MONITORING TECHNIQUE OF ENERGY AND ECOLOGICAL EFFICIENCY OF INDOOR PLANT LIGHTING

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Abstract. The article presents the technique and the monitoring results of energy and ecological efficiency for two growing environments of lettuce (*Lactuca sativa L.).* In a plant growing experiment, under otherwise equal conditions, two different radiation sources were used with different photosynthetic photon flux but practically the same illuminance of 10 kLx in the plant-growing zone. In the first irradiation facility an induction 400 W lamp was installed. The ratio of emission intensity between three spectral bands (blue k_B 400-500 nm, green k_G 500-600 nm and red k_R 600-700 nm) was $k_B : k_G : k_R$ = 22 % : 41 % : 37 %. In the second irradiation facility the sodium lamps with the same wattage were used. The ratio was $k_B : k_G : k_R$ = 10 % : 61 % : 29 %. During the plant growing period the dynamic pattern of irradiance in the plant cultivation zone was recorded; the samples of plants were taken with a certain time interval; dry matter content and the total leaf area in the sample plants were measured. The hodograph curves were plotted in the coordinates of dry matter increments, accumulated in plant leaves, and the increments of optical radiation flow dose up-taken by plants during the growing period. Reference hodograph was plotted for the lettuce plants grown under standard climate parameters and cultivation regimes. The level of energy and ecological efficiency of indoor plant lighting was estimated by the value of the normed sum of squared differences (NSSD) of coordinates of points of the experimental and the reference hodographs. In the first irradiation facility the value of NSSD = 0.0039 arbitrary units is smaller than that in the second IF (NSSD = 0.0016 arbitrary units). This indicates the higher level of energy and ecological efficiency for conditions in the second irradiation facility. The experiment proved that the level of indoor plant lighting energy and ecological efficiency essentially depends on the type of the irradiation source.

Keywords: energy and ecological efficiency, monitoring, indoor plant lighting, lettuce, growth curve, hodograph.

Introduction

Indoor plant lighting is a technological process of growing plants with the aim to produce the yield under controllable environmental factors in both natural exposure and under the flow from artificial irradiation sources (IS). Growing plants under artificial light requires significant power inputs, so environmental and energy issues are of particular relevance [1]. In the indoor plant lighting the useful products are produced by living organisms – plants. Development of agricultural knowledge and practice of production have revealed the need to create energy-efficient agricultural technologies with the minimum negative impact on the environment, which should be based on the most important achievements of fundamental sciences. The laboratory of energy-efficient electric technologies of IEEP (Saint Petersburg) has established a new scientific direction – energy and ecological efficiency (EEE) of the indoor plant lighting. Theoretical basics were formulated and practical experience was gained in energy and ecological analysis and design of irradiation installations in plant growing facilities [2] on the basis of the created hierarchical model of an artificial bio-energetic system (ABES). This system combines technical and power devices, processes, and biological objects (plants), which are used in the indoor plant lighting to provide the required technological steps to receive the finished products [3].

Specific feature of energy and ecological efficiency of the indoor plant lighting as a research area is that the energy efficiency and environmental performance parameters are considered in terms of the applied theory of energy saving, which studies the patterns of substance flows (material and energy) in the ABES [4].

The systemic integrative optimality criterion is the level of EEE in the indoor plant lighting carried over during decomposition to the local optimality criteria in the corresponding optimization problems of individual hierarchical levels of the model. On the basis of the obtained theoretical concepts the practices of designing and estimating the performance of separate energy saving measures were developed [5]; energy and environmentally friendly modes of power technological processes and control algorithms for energy efficiency and eco-friendliness of the system were justified [6; 7]. Energy and ecological efficiency of the indoor plant lighting characterizes the relationship of optical radiation energy flux and the flow of resulting products of photosynthesis in plants.

The use of electric lamps as an IS has come a long way of development from incandescent lamps, open arc and gas-discharge lamps to high-pressure sodium lamps (HPS), which are still the most popular for supplemental lighting in greenhouses [8]. The LED technology today is still relatively expensive, but combing traditional IS with LED makes it possible to both optimize the spectral content for a variety of plants and various physiological processes (growth, flowering, photosynthesis efficiency), and also to create a cost-effective irradiation system. In recent studies, the combinations of LEDs and fluorescent [9] and high-pressure sodium lamps [10] are used to search for the ways to improve the growth and metabolic effects in plants. The use of LEDs in the indoor plant growing is surely a promising direction, but it requires addressing a large number of problems before the LEDs will be used on an industrial scale. Another promising type of IS for the indoor plant growing is fluorescent high frequency electrodeless induction lamps (IL), the emission spectrum of which can be specified by the composition of applied luminophor.

Monitoring of energy and ecological sustainability is aimed at obtaining reliable information on the dynamics of the flows of energy and products of photosynthesis in the indoor plant growing. There is a method in place of integrated energy and ecological survey of power and industrial facilities, including the measurement of power and ecology indicators, identification and comprehensive assessment of on-site energy efficiency factors and environmental conditions, development of a set of measures, which ensure both reduction of actual consumption of energy resources and specific emissions per unit of output [11]. The known method to estimate the efficiency of the photosynthesis process consists of the following steps: the dynamics of light scattering by plant leaves is recorded; the first derivative of the decay curve of light scattering intensity is differentiated; and the leaves transmittance factor is calculated. By the value of the indicator of the functional state of the photosynthetic apparatus the net productivity of photosynthesis may be assessed: the bigger this indicator, the higher the net productivity of photosynthesis [12]. A method is also known to optimize the plant growing conditions, by which the parameters of plant environment in a greenhouse and biometric parameters of plants are measured [13]. It is known that the indicator of fluctuating asymmetry is used as a measure to assess the stability of the organism development [14]. The method is based on the fact that the level of morphogenic abnormalities is minimal only under certain (optimal) environmental conditions, and it increases in a non-specific way under all stress impacts.

Our objectives were (1) to create a method to obtain and interpret the parameters of energy efficiency and environmental friendliness of indoor plant lighting in their interrelatedness; (2) to present the results of the use of this technique in indoor lettuce growing; (3) to verify the hypothesis about the dependence of the level of indoor plant lighting EEE on the type of the irradiation source.

Theory

Growth is one of the important properties of living plant organisms. Changes in a phenotype during the growth period may be modeled via growth curves. Behavior of the growth curves can vary according to the plant type, its phenotype and environmental conditions [15].

A monitoring method is proposed for the EEE of the indoor plant lighting, which includes receiving in the course of an experiment the data on the variation of the flux dose up-taken by the plant during the growing period $H = f(t)$ and deriving the dynamics of the dry matter content $M = f(t)$ accumulated in the leaves of plants during the growing period. It is important not only to obtain reliable information on the flows of the substance synthesized under the optical energy flux, but also to present it in a graphic, informative and easy-to-understand form.

For this purpose, the most convenient is the graphic representation of the influence of additional dose of irradiation flow dH on the increment of dry matter dM synthesized in the plant leaf at various time intervals during the plant growing period t. Such a curve is the hodograph of the vector, which connects the origin of coordinates and the given point on this graph. Tangent of the angle between the vector and the horizontal axis represents the dynamic energy output ratio, i.e. $\text{tg}\alpha = dH/dM = \varepsilon_d$. Hodograph, plotted for plants grown in the standard, most optimal conditions, is taken as reference.

Any variations in the plant growing conditions (temperature, inside climate, nutrition, and irradiation) during the period of plant growing affect the process of photosynthesis and photomorphogenesis.

It is particularly important to identify the influence of the flux dose deviation on the dry matter accumulation. Such deviations, which occurred during the period of plant cultivation, led to the deviation from the reference hodograph. Having plotted the hodograph curve by the experimental data, we may assess the level of indoor plant lighting EEE by the degree of deviation of this curve from the reference.

Materials and methods

The growth and development of plants of early varieties of lettuce Afitsion (*Lactuca Sativa L.*) were investigated. The seeds were sown on 11.11.2015 in a box with prepared peat. Full sprouts emerged on 13.11.2015. The first true leaf was formed on 19.11.2015; then the lettuce was pricked out by three plants in each plastic container with peat (weighing 280-290 g). The containers were placed under irradiation facilities (IF). Mass emergence of the second true leaf (above 70 %) was observed on 21.11.2015; the third leaf – on 25.11.2015; the fourth leaf – on 28.11.2015, at the plant age of 16 days.

The measurements of biometric indicators started on the 18-th day after the pricking out. The experiment was set in a room without natural lighting with the area of 18 m^2. During the growing period an automatic control system maintained the air temperature at +20 to +22 ºC; the air humidity – at 55 to 60 %; and the air circulation – at 0.05 to 0.25 m·s^{-1}. The substrate moisture content in the containers was maintained within 70 to 75 % by metered irrigation water with the temperature of +24 to 25 ºC. The plants were fertilized periodically with 0.1 to 0.15 % solutions of KH_2PO_4, $MgSO_4$ and KNO_3.

A comparative experiment was carried out in the two parts of the room, separated by a light-tight partition. Lettuce plants were placed on the benches across the area with the exposure uniformity being not less than 20 %. Initially 20 pots with plants were placed in each zone. The same illuminance (10 kLx) was maintained by adjusting the suspension height of irradiators over the plant tops. In the first irradiation zone a 400 W induction lamp was installed. The height of the lamp above the plants was 1.17 m. The PAR irradiation was 22.07 W·m^{-2}. The photon irradiance was 102.31 μmol·m^{-2}·c^{-1}. The ratio of the emission intensity between three spectral bands (blue k_B 400-500 nm, green k_G 500-600 nm and red k_R 600-700 nm) was $k_B : k_G : k_R$ = 22 % : 41 % : 37 %. In the second irradiation zone HPS lamps with the same wattage were used. The height of the lamps above the plants was 1.07 m. The PAR irradiation was 17.69 W·m^{-2}. The photon irradiance was 85.89 μmol·m^{-2}·c^{-1}. The ratio was $k_B : k_G : k_R$ = 10 % : 61 % : 29 %. The plants were grown with the round the clock photoperiod (PP=24 h). Spectral irradiance was measured with the spectroradiometer ТКА ВД/04 (Russia) with modified software (Fig. 1).

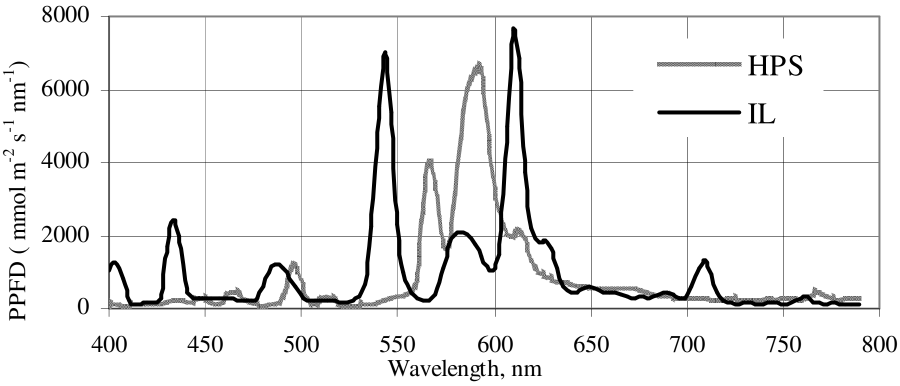

Fig. 1. **Spectral photosynthetic photon flux density**

A model of growth and development of plants was applied, which takes into account the dynamic pattern of the each leaf area of the plant and its weight during the growing period [16]. During the experiment, at certain time points T_n three pots from each table were randomly selected. The leaves from the plants were divided into groups according to their number n in the order of their emergence. The number of leaves per plant N, their geometric dimensions (length A_n and width B_n), the wet weight

$M_\mathrm{n}^{\mathrm{wet}}$ and the yield of dry matter $M_\mathrm{n}^{\mathrm{dry}}$ were recorded. Lettuce plant leaf area was calculated by the formula $S_n = 0.53A_nB_n$, which was derived in preliminary experiments. The obtained experimental data of phenotype (leaves surface area S_Σ, wet weight of leaves M^{wet} and dry matter yield M^{dry}) were approximated with Gompertz curves

$$Y = Y_0 + Y_{\max} e^{-e^{-B(t-T_m)}}, \tag{1}$$

where Y – modelled parameter;
Y_0 – initial value of Y;
$Y_{\max}$ – final or potential value of Y;
B – relative growth rate at time point T_m;
T_m – time point, at which the absolute growth rate has the maximum value; this is also the time point, at which the relative growth rate is B;
t – recording time.

Flow dose increments ΔH, mol, were calculated by the formula

$$\Delta H = E_\Sigma \Delta S \Delta t \frac{PP}{24} 3600 \cdot 10^6, \tag{2}$$

where E_Σ – photon irradiance;
Δt – time interval when tabulating Gompertz curves;
ΔS – increments of leaf surface area during this interval.

By the obtained Gompertz curves the hodographs in the coordinates of dry matter increments, accumulated in plant leaves, and the increments of optical radiation flow dose up-taken by plants during the growing period were plotted.

The hodographs were plotted for two environments of the laboratory experiment. Reference hodograph was plotted for lettuce plant growing under standard inside climate parameters and cultivation regimes (greenhouse complex Vyborzhets Ltd., Saint Petersburg).

Numerically, the degree of deviation of hodographs was calculated by the normed sum of squared differences

$$NSSD = \frac{1}{n}\sum_{i=1}^{n}\sqrt{\left(\Delta M_i - \Delta M_i^{\text{э}}\right)^2 + \left(\Delta H_i - \Delta H_i^{\text{э}}\right)^2}, \tag{3}$$

where n – number of pairs of points to compare the hodographs;
ΔM_i, ΔH_i – values of the increments of dry weight and flux doze for the compared hodograph;
ΔM_i^T, ΔH_i^T – values of the increments of dry weight and flux dose for the reference hodograph.

The smaller the *NSSD* value, the smaller the difference between the compared hodograph and the reference. This value was taken as the level of the indoor plant lighting EEE.

Results and discussion

The 39 days' experiment was completed on 12.21.2015. It was found that in this range of the time the dependence of the number of leaves per plant may be described with expressions

for IL: $N = 0.4841T_n - 4.8254$ ($R^2 = 0.9950$),

for HPS: $N = 0.4921T_n - 4.7460$ ($R^2 = 0.9992$).

The dynamics of the entire wet weight of the plant, the total leaves surface area and the dry matter yield is shown in Fig. 2-4.

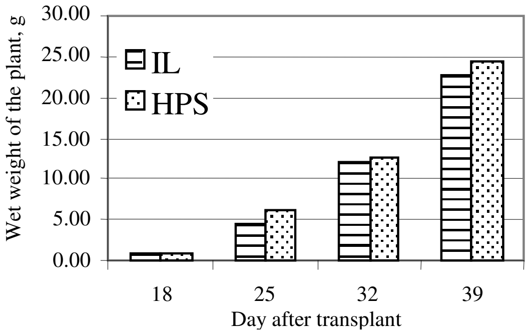

Fig. 2. **Wet weight of the plant**

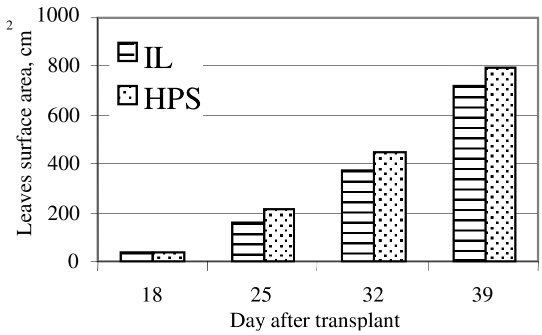

Fig. 3. **Surface area of leaves**

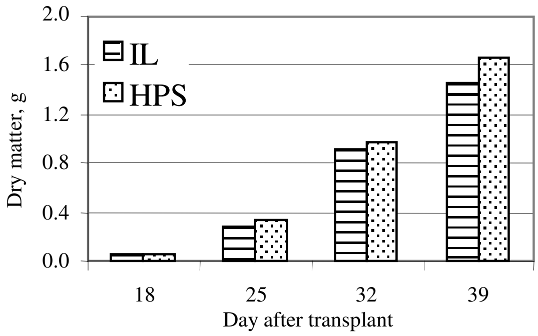

Fig. 4. **Dry matter yield**

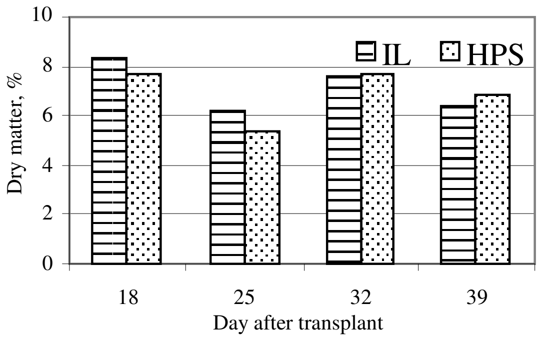

Fig. 5. **Dry matter content**

The dry matter content in the leaves, apparently, has no functional expression depending on the plant age and the irradiation source type (Fig. 5). The average values of the dry matter content were 7.10 % for IL with the standard error $\sigma = 0.97$ and 6.91 % for HPS with the standard error $\sigma = 1.09$.

Integrated indicators are shown in Table 1.

Table 1

Integrated indicators for one lettuce plant

Indicator	**Irradiation source**	
	IL	**HPS**
Leaves surface area S_{Σ}, cm^2	716.39	793.56
Wet weight of leaves M^{wet}, g	22.75	24.35
Dry matter yield M^{dry}, g	1.46	1.66
Radiation dose H_{Σ}, mol	4.71	4.44
Photosynthesis productivity (wet basis), g·day^{-1}·m^{-2}	1.37	1.39
Photosynthesis productivity (dry basis), mg·day^{-1}·m^{-2}	21.34	20.35
Photosynthesis energy-output ratio (wet basis), mol·g^{-1}	0.21	0.18
Photosynthesis energy-output ratio (dry basis), mol·g^{-1}	3.24	2.67

Hodographs plotted by the experimental data for two plant growing environments in comparison with the reference are shown in Fig. 6, while Fig. 7 shows a graphical interpretation of the parameter of proximity for experimental (Exp.) and reference (Ref.) hodographs.

Table 2 presents the parameters of Gomperz curves, which approximate the performance indicators of plant growth.

Table 2

Parameters of Gompertz curves

Parameter	IL		HPS		Ref.	
	$M = f(t)$	$S = f(t)$	$M = f(t)$	$S = f(t)$	$M = f(t)$	$S = f(t)$
Y_0	0.068	0.000	0.056	0.000	0.036	0.000
Y_{max}	1.812	2999.892	2.605	2688.055	3.330	2999.995
B	0.149	0.052	0.109	0.054	0.083	0.051
T_m	30.140	45.922	32.366	42.751	34.595	44.509

In the first IF the value NSSD = 0.0039 arbitrary units is smaller than that in the second IF (NSSD = 0.0016 arbitrary units). This indicates the higher level of EEE in the second IF.

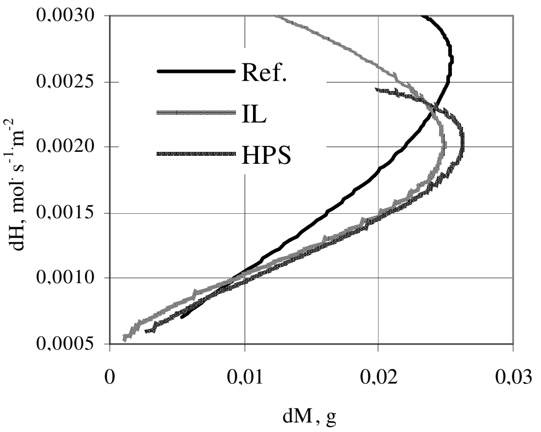

Fig. 6. **Hodographs (experimental and reference)**

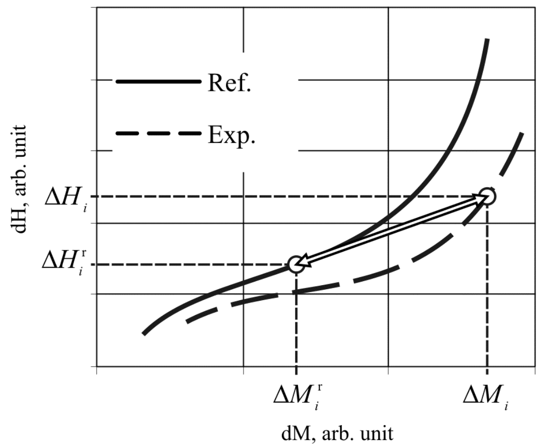

Fig. 7. **Pertains to assessment of the proximity degree of two hodographs**

Conclusions

The experimental results allowed developing the monitoring technique of EEE for different growing environments of plants. It is shown that the level of the indoor plant lighting EEE essentially depends on the type of the irradiation source. The monitoring technique is as follows.

- During the plant growing period the dynamic pattern of irradiance in the plant cultivation zone is recorded.
- Samples of plants are taken at a certain time interval.
- Dry matter content and the total leaf area in the sample plants are measured.
- The dynamic pattern of optical radiation flow dose up-taken by the plant and the dynamic pattern of the dry matter content accumulated in the leaves of the plants during the growing period are determined.
- The level of EEE of the indoor plant lighting is estimated by the hodograph curve shape defined by its characteristic points. These points are plotted in the coordinates of dry matter increments, accumulated in plant leaves, and the increments of optical radiation flow dose up-taken by plants during the growing period. The smaller the deviation degree of the hodograph curve from the reference, the higher the level of energy and ecological efficiency of the indoor plant lighting.

Monitoring results may be used to optimize the process of indoor plant cultivation by the criterion of minimum deviations of the EEE level by varying the irradiation parameters, environmental conditions and other factors.

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