Small-sized irradiation structures for intensive year-round cultivation of green vegetable crops

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Abstract. Full and healthy human nutrition is characterized by the presence of green vegetable crops in the diet, which are rich in vitamins and useful components for humans. The need for them is observed year-round and all-season. Therefore, green vegetable products must be grown not only using traditional industrial technologies, but also in small businesses and private households. The realization of technology is ubiquitous, year-round cultivation of leafy vegetable crops in an artificial environment is possible using small-sized forms of cultivation facilities – irradiation chambers and boxes, grow boxes, phytotrons, etc. In this case, the main technological operation is the necessary light mode for plants: with the spectrum necessary for plants development and growth, with the necessary intensity and mode of irradiation. The developed irradiation units (camera and box) allow growing green vegetables at any time of the year, in any territory allotted for this, in the quantity necessary for consumption, etc. These units allow automatically monitoring the parameters of the air environment and soil, and, if necessary, adjusting it to create a comfortable environment for plant development. Experimental studies and processing of the results allowed concluding that by varying the spectrum and intensity of light-emitting diodes in the developed structures of irradiation units depending on the growth phase of green vegetable crops, it is possible to obtain products of higher consumer and commercial quality, with the necessary biochemical composition and characteristics.

1. Introduction

Full balanced human diets cannot be imagined today without the year-round presence of green vegetable crops, which are valuable sources of vitamins, pectines, dietary fibers and other biologically active substances, including antioxidants. Eating fresh green vegetables is an effective way to correct and prevent damage of biological structures caused by oxidative stress.

To provide useful green products all year round, regardless of the climatic zones of residence and as many people as possible, it is necessary to grow these products not only using industrial technologies, but also in small-scale production, as well as private households and communal apartments.

The realization of technology of year-round cultivation of green vegetable crops is possible using small cultivation facilities – irradiation cameras, compact phytotron and vertical greenhouses, compact greenhouses, grow boxes and similar structures [1-3]. At the same time, the main regulated technological parameter of the artificial environment of growing plants in light-proof structures is the “correct” irradiation of cultivated plants with the spectrum, mode and intensity of radiation necessary for plants development and growth [4].
Light is necessary for the normal development of plants for three reasons. First, it is needed for the process of photosynthesis, in which CO₂ and water are combined in the presence of light to form carbohydrates – food for plants. Secondly, light regulates the appearance of plants, its constitution. Third, the relative duration of periods of light and darkness controls a number of natural physiological processes in plant development.

Intensive light allows increasing the yield, obtaining high-quality commercial products, significantly reducing the growing season. Varying the intensity of light (optical radiation) can coordinate the process of photosynthesis, and therefore the growth and development of plants.

Rest and periods of darkness for green plants also need, as well as light. Without six hours of darkness plans will dropping flowers, falling behind in development. The temperature difference between rest and wakefulness should not exceed 8 °C.

Each of the three main areas of the Photosynthetically active radiation (PhAR) (blue, green and red), taken separately, is not suitable for growing plants under artificial irradiation and isolated from the environment premises, and only radiation, formed in a certain ratio of energy across the spectrum, can ensure the cultivation of full-fledged plants [5-7].

Thus, the spectral composition of light, as well as its intensity and the change of light and dark phase, is a strong morphogenetic factor that regulates both growth and photosynthetic reactions in the life support system of the whole plant. At the same time, the following ratios of energy on the spectrum of PhAR in artificial radiation sources are recommended: 25-30% – in the blue region (380-490 nm), 20% – in the green (490-590 nm) and 50% – in the red region (600-700 nm). That is, for the predicted growth of plants and its normal development, as well as obtaining the necessary amount of plant products with the desired biochemical and taste characteristics, it is extremely important the optimization of the spectral composition of the optical radiation source [8-10].

Light mode is the fundamental of all the influencing factors in the creation of artificial environmental conditions (microclimate) in closed ground structures, as no other agrotechnical technique can replace it.

Small-sized designs of cultivation facilities with an opaque coating are used not only where there is a serious lack of solar radiation, for example, in the northern territories, but also in cases where small spaces are used, not equipped and not ensuring compliance with traditional greenhouse conditions of agrotechnological requirements for growing plants, and which are available in sufficient quantities in utility rooms, basements, garages, storage rooms, etc. Growing plants in this kind of facilities or installations, with the intensive use of electric lighting maximum allows to eliminate the influence of external factors, year-round cultivating plants in comfortable conditions for plants, and thus getting the most out of plants with high quality products.

The purpose of the study presented in the paper is to substantiate the structure of small-sized led irradiation chamber and box, as well as the analysis of studies on growing plants in an artificial environment with a limiting factor – light mode.

2. Materials and method

The rationale for the mode of additional lighting and irradiation of green vegetables. For green crops, including lettuce, on the basis of the analysis of sources of technical and technological information, the following algorithm of the light mode of additional illumination of plants was chosen for implementation [11-13].

Given the lack of natural light and small forms of structures for growing plants, the algorithm of the ratio of light phases will depend on the stage of ontogenesis.

After sowing seeds in the soil before the first shoots irradiation should be carried out only with red light. This contributes to the intensive growth and active growth of the above-ground part, and the rooting of the main root.

When bleached-out sprout has reached the surface of the land, there light-growth and photomorphogenetic reaction: the growth of hypocotyls or mesocotyl sharply suppressed, but at the same time increasing the growth of the epicotyl (first internode) and leaves. The ethylene content in the
hook area is reduced and the hook straightens. The plant turns green and goes to autotrophic type of nutrition. After the appearance of the first green leaf comes an important stage in the development of plants – the growth of the second and third leaves. Here it is necessary to remember that by susceptibility to light, all cultures show the greatest sensitivity to the action of solar radiation in the first period of vegetation (I and III stages of organogenesis – phase of 1-3 leaf). Therefore, violation of irradiation modes during these periods, inhibits growth processes and violates the consistency of physiological functions that define the morphogenetic processes. In that case, if the irradiation in this phase will be insufficient, in almost all cases, there is the death of the main sprout. Therefore, in the following days, the light mode is determined by mixing red (600-760 nm) and blue (430-480 nm) at their ratio R/B=3/1 (relative unit), as in this period, further intensive growth continues and the main task of this period is to increase the proportional height of the plant and the number of leaves on it. Mixing red and blue colors when the claimed ratio R/B=3/1 (relative unit) intensify growth of green mass and plants, however, allows eliminating the elongation and dwarfism of plants, poor tillering, and the presence of leaves with a small area.

At the beginning of full maturity, yellow light (565-590 nm) is added to these ranges, as at this stage of growing plants bloom and seed material is formed.

At the last stage, the stage of full maturity, plants are illuminated mainly blue-green-red spectrum in a ratio of 1/0, 5/0,5 (relative unit), which provides a complete laying of genetic material from the plant to the seed, if the cultivation is carried out in order to obtain seed. If the cultivation is made to obtain green mass, this stage is skipped.

The procedure in the sequential algorithm of operation of the respective optical radiation sources is laid in the program, which fulfills the microprocessor controls light regime. The operating time of optical radiation sources is 14-16 hours at the level of irradiance of at least 17 mol/m²/day. An additional condition for ensuring growth and obtaining a good harvest is the need for the device to maintain the temperature of the environment in the irradiation chamber within 20-25°C, as well as by temporary program to organize timely watering and full fertilization with fertilizers.

Justification of the design of small-sized irradiation chamber and box for growing plants. The main requirements for small-sized structures for the implementation of intensive light culture technology are as follows: installations should occupy as little space as possible and at the same time installations are placed in those areas of premises that people do not use every day or in which there is a minimum amount of time; installations should be technologically effective with maximum automation of agrotechnological processes; installations should consume a minimum of energy, which should be used with maximum efficiency in the main technological operations-additional lighting, watering, maintaining the temperature and humidity of the air and soil, etc.

Recommend to use the irradiation installations of the closed type with an opaque shell, such as – irradiation chambers, phytotron, boxes, shelving installation with cameras, irradiation boxes, in which the entire radiation flux generated by artificial light sources aimed at the plants.

A variant of a constructive solution of a small-form cultivation facility with a fully artificial growing medium and the main limiting factor - light mode is the structure of an irradiation unit (chamber) for growing green vegetable products without the use of natural light (figure 1, a) and the irradiation box (figure 1, b) [14-15].
Figure 1. Appearance: a-small-sized irradiation chamber for year-round cultivation of green vegetables; b-irradiation box. Inside the camera and visible on the shelves of the cassette and prickling out glasses, in which plants of leaf lettuce were grown and planted its seeds.

The developed units for growing plants under completely artificial environment establish and provide the ability to control variables regime of irradiation with specifically specified spectral ratio brightness light-emitting diodes with simultaneous volumetric and uniform surface distribution of optical radiation in the internal volume of the chamber and the box [16].

Structurally, both small-sized units (figure 1) for year-round cultivation of green vegetables consist of the block of microprocessor control and irradiation spaces (at the camera – boxes, and at the box – shelves). The control circuit is equipped with a power supply with an output voltage $U=12\,\text{V}$ and a power $P=250\,\text{W}$, assembled on the basis of Microchip PIC16F1937 microcontroller. As sources of optical radiation, it was selected a COB (Chip-on-Board) RGB led power 3W in number of 32 pieces in the irradiation chamber and 36 – in box, who gathered in the glow matrix line and placed evenly over the whole inner surface of the chamber arch, the ceiling and walls of the box. LEDs are connected in series through resistors in the light lines that make up the electrical circuit. In the end walls of the irradiation chamber and box, to ensure more efficient cooling of LEDs and maintain the necessary parameters of the microclimate, depending on the agricultural technology of crops, fans are mounted with adjustable supply of air flow by means of incoming control commands from the microprocessor unit.

In the process of growing plants, the air temperature was maintained at $+21...+22^\circ\text{C}$ and humidity 45 ... 55%, soil temperature $22...+24^\circ\text{C}$ with humidity at 50 ... 60%. Dosed automatic watering of plants with warm water was organized, and air mobility was carried out by the system of forced ventilation.

Substantiation of the schematic diagram of irradiation installations and study of the characteristics of led sources of optical radiation. As radiation sources have been taken for installation of COB (Chip-on-Board) RGB-led company CHANZON power of 3W each, gathered in a matrix line and placed evenly in each camera module and on each shelf of the box over the whole inner surface of the arch, the
ceiling and walls. LEDs in the matrix-tapes were connected in series through resistors in the light lines, which are placed around the perimeter of the vault of the chamber and the ceiling and walls of the box.

The main electro-optical characteristics chosen for the study of (RGB) LEDs are the following: 1) peak wavelength ($\lambda_{\text{peak}}$) at $I=350$ mA: red (R) - $\lambda_{\text{peak}} = 632$ nm; blue (G) $\lambda_{\text{peak}} = 520$ nm; green (B) $\lambda_{\text{peak}} = 465$ nm; 2) operating temperature range - 40°C/+100°C; 3) luminous flux: red (R) - 40-50 LM; blue (G) - 30-40 LM; green (B) - 70-80 LM.

To control the brightness when mixing the necessary colors in the radiation spectrum in the led irradiator, a control device is used, the principle of which is based on pulse width modulation (PWM). The advantages of such systems are determined to increase noise immunity, increased reliability, control accuracy, and ease of implementation of designs, etc.

The scheme of the control unit for individual processes and the irradiation chamber as a whole is shown in figure 2. It is implemented on the basis of the PIC16F1937 (DD1) microcontroller that is connected to the following key control elements: to gather information about environment settings – humidity sensors and soil temperature SHT10 (DD2) and air DHT11 (DD3); information obtaining – graphic LCD with LED backlight WG128x64 (DD4) with adjustable with the help of divider R2 contrast; for tuning unit – incremental encoder (BR1) with a clock button (SB1) EC11; for process control of additional lighting and ventilation through pulse width modulation (PWM) and field effect transistors with insulated gate IRL3705 (VT1-VT5). The entire circuit is powered by 220 V, via a switching power supply unit (PSU) with integrated voltage stabilizer IC7805 (DA1). DD1 clock source built-in, 32mhz frequency.

One of the criteria for selecting the microcontroller used was the presence of 5 CCP modules (CAPTURE/CMPARE/PWM), which are necessary for PWM operation. At this clock frequency of the microcontroller, PWM can operate at frequencies from 1.95 to 333.3 kHz, with a bit width from 10 to 6.6 bits. Based on the sufficiency and convenience, 8-bit bit rate and 125 kHz frequency were chosen. The duty cycle of each channel is set using an encoder, with the output of the setting value on the display. The program is written in a low-level assembly programming language and has more than 3500 commands, which is associated with the use of a graphical display.

Since the control device operates under the control of an 8-bit processor, it was decided to adjust the color ratio in the numerical version in the range from 0 to 255 units, where 255 corresponds to 100% of the power of the led (crystal), resulting in 16.5 million color combinations.

Before the start of experiments on growing lettuce plants, the modes of operation of led radiation sources were studied and taken for all modes of characteristics (see table 1 and figure 3).
Figure 2. Diagram of the process control unit in the irradiation chamber.
Table 1. Results of research and study of the characteristics of the optical radiation source of the led matrices of the irradiation chamber using the spectrocolorimeter “TKA-VD”.

| Mode (red-blue-green) | PhAR, 400-700 nm | spectrum/PPFD: |
|-----------------------|------------------|----------------|
|                       | Irradiance:      | blue 400-700nm | green 500-600nm | red 600-700nm | far red 700-790nm |
|                       | maximum at a wavelength, kW/m² | kW/m²  | mkmol/cm² | kW/m²  | mkmol/cm² | kW/m²  | mkmol/cm² | kW/m²  | mkmol/cm² |
| R-B-G (255-255-255) Figure 3A | 606 | 39.9 | 174.4 | 9.2 | 73.260 | 8.82 | 38.850 | 11.8 | 62.318 | 99.6 | 0.583 |
| R-B-G (255-0-0) Figure 3B | 582 | 15.3 | 179.4 | 494 | 1.874 | 745 | 3.475 | 14.1 | 74.02 | 5 | 254 | 1.541 |
| R-B-G (170-85-0) Figure 3C | 414 | 17.6 | 82.2 | 494 | 26.267 | 731 | 3.355 | 9.99 | 52.582 | 152 | 0.914 |
| R-B-G (85-170-0) Figure 3D | 2.9 | 1.6 | 79.5 | 485.0 | 2.9 | 1.6 | 79.5 | 485.0 | 2.9 | 1.6 | 79.5 | 485.0 |

![Diagram A](image1.png)

![Diagram B](image2.png)
Figure 3. Measurement of the intensity spectrum of the led matrix-types of irradiation chamber taken on the spectrocolorimeter TKA-VD/04, for modes (blue-red-green): A) to 255-255-255; B) – 255-0-0; C) – 170-85-0; D) – 85-170-0.

3. Research results and discussion

Study of the growth and development of plants of lettuce variety “Typhoon” in radiation structures. The choice of object of study was due to the importance of lettuce as plants with a high content of beneficial nutrients: in terms of the content of vitamin K, lettuce is an absolute leader among vegetables. In addition, it contains organic acids, a large amount of vitamin A, C, as well as E, PP, iron, phosphorus, iodine, copper, sodium, potassium, zinc.

Observations of the growth and development of plants and recording of the results were carried out throughout the period of cultivation (figure 4).

Figure 4. Dynamics of changes in the height of lettuce plants grown in the first and second boxes.

The results of the experiments allow us to say that there is a clear dependence of the development of lettuce varieties “Typhoon” and the quality of the harvest from the modes of irradiation.

Also, the studies were conducted, the results of which revealed that the determining indicators in assessing the yield should be considered the height of plants and the number of leaves collected from plants. Using the results of experimental studies, the mathematical processing of the results was carried out.
For mathematical optimization, the following operating parameters were chosen-irradiation mode (spectral composition of the source) with exposure. As sources of radiation used RGB-LEDs, power 3 W, when the ratio of the capacities R:B:G=255:255:255=0.77:1.12:1.1 (where 255 corresponds to the maximum power of the crystal; R,B,G – red, blue and green color emission LEDs). In all experiments the exposure (irradiation time) was 16 hours.

After processing the experimental data, it was found that:
1) the power of blue and green crystals on the height of the plant is influenced to a lesser extent;
2) power blue and green crystals on number of leaves plants lettuce have influence in a lesser extent.

Thus, we can say that the functional dependence is obtained, which reflects the relationship between the change in the height of the plant and the number of leaves per plant with varying spectral characteristics of LEDs over time.

The maximum accumulation of economically useful biomass is not always a consequence of the maximum photosynthesis of the green leaf, therefore, there is a need to determine the actual growth of new plant biomass, as a controlled parameter, depending on the spectral composition and intensity of irradiation in the process of plant development.

4. Conclusions
The conducted studies of the cultivation process of green vegetables allowed drawing the following conclusions:
1) Small-sized irradiation structures (chambers, boxes, etc.) for year-round cultivation of green crops are a necessity not only to receive all-season useful for human activity products, but also to grow it under climatic restrictions, when there is no possibility to cultivate it in natural growing conditions, as well as in the Arctic, Antarctica and long transport expeditions.
2) Varying the spectrum and intensity of light-emitting diodes in irradiation plants, depending on the growth phase of lettuce plants, it is possible to obtain products of higher consumer and commercial quality with the necessary biochemical composition and characteristics.

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