The effect of far-red light on the productivity and photosynthetic activity of tomato

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Annotation. It is known that far red light is not a source of photosynthetic energy, but affects the adaptation and development processes of plants. Most of these studies are conducted on young plants, but it is important to understand how high-beam light affects the biochemical composition of tomato fruit, which determines the taste and useful properties. The effect of long-range red radiation on the morphological and biochemical parameters of a tomato plant grown under artificial irradiation with LEDs with a different ratio of red and long-range red radiation from 2 to 9 with the same spectral composition in the range 400÷700 nm was studied. The intensity of photosynthesis was assessed by the content of photosynthetic pigments, and the biochemical analysis of tomato fruits included the determination of the concentration of nitrates, ascorbic acid, monosaccharides, and dry matter. It was found that long-range red radiation reduces the stress effect of blue led light, which is expressed in a lower concentration of anthocyanins in tomato leaves. Additional long-range red in the spectrum of LED R26 G81 R93 FR49 mmol/m² s increased the yield of tomato plants ‘T-34’ F1 by 60% compared to HPS, and by 16% compared to led irradiation without the use of additional long-range red (R26 G80 R94 FR10 mmol/m² s). The dry matter content in tomato fruits increased by 8-10%, while the number of fruits per plant increased by 42% compared to HPS and by 21% compared to led irradiation without the use of additional long - range red. The content of monosaccharides in tomato fruits ‘T-34’ F1 in the variant with the use of additional long-range red is 20% higher compared to HPS, and 2 times higher than this indicator compared to LED without the use of additional long-range red irradiation. The use of additional long-range red radiation improves the appearance and nutritional value of tomato fruits.

1. Introduction
It is known that plants perceive optical radiation using photoreceptors. One of these receptors is phytochrome, which has two interconvertible forms that absorb radiation in the red (RA) 660 nm and
far red (FRL) 730 nm spectral region. FRL is not a source of photosynthetic energy; however, it
affects the adaptation and development processes of plants. Depending on the spectral composition of
light, an equilibrium is established between these forms of phytochrome, which affects plant reactions
such as shadow avoidance syndrome, increased leaf area, regulation of leaf chlorophyll synthesis,
photosynthesis rates, and photosystem II electron transport. By changing the Raman / FRL ratio of
radiation, the morphological and biochemical parameters of the plant can be controlled to a certain
extent [1].

In contrast to the abundance of research on relatively young plants, detailed studies of the effects of
far red light at the fruiting stage of crops such as tomato (Solanum lycopersicum) are quite small. In
addition, it is important to understand how FRL affects the biochemical composition of tomato fruits,
which determines the taste and useful properties of tomatoes.

Recent studies have shown that additional FRL radiation added to the main radiation of the 400-
700nm photosynthetically active radiation range increases the growth of tomato fruits mainly by
increasing the distribution of dry weight on the fruit. Additional FRL significantly increased the
proportion of dry mass distributed to fruits during generative growth. FRL also significantly increased
the dry weight of the leaf, especially at the early stage of plant growth. Elongated internodes under
additional FRL led to a more open architecture of the plant, which allowed radiation to penetrate
deeper [2]. It is also known that additional DC increased the total dry weight of tomato plants at the
stage of vegetative growth, as well as the number of fruits per plant and the raw weight of fruits [3].

Experiments on tomato seedlings have shown that when the R:FR ratio decreases from 15 to 2, the
height of the tomato increases 2.4 times, the raw mass of plants increases by 23 %, the dry matter yield
increases by 30%, and the specific energy consumption decreases by 12% [4, 5]. It is also noted that
plants grown with additional FRL radiation had a lower content of chlorophyll per unit leaf area, with
a higher specific leaf area [6].

It has been found that additional FRL during cultivation improves post-harvest cold tolerance for
tomatoes harvested at both the green and red stages of maturation, and, therefore, may be a suitable
technique for extending the shelf life of tomatoes at sub-optimal temperatures. The researchers
hypothesized that DC illumination during cultivation probably protects the integrity of the MG tomato
membranes and thus ensures continuous lycopene synthesis [7].

Studies on soybean plants have shown that a low RA / FRL ratio significantly increased the total
biomass, leaf area, starch and sucrose content, chlorophyll content, net photosynthesis rate, and
quantum efficiency of photosystem II compared to the normal RA / FRL ratio at the same light level.
It was found that a low Raman / FRL ratio can increase the assimilation of photosynthetic CO2; at the
same light intensity, improving the photosynthetic efficiency of photosystems [8].

It is known that phytochrome is a fundamental component of the response of many plants to abiotic
stressors. Previous research has shown that there is a well-organized interaction between phytochrome
and abiotic stresses in plants. Thus, a decrease in RA / FRL contributed to the growth of tomato
seedlings in saline conditions. Under normal conditions, the growth of tomato seedlings was better at a
RA / FRL of 1.2, compared to a higher ratio of 7.4. However, under salinity conditions, a lower RA /
FRL of 0.8 provided tomato seedlings with greater salinity. The plant also accumulated more
photosynthetic pigments and showed increased photosynthetic efficiency [9]. In addition, it was found
that plants respond well to FRL light at the end of the day. Exposure to FRL light at the end of the day
under single-source lighting conditions can affect plant morphology and development in the same way
as adding FRL during the day. For growth chambers and phytotrons with a single light source, using
FRL lamps for 30-60 minutes during the day instead of continuous FRL lighting has an advantage and
can save some of the electricity [10]. The results showed that after long-range red light irradiation at
the end of the day, compared with the control, the height of the plant increased by 26.38%, the fresh
weight of the stem increased by 15%, and the dry mass was distributed more along the trunk. Thus, the
height of tomato plants can be adjusted by changing the intensity of the far red light at the end of the
day and at the same time save energy compared to continuous FRL irradiation [11].
Although mineral nutrients make up only about 8% of the dry matter of tomatoes, they are important factors that affect the taste and health of tomatoes. Using LEDs, you can optimize the quality of light to improve the quality of tomato fruits. A recent study focused on the effect of FRL radiation on the quality characteristics of tomato fruits, including physical and chemical properties, the quality of mineral nutrients, and the subsequent effect on the organoleptic properties of tomato fruits. Plants grown with the addition of Kr / FRL LEDs had a significantly higher fruit mass, dry matter ratio, but lower pH compared to plants grown under HPS lamps. It is noteworthy that RA LEDs increase the concentration of magnesium compared to HPS lamps. The inclusion of FRL light in a combination of Raman LEDs further increased the sodium concentration. Meanwhile, the irradiation of the FRL light does not have any effect on the nitrates, sulfates, phosphates and chloride in the fruit. This observation has not been previously reported, and such changes in the mineral composition of tomato fruits caused by FRL and RA light are phenomenal, given that an equal amount of fertilizer was applied in the production of tomatoes [12].

The use of additional FRL radiation added to the main radiation increases the total sugar content in tomato varieties "Komeett" F1 by 39% for HPS and by 17% when using led light with radiation maxima of 450, 640, 660 nm. The dry matter content in the fruit was at a similar level. This can be attributed to the high FRL content of radiation in the HPS spectrum. Lower nitrate content in tomato fruits was observed in combinations where plants were illuminated with both GPS and led lamps. Plants additionally illuminated with HPS and LED lamps had fruits with higher pulp juiciness, sweeter taste, and higher overall quality [13].

At the same time, other studies show that additional FRL irradiation with LEDs did not significantly affect the physicochemical or organoleptic properties of greenhouse tomatoes. Statistically significant physical and chemical differences (the amount of carotenoids, phenolic compounds, ascorbic acid content) were not noticeable for tasters, and tasters participating in blind testing could not distinguish tomatoes grown under different artificial lighting LED and HPS. However, vegetables grown outdoors were different from vegetables grown in a greenhouse, and many phytochemicals, such as carotenoids and avonols, were in higher concentrations in fruits grown outdoors [14, 15].

Such differences in the results of the study indicate the presence of variety-specific reactions of tomato plants to the spectral composition and radiation power, which requires further research. However, researchers note more positive effects of irradiation of tomatoes with FRL radiation.

The aim of the research is to determine the effect of far red light on the morphological and biochemical parameters of tomato plant fruits and to assess the state of the photosynthetic apparatus of plants by the composition of the main leaf pigments.

2. Methods and materials
The objects of the study were plants of a medium-ripened indeterminate hybrid of tomato 'T-34', selected by the company "Gavrish". Plants were grown under artificial irradiation with different spectral composition of the photosynthetically active radiation. Various combinations of LEDs were used in the irradiators: blue (Bl) with a maximum radiation of 445 nm, white (W) with a color temperature of 4000K, red (Rt) with a maximum radiation of 660 nm, and far red (FRt) with a maximum radiation of 730 nm. the total power consumption of each irradiator was 220 W (table 1). The Raman / FRL ratio in the experimental variants varied from 2 to 9 units with the same spectral composition in the range 400÷700 nm. In the control version, a high-pressure sodium lamp with a power of 400 W (HPS) was used. The distribution of the radiation intensity over the spectral regions is shown in table 1. measurements of the spectral composition and intensity of the photosynthetically active radiation were carried out using a TKA-Spectrum photometer. The irradiation time corresponded to a 16-hour light period. The irradiators were placed in different phytotrons with the same climate regime.
Table 1. Designations and spectral characteristics of irradiators.

| Irradiator  | Radiation intensity (μmol/m² s). Spectral regions (nm) |
|-------------|-------------------------------------------------------|
|             | B (400-500)  | G (500-600)  | R (600-700)  | FR (700-790) |
| LED W+R+FR  | 26          | 81          | 93          | 49          |
| LED W+R     | 26          | 80          | 94          | 10          |
| HPS         | 13          | 155         | 79          | 18          |

For growing tomato seedlings, we used cubes made of mineral wool from Grodan company with a size of 100x100x65 mm. Seedlings were grown under HPS 400 W sodium lamps at a headlight intensity of 250 mmol/M²C. The day/night air temperature was 23/19 °C with a relative humidity of 55-60%. Seedlings were transferred to phytocambers and dived on mats for 30 days after germination with the appearance of 5-6 real leaves, a well-developed root system and tied with a single flower brush. In each fotocamere grew two tomato plants. For better survival of plants, the temperature was maintained at 20 °C and humidity of 80-85% for 2-3 days among the clock. In the future, 21-23 °C during the day and 18 °C at night. The mats were saturated with a nutrient solution three times before the seedlings were placed on them. Immediately after placing the seedlings, watering was carried out 4 times with 80 ml per plant at intervals of 15 minutes, the last one was added with the fungicide Previcur Energy SL 840 0.15% concentration, then preventive treatment was carried out every three weeks. The plants were formed into a single stem with all side shoots removed.

Nutrient solutions for tomatoes were made on the basis of deionized water according to a well-known recipe. To control heating, ventilation, carbon dioxide enrichment, humidity, lighting, and recording of environmental conditions, a personal computer with installed specialized software developed for this laboratory stand was used.

For analysis, medium-tier tomato leaves (5th leaf from the top) were selected at the beginning of fruiting. Samples of plant leaves and fruits were dried in the dark for 2 months at a temperature of +18°C, and the proportion of their dry residue was determined. Leaf plates with removed petioles and large veins and samples of tomato fruits were selected for analysis.

The composition of water used for the preparation of the nutrient solution was determined using the NSAM No. 520-NPP/MS method using the mass spectral (Elan-6100 "Perkin Elmer" USA) and atomic emission (Optima-4300 DV "Perkin Elmer" USA) analysis method. The relative standard deviation for all elements did not exceed 0.2.

The intensity of photosynthesis was assessed by the content of pigments in tomato leaves, such as chlorophyll, a and b, carotenoids, and anthocyanins. Chlorophylls and carotenoids were extracted from the leaves, crushed and kept in 95% ethanol in a water bath at 50-70°C. The absorption density of a chlorophyll solution in ethanol at wavelengths of 440.5; 664 and 649 nm was measured using a Specord M-40 spectrophotometer in a 1 cm thick cuvette. Anthocyanins (An) were extracted from the leaves in a solution of water:ethanol (1:1) + HCl (1%). The absorption density of the anthocyanin solution was measured at a wavelength of 530 nm. The average chlorophyll index (CCI) in each leaf was determined at ten points using a portable Apogee MC-100 chlorophyll meter. For all measurements, the arithmetic mean and the mean square deviation were calculated.

Statistical processing of the obtained data and plotting are performed in Microsoft Office Excel 2010. The data is presented in the form of arithmetic mean and standard deviations.

3. Results and discussion

The content of the main pigments (chlorophyll a (Ca), chlorophyll b (Cb), and carotenoids) is an important indicator of the physiological state of plants. These indicators can be used to judge the intensity of photosynthesis, phase changes, and the presence of stress conditions. With an increased proportion of FRL in the lighting spectrum (LED W+R+FR option in table 2), a decrease in the total content of chlorophylls was observed as one of the symptoms of "shadow avoidance syndrome", but a sufficient percentage of red light in this spectrum prevented the appearance of obvious signs of this
syndrome (elongation, breakage of shoots). When lighting sodium lamps and with higher levels of DK against Sa / Cb was 2.6, and the LED W+R – 2.3, which suggests increased protective and adaptive response of tomato plants in this range of illumination, it also confirmed a high content of anthocyanins, derivatives of flavonoids, in comparison with other variants of experience. Anthocyanins are considered to be a protective filter of the cell against the destructive photodynamic action of light and UV radiation [16]. The strongest absorption maximum of anthocyanins is 265-280 nm and 510-560 nm. In the HPS spectrum, the blue band of radiation has a maximum at 460 nm, while the maxima of the blue band of LED radiation and the chlorophyll Soret band are almost identical (440-445 nm). The intensity of HPS radiation in the blue region is only 1.5-2 times less than the intensity of the radiation flux in this region in LED (table 1), while the efficiency of anthocyanin synthesis in the LED W+R sample is more than an order of magnitude higher than in other experimental variants. Taking into account the correlation of the anthocyanin content with the intensity of the blue band of LED radiation, it was assumed that the synthesis of anthocyanins initiates light that excites the transition to a new energy level in chlorophyll $S_0 \rightarrow S_2$ [17]. This effect of blue radiation is qualified as a stress factor [18]. However, DC radiation reduces this stressful effect, since the content of anthocyanins in the led W+K+AK lighting variant was significantly lower with a comparable content of chlorophylls and carotenoids. The absence of UV-A in the spectrum of LED and HPS (table 1) excludes the effect of UV radiation as a stress factor for tomatoes [19]. In normally developed leaves, carotenoids are 3-5 times less than chlorophylls, so we can judge the absence of significant stress and degradation of chlorophyll in the leaves of the studied tomato plants in all variants of the experiment.

### Table 2. Results of the photosynthetic activity analysis of tomato ‘T-34’ F₁ leaves

| Light spectrum combination (illuminator) | Chlorophyll ($C_a$) (mg / g) | Carotenoids ($C_b$) (mg / g) | Anthocyanins ($C_{AH}$) | Chlorophyll Content Index (CCI) | Dry matter content (%) |
|----------------------------------------|-------------------------------|-----------------------------|--------------------------|-------------------------------|------------------------|
| LED W+R+FR                             | 2.09                          | 0.81                        | 0.62                     | 34.45 ±5.3                   | 18.86                  |
| LED W+R                               | 2.43                          | 1.04                        | 0.71                     | 41.30 ±5.9                   | 14.95                  |
| HPS                                    | 2.78                          | 1.09                        | 0.75                     | 41.87 ±6.6                   | 14.91                  |

Despite the lower average index of chlorophyll in the plants of variant, the variant with the addition of far-red spectrum (LED W+R+FR) were observed relatively uniform distribution of chlorophyll index (CCI) on the tiers of the leaves of tomato plants (Fig.1) except for the top leaves that were used an excessive amount of K+DK, in addition over 9 sheet was located and the first inflorescence was active outflow of assimilates. The efficiency of photosynthesis of tomato plants for this variant of the experiment was higher, which is confirmed by the highest content of dry matter in the leaves.
The main indicators of productivity of tomato plants (yield, number of fruits, average fruit weight) of the control variant (using sodium lighting) were inferior to the variants of the experiment using LEDs (table 3). In the variant with added DC (LED W+R+FR), the most optimal ratio of these indicators and the percentage of dry matter in the fruits of the studied tomato plants was observed, in addition, the content of monosaccharides in them is 20% higher than in the control variant. The nitrate content in all variants of the experiment is below the maximum permissible values for tomato products produced in both open and protected ground conditions.

Table 3. Quality indicators of tomato ‘T-34’ F₁

| Light spectrum combination (illuminator) | Harvest, g | Number of fruits, pcs. | The average fruit weight, g | Dry matter, % | Monosugar, % | Ascorbic acid, mg% (or mg / 100 g) | Nitrates NO₃⁻, mg / kg |
|------------------------------------------|------------|------------------------|-----------------------------|--------------|--------------|-----------------------------------|---------------------|
| LED W+R+FR                               | 6192±96    | 128±6                  | 96.75±8.4                   | 5.52±0.05    | 2.57±0.03    | 24.64                             | 118.8±16            |
| LED W+R                                  | 5340±120   | 106±7                  | 100.74±19.4                 | 5.01±0.07    | 1.29±0.02    | 26.40                             | 138.0±29            |
| HPS                                      | 3874±111   | 90±5                   | 86.09±17.9                  | 5.12±0.035   | 2.14±0.04    | 26.40                             | 117.8±13            |

The content of ascorbic acid in the LED W+R+FR variant was slightly lower than in other variants of the experiment, however, taking into account all the advantages of this lighting option (in terms of photosynthetic activity and morphophysiological indicators), we recommend this spectrum for more successful cultivation of tomato plants ‘T-34’ F₁.

4. Conclusion
1. Additional FRL in the lighting spectrum (R26 G81 R93 R10) increased the total dry weight of tomato leaves by 26%, with a lower content of chlorophyll in the leaves, the efficiency of plant photosynthesis was higher than without the use of additional FRL. Additional FRL in the lighting spectrum reduces the stress effect of the blue LED band, since the anthocyanin content in this lighting option was significantly lower than without the use of additional FRL (R26 G80 R94 R10) with a comparable content of chlorophylls and carotenoids.
2. Studies have shown that additional FRL in the spectrum of led lighting R26 G81 R93 R49 increased the yield of tomato plants ‘T-34’ F₁ by 60% compared to HPS, and by 16% compared to
led irradiation without the use of additional FRL (R26 G80 R94 FR10). The dry matter content in tomato fruits increased by 8-10%, while the number of fruits per plant increased by 42% compared to the control variant (HPS) and by 21% compared to led irradiation without the use of additional FRL. The use of additional FRL improves the appearance and nutritional value of tomato fruits.

3. The content of monosaccharides in tomato fruits ‘T-34’ F1 in the variant with the use of additional FRL is 20% higher compared to HPS, and 2 times higher than this indicator compared to led irradiation without the use of additional FRL. The content of ascorbic acid when using additional FRL is slightly lower (7%) than in other variants of the experiment, and the content of nitrates is 16% less than when using led irradiators without FRL and approximately corresponds to the content of nitrates when growing under HPS. The results obtained suggest a positive effect of additional FRL on the content of monosaccharides and nitrates in the fruit of tomato ‘T-34’ F1.

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