International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

# PO194

# PHOTOBIOLOGICAL RESEARCHES – A WAY TO OPTIMIZE LED'S PLANT LIGHTING

**Leonid Prikupets et al.**

DOI 10.25039/x46.2019.PO194

from

CIE x046:2019

Proceedings
of the
29th CIE SESSION
Washington D.C., USA, June 14 – 22, 2019

(DOI 10.25039/x46.2019)



CIE Central Bureau
Babenbergerstrasse 9
A-1010 Vienna
Austria
Tel.: +43 1 714 3187
e-mail: ciecb@cie.co.at
www.cie.co.at

# PHOTOBIOLOGICAL RESEARCHES – A WAY TO OPTIMIZE LED’S PLANT LIGHTING

Prikupets, L.[1], **Bartsev, A.[1],** Shakhparunyants, A.[1], Terekhov, V.[1], Boos, G.[2], Tarakanov, I.[3]
[1] Russian lighting research institute named after S.I. Vavilov (VNISI), Moscow, RUSSIAN FEDERATION
[2] National Research University "Moscow Power Engineering Institute" (MPEI), Moscow, RUSSIAN FEDERATION
[3] Timiryazev Agricultural Academy (RSAU – MTAA) named after K.A. Timiryazev, Moscow, RUSSIAN FEDERATION

prikup@vnisi.ru

DOI 10.25039/x46.2019.PO194

## Abstract

Currently, the problems of using LEDs for plants growing are moving into a practical plane, largely due to the rapid expansion of the use of vertical multi-tiered systems for lettuces and other greens cultivation. The optimal lighting technologies with a reasonable choice of spectra and photosynthetic photon flux density (PPFD) levels should be developed for these applications.

The report presents the results of the first phase of a photobiological research, the ultimate goal of which is to optimize the spectrum of LED phytoradiators and the level of PPFD when growing lettuces and other greens in greenhouses and vertical multi-tiered installations for plants cultivation under photoculture conditions. The results are presented as a series of productivity light curves (action spectra) for lettuce and basil plants when irradiated with a quasimonochromatic light in three PAR ranges: blue, green and red. In the experiment, the levels of PPFD varied over a wide range (70 ÷ 230 μmol/(s·m$^2$). “Rough” spectra of plant productivity are presented for two different levels of PPFD (70 and 100 μmol/(s·m$^2$)).

*Keywords:* photobiological researches (PBR), “light curve”, photosynthesis, light culture, LED phytoirradiator (PIR), photosynthetically active radiation (PAR), action spectrum, photosynthetic photon flux density (PPFD)

## 1 Introduction

Lettuces and other greens are one of the most common groups of vegetables grown in greenhouses in Russia (Fig. 1). The interest in them deepens due to the development of a promising new technology of growing plants in vertical multi-tiered installations such as City Farms, based on the use of LED phytoirradiators (PIR). Lettuces and other greens are an excellent object for the optimization of basic parameters of LED lighting installations.

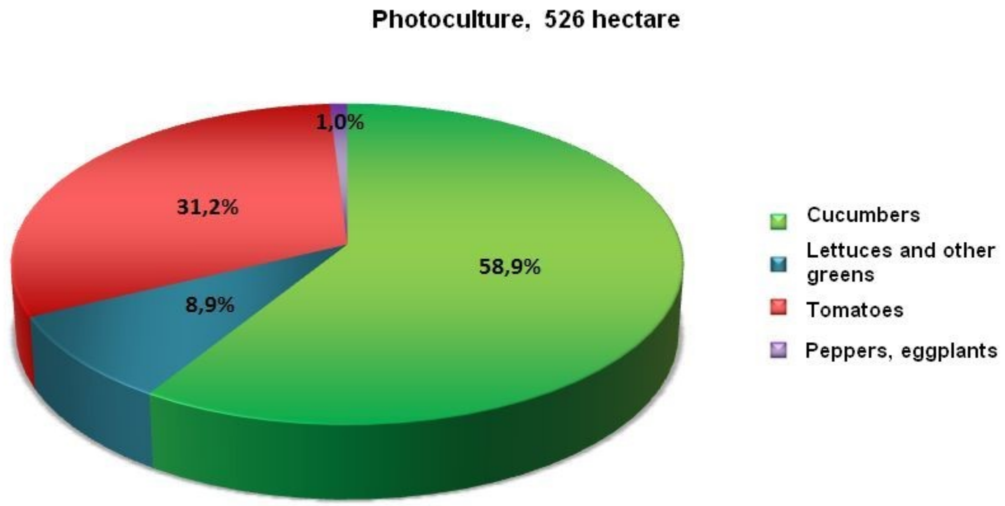



**Figure 1 – The areas occupied by vegetables photocultures in the greenhouses of Russia in 2019**

The possibility of creating quasi-monochromatic LED PIRs for the main ranges of photosynthetically active radiation (PAR), which determine the formation of biomass, morphogenesis and plant metabolism, stimulate relevant photo-biological researches (PBR) worldwide. The famous McCree curve (McCREE, 1972), which describes the action spectrum of photosynthesis that was obtained *in vitro* by means of a rather complex optics for individual plant leaves at low levels of PPFD and has been a kind of a "Gospel for photobiologists" for almost half a century, is subject to doubt (Web-page, 2019).

PBR aimed at optimizing the lighting parameters for plants growing have their history in Russia. Earlier, in the 90s of the last century, favorable spectra for photocultures of cucumbers and tomatoes (TIHOMIROV & PRIKUPETS, 1992), which are considered by many as basic for these vegetables (TIHOMIROV & PRIKUPETS, 1994), were determined using colored metal halide lamps as:

$$\text{Cucumbers: } E_{\Delta\lambda\ blue} / E_{\Delta\lambda\ green} / E_{\Delta\lambda\ red} = (15\text{-}20)\ \% / (35\text{-}45)\ \% / (40\text{-}45)\ \% \tag{1}$$

$$\text{Tomatoes: } E_{\Delta\lambda\ blue} / E_{\Delta\lambda\ green} / E_{\Delta\lambda\ red} = (10\text{-}20)\ \% / (15\text{-}20)\ \% / (60\text{-}75)\ \% \tag{2}$$

where $E_{\Delta\lambda\ blue} / E_{\Delta\lambda\ green} / E_{\Delta\lambda\ red}$ are correspondingly irradiances in blue, green and red PAR ranges.

Thanks to LEDs, a new effective research tool falls into photobiologists hands enabling them to carry out PBR of the effects of various PAR ranges on the productivity and quality of plant biomass in a wide range of PPFD that is of interest to practical photoculture (PRIKUPETS, 2018). This is the task that the authors of this paper set for themselves, choosing as the object of research a group of green plants (exemplified by the "Landau" lettuce and the "Russian giant" basil, which belong to plants that have good perspectives with regard to commercial plants cultivation in industrial greenhouses and such installations as City Farms).

## 2 PBR methodology and the experimental setup

We studied the reaction of plants, that is the total weight of commercially useful biomass (productivity) (in our case, the average weight of the useful biomass in one pot used in the experiment), to quasimonochromatic radiation for different PAR ranges and PPFD levels varied within wide limits.

As a result of the PBR conducted for each spectral option we expected to get a series of "light curves", on the basis of which the actual efficiency of different PAR ranges could be assessed, and the direction of looking for optimal requirements for PIR spectra and the PPFD level when growing plants using photoculture technology could be determined.

Especially for PBR, we developed and manufactured a series of quasi-monochromatic PIRs, in which Cree (USA) color LEDs were used. The spectra of optical radiation of quasi-monochromatic PIRs used in the PBR are presented in Fig. 2.

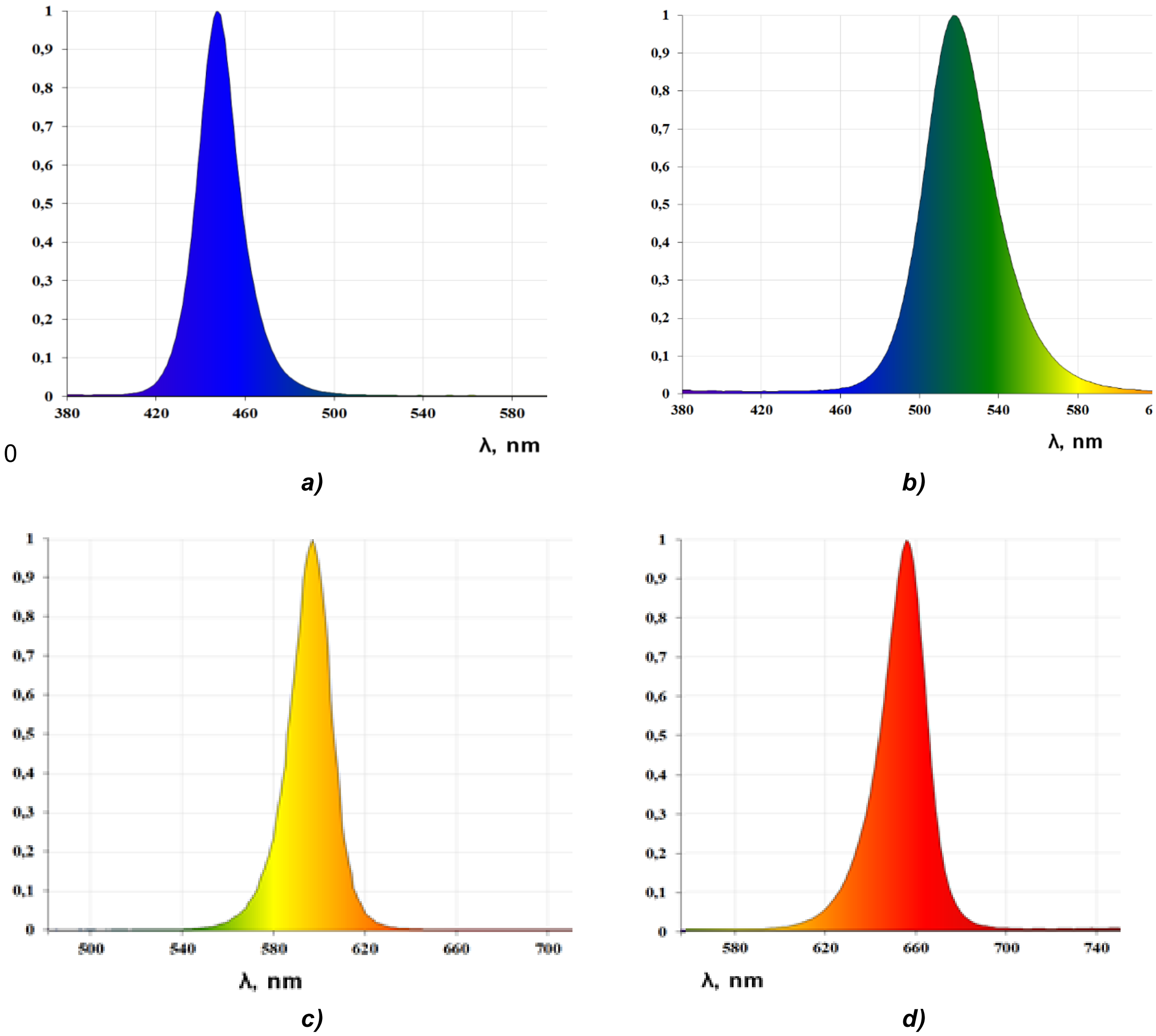



**Figure 2 – The spectra of quasi-monochromatic PIRs used in PBR:**
**a – "blue" ($\Delta\lambda_{0,5}$ = 435 ÷ 458 nm, $\lambda_{max}$= 447 nm),**
**b – "green" ($\Delta\lambda_{0,5}$ = 500 ÷ 540 nm, $\lambda_{max}$= 518 nm),**
**c – "amber" ($\Delta\lambda_{0,5}$ = 585 ÷ 605 nm, $\lambda_{max}$= 597 nm),**
**d – "red" ($\Delta\lambda_{0,5}$ = 645 ÷ 666 nm, $\lambda_{max}$= 656 nm)**

Fig. 3 shows the ranges of intensive absorption of PAR by the main photopigments of plants. It is easy to see that the radiation of "blue", "green" and "red" PIRs are in the sensitivity zones of most plant photopigments.

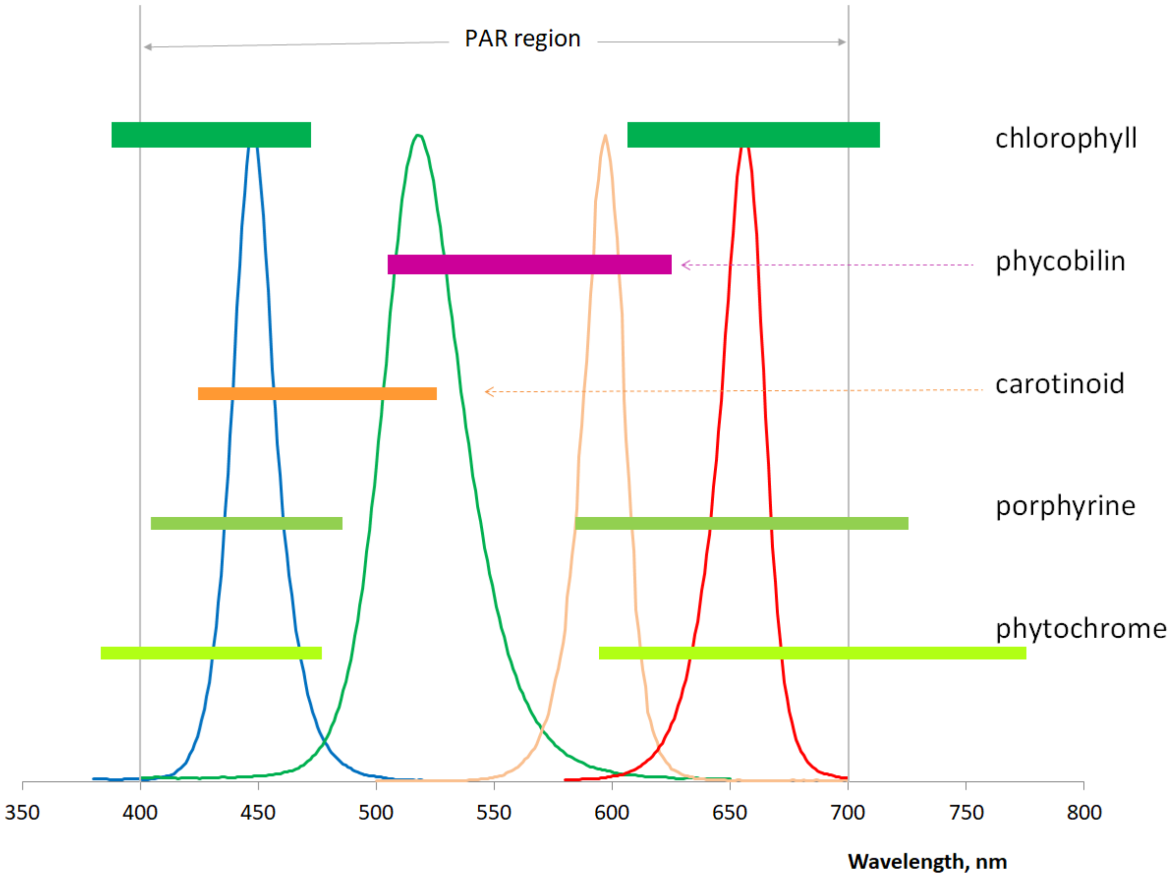



**Figure 3 – Spectral ranges of the effective absorption of the main plant photopigments**

PBR were performed in the phytotron of RGAU-MSHA named after K.A. Timiryazev, Moscow, in a specially constructed research complex consisting of six experimental facilities with various PIRs. A general view of experimental installations with red, blue, and green emission spectra is shown in Fig. 4.

**Figure 4 – General view of experimental irradiation facilities for various PAR ranges**

As a part of phytoradiators, adjustable controlgears "OT180W/UNV1250C (Osram)" were used, allowing to regulate the output current within 350 ÷ 1300 mA and, accordingly, to change the power of the irradiators in order to provide approximately the same PPFD level on the technological area.

The PPFD level in each experimental setup varied from 60 to 300 μmol/(s·m$^2$), which made it possible to plot light curves for fixed PPFD values. For each spectral option, at least 4 vegetations were carried out (at different PPFD levels), and the results of one of such a vegetation are presented in Figure 5.


**Figure 5 – The results of the "Landau" lettuce vegetation for different spectral options and the PPFD level of 100 μmol/(s·m$^2$) for "red", "blue" and "green" radiation and 70 μmol/(s·m$^2$) for "amber" radiation:**
**1 – "Red" ($\Delta\lambda_{0,5}$ = 645 ÷ 666 nm, $\lambda_{max}$= 656 nm);**
**2 – "Blue" ($\Delta\lambda_{0,5}$ = 435 ÷ 458 nm, $\lambda_{max}$= 447 nm);**
**6 – "Green" ($\Delta\lambda_{0,5}$ = 500 ÷ 540 nm, $\lambda_{max}$= 518 nm);**
**7 – "Amber" ($\Delta\lambda_{0,5}$ = 585 ÷ 605 nm, $\lambda_{max}$= 597 nm)**

To measure the PPFD in the PAR region, a Li-190R quantum sensor with a Li-250A data logger (Li-COR, United States) was used, and a portable spectrometer MK 350S (UPRtek, Taiwan) was used to measure PIR spectra. The work carried out earlier showed that the indicated measuring devices provide the necessary accuracy and reliability of measurements (BOOS, et al., 2018), (PRIKUPETS, et al., 2018).

Apart of the above-mentioned lighting parameters, the remaining experimental conditions met the requirements adopted in the phytotron for growing lettuces and other green plants.

## 3 Research results analysis

Currently there is no doubt that photosynthesis is a quantum process in which the quantum yield (or intensity of photosynthesis) is determined by the number of absorbed photons in the PAR range. On this basis there was developed a system of photosynthetic photon values, currently being actively introduced into the practice of radiation metrics for protected soil facilities, primarily greenhouses, for plants photoculture.

This paper discusses the special aspects and common features of the reactions of plants belonging to different species (lettuce and basil) to the radiation in three main PAR ranges. The measured data in the form of light productivity curves are shown in Fig. 6. Each light curve point was obtained as an arithmetic mean of 4 measurements, while the average standard deviation was ± 10.3% for lettuce and ± 18.5% for basil.

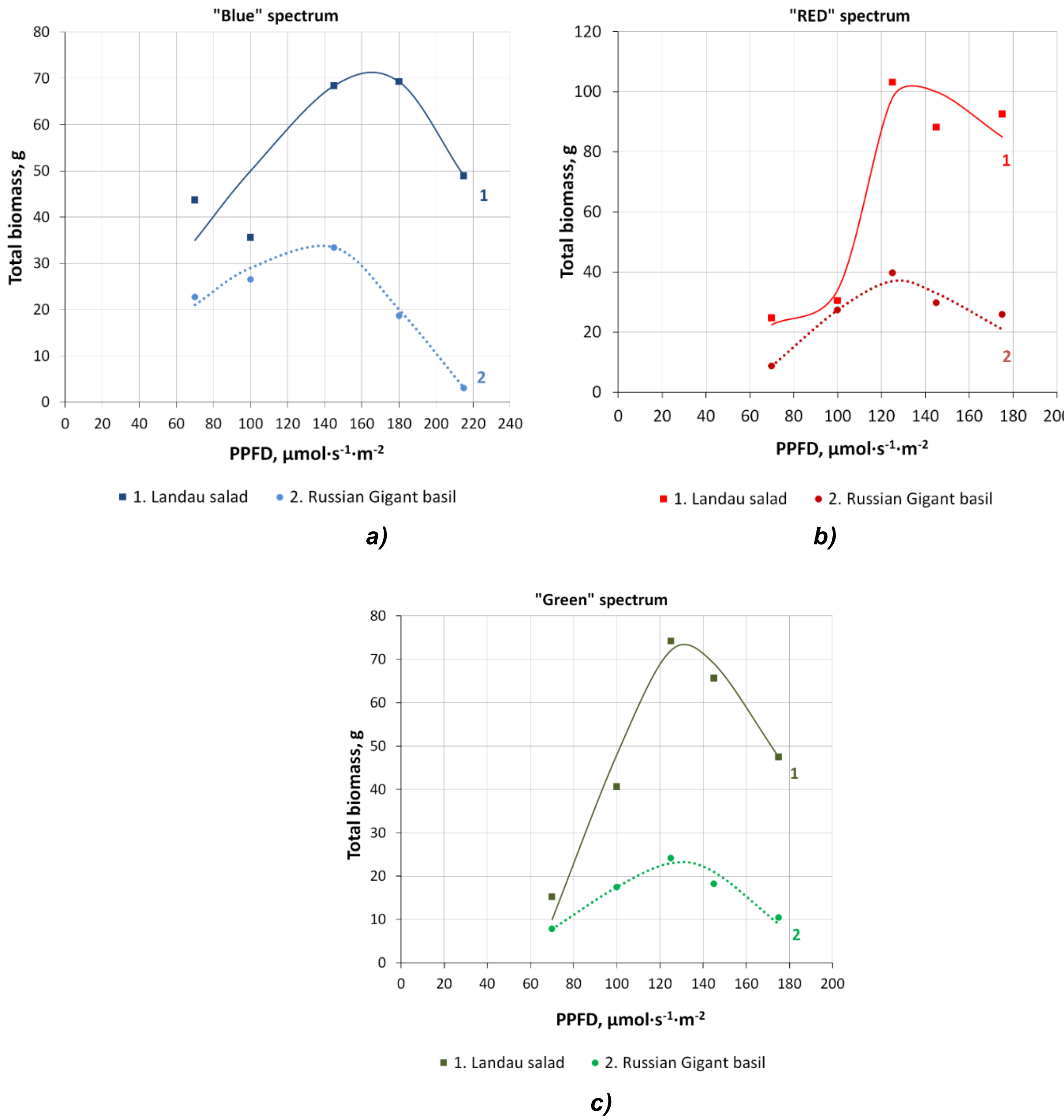



**Figure 6 – Light curves for lettuce and basil productivity when irradiated in different PAR ranges: a – blue; b – red; c – green.**

Let's consider the effect of each PAR range on the productivity of lettuces and other greens separately.

*"Blue Light Factor"*

For blue light (Fig. 6a), the length of the "ascending segment" of the light curve for lettuce is the greatest, and maximum values of productivity were obtained with a PPFD of about 170-180 µmol/(s·m$^2$) for lettuce and 130-150 µmol/(s·m$^2$) for basil. At the same time, if for basil the productivity is close to limit values obtained in real PBRs, then for lettuce it is much smaller than the maximum productivity obtained for a this culture when irradiated in the red PAR range.

*"Red Light Factor"*

In general, the radiation in this spectral range turned out to be the most favorable for both lettuce and basil. The analysis of the dependence of the productivity of lettuce on the PPFD level (Fig. 6b) indicates a rather sharp response of plants to low-energy quanta of red radiation; for low PPFDs the latter is less effective than blue radiation, for moderate PPFDs (100 μmol/(s·m²) the effect is slightly weaker than for blue and even green radiation, but in the region of higher PPFDs of about 130 ÷ 140 μmol/(s·m²) the maximum level of productivity was obtained in the red PAR range in all experiments.

The red range proved to be the most effective for basil as well. However, for this culture the effect of PPFD level on productivity was less pronounced.

The fact that maximum values of the productivity of both cultures were obtained under red light with PPFD less than 150 μmol/(s·m²) indicates good perspectives of spectra with a predominance of radiation in the red PAR range for the commercial cultivation of lettuces and other greens.

*"Green light factor"*

As stated in (BUGBEE, 2016), opinions about the effect of green light on plant productivity range from "harmful" to "very useful". With this in mind, we attached great importance to obtaining our own data, fully understanding that the effect of green light should depend on the level of PPFD and the width of the "green" PAR range. In our case, it was $\Delta\lambda_{0.5}$ = 500 ÷ 540 nm with $\lambda_{max}$ = 518 nm. For lettuces, the productivity turned out to be higher with green radiation than with blue radiation, and with markedly lower PPFD levels than in the latter case (see Fig. 6a, 6c).

The results of these PBR clearly show that the green spectral range is by no means an "outcast" in case of lettuce cultivation, and at PPFDs of the order of 100 μmol/(s·m²) the green light provides even higher productivity than red or blue light.

Note that plant cultivation under quasimonochromatic radiation, i.e. in the lighting mode when only a part of the PAR spectrum is "employed" throughout the vegetation period, makes it possible not only to obtain direct data on the effectiveness of one or another PAR range, but to evaluate the capabilities of the plant as a self-regulating system as well.

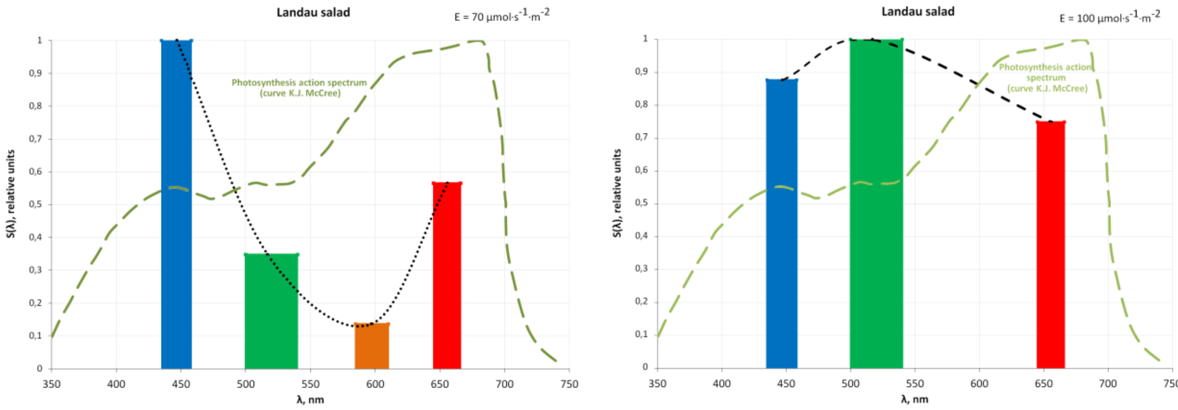
*"Amber light factor"*

A direct confirmation of the assumption about the low efficiency of the amber PAR range, where the radiation is virtually absorbed only by such plant photopigments as porphyrins and fikobilins (see Fig. 3), was obtained in an experiment conducted with a specially manufactured amber (PIR at PPFD level 70 μmol/(s·m²). That's why this LED PIR was not used in further experiments.

The conclusions drawn are additionally confirmed by so-called ***"rough" action spectra***[1] of the biomass synthesis of the two studied cultures (Fig. 7, 8). The action spectrum is understood here as the response of plants (productivity, expressed in a.u.) to the radiation of different wavelengths at a constant level of photosynthetic photon exposure.

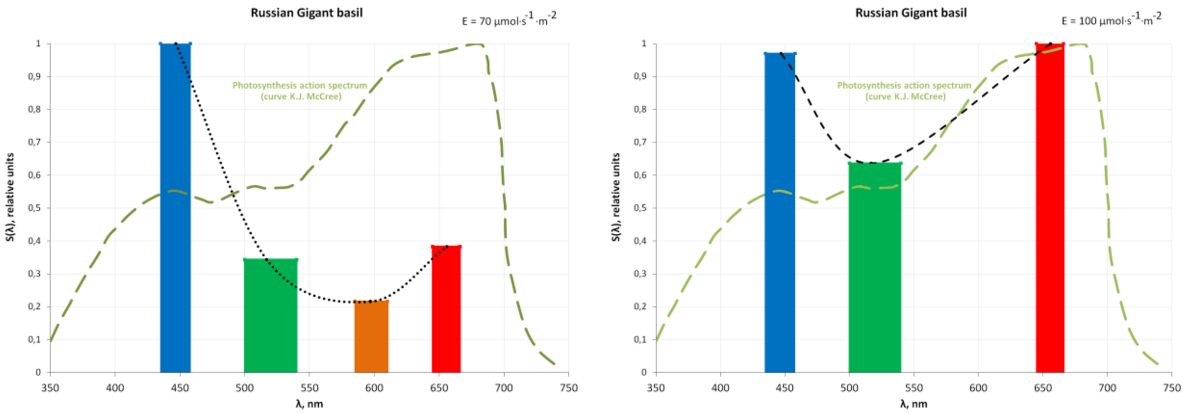
The action spectrum makes it possible to determine the influence of a certain photopigment on the biomass synthesis.

[1] The concept of a "rough" action spectrum was introduced in (TOKHVER, 1975) and is used in cases where the width of the selected spectral range is several tens of nm.




*a)* *b)*

**Figure 7 – "Rough" action spectra (black dotted or dashed line) for lettuce biomass production with PPFD of:**
**a – 70 µmol/(s·m$^2$), b – 100 µmol/(s·m$^2$)**




*a)* *b)*

**Figure 8 – "Rough" action spectra (black dotted or dashed line) for basil biomass production with PPFD of:**
**a – 70 µmol/(s·m$^2$), b – 100 µmol/(s·m$^2$)**

As it follows from the data in Fig. 7 and 8, the appearance of a productivity action spectrum is highly dependent on the PPFD level, and the efficiency of one or other PAR range can be cardinally different depending on this level. Of the 4 rough productivity action spectra shown in Fig. 7 and 8 only the data for PPFD = 100 µmol/(s·m$^2$) could be considered to some extent close to the photosynthesis spectrum of McCree. Hence, it follows that the ambiguity of the results of many PBIs carried out for one, less often two, PPFD levels with conflicting data is quite understandable, as indicated, for example, in (BUGBEE, 2016).

## 4 Conclusion

The photobiological studies carried out show the great potential of LED light sources in solving the problem of developing reasonable requirements for lighting systems for photoculture of various species.

In this investigation data were obtained on the effect of main PAR ranges on the productivity of two types of vegetative plants in a wide range of PPFD, and the maximum efficiency of the red PAR range was confirmed.

The results of the PBR, presented in the report, show that the plant response (productivity) greatly depends on the lighting spectral composition and PPFD, and the search for universal action spectra for plant productivity is questionable. Productivity action spectra, even for vegetative plants, depend on the exposure level and, generally speaking, should be evaluated with two-dimensional scales (λ, E).

Summarizing what has been said, we note that there is currently no alternative to the experimental method for optimizing the basic lighting parameters for photoculture of plants.

These studies were carried out with the financial support of the Ministry of Science and Higher Education of the Russian Federation, Agreement No. 14.576.21.0099 on the provision of subsidies dated 09/26/2017. Agreement ID: 0000000007417PD20002. The unique identifier of the work (project) is RFMEFI57617X0099.

## References

BOOS, G., PRIKUPETS, L., ROZOVSKY, E. & STOLYAREVSKAYA, R., 2018. Standardization of Lighting Fixtures and Installation for Greenhouses. *Light & Engineering*, Vol. 26( 4), pp. 18-24..

BUGBEE, B., 2016. *Plants, Soils, and Climate Faculty Publications.* s.l., s.n., p. 763.

McCREE, K., 1972. The action spectrum, absorbance and quantum yield of photosynthesis in crop plant. In: s.l.:Agric. Meteorology, pp. 192-216.

PRIKUPETS, L., 2018. Technological Lighting for Agro-Industrial Installation in Russia. *Light & Engineering*, Vol. 26(4), pp. 7-17.

PRIKUPETS, L., BARTSEV, A. & SHAKHPARUNYANTS, A., 2018. *Measurements of photosynthetic photon flux (PPF) and flux density (PPFD) for greenhouse LED irradiators.* Taipei, PROCEEDINGS of CIE 2018 "Topical Conference on Smart Lighting", pp. 564-569.

TIHOMIROV, A. & PRIKUPETS, L., 1992. Optimizacija spektra izluchenija pri vyrashhivanii ovoshhej v uslovijah intensivnoj svetokul'tury (Optimization of radiation spectrum for vegetable growth in the conditions of intensive photoculture). *Svetotehnika*, 3, pp. P. 5-7. (In Russian)..

TIHOMIROV, A. & PRIKUPETS, L., 1994. *Optimization of lamp spectrum for vegetable growth, in Proc. 1994 International Lighting in Controlled Environments Workshop..* Madison, Univ of Wisconsin, pp. 31-38.

TOKHVER, A., 1975. Fitokhrom, yego osnovnyye formy i ikh svoystva (Phytochrome, its main forms and their properties). In: *Fotoregulyatsiya metabolizma i morfogeneza rasteniy.* s.l.:Nauka, pp. 56-65.

Web-page, 2019. *Redefining The McCree Curve At Utah State University.* [Online] Available at: https://fluence.science/redefining-the-mccree-curve-at-utah-state-university/ [Accessed 20 04 2019].