COMPARATIVE EVALUATION OF TOMATO TRANSPLANT GROWTH PARAMETERS UNDER LED, FLUORESCENT AND HIGH-PRESSURE SODIUM LAMPS

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Abstract. The objective of this study was to evaluate the effect of difference in light quality on growth, photosynthesis energy consumption (PE) and production (PP) parameters of tomato transplants. Tomato transplants were grown with 10 h dark and 14 h light under photon flux 140 $\mu mol \cdot s^{-1} \cdot m^{-2}$ under light emitted diodes (LED), fluorescent (FL) and high-pressure sodium (HPS) lamps. Light quality from LED irradiator was close to nominal for tomatoes, from FL – an equal share of energy in spectral bands, from HPS irradiator – a maximum in the red-yellow region. Most PP (and lowest PE) on a wet weight and dry matter was observed in plants grown under HPS, the lowest PP (and most PE) on a wet weight under LED, on dry matter – under FL. The closest negative correlation between the chlorophyll content in the leaves and the PE on dry matter when using LED was revealed.

Keywords: tomato transplants, light quality, growth parameters, chlorophyll content, energy consumption, photosynthesis production.

Introduction

Nowadays, tomato (*Solanum Lycopersicum* L.) is one of the major vegetable crops throughout the world. It is grown in both tropical, sub-tropical and temperate areas [1]. Consumer demand for tomatoes all year long is increasing continuously [2]. Light is the main environmental factor affecting plant growth and biomass production. Insufficient light intensity or quality limits the growth and the development of tomato transplants, especially during the first inflorescence development and therefore their quality worsens [3]. At the northern latitudes tomatoes are grown in the greenhouses: planted in mid-winter and harvested until late autumn [4; 5]. The environment conditions for transplants in outdoor growing, especially in northern latitudes, are unfavorable due to low natural light and short light days. Artificial irradiation in the photosynthetically active radiation (PAR) contributes to intensify the process of transplant growth and production of the earlier harvests from mature plants [6]. Spectral quality can have profound effects on the growth, development, and physiology of plants [7; 8].

Researches have shown that different types and cultivars of plants require different flux light quality, and the productivity optimum is pointed quite clearly. In accordance to current industry techniques flux light quality is characterized by the ratio of the emission intensity between three spectral bands of PAR: blue k_B (400-500 nm), green k_G (500-600 nm) and red k_R (600-700 nm). For some plant types spectral ratios to ensure the best results are found. For tomato these ratios are $k_B : k_G : k_R = 15\ \% : 17\ \% : 68\ \%$ [9]. The ratios of blue, red and far red (700-800 nm) are also important for normal photomorphogenesis of various plant types [10; 11]. Blue light effects on decreased elongation growth [12-14] and leaf area expansion [15; 16] in tomato and cucumber transplants were also described.

According to the data of various authors, the addition of green light in combination with blue and red light affects the growth processes as well as the development of plants, because green light penetrates the foliage better and its deeper layers use green light for photophysiological processes more effectively [17]. The supplemental yellow light especially enhanced tomato transplant elongation. The hypocotyls of these plants as well as the first internodes were long. Other authors also indicate that yellow light enhanced internode elongation of various plants [18]. Some authors noticed that such plants had delicate stems, small leaves, reduced fresh and dry weight [19]. Other authors state that yellow light increased the leaf area [20]. Red light induces hypocotyl elongation and expansion in the leaf area [21]. Whereas specific responses of plants to a light quality may sometimes be predictable based on published research, the overall plant response is generally difficult to predict due to the complicated interaction of many different responses [22]. Flux energy is the basis of photosynthesis processes and indoor cultivation of useful plants. Its application in hothouse vegetable growing puts forward special requirements to efficiency of power and material resources usage. The main drawback of the currently used light sources (LS) is insufficient efficiency converting electrical energy into flux [23].

The overwhelming majority of processes in agriculture may be described as power technological processes (PTP), i.e. the processes, which are based on transformation of the input energy at the beginning of the process into the products at the end of the process. The defining competitiveness factor of the made products is its energy consumption [24]. The technological process of plant irradiation (TPI) is a special type of PTP. Light quality affects on the TPI energy consumption [25].

Our objective was to evaluate the differences in some growth, photosynthesis energy consumption and production parameters of tomato transplants grown under different LS: light-emitted diodes (LED), fluorescent lamps (FL) and high-pressure sodium (HPS) lamps.

Materials and methods

The growth, development and quality parameters of transplants medium early varieties of tomato Flamingo F_1 were investigated. As the soil peat was taken made from "Pelgorskoe-M" Leningrad region, acidic (pH 3.6), with the 10 % decomposition degree, 55 % humidity and a low content of major nutrients. The acidity of the peat was neutralized with chalk to pH 6.2. Dressing the peat with main nutrients and trace elements was made. The content of mobile forms of major nutrients was brought to levels, $mg \cdot l^{-1}$: NH_4^+ – 20; NO_3^+ – 194.5; K^+ – 189.6; Ca^{2+} – 160; Mg^{2+} – 60; Mn^{2+} – 0.5; Cu^{2+} – 0.05; Mo^{6+} – 0.05; B^{3+} – 0.05. The content of P^{5+} was 20 mg · $(100\ g)^{-1}$ dry peat. EC – 1.0 $mS \cdot cm^{-1}$.

Sowing was done on 13.03.2014 in a box with peat. Shoots appeared on 15.03.2014. After a three day persistent exposure, the seedlings were transferred to 16 hours a day photoperiod. After picking on 14-day-old transplants were transferred to a light room, where they were irradiated under different LS within 30 days 14 hours a day photoperiod. The plant density was maintained at 25 plants per 1 m^2. The transplants were grown in containers with a volume 663 cm^3. The research was carried out in a light room, divided into three zones opaque partitions. During growing the automatic control system maintained +21...+22 ºC air temperature; 55...60 % humidity; 0.05...0.25 $m \cdot s^{-1}$ air mobility. The humidity of the substrate in the containers was supported within 70...75 % of metered irrigation water with 24...25 ºC temperature. Fertilizing transplants was performed periodically with 0.1...0.15 % solutions of fertilizers KH_2PO_4, $MgSO_4$ and KNO_3 with electrical conductivity EC = 2.0...2.5 $mS \cdot cm^{-1}$.

For irradiation the following irradiation facilities were used.

In the first zone an experimental LED irradiator of our own making, consisting of three panel radiators of the total size 1.0x0.73 m was used. The LED type ARPL-Star-3W in the amount of 225 with the power unit HTS-200M-12 were used. The desired light quality was provided by proportions between blue (luminous flux 1.28 Lm, 90 pcs), green (luminous flux 56.5 Lm, 45 pcs) and red (luminous flux 36.7 Lm, 90 pcs) LEDs, as well as the magnitude of the current through the LEDs. The total luminous flux was 5961 Lm. Light quality from LED irradiator was close to nominal for tomatoes [6].

In the second zone an illuminator ЛСПО with electronic ballast of 42 kHz frequency was used. The illuminator was equipped with two FL L58W/77 Fluora OSRAM, the light output 2250 Lm, and two lamps PHILIPS MASTER TL-D Xtra 58W/840, the light output 5200 Lm. Total luminous flux was 14900 Lm. Light quality from FL irradiator had an equal share of energy in spectral bands.

In the third zone the irradiation facility consisted of two irradiators ЖСП 64-400-001 "Флора" with HPS lamps ДНаЗ 400 and electronic ballast. Total luminous flux was 106000 Lm. Light quality from HPS irradiator had a maximum in the red-yellow spectral region.

Spectral irradiance was measured with a spectroradiometer ТКА ВД/04, the measurements were converted to *PPF*. The amount of the chlorophyll content (in relative values) in the each leaf of the plants was estimated with the chlorophill content index (CCI) in the process of growing with a chlorophill content meter CCM 200. The leaf areas were determined by the photogrammetric method.

The plants were placed at square, uniform exposure which was not less than 20 %. Originally 20 pots with plants in each zone were placed. The photosynthetic photon flux (*PPF*) 140 $\mu mol \cdot s^{-1} \cdot m^{-2}$ was supported with the change in suspension height irradiators over the tops of the plants (Fig. 1).

LED FL HPS

Fig. 1. **Irradiation facility with different LS**

The photosynthesis energy consumption (*PE*) and production (*PP*) parameters for each leaf of the plants on the 42-nd day of the study were determined with the next method. During the study the amount of leaves *n*, pieces, on plants grown under each type of LS at times *T*, days, was determined and approximately the data obtained with the equations

$$n = \alpha \ln(T) - \beta , \quad (1)$$

where α, β – constant coefficients for a given LS type.

The times of occurrence of the *n*-th leaves were found from equation (1)

$$T_n = \exp\left(\frac{n+\beta}{\alpha}\right). \quad (2)$$

The "age" of the *n*-th leaf on the date of completion of the study

$$T_n^{\text{в}} = T^{\text{к}} - T_n , \quad (3)$$

where T^{K} – day at the end of the study, T^{K} = 42 day.

The *PP* value of the *n*-th leaf, $g \cdot m^{-2} \cdot day^{-1}$, was determined with the formula

$$PP_n = \frac{M_n}{S_n T_n^{\text{в}}} , \quad (4)$$

where M_n – wet weight or dry mass for the *n*-th leaf, g;
S_n – area of the *n*-th leaf, m^2;

The *PE* value of the *n*-th leaf was determined with the formula

$$PE_n = \frac{H_n}{M_n} , \quad (5)$$

where H_n – radiation dose, which, if the functional dependence of changes in the leaf area from time $S_n(T)$ is known, is determined with the formula

$$H_n = PPF \int_0^{T_n^{\circ}} S_n(T) dT , \quad (6)$$

where *PPF* – photosynthetic photon flux on plants, *PPF* = 140 $\mu mol \cdot s^{-1} \cdot m^{-2}$;
T_n° – duration of irradiation on the n-th leaf, sec, is determined with the formula

$$T_n^{\circ} = 3600 \cdot Ph \cdot T_n^{\text{в}} , \quad (7)$$

where *Ph* – photoperiod, *Ph* = 14 h.

Under the assumption of linear dependence of the change of the leaf area over time since its appearance on the stem the expression for the dose takes the form

$$H_n = \frac{1}{2} PPF \cdot S_n \cdot T_n^{\circ} . \quad (8)$$

Based on the above expressions for the specific leaf the *PP* value, $m^{-2} \cdot day^{-1}$, and *PE*, $mol \cdot g^{-1}$, are related by the expression

$$PE_n = \frac{k^F}{PP_n}, \tag{9}$$

where k^F – coefficient, in this study $k^F = \frac{1}{2} PPF \cdot 3600 \cdot Ph$ =3,528 mol·m^-2·day^-1.

For all plants, the average value of PE

$$\overline{PE} = \frac{H_\Sigma}{M_\Sigma} = \frac{\sum_{n=1}^{N} H_n}{\sum_{n=1}^{N} M_n}. \tag{10}$$

Then the average value PP

$$\overline{PP} = \frac{k^F}{\overline{PE}}. \tag{11}$$

Results and discussion

The LED used in this study had enough narrow spectral output (25 nm band at half peak height), in contrast to the broad spectrum FL or HPS lamps (Fig. 2).

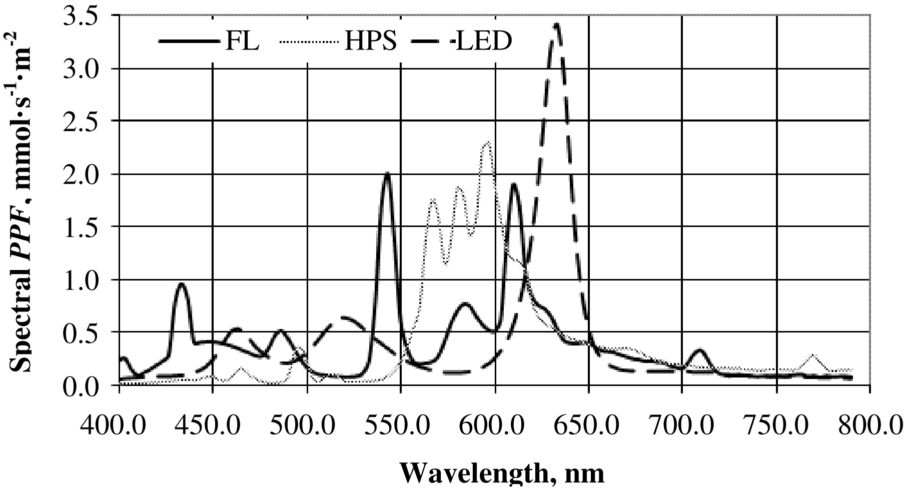

Fig. 2. **Spectrum density of PPF**

Table 1 shows the parameters of the radiation environment of plants.

Table 1

Parameters of the radiation environment of plants

Parameters	LS		
	LED	**FL**	**HPS**
PPF, μmol·s^-1·m^-2	140.0	140.0	140.0
PAR irradiance, W·m^-2	29.1	30.56	28.40
Illumination, Lx	7800	13400	16100
The composition of PAR flow, % k_B (400-500 nm)	19.3	32.1	7.2
k_G (500-600 nm)	24.3	33.6	52.8
k_R (600-700 nm)	56.4	34.3	40.0

Because of the differences in the light quality, the lights with the same PPF, μmol·s^-1·m^-2, have not the same the PAR irradiance, W·m^-2, and illumination, Lx, values. Spectroradiometer scan showed that the HPS irradiator provided 28.5 % more than the LED irradiator and 19.2 % more than the FL irradiator of green radiation. The LED irradiator provided 16.4 % more than the HPS irradiator and 22.1 % more than the FL irradiator of red radiation.

Fig. 3 shows the appearance of the 44-day plant grown under different LS. The best look for further production of tomato fruit had the transplants grown under FL.

LED FL HPS

Fig. 3. **Appearance of the 44-day plants grown under different LS**

Fig. 4 shows the dynamics of the leave amount on the plants under different LS and expressions approximating the experimental data. The highest rate of appearance of leaves was observed under HPS, and the lowest - under LED. So, the 10-th leaf under HPS appeared on the 36-th day, under LED – on the 41-th day.

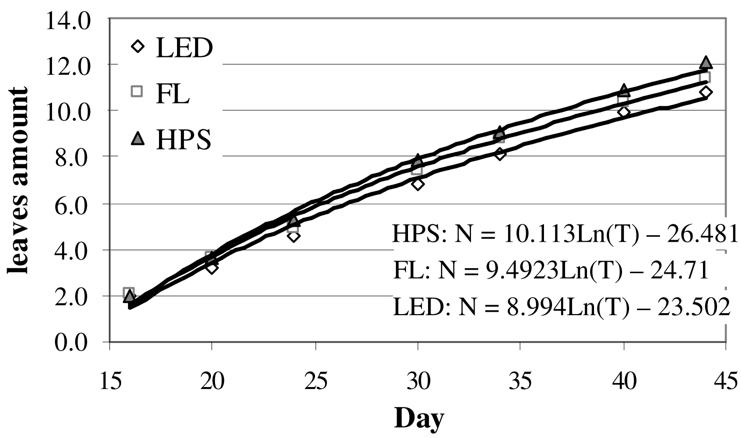

Fig. 4. **Dynamics of the number of leaves on plants under different LS**

Table 2 shows the characteristics of the 44-day tomato transplants.

Table 2

Characteristics of the 44-day tomato transplants

Parameters X	**LED**		**FL**		**HPS**	
	$\overline{X}$	σ_X	$\overline{X}$	σ_X	$\overline{X}$	σ_X
Plant height, cm	47.43±1.74	5.51	48.53±1.46	5.84	68.75±1.79	3.73
The number of leaves, pcs	10.8±0.2	0.63	11.44±0.16	0.63	12.08±0.54	0.73
Internodes, mm	49.3±1.65	11.2	48.86±1.63	18.39	65.06±2.57	25.30
Stem diameter, mm	6.6±0.21	0.67	7.18±0.09	0.38	7.16±0.16	0.54
Wet weight of the plant, g	31.29±4.13	13.05	52.58±1.60	6.41	55.42±3.51	12.17
Stem density, $g \cdot cm^{-3}$	1.86±0.17	0.54	2.71±0.10	0.38	1.99±0.07	0.24
Dry matter, %	10.10±0.32	0.65	11.39±0.26	0.52	12.43±0.28	0.57

The transplants grown under HPS had a higher plant height, elongated stem, most amount of leaves, wet weight and dry matter content. The transplant grown under LED had the lowest values of biometric parameters.

Fig. 5 shows the CCI values for individual leaves (numbering is from the root) of the transplants grown under different LS.

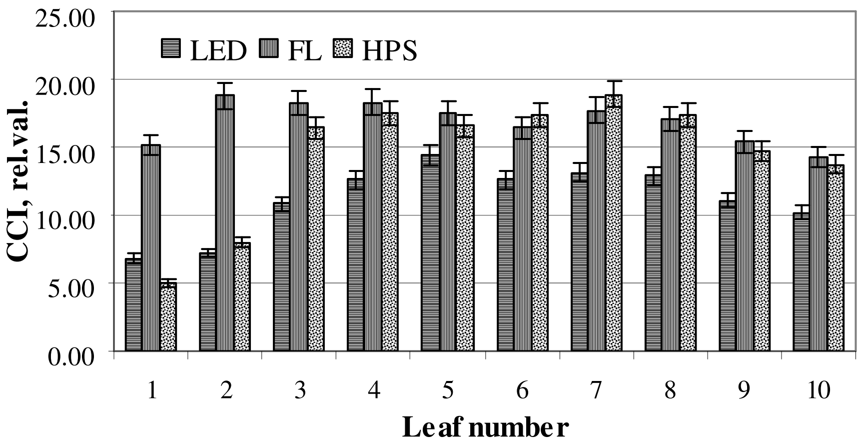

Fig. 5. **CCI values for leaves of tomato plant grown under different LS**

The plants, grown under LED and HPS, have the lowest chlorophyll content in the leaves of the lower tier. In more upper storeys the CCI increases. The plants grown under FL, have more evenly distributed chlorophyll content in the leaves of the crown.

Table 3 summarizes some integral parameters of productivity and efficiency of photosynthesis in plants grown under different types of LS.

Table 3

Parameters of productivity and efficiency of photosynthesis

Parameters	LS		
	LED	**FL**	**HPS**
The total surface area of leaves, cm^2	669.9±33.5	1187.3±59.4	1111.7±55.6
The total mass of leaves, g wet weight	14.11±0.71	25.27±1.26	27.07±1.33
dry matter	1.37±0.06	1.62±0.07	3.15±0.14
The radiation dose H_{Σ}, µmol	4.62±0.23	7.68±0.37	7.22±0.28
The average value of CCI, relative values	11.2±0.4	16.9±0.6	14.6±0.7
Average $\overline{PE}$, $mol \cdot g^{-1}$ on wet weight	0.33±0.02	0.30±0.02	0.27±0.01
on dry matter	3.37±0.17	4.73±0.24	2.29±0.09
Average $\overline{PP}$, $g \cdot m^{-2} \cdot day^{-1}$ on wet weight	10.77±0.43	11.61±0.58	13.23±0.65
on dry matter	1.05±0.04	0.75±0.03	1.54±0.07

The greatest total leaf area, and hence the dose of the PPF received by the leaves to the end of the experiment, had the transplants grown under FL, the lowest – under LED. This same pattern corresponds to the amount of chlorophyll in the leaves. However, the greatest total mass of leaves and the amount of dry matter was observed in the plants grown under HPS lamps, the minimum value of the mass in LED.

In general, most PP (and lowest PE) on a wet weight and dry matter was observed in the plants grown under HPS, the lowest PP (and most PE) on a wet weight under LED, on dry matter – under FL.

To identify the relationship between the chlorophyll content in the leaves of plants and PP and PE parameters the correlation analysis was made (Table 4). A weak correlation is revealed between CCI_n and PP_n on wet weight and dry matter for the plants grown under LED and HPS lamps. Quite a strong correlation is revealed between CCI_n and PE_n on dry matter for the plants grown under LED and HPS lamps and on wet weight for the plants grown under FL.

Table 4

Results of correlation analysis

Correlation parameter R	LS		
	LED	**FL**	**HPS**
between CCI_n and PE_n on wet weight R_{wet}	-0.124	-0.699	0.192
on dry matter R_{dry}	-0.120	-0.694	0.125
between CCI_n and PE_n on wet weight R_{wet}	-0.305	0.639	-0.398
on dry matter R_{dry}	-0.754	0.017	-0.600

The closest negative correlation between the chlorophyll content in the leaves and the efficiency of photosynthesis on dry matter when using LED was revealed.

Conclusions

1. A model of a plant, taking into account the dynamics of changes in the area of each leaf of the plant and its weight in the process of growing, is presented. A method is developed for estimating the energy efficiency of photosynthesis in its energy intensity, calculated as the ratio of the dose of radiation flux incident on the surface of the leaves, the weight of the matter obtained in the process of photosynthesis. It is shown that photosynthetic productivity is inversely proportional to its energy consumption.
2. Processing of the experimental data with the presented method on the cultivation of tomato transplants under various LS confirmed that the PPF light quality significantly affects the efficiency of photosynthesis and the utilization of carbon and light food.
3. Most photosynthesis production (and lowest energy consumption) on a wet weight and dry matter was observed in the plants grown under HPS, the lowest photosynthesis production (and most energy consumption) on a wet weight under LED, on dry matter - under FL.
4. The closest negative correlation between the chlorophyll content in the leaves and the efficiency of photosynthesis on dry matter when using LED was revealed.

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