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SHORT REPORT

OPTIMIZATION OF LAMP SPECTRUM FOR VEGETABLE GROWTH*

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An increase in the demand for and production of vegetables in the winter, mainly in northern and Siberian regions, inevitably leads to mass building of structures for growing plants under completely artificial conditions. It is required to create an industrial lighting technology whose main parameters (spectrum, irradiance, photoperiod) should be assigned carefully and should uniquely determine, along with other important characteristics of the artificial climate, the productivity of the plant-production facility.

The most widespread crops grown in our country under indoor conditions are cucumber and tomato plants, which account for more than 98% of the area of greenhouses. These plants are good prospects for growing completely under intense artificial lighting conditions (photocultures). Optimization of the main parameters of optical radiation when growing these plants is the most important task of achieving their profitable production.

At present considerable experience has been gained in studying the dependence of productivity of cucumber and tomato communities on irradiation conditions. Fundamental studies of the Agrophysical Research Institute of the Russian Academy of Sciences, Timiryazev Institute of Plant Physiology of the Russian Academy of Sciences, Timiryazev Agricultural Academy, and other institutes create a good basis for a detailed study of the given problem. Commercial sources of radiation substantially differing in spectral characteristics in the region of photosynthetically active radiation (PAR) were used in the studies (Table 1).

TABLE 1 Spectral Characteristics of Light Sources.

Light source	Approximate ratio of radiant fluxes in three PAR ranges, %		
	400-500 nm	500-600 nm	600-700 nm
Incandescent lamp	14	34	52
DKsT lamp	35	31.5	33.5
DRV750 lamp	25.5	46	28.5
DRLF400 lamp	26	56	18
DNaT400 lamp	7	56	37
DRI2000-6 lamp	39	43	18

One of the first studies of a cucumber variety "Klinskie" photoculture is reported in (Moshkov, 1966) and it is noted that the use of type DRL400 lamps with PAR irradiance 80-120 W/m^2 produced good results.

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In experiments with cucumber variety "Dyadya Stepa" three types of lamps with a different spectrum were used: DRLF400, DRV750, and DR12000-6 (Sharupich, 1982). Unfortunately, each type was used in its "own" range of PAR, the boundaries of which were selected with consideration of the energy efficiency in the PAR region and unit power of the lamp. With irradiation of the plants by a spectrum with a small share of radiation in the red region (DRLF400) and with variation of irradiance E_{PAR} within 35-100 W/m^2, the productivity of the community did not exceed 17 kg/m^2. In experiments with DRV750 lamps (increased share of radiation in the red part) with an increase of E_{PAR} from 35 to 200 W/m^2, maximum productivity increased to 23 kg/m^2. Finally, for E_{PAR}=300-400 W/m^2 (DRI2000-6), productivity of the community increased to 30 kg/m^2. The author (Sharupich, 1982) concluded that the range E_{PAR} = 80-150 W/m^2 is preferable for a cucumber culture, and an evaluation of the favorable spectrum is possible only at the qualitative level.

Detailed studies of potential productivity of tomatoes under photoculture conditions were carried out by the author (Moshkov, 1966) and were continued by his successors. The main sources of radiation in the experiments were 300-W metallized incandescent lamps, the spectrum of these sources was most suitable for intense growing of tomatoes under artificial conditions. A tomato variety Pushkinskii yield, of about 22 kg/m^2 was obtained with E_{PAR} of about 250-300 W/m^2 under conditions with water screens.

In the next study (Ermakov, 1987), 1000-W halogen lamps (HLs) and 400-W high-pressure sodium lamps (HPSLs) were used and the conclusion about the special significance of the long-wave part of PAR for the vital activity of tomato plants was confirmed.

It should be noted that the spectrum of type DKsTV6000 lamps having close to equi-energy in the PAR region, was used in photobiological studies of the Timiryazev Agricultural Academy (Leman, 1976), and also was quite effective for tomato photoculture. To develop well-founded requirements imposed on the spectrum when growing tomato and cucumber plants under intense photoculture conditions, it is necessary to conduct experiments with broad variation in the spectrum within the PAR. Such experiments were conducted by the Institute of Biophysics, Siberian Branch, Russian Academy of Sciences (IBF SO RAN) jointly with the All-Union Lighting Research and Development Institute (VNISI) in 1986-1989.

Using the method of Tikhomirov, (1983) and a series of selective metal halide lamps (MHLs), the PAR region was divided into three spectral ranges: 400-500 nm ("blue"), 500-600 nm ("green"), and 600-700 nm ("red"). The spectra of these lamps with filters are shown in Figure 1. The required spectral distribution and level of irradiance were achieved by combining lamps in a multilamp lighting fixture. Cucumber variety "Moskovskii Teplichnyi" and tomato variety "Starfire" were grown in 1 m^2 chambers with adjustable temperature and humidity characteristics until the final tomato crop was obtained. The environmental parameters (except the varied spectrum) were maintained at optimal levels: humidity 60-70% (cucumbers) and 60-70% (tomatoes), air temperature during irradiation 25 ± 1 °C (cucumbers) and 28 ± 1 °C (tomatoes), night temperature 20 ± 1 °C (cucumbers) and 25 ± 1 °C (tomatoes), photoperiod 14 hr (cucumbers) and 16 hr (tomatoes).

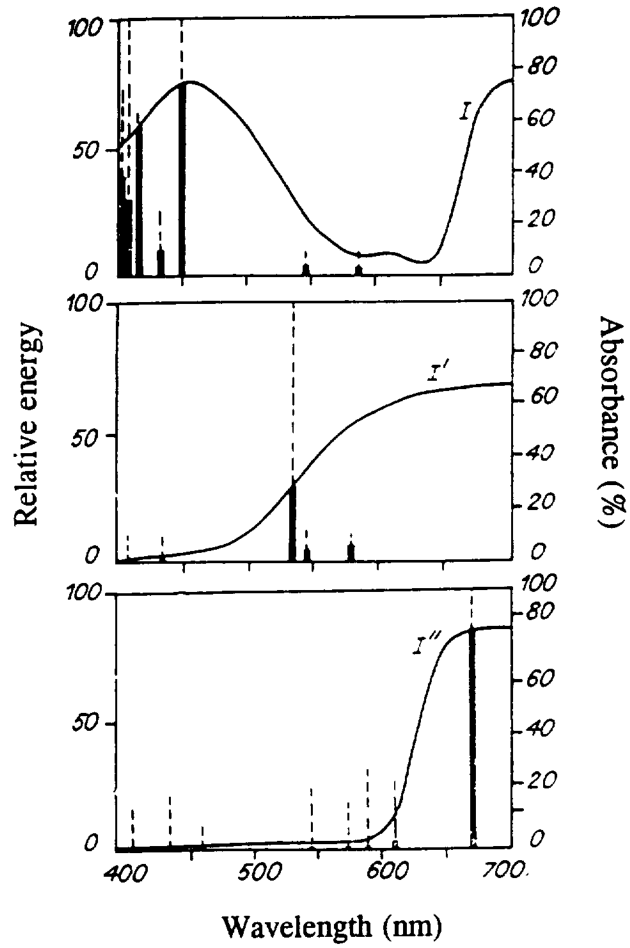


Fig. 1. Spectra of lamps and absorbance of filters utilized for irradiation of plants. Spectral emissions of lamps shown by vertical lines for a) blue mercury-gallium-indium lamps, b) green mercury-thallium lamps, c) red mercury-thallium lamps based on relative energy emission of the strongest waveband. Dashed vertical lines are the relative energy without filters and solid vertical lines are the relative energy with filters. Absorbance of specific filters(T,%) utilized with each lamp is shown by the solid line curve.

In each experiment PAR was maintained at the level 100 ± 10 W/m^2. By means of a planer water screen, and when necessary glass heat-protecting filters, the share of IR radiation was established at a level of about 25% of the radiation in the PAR region. The spectral distribution of irradiance was checked by a portable PDSF spectrophotometer.

Sixteen experiments with cucumbers and seven with tomatoes were carried out with various spectral combinations. The results of the experiments (nine characteristic experiments were selected for cucumbers) are given in Tables 2 and 3.

TABLE 2 Productivity of Cucumber Variety "Moskovskii Teplichnyi" with Variation of the Spectrum in the PAR Region.

Ratio of irradiance in three PAR ranges, (%)			Fruit yield (kg/m^2)	Period of growth (days)	Average daily fruit yield, (g/m^2)
E_b (400-500m)	E_g (500-600m)	E_r (600-700m)			
40	20	40	20.8±1.6	80	260.0±20.0
60	20	20	16.1±1.3	90	178.8±14.4
20	60	20	17.5±1.2	80	218.3±15.0
40	40	20	18.2±1.6	85	214.2±18.8
34	33	33	22.5±1.9	75	200.0±29.3
15	35	50	22.1±1.5	70	322.8±21.9
25	35	40	25.2±1.5	75	336.0±20.0
15	45	40	27.4±1.7	70	391.4±24.3
20	40	40	27.5±1.3	70	392.9±22.9

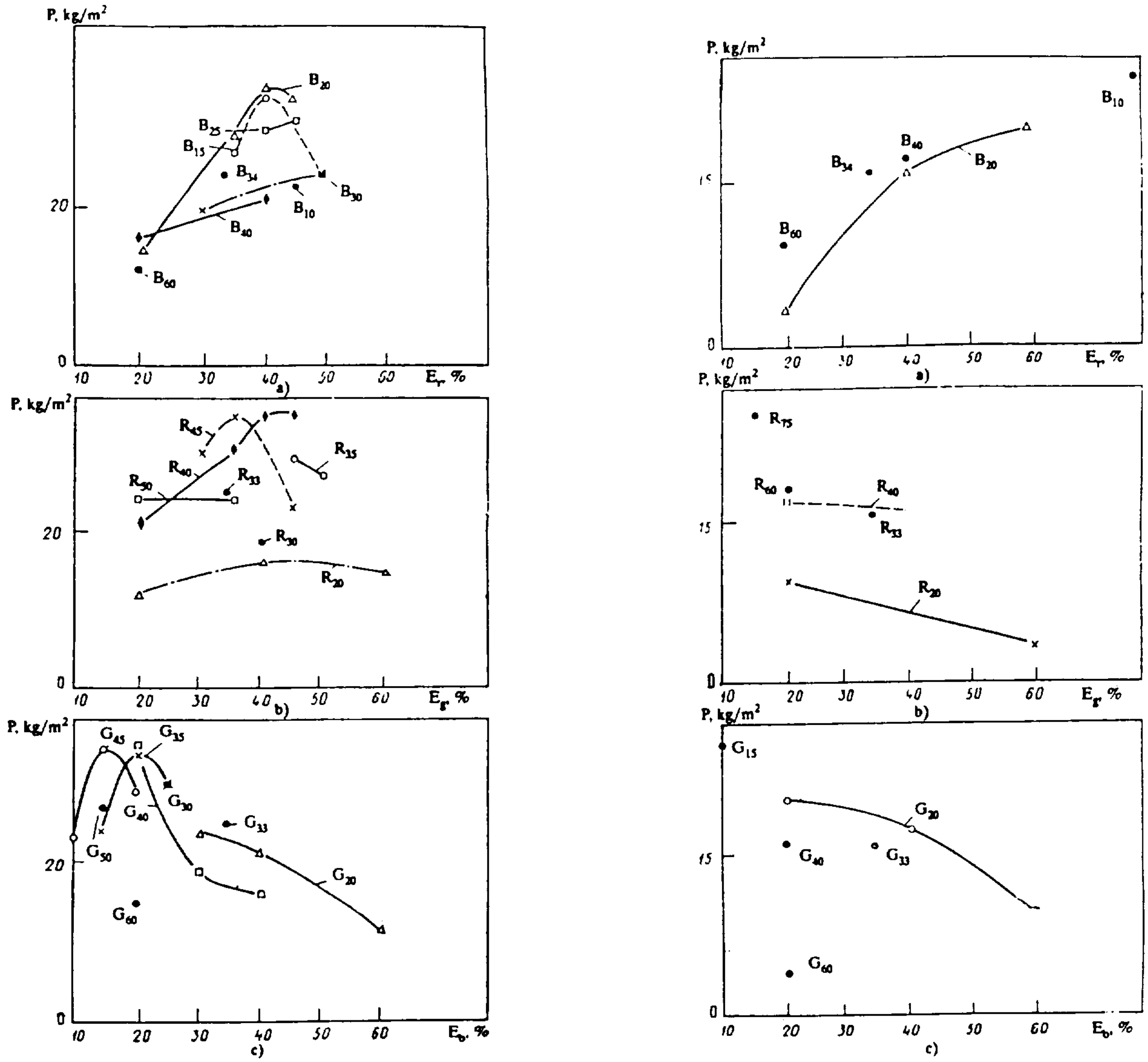
TABLE 3 Productivity of Tomato Variety "Starfire" with Variation of the Spectrum in the PAR Region.

Ratio of irradiances in three PAR ranges, %			Fruit yield (kg/m^2)	Period of growth (days)	Average daily fruit yield, (g/m^2)
E_b (400-500m)	E_g (500-600m)	E_r (600-700m)			
60	20	20	13.2±0.9	130	101.5±7.0
20	60	20	11.1±0.7	120	92.5±5.8
20	20	60	16.9±1.2	100	169.0±12.0
40	20	20	15.7±1.0	120	131.0±8.0
20	40	40	15.5±0.9	110	141.0±8.0
34	33	33	15.4±1.1	110	140.0±10.0
10	15	75	18.5±1.2	100	185.0±12.0

Assuming total productivity of the crop P, kg/m^2, is a function of the share of irradiance in each of the three spectral ranges (E_b, E_g, E_r) of the total E_{PAR} and taking into account the equation of the relation existing for these variables, we obtain a system of equations.

$$P - f(E_b, E_g, E_r);$$
$$E_b + E_g + E_r = 100\%$$

We reduce the problem to three-dimensions and, drawing sections along one of the variables in accordance with its values realized in the experiments, we represent the results obtained in the form of Figure 2. For each of the vegetables we obtained six families of curves, but we have limited ourselves here to three characteristic relations (the results of all 16 experiments with cucumbers were taken into account).



Cucumber

Tomato

Fig. 2. Dependence of productivity of cucumbers and tomatoes on share of radiation of one of the three spectral ranges (E_b, E_g, or E_r) with total irradiance E_{PAR} = 100W/m^2:1) P = $f(E_r)$, E_b is a parameter (B_{25}, for example, means that the share E_b = 25%; b) P = $f(E_g)$, E_r is a parameter; c) P = $f(E_b)$, E_g is a parameter.

Before the main series of experiments on the cucumbers, an attempt was made to evaluate the photophysiological significance of each of the three PAR ranges. It was found that for irradiance E_{PAR} = 50 W/m^2 cucumbers, unlike many other plant species, are not formed either with only blue or green rays, and even with a high level E_{PAR} = 100 W/m^2 an extremely low yield was obtained only in blue rays.

The character of the dependence of the productivity of cucumbers on an increase of the share of radiation in the green and red ranges of PAR is about the same. There are fairly distinct optima of productivity for E_g = E_r = 35-45% of the total level. With an increase of the share of radiation in any of the indicated ranges above 45% (and corresponding decrease of the share of radiation in the other range), the productivity of the plants decreases markedly. The presence of blue radiation in the spectrum is necessary, but in a small dose. The dependence of productivity on the share of blue radiation reaches a maximum when E_b = 15-20%. It is interesting to note that with a decrease of the share of green radiation, the position of the maximum of the productivity curve shifts toward E_b.

Thus with respect to a cucumber photoculture, we need speak about the preference of a "balance" of radiation in ranges 500-600 and 600-700 nm with the small addition of radiation in the range 400-500 nm. The best results for commercial technology are obtained with a spectral ratio E_b:E_g:E_r = 15-20%:35-45%:40-45% (USSR, 1991).

As follows from the results of experiments on cucumbers (see Table 2), optimization of the spectrum creates additional possibilities for reducing the cost of production due to a noticeable reduction of the period of growth. Substantially different conclusions about preferable spectra follow from an analysis of the results of experiments on tomatoes (see Fig. 2 and Table 3). The qualitative and quantitative effect of each of the three PAR ranges on the formation of the tomato crop is displayed rather clearly, despite the smaller number of experiments with a fixed spectrum than for cucumbers. We note the most important significance of radiation is the region 600-700 nm to acheive a high productivity of the tomato community. With a change in the share of E_r over 20-75%, the tomato yield can differ by almost 1.7 times; the maximum level of productivity in the experiments was achieved for E_r = 75%, although there are signs of saturation of the dependence already for E_r = 60-65%. Radiation in ranges 400-500 and 500-600 nm, conversely, is needed in insignificant shares, satisfying evidently, photomorphogenetic processes in plants. Thus, already for E_b = E_g = 15-20% against the background of a high share of red radiation, a drop of tomato productivity is observed. For E_r = 35-40% an increase of radiation in the green region weakly affects productivity, an increase of the share of red radiation for E_r = 20-40% can lead even to an increase of yield. However, all these effects are observed against the background of a low level of tomato productivity.

The requirements imposed on preferable spectral characteristics for tomato photocultures formulated on the basis of the studies are: E_b:E_g:E_r = 10-20%:15-20%:60-75%.*

The requirements imposed on the spectrum for growing tomatoes and cucumbers can be regarded as optimal.

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*A team of authors of IBF SO RAN and VNISI applied for a patent on a method of growing tomatoes under artificial conditions and a favorable decision was obtained.

The experimental data permit us to make an estimate of the correspondence of the spectral requirements in the PAR region to the spectrum of certain commercial light sources to the productivity of tomatoes and cucumbers. The data are given in Table 4, where the level of maximum productivity corresponds to the experimental results with the recommended optimal spectral ratios. Lower productivity values were obtained with the use of combinations close or corresponding to the PAR spectrum of commercial lamps (DRLF, DNaT, DRI, etc.).

TABLE 4. Calculation of the PAR efficiency of some types of light sources for cucumber and tomato culture. Productivity estimated based on maximum productivity determined in previous experiments of Tables 2 and 3.

	Productivity (% of maximum)	
Lamp Type	Cucumbers	Tomatoes
DksT	81	95
Incandescent	78	84
DNaT	70	83
DRI	66	70
DRLF	64	60

As is seen, not one of the commercial light sources can be recommended for efficient use in commercial technology of cucumber culture, and the least suitable for this purpose are DRLF400 lamps; the spectrum of lamps with a high radiation efficiency in the PAR region (DNaT400 and DRI2000-6) are almost equal to the spectrum of DRLF400 lamps. We note that the requirements imposed on the "ideal" spectrum for growing cucumbers can be rather simply realized by selecting the appropriate filling of the MHLs. Work is presently underway to create such lamps.

Type DRLF400 lamps were also least acceptable for irradiating tomatoes. The creation of a special grow light on the basis of MHLs with a spectrum close to that in the PAR region of incandescent lamps (ILs) is a technically more complex problem. However, as the results of our experiments, confirming the conclusions of (Sharupich, 1982), showed, under conditions of an intense tomato culture, the use of HPSLs provides a sufficiently high level of productivity. For large conveyor-type plant production facilities, it would be expedient to create 700- or 1000-W HPSLs.

REFERENCES

Ermakov, E.I., Intensive Plant Cultivation systems [in Russian], Agropromizdat, Leningrad, 1987.

Leman, V.M., Plant Photoculture Textbook [in Russian], Vysshaya Shkola, Moscow, 1976.

Moshkov, B.S, Growing Plants Under Artificial Lighting [in Russian], Kolos, Leningrad, 1966.

Sharupich, T.S., Candidate Dissertation Abstract: Investigation of Systems for Artificial radiation of Plants in Lightproof Structures [in Russian], Krasnoyarsk, 1982.

Tikhomirov, A.A., et al., Problems of Optimizing the Spectral and Energy Characteristics of Plant Grow Lights [in Russian], Izd-vo IBF SO AN SSSR, Krasnoyarsk, 1983.

USSR Patent 1620062, "Method of growing cucumbers under artificial light," Otkrytiya. Izobreteniya, No. 2, 1991.