FR) 140 µmol m^{-2} s^{-1} in each zone was maintained by varying the height of the lighting facilities above the plant tops. The unevenness of irradiance in the zones characterized by the coefficient $z = Emax/E_{av}$ did not exceed 10%.

In the first zone, the installed lighting system consisted of eight fluorescent lamps OSRAM L58W / 840 LUMILUX Cool White (5000–7000K) and eight lamps OSRAM L58W / 77 FLUORA (Germany), mounted on the standard frame, alternating the lamp types. In the second zone, the installed lighting system had the same lamps as in the first zone and PCB Star LEDs (China) with the wavelengths of red 630 and far-red 735 nm (40 pieces each) were added.

Photon flux density (PFD) was measured with a TKA VD / 04 (Russia) device. The results are shown in Fig. 1.

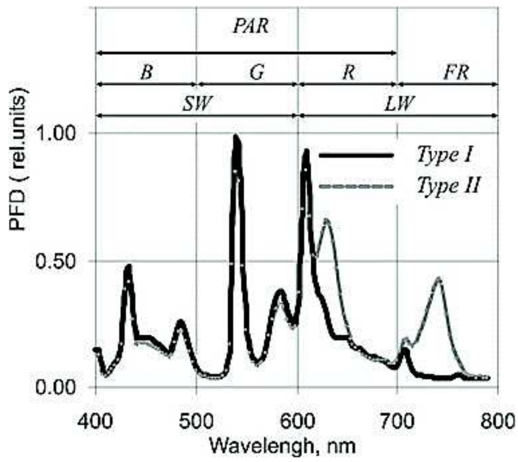

Figure 1. Photon flux density.

The methodological challenge in searching for the plant response to the light quality of radiation is that it is difficult to describe this composition by one indicator. In this study, the radiation fluxes in the blue and green wavelengths were totalled and considered as the radiation in the short-wavelength band (SW) of total radiation (PAR+FR). The radiation fluxes in the red and far-red wavelengths were totalled and considered as the radiation in the long-wavelength band (LW) of total radiation.

This approach made it possible to introduce a coefficient characterizing the share of long-wave radiation energy in the total radiation flux.

$$K_L = \frac{F_{LW}}{F_{SW} + F_{LW}}, \tag{1}$$

where F_{SW}, F_{LW} is radiation flux in SW and LW bands, correspondingly.

This coefficient was used to describe the spectrum type in the experiment variants: Type I – the spectrum with a smaller share of the long-wave radiation energy (K_L = 0.37); Type II – the spectrum with a larger share of the long-wave radiation energy (K_L = 0.50). In order to change the light quality, an additional flux from the LEDs was used, which increased the K_L value. To maintain the same level of PFD, the height of the lighting systems over the plant tops was different (0.38 m for Type I spectrum and 0.71 m for Type II spectrum). Illumination in the plant growing zones was 11.9 kLk and 9.7 kLk, respectively. Due to this difference, the plants in the experiment looked more illuminated under Type I spectrum.

In the series of measurements on different DAEs, the main biometric parameters of tomato plants were recorded: 1) stem neck diameter *D* (with a calliper), 2) number of leaves *N*, 3) height of hypocotyl *H* (with a ruler), 4) wet mass of the plant *M* (with scales), 5) leaf surface area *S* (by taking a pictures with a digital camera), and 6) dry matter content ν (by oven drying at 105 °C).

Variation dynamics in the stem diameter *D(t)* and the number of leaves *N(t)* were approximated by logarithmic curves. For example, the number of leaves

$$N(t) = Y_m (1 - e^{-B(t-T_m)}). \tag{2}$$

Variation dynamics in the height of hypocotyl *H(t)*, the wet mass *M(t)* and the leaf surface area *S(t)* were approximated by the Gompertz curves. For example, for the height of hypocotyl

$$H(t) = Y_0 + Y_m e^{-e^{-B(t-T_m)}}. \tag{3}$$

The dry matter content $\nu(t)$ was approximated by the polynomial

$$\nu(t) = At^2 + Bt + C. \tag{4}$$

Parameters Y_m, Y_0, T_m, *A. B, C* in the formulas 2-4 are approximating coefficients. They were obtained for both types of the spectrum. The best-fitting growth curve was selected based on the residual sum of square (Karadavut et al., 2008).

The energy and inside environmental conditions were assessed by the plant growth friendliness factor (K_G), which showed how close was the adopted lighting practice to the suitable optimal or best available technique (BAT).

The closeness degree was estimated by the normalized Euclidean distance between the two trajectories for the real conditions (*R*) and for the optimal (BAT) conditions (*O*) in the *n*-dimensional factor space of the biometric parameters of plants. Symbolically, this can be expressed as

$$K_G = \begin{cases} \frac{1}{k}\sum_{t=1}^{k}\delta_t^{R-O} \\ O \in BAT \end{cases}, \quad (5)$$

where δ_t^{R-O} is the mentioned normalized Euclidean distance.

Since the functional time dependences of plants' biometrics are given in the analytical form (equations 2–4), the expression for the plant growth friendliness factor takes the form

$$K_G = \frac{1}{T}\int_0^T \sqrt{\sum_{i=1}^{n} w_i \left(\frac{Y_i^R(t) - Y_i^O(t)}{Y_i^O(t)}\right)^2}\, dt, \quad (6)$$

where T is the estimated time period, $Y_i^R(t)$ and $Y_i^O(t)$ are the functional time dependences of the i-th parameter for real (R) and optimal (O) techniques, respectively, w_i is the weighting factor of the i-th parameter.

Optimal plant biometrics was taken from the expert opinion obtained during the interviews.

One-factorial experiments were arranged in three replications, with the mean values being calculated from six plants per replication. The curves were approximated in Excel 2013. The data were processed with STATISTICA 7.0 software packages. Statistical differences were analyzed using a 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

According to expert estimates, Type I spectrum with the smaller share of LW radiation was found more favourable for plants (Fig. 2). The plants under such radiation were stronger and better met the transplant quality standards. Figs 3 and 4 show, respectively, the dependence between the number of leaves on a plant and time, and the dependence between the neck diameter and time. Plants under the radiation spectrum with bigger K_{LW} had the more significant height and wet mass, but the smaller leaf area.

Statistically significant differences in these parameters in plants grown under the different radiation spectrum were not identified.

Figure 2. Tomato plants.

Figs 5, 6, and 7 show the dependencies between the hypocotyl height, its wet mass, and the leaf area and time. Dependencies have a characteristic sigmoid look. Fig. 8 shows the dependence between the plant dry matter content and time.

At the end of the experiment, the higher dry matter content was observed in plants exposed to radiation with lower K_L. The solid line in Figs 3 to 8 shows the development path of specific biometric parameters; it is plotted according to the expert estimates, based on the desired values of these parameters at any time point.

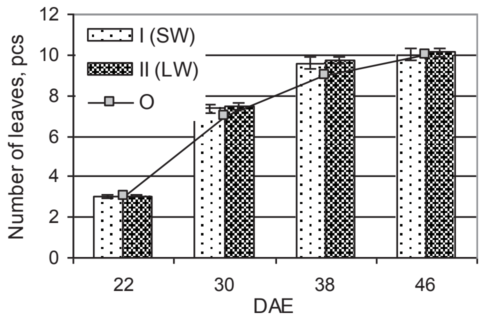

Figure 3. Number of leaves.

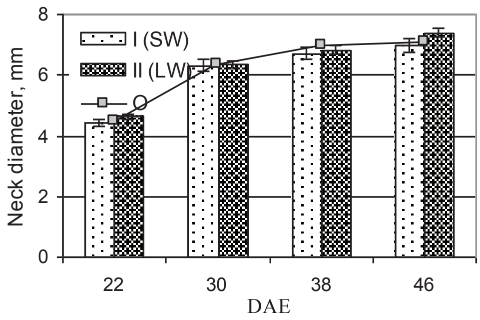

Figure 4. Neck diameter.

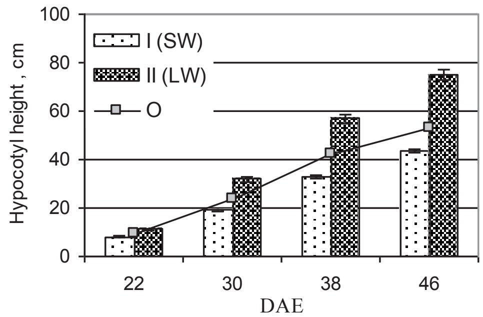

Figure 5. Hypocotyl height.

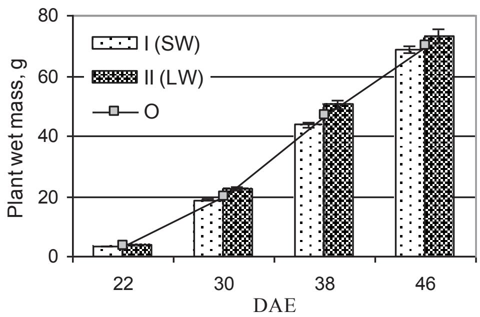

Figure 6. Plant wet mass.

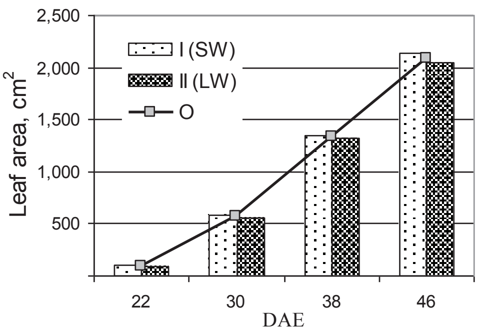

Figure 7. Leafarea.

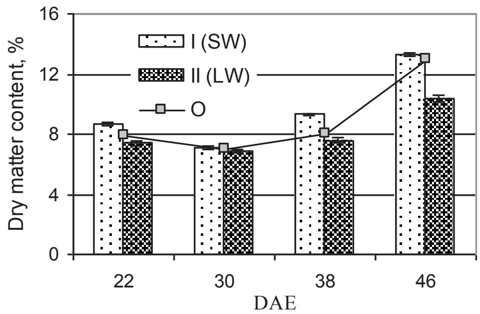

Figure 8. Dry matter content.

Table 1 presents the coefficients of approximation curves for the dynamics of specific biometric parameters for both types of spectrum, as well as for the optimal techniques.

The values of K_G calculated by the formula 6 are 0.22 rel. units for Type I spectrum and 0.38 rel. units for Type II spectrum. K_G increases with an increase in the share of the longwave radiation.

The proposed approach associated with K_G-based assessment is confirmed by the previously obtained knowledge that the blue radiation has a favourable effect on plant development at an early stage (Hoffmann et al., 2015). Insufficient light intensity or its inadequate light quality impairs the growth and development of tomato transplants, especially during the initiation of the first flower cluster that lowers the quality of transplants (Brazaityte et al., 2010).

Table 1. Coefficients of approximation curves

Parameter	Values		
	I (SW)	II (LW)	O
Model of the number of leaves $N = f(t)$, pieces			
Y_m	10.686	10.806	11.000
B	0.110	0.110	0.087
T_m	19.027	19.034	18.325
Model of the stem neck diameter $D = f(t)$, mm			
Y_m	6.984	7.594	7.213
B	0.161	0.098	0.143
T_m	15.724	12.355	15.175
Model of the plant height $H = f(t)$, cm			
Y_0	5.296	5.008	6.941
Y_m	50.345	89.360	54.019
B	0.098	0.100	0.126
T_m	32.684	31.865	31.366
Model of the plant wet mass $M = f(t)$, g			
Y_0	-0.674	-0.311	0.716
Y_m	117.900	101.137	97.802
B	0.077	0.096	0.097
T_m	37.706	34.126	35.004
Model of the leaf area $S = f(t)$, cm^2			
Y_0	-28.304	-37.546	-27.950
Y_m	3772.168	3366.178	3386.076
B	0.075	0.080	0.081
T_m	38.072	36.783	36.788
Model of the dry matter content $\nu = f(t)$, %			
A	0.022	0.013	0.023
B	-1.287	-0.755	-1.345
C	26.337	17.823	26.592

For optimizing plant growth, it is quite possible to use only a rather simple K_G-based approach, which does not encapsulate the notion of the crop yield formation as such. This approach is designed to describe the dynamics of plant development adequately in the various environments and/or to give a short-term forecast of these dynamics based on extrapolation of the initial data. Similar approaches are quite popular in the practice of plant cultivation.

Such empirical method is associated with the comprehension of experimental data and selection of the most appropriate (usually simple) formulas or a system of equations for their adequate description. This method of quantitative generalization and approximation of experimental data often makes it possible to understand the mechanisms responsible for the plant response (Medina-Ruíz et al., 2011). Changes in the phenotype during the growth can be modelled using the growth curves. The properties of these curves depend on the plant species, its phenotype and environmental conditions (Karadavut et al., 2008).

The ratio of energy shares in the shortwave and longwave band of the total flux was used as an indicator of the light quality of radiation. This indicator allows to express the diversity of spectral information by one number quantitatively. The changes in biometrics of tomato plants in the growth process were described by mathematics.

As a result of the empirical approach based on the experimental data, the suitable, rather simple, formulas for the main biometrics of plants were chosen. The dependence of plant biometrics on the proposed indicator K_L was revealed. The shift of the share of long-wavelength band (R+FR) from 37% to 50% (by 13%) was found to lead to a significant difference in almost all biometric parameters of plants in their cultivation process and to variation in the plant growth friendliness factor K_G from 22% to 38% (by 16%).

In previous studies, we proposed a method for monitoring the energy and ecological compatibility in various plant growing conditions (Rakutko et al., 2016). In this study, a similar approach was applied for growing tomato transplants under different light quality. The obtained data can be used to optimize the process of growing plants by varying the lighting parameters, environmental conditions and other factors.

CONCLUSIONS

The experiments confirmed the possibility to present the light quality of the radiation, usually given by the dependence of the radiation energy at each wavelength, with one number, namely the K_L indicator, which was numerically determined as the ratio of long-wave flux to the total flux.

A similar approach was applied to present the dynamic pattern of plant biometrics with K_G indicator, which characterized the proximity of real and optimal plant growing techniques.

The study experiments with tomato transplants demonstrated that the empirical dependence of K_G on K_L was a convenient tool for assessing the effectiveness of artificial plant lighting.

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