Influence of lighting spectral characteristics on the lettuce leaf optical properties

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Abstract. The paper concerns the efficiency of light absorption with different spectral composition by lettuce leaves, and the optimal conditions of light environment and mineral nutrition to increase the productivity and quality of plant products grown under artificial lighting. The greatest positive effect has been achieved on the productivity and quality of the lettuce plants Typhoon variety when been grown on the 1N Knop nutrient solution and illuminated with quasi-continuous spectrum in a limited wavelength range in the yellow area with addition of ~ 10-20% of the total photosynthetically active radiation (PAR) in the near infrared. The most efficient conditions results in the increase on amount of absorbed photon energy by ~ 40% per gram of plant leaf surface over 10 days when rapid biomass growth and plant development take place. It is proposed to use the index of light absorption, describing the absorption increment with biomass growth, as an indicator for the intensity of light energy processing into biomass.

1. Introduction

The most important in the absorption and processing of light by plants are undoubtedly the photosynthetic pigments of the leaf. However, when studying the relationship between the content in the leaves of pigments and the magnitude of the absorption coefficient of radiant energy \( K(\lambda) = \frac{\log(I_0/I)}{C\cdot d} \) (where \( I_0 \) – intensity of light, falling on the leaf, \( I \) – intensity of light, transmitted and reflected by the leaf, \( C \) – pigments concentration, \( d \) – substance thickness), it is established in the red and blue regions of the spectrum the deviation from the Beer–Lambert–Bouguer law, suggesting that other molecules of the same substance surrounding it in a solution do not affect the ability of a molecule to absorb the light [1]. In the green part of the spectrum, the deviation from the law of light absorption is much smaller. It has been suggested that the inconstancy of the values of the absorption coefficient with a constant chlorophyll content is associated with a complex structural organization of leaf blades and, in particular, with the presence of air-filled cavities, which is the reason for disagreement with Beer–Lambert–Bouguer law for absorption of the radiant energy by the leaves.

The spectral maximum of the photosynthesis efficiency coincides with the maximum absorption of the photosynthetic pigments [2]. But at the same time, the averaged photosynthetic response curve proposed by McCree [3], which is a photosynthetic activity under different wavelengths of the
incident light, differs from the absorption spectrum of the main pigments. The action spectrum of photosynthesis is expressed in the number of quanta used to restore a certain amount of carbon dioxide or to release an equivalent amount of oxygen, due to the fact that according to the photochemical equivalence law, the same photochemical effect is achieved by absorbing the same number of quanta, but not the same amount of energy. It should be noted that the curve of the photon flux assimilated by the plant is based on short measurements of photosynthesis in a single leaf under low illumination.

The optical parameters of the leaves are associated with the dynamics of photosynthesis, biochemical reactions, and are also sensitive to changes in external conditions [4,5]. Of greatest interest is the effect of various spectral photosynthetically active radiation (PAR) regions. In [6,7], it was suggested that changes in the leaves spectral properties depending on the radiation spectral characteristics and its intensity. In particular, the absorption coefficient of leaves illuminated by an incandescent lamp was less than when illuminated by sunlight. A series of experiments [1], carried out subsequently, showed that this change is not related to differences in the intensity of the irradiating light, but is due to a change in the spectral composition of the illumination. The influence of mineral nutrition on the nature of the change in the absorption coefficient at the wavelength lying in the absorption band of chlorophyll was also noted [8].

The advent of powerful superbright and modular LEDs has expanded the technical capabilities to increase the productivity and efficiency of growing plants in greenhouses [9]. However, the full potential of LEDs can be used only by understanding the mechanisms of light flux and radiation spectrum influence not only on the morphological parameters [10] but also on the plant ability to absorb light and perceive various emission bands. Along with widely presented studies of the red and blue radiation and their combination influence [11,12], it is of interest to study the effects of a complex spectra simulating other light sources that have proved their effectiveness (for example, natural light, HPS lamps, etc. [13]).

Thus, the purpose of this work was to study the influence of the light environment with different spectral composition in presence of the variable level of mineral nutrition on the lettuce leaf light absorption.

2. Materials and methods

Lettuce (Lactuca sativa L.) Typhoon variety were grown using thin-layer panonics in an automated plant growing light equipment [14] using six variants of light sources differing in spectral composition and the presence of radiation in the near IR range. The magnitude of irradiation from various light sources was set equal to 70-75 W/m² PAR, the duration of the light period was 14 hours per day. The air temperature was maintained at + 20-22 °C during the day and + 18-20 °C at night, the relative air humidity was 65-70%. As a source of mineral nutrition was used a Knop solution [15] in full concentration (1N) and in 1:1.4 (0.7N) and 1:2 (0.5N) ratio with water.

In the first series of experiments, the plant growth area was divided by lightproof material into 5 zones, in which light sources were: 1) S – high-pressure sodium lamps (HPS), 2) Y – LED analogue of HPS (LLC "O2 Lighting Systems" and ARI), emitting yellow light with radiation peaks at wavelengths of 450 nm, 500 nm, 595 nm and the ratio of the peak intensities 1:3:13, 3) P – LED lamps (LLC "O2 Lighting Systems") like currently used in greenhouses, emitting pink light and having radiation maxima at 450 nm, 665 nm with an intensity ratio of 1: 2, 4) W – LED lamps with white light and maxima intensity ratio 1:1 on wavelengths 450 nm and 600 nm, 5) B – LED lamps with white light and maxima intensity ratio 1: 3 on wavelengths 450 nm and 600 nm. In fact, the Y lamp differs from W and B in a higher intensity of radiation in the green and red parts of the spectrum, and the P lamp has an offset maximum in the red region from 600 nm to 665 nm.

In the second experiment, to study the action of the infrared region, Y lamps were used with the addition of: 1) YL – LEDs emitting warm white, 2) YG – halogen lamps with the same spectrum in the visible region and the presence of the IR component. The additive of PAR to the Y lamp was ~10% intensity and was almost the same for both variants. Thus, the difference in the illumination of plants was only in the presence of the infrared component in one of the options.
To measure the spectra of absorbed energy by lettuce leaves during their life-sustaining activity, we used a spectrometric method based on system of two integrating spheres – the sample under study is placed between the spheres, one of which records the reflected light and the other one transmitted [16]. The absorption spectra were recorded for a 85 mm$^2$ region for the leaf base on the 21st and 31st days of development, and for the tip on the 31st day of plant development. The object selection was made throughout the hall growth zone.

The reaction of the lettuce to the light and root area simulated conditions was also evaluated in terms of growth, net productivity, and the biochemical composition of the resulting plant products.

3. Results and discussion

Morphological parameters and productivity of lettuce made it possible to draw the following conclusions on the influence of light and nutritional conditions of growth. The maximum height (20 cm), area (97 cm$^2$) and productivity (5990 g/m$^2$) of plants were recorded when growing them in a 1N solution and illuminated with HPS lamps. Under Y and P lamps, the height of the plants was reduced by 20%, while under W and B variants the difference reached 40%. Stronger contrast is noticeable in the size of the area, where the difference between the parameters of plants illuminated by S and W, B sources reaches almost 70%. This indicates a slow development of the lettuce when it is irradiated with white light emitted by an industrial lamp. The dry matter content in the roots is higher for the S variant, but in the others it does not differ significantly (by 7-22%). At the same time, the percentage of dry matter in the leaves, on the contrary, is minimal for S lamps. The minimum difference in the productivity of lettuce, illuminated by the HPS and the LED analogue is 44%, in other cases this interval only increases to 80%. This effect is due to the formation of a smaller area assimilating the radiant energy on the leaves surface under the LED, and judging by the higher accumulation of dry matter in the leaves with a significantly lower plant mass, it can be assumed that the substances of a protective nature accumulating in the leaves. The formation of these substances is associated with the energy and resources expenditure and adversely affects the productivity and quality of the plant products. An indirect confirmation of this fact is an increased absorption of leaves in the region of 470–640 nm for plants illuminated with white light. Perhaps this is due to the increased content of pigments that perform protective functions and are synthesized under stress conditions – carotenoids with an absorption maximum in the region of 480 nm and anthocyanins, absorbing in the region of 500-520 nm.

The biochemical values of lettuce depending on the conditions of its lighting and the composition of the nutrient solution also were determined. It is noted an increase in the content of vitamin C and the amount of sugars and a decrease in the amount of nitrates when grown in a 0.5 N solution compared with other types of mineral nutrition. The nitrogen content varies slightly and is maximal for a lettuce lighting by P and W lamps in a 1N solution. The amount of phosphorus is minimal in samples illuminated with HPS lamps and is maximum when irradiated with a LED analogue. The potassium content is the smallest in samples grown in a 0.5N solution under S, B light sources and the highest for lettuce irradiated with W in a 1N solution. The level of calcium falls in the 1N-0.7N-0.5N nutrient solution for S, P, B light sources and conversely increases for Y and W variants. The maximum magnesium content in lettuce is noted under S and P light sources. The lack of magnesium, which is known as a chlorophyll component, leads to photosynthesis efficiency decrease. The content of lead and cadmium exceeded the maximum permissible values only under the B lamp in the version with 0.5 N solution.

The most significant difference in the spectral characteristics of a HPS lamp from LED is the presence of an infrared component. Since we tried to model the emission spectrum of the HPS in the visible region with the help of LEDs (lamp Y), but we found significant differences between the morphological and biochemical data of plants, it is likely that obtaining improved indicators of lettuce productivity during the growth under the HPS lamps is due to the presence of infrared in its spectrum. In this regard, we conducted an experiment to add to the existing LED module Y, modulating the radiation of a sodium lamp, YG – a halogen lamp which is an IR radiation source and YL – an LED
lamp with a spectrum in the visible region, similar to a halogen source. With the same irradiation spectra in the PAR region, height, mass of plants and roots, as well as productivity were higher for the variant YG ~ 30%, and the leaf area differed by 20%. That is, we can say that the presence of the IR component in the spectrum of illumination leads to more efficient growth and development of plants.

During the growing season of lettuce, illuminated by a different radiation spectrum, on 21 (dot curve) and 31 (straight curve) days of plants development, light absorption spectra were taken from the base and top of the leaf surface (figure 1). A difference was obtained in the spectral lines shape for samples illuminated with HPS (S), yellow (Y), pink (P) and two variants of white (W, B) light sources. There are practically no differences between the absorption spectra of plants grown under YL and YG, since in the visible region their emission spectra almost completely coincide. In the region of 470–640 nm, differences in intensities reach 15%, although the magnitudes of the absorption coefficients at the main maxima of the 440 and 667 nm wavelengths in most cases coincide. It is also important to note the difference between the absorption spectra of 21-day and 31-day plants: in the first case, the spectra show the presence of more distinct maxima at 480, 500, 590 and 620 nm. The absorption spectral lines shape of lettuce grown at a solution concentration of 0.7N and 0.5N is qualitatively the same as under growth conditions in a 1N solution. For them, it is also possible to note differences in the absorption coefficients in the region of 470–640 nm for S, Y, P lamps and W, B lamps.

![Figure 1. Light absorption spectra by the top of the 31-day lettuce leaf surface (straight curve) and the base of 21-day lettuce (dot curve) grown in 1N solution under illumination: S – HPS, Y – LEDs emitting yellow light, P – LEDs emitting pink light, W – white light with a maximum ratio of 1:1, B – white light with a maximum ratio of 1:3, YL – Y lamp with the addition of LEDs emitting warm white, YG – Y lamp with halogen lamps adding.](image)

To estimate the influence of lighting parameters on light absorption by lettuce leaves, we proposed to use an evaluation version of a value that potentially describes an absorption increment on biomass growth and we designated it as light absorption index $I$. For the initial absorption, we took the average value between the absorption of a 21-day lettuce leaf which total area comparable to the window of...
the integrating sphere, and the base of the 31-day leaf, presumably not differ in its structure from the same area in earlier development period. The difference between the absorption of the "new" and "old" parts of the leaf is normalized to the biomass accumulated over the period between measurements, reflecting the increase of the leaf area and thickness and also accumulation and development of pigments per unit of the measured surface. Thus, the light absorption index \( I \) is calculated using the following formula:

\[
I = \frac{\Delta A}{\Delta m} = \frac{A_{31U} - A_{31D} + A_{21D}}{2} = \frac{A_{31U} - A_{31D}}{m_{31} - m_{21}}
\]

where \( A_{31U} \) – integral light absorption in the range of 400-700 nm by the top of the 31-day leaf, (%), \( A_{31D} \) – integral light absorption by the base of the 31-day leaf (%), \( A_{21D} \) – integral light absorption by the base of the 21-day leaf (%), \( m_{31} \) – mass of the 31 day lettuce leaf (g), \( m_{21} \) – mass of 21 day lettuce leaf (g). The calculated values of the light absorption index for all investigated variants of illumination, differing in spectral characteristics, are shown in table 1.

Table 1. Light absorption index for lettuce leaves growing under different lighting conditions and different concentrations of mineral nutrition.

| Concentration of Knop nutrient solution | Light absorption index for different lighting conditions, %/g | Y   | P   | S   | W   | B   | YL  | YG  |
|----------------------------------------|-------------------------------------------------------------|-----|-----|-----|-----|-----|-----|-----|
| 0.5N                                   |                                                             | 45±6| 39±4| 26±2| 16±1| 16±1|     |     |
| 0.7N                                   |                                                             | 48±8| 33±4| 26±2| 20±1|     |     |     |
| 1N                                     |                                                             | 40±7| 22±4| 41±4| 12±2| 28±1| 40±15| 33±15|

It is interesting to note the coincidence of the index values for lighting with a sodium lamp and its LED analogue with and without additional infrared radiation when growing lettuce at a concentration of 1N solution. These conditions were most effective and led to rapid biomass growth and better plant development.

4. Conclusion
This study revealed the influence of light spectra on the absorption spectra of plant leaves. Light sources according to the degree of positive influence on plants of their spectral composition of light are arranged in a row: HPS lamp > analog HPS lamp based on LEDs with the addition of the infrared range > LED analogue HPS lamp with the addition of warm white light and without > LED module with maximum radiation at 450nm, 665nm, analogue used in greenhouses > LED with white phosphor emitting radiation with a 1:3 ratio of maximum emission peaks at 450nm to 600 nm wavelengths > LED emitted white with the 1:1 ratio of maximum emission peaks at 450nm to 600 nm.

Based on the conducted comprehensive studies, it was found the greatest positive effect of the quasi-continuous spectrum in a limited range in the yellow region with the addition of ~ 10-20% IR on the productivity and quality of Typhoon lettuce growing on a 1N Knop nutrient solution. The difference between the absorption spectra of 21-day and 31-day plants is noted: the spectra show the presence of more distinct maxima at 480, 500, 590 and 620 nm for 21-day lettuce.

The most efficient conditions results in the increase on amount of absorbed photon energy by ~ 40% per gram of plant leaf surface over 10 days when rapid biomass growth and plant development take place. It should be noted that the value of the light absorption index below 20%/g corresponds to samples with minimal results on productivity and growth characteristics.

The influence of the light spectral composition characteristics on the lettuce leaves light absorption found in the study shows that analyzing the absorption spectrum of a plant leaf can be a
phytonomonitoring method. Proposed spectrometric method gives information on the radiation absorption from a lighting source and the photosynthetic reaction associated with it, as well as characterizes the plant needs in PAR.

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