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THE INFLUENCE OF DIFFERENT LIGHT SOURCES ON PHOTOSYNTHETIC PERFORMANCE AND PRODUCTIVITY OF *Cucumis sativus* L. HYBRID TRISTAN F_1 IN AEROPONIC PHYTOTRON FACILITIES

L.Yu. MARTIROSYAN[1, 3], A.A. KOSOBRYUKHOV[1, 2], V.V. MARTIROSYAN[1], Yu.Ts. MARTIROSYAN[1, 3] ✉

[1]*All-Russian Research Institute of Agricultural Biotechnology,* 42, ul. Timiryazevskaya, Moscow, 127550 Russia, e-mail levon-agro@mail.ru, valentbond@mail.ru, yumart@yandex.ru (✉ corresponding author);
[2]*Federal Research Center Pushchino Scientific Center for Biological Research RAN, Institute of Basic Biological Problems,* 2, ul. Institutskaya, Pushchino, Moscow Province, 142290 Russia, e-mail kosobr@rambler.ru;
[3]*Emanuel Institute of Biochemical Physics RAS*, 4, ul. Kosygina, Moscow, 119334 Russia
ORCID:
Martirosyan L.Yu. orcid.org/0000-0003-1769-6377
Martirosyan V.V. orcid.org/0000-0003-1178-8887
Kosobryukhov A.A. orcid.org/0000-0001-7453-3123
Martirosyan Yu.Ts. orcid.org/0000-0001-8825-2381

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Abstract

Global climate change and anthropogenic pollution of the environment pose serious problems for agricultural producers. Drought or flooding of fields, the emergence of new diseases and pests, and reduction of agricultural land pose serious problems in providing food for the growing population. Moreover, more than half of the world's population lives in cities, and this proportion is expected to increase to 67 % at 2050. To meet the growing needs of the population of megacities, new non-standard approaches and technologies are needed to increase the production of fresh vegetables, fruits, and berries. Vertical plant growing in the so-called "city farms" is a promising resource-saving method of compact multi-tier cultivation of various plants, especially greens, vegetables, medicinal and ornamental plants. The use of hydroponics and aeroponics allows a new type of agriculture that combines biotechnology, industrial architecture, design and successfully integrates into urban infrastructure. A significant increase in the production and yield of basic food vegetable crops, especially in "city farms" necessitates understanding needs of plants for light, mineral nutrition and other equally important factors, e.g., temperature, humidity, CO_2 content. Under the conditions of a phytotron that imitates a "city farm" model, we compared the effects of high-pressure sodium lamps (HPSLs) DNaT-600 traditional for greenhouse plant lighting and alternative light-emitting diode phytolamps (LEDs) on photosynthesis and, ultimately, the production process in *Cucumis sativus* L. Tristan F_1 hybrid as a cucumber crop usually cultivated in greenhouses. In treatments 2 and 3, LED irradiators and DNaT-600 lamps at a radiation intensity of 305 and 413 μmol photons $\cdot$ m^{-2} $\cdot$ s^{-1} and a temperature of 25 and 26 °C, respectively, provided formation of an effective photosynthetic apparatus capable of performing at an increase in light intensity up to 1200 μmol photons $\cdot$ m^{-2} $\cdot$ s^{-1}. The LEDs of treatment 2 can serve as a single light source when growing cucumbers in a "city farm". These irradiators are characterized by a smaller proportion of blue (λ_{max} = 450 nm) and far red (λ_{max} = 730 nm) light and a larger proportion of red (λ_{max} = 660 nm) light in the spectrum. However, for early harvesting, the DNaT-600 lamps with the standard plant lowering method are preferable. The period of growing plants under DnaT-600 irradiation in the "city farm" simulating aeroponic phytotron with a limitation of the phytolamp height of 1.5 m without plant lowering, ended 12 days earlier than under LED irradiators. Nevertheless, the yield during the growing season was higher for DNaT-600 than for LED irradiators with the same energy consumption. The data obtained are helpful in the design and creation of modern biotechnological enterprises, such as vertical "city farms" for the food production and biotechnological enterprises for production of biopharmaceuticals.

Keywords: *Cucumis sativus* L., photosynthetic apparatus, LED phyto lamps, growth processes, aeroponic phytotron, city farms

The right choice of the light regime for growing plants, taking into account their species characteristics, development stage, and physiological state, is important for obtaining products under photoculture conditions [1-3]. In this case, one of the main light sources is LED irradiators (LEDs) [4-6]. By using the programs for controlling the light conditions of growing, they allow to targetedly influence on the production process by accelerating or slowing down certain phases of plant growth and development [7-9].

Currently, LEDs with peak emission wavelengths in all spectrum ranges are commercially available. The combination of red and blue LEDs is most often used to ensure the growth and development of many plants, especially green crops [10, 11]. The use of these LED irradiators positively influences on the increase in the rate of photosynthesis and the accumulation of plant biomass [12, 13]. Red light spectrum (RS) range is important for the normal growth and development of plants, the formation of the photosynthetic apparatus and its further activity, the synthesis and accumulation of photoassimilates [6, 14, 15]. Blue light spectrum (BS) range is necessary for the formation of chloroplasts, accumulation of chlorophyll, opening of stomata, and photomorphogenesis of plants [16]. For different crops, the ratio of red and blue spectrum fluctuates in a significant range - from 2:1 to 9:1 [8, 17]. Besides RS and BS, other ranges should also be present in the irradiation spectrum of plants. Previously, the following ratio of the spectral regions of the irradiators was considered the most effective: 25-30% in the blue region (BS), 20% in the green light (GL), and 50-55% in the red light (RL) [18]. Such irradiation ensures the growth, morphogenesis, and productivity of plants. The presence of other spectral regions is important, i.e., a small fraction of ultraviolet (UV), far-red light (FRL) and infrared (IR) light. In a study of Qian et al. [2], UV light was used as a growth regulator in cucumber plants, the presence of UV radiation led to an increase in the degree of stomata opening, the rate of photosynthesis and transpiration. Pretreatment with UV-A (long wavelength radiation) produces robust tomato seedlings that are suitable for transport to production nurseries and greenhouses [19].

A change in the RL/FRL ratio can have a significant effect on plant morphology [20] and the activity of a number of physiological processes [21, 22]. When plants are illuminated with RL (λ_{max} = 660 nm), the stable form of phytochrome (Ph_r, phytochrome red) is converted into Ph_{fr} (phytochrome far red). An increase in the proportion of far-red light (λ_{max} = 730 nm) leads to the transformation of the Ph_{fr} back into the Ph_r form. As a result, various changes occurs, for example, lengthening of the hypocotyl, an increase in the length of internodes, and the distribution of assimilates.

The importance of certain areas of the spectrum is evidenced by studies [23-25], showing that a change in the maximum irradiation of plants even within the same spectral regime (red, green, blue, significantly affects the characteristics of the production process.

For different crops, the ratio of spectral irradiation ranges which are most favorable for growing plants is not the same [25]. Additional spatial restrictions for vertical plant growing arising in the context of multi-tier aeroponic “city farms” should also be taken in account [26]. Therefore, physiological processes that make it necessary to change the irradiation spectrum depending on the culture, optimization of the light regime for plant growing continue to be an area of primary focus [27, 28] and require further research.

In this work, we have shown that LEDs could be successfully used to regulate growth processes, but the energy efficiency of their industrial use remains questionable. In our study, irradiation with sodium lamps, the spectrum of which is close to that of the sun, promoted the acceleration of plant growth and development more than irradiation with LEDs of the same power. An exception was one option, in which the combination of the spectral characteristics of the LEDs and temperature turned out to be optimal for the growth, development and formation of plant productivity, comparable to that when using high pressure sodium lamps (DNaT-600). It is worth mentioning that DNaT-600 has a high proportion of infrared radiation in the spectrum, which under conditions of "city farms" can lead to a heat shock to plants. This can be avoided by lowering into the gutters of the aeroponic-hydroponic installation (patents RU 88246 U1, RU 131569 U1).

The purpose of this work is a comparative study of the effect of LED irradiators (LEDs) of different spectral composition and intensity and high-pressure sodium lamps (DnaT-600) (at the same energy power of all irradiators) on the parameters of the production process in cucumber plants in aeroponic cultivation conditions according to the "city farm" model.

Materials and methods. The studies were carried out on cucumber (*Cucumis sativus* L.) plants of the Tristan F1 hybrid (Enza Zaden, the Netherlands). Hybrid Tristan F1 forms balanced plants of the generative type with stable (without pronounced interruptions) fruiting. The hybrid is demanding on the relative humidity of the air during all periods of development and fruiting. Fruits (length 22-25 cm, weight 260±20 g) are characterized by a very high uniformity and marketability, which is close to 100% [28].

Seedlings were obtained from previously prepared seeds (patents RU 180527U1, RU 2675932C1, RU 2708829C1) in an aeroponic installation developed by us (RU 199457U1) under the LEDs at a light intensity of 100±5 μmol photons $m^{-2} \cdot s^{-1}$ (16 h day/8 h night). On days 19-20 (the phase of 3-4 true leaves), the plants in holders were transferred to the phytotron and placed in the troughs of our aeroponic modules (patents RU 88246U1, RU 131569 U1) under the LEDs developed by us with different spectral characteristics (variants 1, 2, and 4 of the experiment) and under the DNaT-600 lamps (MASTER GreenPower 600W 400V, Philips, the Netherlands; variant 3 of the experiment). The phytotron room with a volume of 120 m^3 was divided into four identical compartments (30 m^3 in each variant of the experiment) using opaque reflective screens. The distance from the illuminators to the surface of the gutters (planting field) was 1.5 m (accounting for restricted location of illuminators height wise in the conditions of the "city farm"), the density of the placement of plants in the gutters of aeroponic modules was 4.8 per 1 m^2 (12 plants per variant).

The set ambient temperature regimes in the phytotron room corresponded to those recommended for the Tristan F_1 hybrid and depended on the phase of plant development and the cultivation technology. In all variants, the first 2-3 days after planting, the temperature remained low (20-22 °C), then they switched to a constant temperature regime 25±1 °C (day)/20±1 °C (night) with a photoperiod of 16 hours (day)/8 hours (night). The ambient temperature regime was maintained in an automatic mode using the air conditioning and ventilation systems, the root zone (21±1 °C) was maintained by cooling the nutrient solution in an automatic mode using a G 30 Polar device (UBC Group, China). The humidity in the phytotron room (75±5%) corresponded to the optimum for the hybrid. The concentration of CO_2 in the air was 420±22 μmol $CO_2 \cdot mol^{-1}$.

Temperature, relative humidity, and CO_2 concentration were monitored using an E + E EE244 wireless sensor (E + E Elektronik, Austria) which was integrated into the process control system in the phytotron. Spectral parameters were monitored using an ASENSEtek PG100N spectrometer (UPRtek Corp., Taiwan).

The nutrient solution was prepared based on commercial fertilizers (Yara International ASA, Northway). The used fertilizer was Kristalon cucumber ($N_{14}P_{11}K_{31}$), calcium nitrate, magnesium nitrate with the concentration of the main fertilizer 1 g/l, 0.8 g/l $Ca(NO_3)_2$, 0.3 g/l $Mg(NO_3)_2$, the pH of the solution was corrected with orthophosphoric acid (chemically pure grade, OOO KhimMed, Russia). A finely dispersed aerosol obtained from the solution containers was supplied directly to the root zone using high-pressure pumps and special nozzles (each variant of the experiment had an individual nutrient solution supply scheme). Then the condensed solution flowed down the chute back into the containers. The periods of feeding the nutrient solution alternated with periods without feeding, during which aeration of the plant root system took place. The hybrid has a powerful and active root system, but, according to the originator (Enza Zaden, the Netherlands), it does not tolerate high salt concentrations, therefore, in the experiment, the optimal values of the conductivity of the nutrient solution were controlled (2.3±0.2 mS/cm, pH 5.8±0.2). We used ST320 pH electrodes, STCON3 conductometric electrodes (OHAUS Corp., USA), which were integrated into the plant cultivation process control system in the phytotron.

The intensity of photosynthesis was determined on day 10 of the growing and before the onset of the fruiting period on day 20 of the growing; on day 20, the parameters of the variable fluorescence of chlorophyll a (Chl a) were also measured. Measurements were carried out in the leaves of the 2nd and 3rd upper tiers on plants with 10-14-tiered leaves..

The activity of photosynthesis under LEDs and DNaT-600 lamps was assessed by the rate of CO_2 exchange of leaves using a portable infrared gas analyzer Lcpro+ (ADC BioScientific, Ltd, Great Britain) at a light intensity of 300 μmol photons $\cdot$ m^{-2} $\cdot$ s^{-1}, as well as at light saturation 1200 μmol photons $\cdot$ m^{-2} $\cdot$ s^{-1}. The dependence of the photosynthesis rate on the light intensity was taken into account in the range from 0 to 1200 μmol photons $\cdot$ m^{-2} $\cdot$ s^{-1} at a CO_2 concentration in the air of 420±22 μmol $CO_2 \cdot$ mol^{-1}. For this, the level of light intensity was sequentially increased from 0 to 1200 μmol photons $\cdot$ m^{-2} $\cdot$ s^{-1}. The light curve was fitted using the Prioul and P. Chartier model [29] with Photosyn Assistant software (http://www.ddsci.com/) [30].

To study the reactions of the light stage of photosynthesis, we used the method of variable fluorescence Chl a, which characterizes the activity of photosynthetic system II (PS II) [31]. Variable fluorescence was recorded using a portable PAM fluorimeter (PAM-Junior, Heinz Walz GmbH, Germany). Leaves were kept in the dark for 20 min, after which the level of minimum (F_o) and maximum (F_m) fluorescence was measured. The potential quantum yield of PS II was found as $F_v/F_m = (F_m - F_o)/F_m$, where F_v is variable fluorescence. The real quantum yield of PS II Y(II) was calculated by the formula $Y(II) = (F'_m - F_t)/F'_m$, where F'_m is the maximum fluorescence of Chl a in light-adapted samples, F_t is the stationary level fluorescence of Chl a in light-adapted samples. The values of the coefficient of non-photochemical quenching of fluorescence Chl a of PS II (NPQ) were determined by the formula: $NPQ = (F_m - F'_m)/F'_m$. The relative rate of electron transport through PS II was calculated as ETR = Y(II) × PPFD × 0.5, where PPFD is the flux density of quanta of photosynthetically active radiation (PAR).

Plants were grown in one stem, all side shoots were removed. To maintain uniformity in planting, the plants were not lowered (unlike the technology commonly used in greenhouses). The position of the stem was kept strictly vertical to avoid mutual shading of the plants. The first harvest was obtained 38-42 days after planting. Fruits were harvested with a weight of about 220 g. The yield was uniform throughout the growing season and was greatest from the middle layer (at a height of about 80-100 cm).

Three cycles of plant cultivation were carried out. Since the general patterns did not differ in the series of experiments, the data for one cycle are presented (the average data for the three cycles are given for the yield). When determining the activity of photosynthesis and the variable fluorescence Chl a, the sample size (n) was 8, the analytical repetition of measurements in the experiments was 4-5 times. Statistical processing was performed using the Statistica Base software (StatSoft Inc., USA). The tables show the arithmetic mean values (M) with standard error (±SEM). The significance of the differences was determined by the Student's t-test at P = 0.95.

Results. The objective of this work was to assess the intensity of CO_2 gas exchange, the activity of the light stage of photosynthesis (according to the indicators of the variable fluorescence Chl a) and to determine the yield of cucumber plants grown for a long time by the aeroponics method in a phytotron under LEDs or DNaT-600 lamps with specified intensity and spectral composition of irradiation (variants 1-4 of experiment, Fig.).

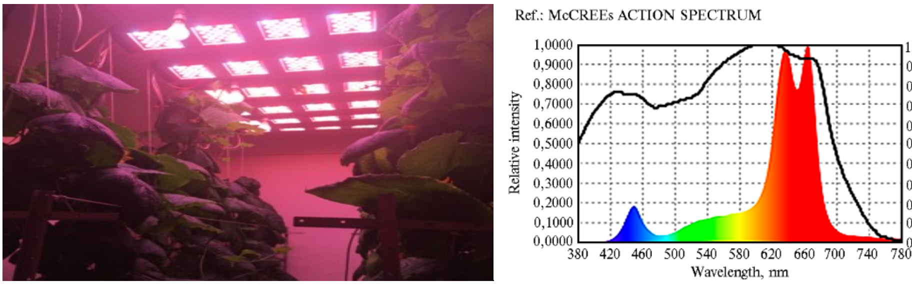
According to the variants (1, 2, 3 and 4), the light intensity levels in the range of 400-780 nm were 193±7.0, 305±12.5, 418±47.6, 309±11 μmol photons · m^{-2} · s^{-1}, respectively (Table 1). The energy power of all irradiation sources was 1200 W, but LED irradiator in variant 1 was dimmed to 75% of the initial power (see Table 1). For LEDs, the spectra in variants 1 and 4 differed from the spectrum in variant 2 in the near infrared region of 701-780 nm (a decrease in irradiation by 12%) and in the region of 400-499 nm (an increase of 12%). As a result, in variants 1 and 4 the portion of blue light was slightly higher than in variant 2.

At a light intensity of 300 μmol photons · m^{-2} · s^{-1}, the rate of photosynthesis as per variants was 4.1±0.2, 5.2±0.3, 5.6±0.5, and 4.7±0.4 μmol CO_2 · m^{-2} · s^{-1}, respectively. At 1200 μmol photons m^{-2} · s^{-1}, plants in variants 2 and 3 showed higher gas exchange rates (7.9±0.5 and 7.6±0.6 μmol CO_2 · m^{-2} · s^{-1}) than plants in variants 1 (75% of the initial LED power) and 4, the 4.4±0.3 and 5.1±0.4 μmol CO_2 · m^{-2} · c^{-1}, respectively. Analysis of the light curves of photosynthesis (Table 2) assesses the balance between the absorption of CO_2 and its release during dark respiration.

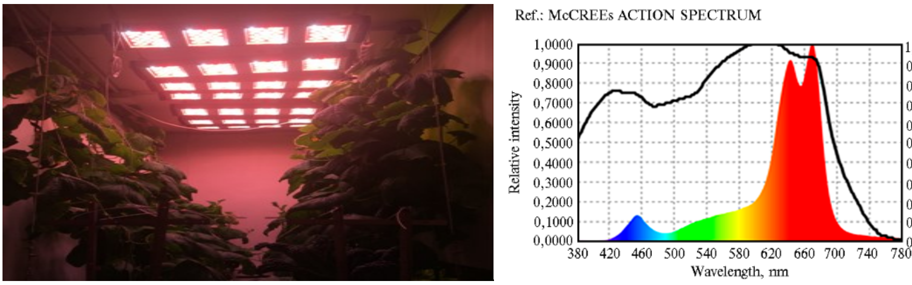
In all variants of the experiment, the plants had a positive carbon dioxide balance. In absolute terms, the difference between the absorption and release of CO_2 in the processes of photosynthesis and dark respiration was 3.1, 7.0, 5.1 and 3.1 μmol CO_2 · m^{-2} · s^{-1} as per the variants. According to the gas exchange data, it could be expected that the productivity of plants in variants 2 and 3, as a result, would be higher than in the other two variants of the experiment.

Other indicators of the light curve of photosynthesis provide additional information about the efficiency of the use of light energy by plants. In variants 1, 2 and 3, the quantum yield of photosynthesis turned out to be below 0.04, although in natural conditions of plant growth the average value is 0.04-0.07 [31]. Only in variant 4, the quantum yield was equal to 0.046 (see Table 2). We associate the observed low values of the quantum yield with the formation of a large leaf surface in plants.

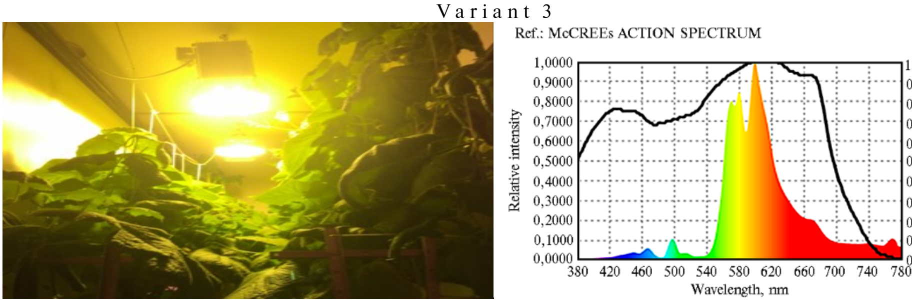
Variant 1



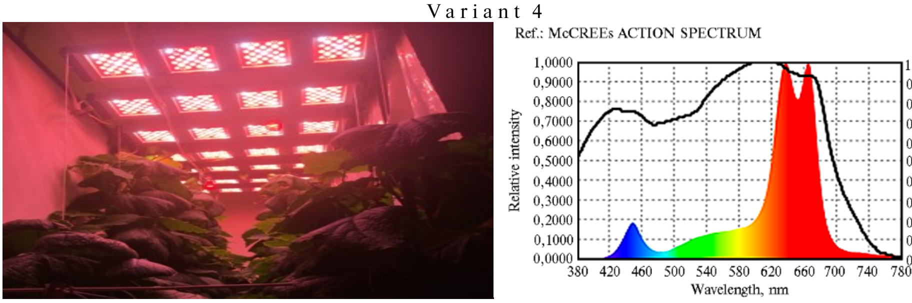
Variant 2



Variant 3



Variant 4



Spectral characterization of LEDs and DNaT-600 lamps used for growing cucumber (*Cucumis sativus* L., hybrid Tristan F1) plants by aeroponic technology in a phytotron facility. For the spectral composition of phyto-luminaires, see the Table. 1.

1. Energy power (P) and spectral characterization of phyto-luminaires for growing cucumber (*Cucumis sativus* L., hybrid Tristan F1) plants by the aeroponic technology in a phytotron facility as per test variants

Spectral range, nm	Light intensity for each variant, μmol photons $m^{-2} \cdot s^{-1}$			
	1 (P = 945 W)	2 (P = 1200 W)	3 (P = 1200 W)	4 (P = 1200 W)
PPFD (400-700)	193,00	304,86	412,98	309,02
PPFD IR (701-780)	7,227	12,432	47,650	10,955
PPFD R (600-700)	153,03	245,59	207,05	245,94
PPFD G (500-599)	28,224	43,831	190,58	44,329
PPFD B (400-499)	11,748	15,437	15,348	18,749
PPFD UV (380-399)	0,0579	0,1420	0,6102	0,1087
Total PPFD (380-780)	200,28	317,34	461,43	320,08

N o t e. PPFD — photosynthetic photon flux density.

2. Analysis of light curves of CO_2 gas exchange in leaves of cucumber (*Cucumis sativus* L., hybrid Tristan F_1) plants in growing by the aeroponic technology in a phytotron facility depending on the light and temperature conditions as per test variants (n = 8 with 5-fold analytical repeatability of measurements, M±SEM)

Parameter	Variant 1, 75 %, 23 °C	Variant 2, 100 %, 25 °C	Variant 3, 100 %, 26 °C	Variant 4, 100 %, 24 °C
Maximum CO_2 absorption rate, μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$	4.4±0.4[a]	7.9±0.5[b]	7.6±0.6[b]	5.1±0.5[a]
Dark respiration rate, μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$	–1.3±0.3[a]	–0.9±0.2[a]	–2.5±0.3[b]	–2.0±0.4[b]
Quantum yield of photosynthesis	0.039±0.012[a]	0.024±0.003[b]	0.036±0.006[a]	0.046±0.016[c]
Light intensity at saturation of the light curve of photosynthesis, μmol photons $\cdot m^{-2} \cdot s^{-1}$	144±11[a]	363±17[b]	278±17[c]	423±19[d]
Light compensation point, μmol photons $\cdot m^{-2} \cdot s^{-1}$	32±7[a]	36±5[a]	69±6[b]	153±8[c]

N o t e. The percentages of the initial energy power of the irradiators (1200 W) and the actual temperatures that were set in the phytotron compartment, depending on the type and used power of the irradiator are indicated. Characteristics of phytolamps by variants of the experiment, see Figure, Table 1.
[a, b, c, d] The mean values in a row, marked with the same letter, do not differ statistically significantly at p ≤ 0.05.

In variants 2 and 4, the light intensity at saturation of the light curves of photosynthesis was higher (363 and 423 μmol photons $\cdot m^{-2} \cdot s^{-1}$, see Table 2) compared to the irradiation intensity during cultivation (305 and 309 μmol photons $\cdot m^{-2} \cdot s^{-1}$, see Table 1). In these variants, Chl a works more efficiently; therefore, the rate of dark reactions of photosynthesis in the leaves of the upper tiers did not become a limiting factor.

The maximum rate of photosynthesis at the plateau of the light curve in plants grown under LEDs in variant 1 was the lowest in comparison with other variants. The saturation of the photosynthesis rate curve began at a light intensity of 144±11 μmol photons $\cdot m^{-2}$ s^{-1} (see Table 2) which is lower than the light intensity during plant growth (193.00 μmol photons $\cdot m^{-2} \cdot s^{-1}$, see Table 1) and is apparently associated with the limitation of the rate of dark reactions of photosynthesis.

Analysis of the activity of light reactions of the photosynthetic apparatus by the parameters of variable fluorescence shows (Table 3) that the maximum quantum yield of the photochemical reaction in PS II (F_v/F_m) was comparable in plants in variants 2, 3, and 4 and turned out to be slightly higher in variant 1 with a reduced light intensity. In plants grown under LEDs, the real quantum yield Y(II) of the primary photochemical reaction of PS II in all variants was higher in comparison with plants under DNaT-600, especially variants 1 and 4.

3. Variable leaf fluorescence parameters of cucumber (*Cucumis sativus* L., hybrid Tristan F_1) plants in growing by the aeroponic technology in a phytotron facility depending on the light and temperature conditions as per test variants (n = 8 with 4-fold analytical repeatability of measurements, M±SEM)

Parameter	Variant 1, 75 %, 23 °C	Variant 2, 100 %, 25 °C	Variant 3, 100 %, 26 °C	Variant 4, 100 %, 24 °C
Fv/Fm	0.782±0.007[a]	0.744±0.005[b]	0.741±0.003[b]	0.743±0.005[b]
ETR	32.6±2.0[a]	40.9±3.1[b]	51.0±3.4[b]	31.8±2.3[a]
Y(II)	0.409±0.010[a]	0.342±0.006[b]	0.260±0.007[c]	0.467±0.010[d]
NPQ	1.020±0.100[a]	0.812±0.080[b]	1.019±0.110[a]	0.533±0.060[c]

N o t e . Fv/Fm — potential quantum yield of the photosystem II (PS II), ETR — relative electron transport rate through PS II, Y(II) — actual quantum yield of PS II, NPQ — coefficient of non-photochemical quenching of PSII chlorophyll a fluorescence. The percentages of the initial energy power of the irradiators (1200 W) and the actual temperatures that were set in the phytotron compartment, depending on the type and used power of the irradiator are indicated. Characteristics of phytolamps by variants of the experiment, see Figure, Table 1.
[a, b, c, d] The mean values in a row, marked with the same letter, do not differ statistically significantly at p ≤ 0.05.

The electronic transport rate (ETR) was slightly lower under LEDs compared to DNaT-600 lamps. A higher rate of electron transport in plants under DNaT-600 lamps could lead to an increase in the synthesis of high-energy equivalents (in particular, ATP NADP-H_2), providing high rates of CO_2 absorption both at a radiation intensity in the PAR region of 412.98 μmol photons · m^{-2} · s^{-1} (see Table 1) and at high irradiation intensity (1200 μmol photons · m^{-2} · s^{-1}). In the variant 4 (under LEDs), a decrease in non-photochemical quenching (NPQ) was observed, which characterizes a decrease in thermal dissipation when light energy is used not for photosynthetic processes, but for maintaining the proper rate of other biochemical reactions.

4. Growth parameters of cucumber (*Cucumis sativus* L., hybrid Tristan F_1) plants in growing by the aeroponic technology in a phytotron facility depending on the light and temperature conditions as per test variants (N = 3, M±SEM)

Parameter	Variant 1, 75 %, 23 °C	Variant 2, 100 %, 25 °C	Variant 3, 100 %, 26 °C	Variant 4, 100 %, 24 °C
Plant height, cm/number of leaf tiers	88/18	119/21	148/27	101/19
Yield, kg/m^2:				
on day 43 of growth	16.6±1.0^a	21.5±1.1^b	24.7±1.1^c	17.6±1.2^a
on day 55 of growth	19.4±1.1^a	27.3±1.3^b	0	20.5±1.1^a
Average yield increase in additional (compared to control) growing season, %	14.4^a	26.9^b		16.5^a
Duration of productivity period, days	55	55	43	55
Temperature difference vs control	–3	–1		–2
Lagging behind control in terms of the first harvest of marketable harvest, days	13	5		7

N o t e. In each variant, the yield for three cultivation cycles was assessed for 36 plants. Variant 3 (DNaT-600 lamps) was a control. The percentages of the initial energy power of the irradiators (1200 W) and the actual temperatures that were set in the phytotron compartment, depending on the type and used power of the irradiator are indicated. Characteristics of phytolamps by variants of the experiment, see Figure, Table 1

$^{a, b, c}$ The mean values in a row, marked with the same letter, do not differ statistically significantly at $p \leq 0.05$.

With high activity of the photosynthetic apparatus of leaves under DNaT-600 lamps, one could expect an increase in the rate of growth and development of plants. Indeed, when growing plants in aeroponic installations with limited height (according to the “city farm” model with a trellis height of 1.2 m), plants under DNaT-600 lamps significantly outpaced plants in other variants both in growth rate and in the onset of the fruiting phase (Table 4). Conventionally, the fruiting process in the experiment under DNaT-600 lamps can be divided into three stages. The first stage is rapid growth, development, and advancement in the formation of fruits in comparison with other variants where LEDs were used; the second stage is active uniform fruiting; the third - a slowdown in fruiting and a stop of the growing season due to the fact that, in the given spatial conditions, the plants have reached their maximum height.

The rapid growth and development of plants under DNaT-600 resulted in an earlier first harvest (by 13, 5 and 7 days, respectively) (see Table 4) than with LED irradiation, and also to an advance of the first maximum of harvest for variant 3 compared to variants 1 and 4 by 10 and 7 days, respectively.

The vegetation and harvesting periods with DNaT-600 irradiation was 43 days (the growth stopped, since the plants reached the maximum stipulated height of the trellis). By this time, under DNaT-600 irradiation, the total yield (see Table 4) exceeded that in all variants with LED irradiators, i.e., by 32.8% compared to variant 1, by 13.0% to variant 2, and by 28.7% to variant 4. To obtain additional data, we extended the observation of plants that retained their viability under LED irradiator (variants 1, 2 and 4) by 12 days (until the onset of a pronounced slow-down of the production process on day 55). The yield increase was 14.4% (variant 1), 26.9% (variant 2), and 16.5% (variant 4) compared to the yields for these variants at the date of completion of plant vegetation under DNaT-600 (variant 3). Only then (that is, in terms of the total output for 55 days), the yield in variant 2 exceeded that in variant 3 (DNaT-600) by 10.5%; in other variants (1 and 4), the total yield of marketable products for 55 days was still less than that of plants under DNaT-600 for 43 days. When comparing the cost of electricity and the resulting increase, the advantage of a faster plant growth with DNaT-600 irradiation is obvious The data obtained are comparable with the total productivity of this hybrid in industrial greenhouses, where the growing season, according to the originator, usually lasts 90-110 days, and the yield is 35.7-50.0 kg/m^2.

The reason for the shortened growing season and the corresponding decrease in yield under DNaT-600 lamps is associated with the physiological aging of plants [32], as well as with an excess of IR radiation. This factor must be regarded when growing plants under DNaT-600 lamps in "city farms" (that is, with height restrictions). Note that the aeroponic installation and technology developed by us, in this case, have an advantage over growing on substrates. The design of the aeroponic installation allows the stems to be lowered, to place them inside the aeroponic trough, which contributes to an increase in the rooting volume and rejuvenation of vegetative plants. However, in our experiment, when using this technique, the DNaT-600 lamps would have an additional advantage, which would affect the objectivity of the comparison of the DNaT-600 and LED irradiators.

It is worth noting that with the general automatic regulation of the temperature in the phytotron, its own temperature gradient was established in each compartment, depending on the type and power of the irradiator. This property of the luminaires affects the entire production process, so it was decided not to level the actual temperature difference. The ratio of thermal and light energy for LED and sodium lamps was different. According to data of MechaTronix Co., Ltd. (Netherlands), in LED phyto-lighting 35% of the energy is converted into convection heat, 15% is emitted in the form of radiation heat, and only 50% falls on the light energy in the PAR region within the given spectrum boundaries. In phyto-luminaires with DNaT-600 lamps, the efficiency in the PAR region is 34%, 55% of the energy is emitted in the form of radiation heat, and 11% in the form of convection heat [33, 34]. This factor must also be regarded when designing phytotrons for "city farms" to create the necessary temperature conditions.

Comparison of data on the yield and wavelength distribution in the spectra of LED irradiators (see Fig.) shows that an increase in the proportion of RL in the wavelength range 600-700 nm led to an increase in plant productivity. In terms of radiation intensity in this area, the LED irradiators in the 2nd variant were superior to DNaT-600 lamps by 40 μmol photons $\cdot$ m^{-2} $\cdot$ s^{-1}. In addition, the maximum intensity of the luminous flux inside the RL of the spectral region for the irradiators in variant 2 is at λ_{max} = 660 nm in contrast to the DNaT-600 lamps which have a maximum at 610 nm. That is, LEDs were optimized for the red spectrum at wavelengths λ = 630-680 nm (in the region of maximum absorption of chlorophyll).

The differences that we observed between the variants of the experiment can be associated with a longer high activity of the photosynthetic apparatus with a slow increase in the leaf area and plant growth in general. A similar pattern was described earlier in the work of Chermnykh et al. [35] who showed that in cucumber plants, leaves with a relatively low growth rate are able to carry out active photosynthesis for a long time (in contrast to leaves which quickly reach their maximum size). Our data indicate that plants grown at a higher PAR (variants 2 and 3) and a temperature optimal for the growth of the Tristan F_1 hybrid more efficiently use high-intensity light than plants in variants 1 and 4 (see Table 2) at temperatures below the optimum for the hybrid under study. These results make it possible to assess the possibility of using LEDs in the formation of irradiation regimes for plants in cultivation facilities of various types. With relatively comparable energy costs of DNaT-600 and LEDs, the latter benefit from the duration of use in the process of growing plants [36]. However, we note that the payback of the LED in comparison with the DNaT-600 is achieved much later and there is generally no correct justification of the economic efficiency of the LEDs. It is reported [37] that the long term use of LED irradiators led to a decrease in energy costs (up to 70%) compared to traditional light sources, in particular, when growing cucumber seedlings [38] and seedlings of ornamental crops [39]. According to other authors, due to high capital costs, five-year energy costs per mole of photons produced are 2.3 times higher for LED irradiators. For both technologies, long-term costs are low as compared to the cost of electricity consumed [40].

Comparison of variant 2 with variants 1 and 4 shows that even small changes in the LED spectrum lead to significant changes in growth and production processes (see Table 4). LEDs are characterized by a smaller portion (by 12%) blue (λ= 450 nm) and a larger (by 12%) far red (λ = 730 nm) light (see Table 1). Also, in variant 2, the red part of the spectrum with λ = 660 nm is also 12% higher than that of the red one with λ = 630 nm (see Fig.). The LEDs we used in variant 2 could be effectively used as the only light source when growing cucumber plants in closed premises.

However, further research is needed to better understand how plants respond to changes in the spectral composition of light in vegetation structures (greenhouse, phytotron, "city farm") and how to adjust the intensity and spectrum of light in order not only to speed up production processes with a quality crop, but also to optimize energy consumption. The energy costs make up to 35-40% in the cost of the product, sometimes even more, depending on the region. Although today LEDs for growing plants are not inferior in efficiency to traditional lamps DNaT-600, it is still far from the creation of "ideal" phytolamps. Further research is needed to determine the regulatory role of all PAR sites, the effect of near infrared light (in addition to a single LED light source) on growth, morphology, fruit quality and, in general, on the production process in cucumber plants.

Thus, in cucumber plants, at 305 and 413 μmol photons $\cdot$ $m^{-2} \cdot s^{-1}$ (variants 2 and 3, the LED and DNaT-600 lamps, respectively) and temperatures of 25 and 26 °C, a photosynthetic apparatus is formed that can work effectively when the light intensity is increased to 1200 μmol photons $\cdot$ $m^{-2} \cdot s^{-1}$. In variants 2 and 3 as compared to variants 1 and 4 (LEDs), high values of the CO_2 balance (photosynthesis—respiration) were revealed. When using LEDs, the real quantum yield Y(II) of photosystem II in the light is higher, and the ETR is slightly lower than for DNaT-600 lamps. In variants 2 and 4, the coefficient of non-photochemical quenching of fluorescence (NPQ) decreased. This elucidates the effects of different parts of the light spectrum on cucumber plants, the slowed growth of plants under LEDs and explains the greater yield during active fruiting period under DNaT-600 lamps. When plants are irradiated with DNaT-600 (variant 3), a leaf surface is formed faster and plant growth in height is accelerated. DNaT-600 lamps also provides earlier yielding of the Tristan F_1 hybrid plants. In an aeroponic phytotron simulating a "city farm" conditions with a 1.5 m height limitation of the lamp position, the use of DNaT-600 lamps leads to a shorter growing period, by 12 days (without plant lowering), than under the LEDs with a higher total yield than under the LEDs. Plants grew more slowly under LEDs, which made it possible to extend the growing season by another 12 days (until a visible decrease in productivity). During this period, the optimal distance between the top of the plants and the lamp was established (about 0.3 m) which contributed to high fruiting. Ultimately (taking into account the additional vegetation time), the LEDs in variant 2 provided a higher yield than the DNaT-600, but the energy consumption was also higher. Continuation of these studies is necessary to determine the role of different regions of photosynthetically active radiation and the influence of other spectral regions (for example, near infrared and UV-A radiation) on the production process and the quality of marketable products in cucumber plants. This is necessary to use the LED as the only light source, especially when designing and creating “city farms”.

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