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Results of Experimental Research on Computerized Intellectual Monitoring Means of Effective Greenhouse Illumination

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Abstract

Industrial greenhouses are complex technological facilities where control and managing of the cultivation regimes affecting the efficiency of evapotranspiration and photosynthesis should be provided. The paper solves the relevant scientific and applied problem of evaluating and analyzing the metrological and functional characteristics of effective illumination sensors. The subject of the research is the metrological characteristics of means of metrical monitoring of effective illumination in the visible optical range for protected horticulture. The object of the study is the processes and factors which affect the metrological characteristics of the serial low-cost sensors of effective illumination in the visible optical range. The findings presented in this paper focus on solving the relevant scientific and applied problem of limited results of experiments on serial low-cost sensors of effective illumination in the visible optical range and their subsequent mathematical analysis to evaluate metrological characteristics. Promising areas of the research on the metrological provision of modern computerized systems for monitoring and controlling the effective illumination of industrial greenhouses are justified. The research results can be integrated into modern methods and means of computerized metrical monitoring and automatic control of technological regimes of greenhouse cultivation.

Keywords

Effective illumination, Greenhouse, Error, Conversion characteristics, Computerized meter.

Currently, a wide range of scientific and technical research is devoted to the development of computerized technologies for the study of production processes in the agricultural segment of the national economies (Polat, 2017; Wamelink et al., 2018). The relevance of the research in this subject area is due to the high rates of research intensity of modern protected horticulture. One of the most promising approaches to its optimizing, in terms of improving the quality of cultivated products and reducing energy consumption, is the creation and implementation of modern computerized measuring systems for monitoring and controlling the greenhouse microclimate parameters.

Industrial greenhouse complexes are engineering structures, where control and managing of microclimatic parameters affecting the efficiency of the processes of evapotranspiration and photosynthesis should be provided (Darabpour et al., 2018). This, in turn, determines the rates of production, volumes and quality of vegetable greenhouse produce.

Thus, in order to maintain the required indicators of the illumination regime for cultivating crops in greenhouse conditions, it is necessary to carry out online monitoring of the effective illumination in the visible optical range taking into account daily dynamics of natural light by means of measuring control with the required metrological characteristics. The total relative measurement error should not exceed ±10% (Both et al., 2015).

The need to develop and design systems for measuring control of effective illumination in the visible optical range in real time with their subsequent full-scale tests is substantiated by the fact that, currently, scientific literature provides limited research on results of the regression analysis of the illumination sensors conversion characteristics with a detailed analysis of their metrological parameters.

Based on this, the main purpose of the paper is to conduct studies on the evaluation and analysis of the metrological and functional characteristics of the serial sensors of effective illumination in the visible optical range. This will contribute to the development of scientific and applied bases for increasing the productivity of industrial greenhouses through the development and implementation of highly efficient methods and means of metrical monitoring and control modes of crops illumination.

The subject of the research is the metrological characteristics of means of metrical monitoring of effective illumination in the visible optical range for protected horticulture.

The object of the study is the processes and factors which affect the metrological characteristics of the serial low-cost sensors of effective illumination in the visible optical range.

The findings presented in this paper focus on solving the relevant scientific and applied problem of limited results of experiments on serial low-cost sensors of effective illumination in the visible optical range and their subsequent mathematical analysis to evaluate metrological characteristics. The research results can be integrated into modern methods and means of computerized metrical monitoring and automatic control of technological regimes of greenhouse cultivation.

Current research findings

The main approaches to the development and design of modern systems of local and remote monitoring of parameters of agricultural and technical facilities by means of modern sensor and microprocessor technologies using current research methods are presented in (Vu, 2011; Ahn et al., 2017; Changizian et al., 2017; Laktionov et al., 2017; Pash et al., 2017; Shirsath et al., 2017; Zade et al., 2017; Drapaca, 2018). For example, modern approaches to biological object modeling, such as mathematical modeling of engineering systems, in view of various destabilizing effects are presented in the paper (Drapaca, 2018); the main approaches to the environmental factors which are distributed in space and time, and affect the quality of technical systems are presented in the paper (Pash et al., 2017); the study (Changizian et al., 2017) focuses on the results of research on ensuring effective control of photoelectric signals in technical objects.

Having analyzed and logically generalized the existing results of the research on structural and algorithmic organization of such systems, it has been established that the subsystem of control and management of the technological regime of artificial illumination is an integral structural unit of these systems. The rate of photosynthesis and, consequently, the accumulation of plant biomass, depend on the amount of energy transformed into biochemical bonds. This fact is confirmed by the fundamental results of studies on biophysical and biotechnological principles of greenhouse artificial illumination, which are listed in Table 1.

The need to control the technological regimes of illuminating the greenhouse crops is also specified by regulatory documents (American Society of Agricultural and Biological Engineers, 2008; Food and Agriculture Organization of the United Nations, 2013; Both et al., 2015; Food and Agriculture Organization of the United Nations, 2017). The results of the analysis of *a priori* information about the existing requirements for the illumination regimes of protected horticulture are presented in Table 2.

Materials and methods

Components

Sensors

Having analyzed the existing studies on the development of illumination monitoring systems, we can state that integrated sensors based on photodiodes and photoresistors are most widely used (Boselin Prabhu et al., 2014; Arif and Abbas, 2015; Zhou and Duan, 2016; Li, 2017; Laktionov et al., 2018). In this paper, typical sensors based on a photodiode (GY-302 BH1750FVI) and a photoresistor (KY-018) have been selected for the research according to the following criteria: satisfactory technical characteristics specified by manufacturers; compatibility with the microprocessor platform Arduino Mega 2560, which is widely used in designing the monitoring systems for agricultural facility parameters (Putera et al., 2015; Laktionov et al., 2017; Maulana et al., 2018; Suganthi Jemila and Suja Priyadharsini, 2018); affordable price range. The main technical characteristics of the GY-302 BH1750FVI (Light intensity Sensor Module GY-30 BH1750FVI, 2018) and KY-018 (KY-018 Photoresistor Module, 2018) sensors are given in Table 3, the physical configuration of the sensors is shown in Figures 3 and 6.

Sample meter

As this functional unit, the Benetech GM1020 digital luxmeter with a USB interface and a rotating photo sensor is used when implementing the method for evaluating the metrological characteristics of the illumination sensors (Benetech Digital Lux Meter GM1020, 2018). The main technical characteristics of this luxmeter are shown in Table 4.

Source of artificial lighting

To implement the illumination unit, full-spectrum COB Cree CXA1304 (Cree® XLamp® CXA1304 LED, 2018) LEDs were used. The main technical characteristics of this model of LEDs are shown in Table 5, the physical configuration of the LEDs is presented in Figures 3 and 6. The result of a series of pulse measurements of LED parameters under 400 mA constant current and 9 V is also shown in Figure 1 (Cree® XLamp® CXA1304 LED, 2018). There are six discrete LEDs in the matrix under question. During the maximum efficiency operation mode (the electric current is 400 mA and the power is 3.6 W), the emission characteristics of a LED are presented in Table 6.

LED power control unit

This function module consists of step-down DC-DC converters to reduce voltage and limit current through a 12 V power line. This unit uses a XL4015E1-based converter (XLSEMI XL4015E1, 2018). Its specifications are presented in Table 7, the physical configuration is shown in Figure 3. As a result of previous laboratory tests, the need to equip this unit with an active cooling system to improve its technical and operational characteristics has also been established.

Microprocessor platform

The Arduino Mega 2560 board (Arduino Mega 2560, 2018), which is based on an ATmega2560 microchip with the frequency of 16 MHz, is used as a microprocessor module of the system under study. This board is selected according to the following criteria: the required number of analog and digital ports, the amount of flash memory (more than 64 kB, which corresponds to the size of the original sketch), the width of the analog-to-digital converter and the cost. The physical configuration of this function module is presented in Figure 3.

Switching unit

As a power load switching unit, a four-channel relay module SONGLE SRD-05VDC has been used (Songle Relay, 2018). This relay is controlled by the voltage of 5 V and is capable of switching the load with parameters up to 10 A–30 V DC voltage and 10 A–250 V AC voltage. The physical configuration of this functional unit is shown in Figure 3.

Real time clock module

This module is an integrated DS1302 assemblage, which is programmed to record the current time (Real Time Clock DS1302, 2018). In addition to the chip of a real-time clock, this module contains an I^{2}C EEPROM 24C32 chip. This functional unit is connected to the Arduino Mega microcontroller via a standardized I^{2}C interface. The physical configuration of the module is shown in Figure 3.

Temperature sensor

In this research, a DS18B20 digital temperature sensor (Maxim Integrated Products DS18B20, 2018) is used, which is connected to the Arduino microprocessor platform via a 1-Wire interface. The physical configuration of the sensor is shown in Figures 3 and 6. The main characteristics of this model are shown in Table 8.

The subsystem of greenhouse optimum temperature maintenance

This system is a heating element that has two power modes with directional air flow and a pipeline, which is a heating circuit. This technical implementation allows uniformly heating the entire greenhouse growing zone (see Figure 2). The power of the heating element is supplied from a source of alternating voltage of 220 V. The technical characteristics of the heating element are presented in Table 9.

Software

The approaches to the study of computerized means of metrical monitoring of the effective greenhouse illumination in the visible optical range, which are used

Table 1. The results of the analysis and logical synthesis of existing research findings on the influence of illumination parameters on cultivation efficiency.

Research subject	Obtained result	Name of the authors	Research year	Ref.
The study of the physical principles of density distribution of the photosynthetic photon flux by methods of numerical simulation and experimental tests	The method for calculating the density distribution of the photosynthetic photon flux in greenhouse conditions has been substantiated	Castellano, S., Santamaria, P. and Serio, F.	2016	Castellano et al. (2016)
The study of productivity and obtaining photosynthetic characteristics of heat-resistant and heat-sensitive *Lactuca sativa* lines, depending on the duration of LED lighting exposure	The effect of different periods of red and blue spectrum LED illumination on the growth regime and photosynthetic characteristics of heat-resistant and heat-sensitive *Lactuca sativa* in greenhouse conditions has been studied	He, J., Kong, S. M., Choong, T. W. and Qin, L.	2016	He et al. (2016)
Evaluation of the influence of illumination quality characteristics on the amount of phytochemicals accumulated in greenhouse vegetables	A critical review and analysis of the effect of illumination quality on the amount of phytochemicals accumulated in greenhouse vegetables has been conducted. Prospective research directions in the field of LED technology for greenhouse illumination systems has been established	Zhong, H. B., Qi Ch.Ya. and Wen, K. L.	2015	Zhong et al. (2015)
Evaluation of the effect of red and blue LED illumination on improving the growth and content of bioactive compounds in Acyanic and Cyanic *Ocimum basilicum L. Microgreens*	It has been found that LED lighting in the blue and red regions of the spectrum has significant potential for improving growth parameters in Acyanic and Cyanic *Ocimum basilicum L. Microgreens*	Lobiuc, A., Vasilache, V., Pintilie, O., Stoleru, T., Burducea, M., Oroian, M. and Zamfirache, M.	2017	Lobiuc et al. (2017)
The effect of short-term red region illumination on the growth of greenhouse crops	The effect of short-term red region illumination at wavelengths from 638 to 665 nm on the quality of crops has experimentally been evaluated	Brazaitytė, A., Sakalauskiene, S., Viršile, A., Jankauskienė, J., Samuolienė, G., Sirtautas, R., Vaštakaitė, V., Miliauskienė, J., Duchovskis, P., Novičkovas, A. and Dabašinskas, L.	2016	Brazaitytė et al. (2016)
Comparative analysis of various illumination systems for horticultural production of crops	The calculations have been carried out followed by critical analysis of various illumination systems for horticultural enterprises from the point of view of energy saving	Garcia-Caparros, P., Chica, R. M., Almansa, E. M., Rull, A., Rivas, L. A., García-Buendía, A., Barbero, F. J. and Lao, M. T.	2017	Garcia-Caparros et al. (2017)

Analysis of the current state and recent advances in the field of gardening involving LED technology	Analysis and synthesis of dependencies of various anatomical, morphological, physiological, photosynthetic and metabolic parameters on the characteristics of LED illumination	Bantis, F., Smirnakou, S., Ouzounis, T., Koukounaras, A., Ntagkas, N. and Radoglou, K.	2018	Bantis et al. (2018)
Improving the efficiency of crop production involving LED technology	It has been proved that precise control of the light power depending on environmental parameters or certain physiological parameters, as well as the energy efficiency of crop production facilities, can be optimized by adjusting the parameters of LEDs	Gómez, C. and Izzo, K. G.	2018	Gómez and Izzo (2018)
Quantitative evaluation of changes in growth, metabolism, yield and composition of flour in wheat, depending on the spectral composition and intensity of LED illumination	It has been proved that LEDs are an effective tool for experimental cultivation of wheat, and they also allow optimizing growth conditions, metabolic processes, yield parameters and product quality	Monostori, I., Heilmann, M., Kocsy, G., Rakszegi, M., Ahres, M., Altenbach, S. B., Szalai, G., Pál, M., Toldi, D., Simon-Sarkadi, L., Harnos, N., Galiba, G. and Darko, E.	2018	Monostori et al. (2018)
The influence of the spectral composition of white LEDs on the growth of Spinach (*Spinacia oleracea*)	The results showed that different methods of illumination affect Spinach growth parameters differently	Burattini, C., Mattoni, B. and Bisegna, F.	2017	Burattini et al. (2017)
Solar radiation distribution inside a greenhouse prototypal with photovoltaic mobile plant and effects on flower growth	The patterns of distribution of solar radiation, the dynamics of temperature and humidity, as well as the intensity of illumination and the resulting indicators of floristic production have been obtained	Colantoni, A., Monarca, D., Marucci, A., Cecchini, M., Zambon, I., Di Battista, F., Maccario, D., Saporito, M. G. and Beruto, M.	2018	Colantoni et al. (2018)
Quantitative evaluation of the effect of various types of light sources on the parameters of pepper seedling growth	The effect of the intensity and spectral composition of various sources of artificial light on the qualitative and quantitative characteristics of pepper seedlings has been analyzed	Demirsoy, M., Balkaya, A. and Kandemir, D.	2018	Demirsoy et al. (2018)
The effect of long-lasting LED illumination of the red and blue regions of the spectrum on the anatomy of the leaves and the photosynthetic efficiency of ornamental plants	Leaf anatomy, stomatal traits and conductance, leaf hydraulic conductance, and photosynthetic efficiency were investigated in ornamental plants after eight weeks under LED light	Zheng, L. and Van Labeke, M.	2017	Zheng and Van Labeke (2017)
The study of the effect of continuous illumination of the red, blue and green LEDs on the reduction of nitrate content and enhancement of phytochemical concentrations	The possibility of round-the-clock continuous use of red and blue LEDs in combination with green light to reduce nitrate content and improve the quality of the salad has been established	Bian, Z., Cheng, R., Yang, Q., Wang, J. and Lu, C.	2016	Bian et al. (2016)

Table 2. Regulated information about the illumination regimes under protected horticulture conditions.

Regulated information	Name of the authors or organizations	Research year	Ref.
The requirements for locations of measuring, frequency and accuracy of metrical control of effective illumination in greenhouse conditions are regulated: at canopy level, in center of growing area; preferably continuous, but not least hourly; total relative error should not exceed ± 10%	Both, A. J., Benjamin, L., Franklin, J., Holroyd, G., Incoll, L. D., Lefsrud, M. G. and Pitkin, G.	2015	Both et al. (2015)
The optimal light regimes for growing crops in greenhouse conditions have been established: for tomatoes – from 10,000 to 15,000 lx; for pepper – about 5,500 lx during 18 hr	Food and Agriculture Organization of the United Nations	2017	Food and Agriculture Organization of the United Nations (2017)
It is stated that effective illumination is a mandatory parameter for regulating the carbon dioxide content in the crop growing area, as well as for controlling the temperature regime for growing greenhouse crops	American Society of Agricultural and Biological Engineers; Food and Agriculture Organization of the United Nations	2008; 2013	American Society of Agricultural and Biological Engineers (2008), Food and Agriculture Organization of the United Nations (2013)

in this research, are based on modern achievements in the theory of experiment planning, the theory of errors and the concept of uncertainty, the theory of physical modeling, and experimental methods of laboratory testing of a prototype measuring system.

To implement the main stages of aggregating and processing the results of observations of the effective greenhouse illumination in the visible optical range, the following modern software have been used:

- the software for the microprocessor subsystem has been developed and tested by means of Arduino IDE;
- the database of experimental studies has been accumulated by means of MS Excel and LuxLab; and
- regression analysis of the conversion characteristics of illumination sensors and evaluation of measurement errors have been performed by means of Mathcad.

Table 3. Technical characteristics of illumination sensors under testing.

Integrated sensor GY-302 BH1750FVI based on photodiode	KY-018 module based on photoresistor
It has a direct digital output; it is insensitive to background light; spectral response is close to visual sensitivity; supply voltage ranges from 3 to 5 V; working range of measurements is from 0 to 10^5 lx; I^2C connection interface	Built on the basis of the VT83N1 photoresistor type, which relates to sensors of a parametric type and is included in the voltage divider circuit; it allows measuring in the working range from 10 to 10^4 lx with a relative error of no more than ±10%

Table 4. Basic technical specifications of the Benetech GM1020 luxmeter.

Specification, unit	The value specified by the manufacturer
Range of illumination measuring, lx	From 0 to $2{\cdot}10^5$
Illumination measurement error, %	±3 (to 10^4 lx); ±4 (above 10^4 lx)
Operating temperature range, °C	From 0 to 40°C
Measurement speed, units·sec^{-1}	2
Additional functionality	USB interface; specialized software; built-in temperature meter

Research methodology

The method of standard devices has been chosen as the basic methodology for carrying out the research on evaluation of the metrological characteristics of measuring channels of effective illumination. This method is one of the most common and thoroughly studied methods of metrological verification and certification of metrical instruments of various physical and chemical quantities. The generalized block diagram of the setup for evaluating the metrological characteristics of the meters under study is shown in Figure 3. The algorithm for conducting laboratory tests is shown in Figure 4. The number of iterations during the research is equal to the number of control points for metrological certification of measuring instruments, namely 14 (Laktionov et al., 2017). The inquiry period of the measuring channels is 1 second, which meets the requirements. The distance from the light source to the surface of sensitive elements of the system is 0.1 m. The measurement conditions are as follows: the temperature is 20 ± 0.5°C, the relative humidity is 70%.

Laboratory setup

The laboratory setup of an automated greenhouse has been designed and constructed in the laboratory of information-measuring systems of the Department of Electronic Engineering in the SHEE “Donetsk National Technical University”.

Taking into account the basic principles of the theory of physical modeling, the designed laboratory setup meets the conditions of geometric similarity to real objects. The constant of the model-nature linear similarity is equal to:

$$k_l = \frac{h_{real}}{h_{model}} = \frac{a_{real}}{a_{model}} = \frac{b_{real}}{b_{model}} = 65, \tag{1}$$

Table 5. Technical Specifications of COB Cree CXA1304 LEDs.

Specification, unit	The value specified by the manufacturer
Power supply, V	From 9 to 10.5
Maximum power, W	9
Color temperature, K	3,000
Color rendering, CRI	From 93 to 95
Brightness, lm	From 330 to 366
Beam angle, °	115
Operating temperature, °C	From –40 to 85

Table 6. Emission characteristics of a LED under operation mode of 3.6 W.

Units	0.1 m above the surface	0.2 m above the surface	0.3 m above the surface
PAR, μmol·m^{-2}·s^{-1}	170	51	24.5
Illumination, lx	10,400	3,010	1,450
Power, W·m^{-2}	34.8	10.5	5

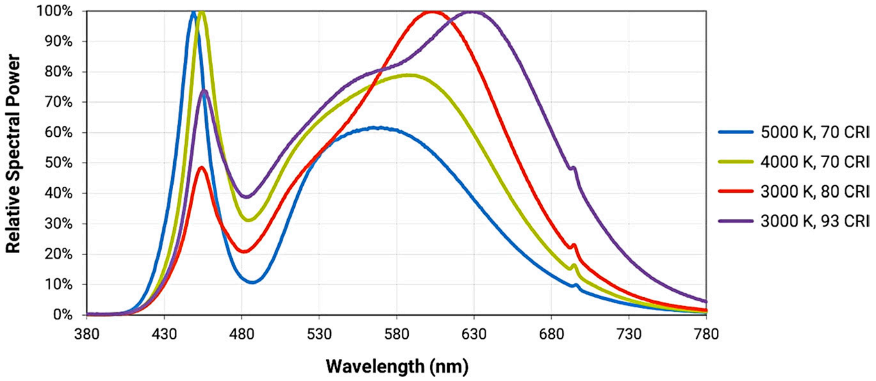

Figure 1: Spectral characteristics of COB Cree CXA1304 LEDs [41].

where k_l – linear similarity constant; h_{real}, a_{real}, b_{real} – height, length, and width of the standard all-year greenhouse, correspondingly; h_{model}, a_{model}, b_{model} – height, length, and width of the designed model of the automated greenhouse, correspondingly.

The physical configuration of the laboratory sample of the greenhouse is shown in Figure 5. The physical configuration of the setup for recording the conversion characteristics of the illumination sensors under testing is presented in Figure 6. The setup is equipped with the following technological systems: drip irrigation; ventilation; artificial lighting; air heating and moistening.

The laboratory tests of the greenhouse model allowed us to establish that it meets the mandatory condition of referring the processes in the model and real greenhouses to the same class of phenomena.

Research findings

Research results on the measuring channel of effective illumination on the basis of GY-302 photodiode of BH1750FVI module

To determine the conversion characteristics and the value of the main measurement error, experimental studies of the measuring channel of effective illumination at ambient temperature (20 ± 0.5)°C have been carried out. To exclude transients in the measuring channel of effective illumination (E_v, lx), measurements have been carried out during 120 sec. The illumination value has been measured by the standard Benetech GM1020 luxmeter (Benetech Digital Lux Meter GM1020, 2018). The value change during 100 sec is shown in Figure 7. When analyzing the experimental

Table 7. Technical specifications of XL4015E1-based DC-DC converters.

Parameter, units	The value specified by the manufacturer
Voltage input, V	From 8 to 36
Voltage output, V	From 1.25 to 32
Current output, A	5
Power output, W	75
Frequency, kHz	180
Efficiency, %	95
Operating temperature, °C	From –40 to +85

Table 8. Technical specifications of the DS18B20 sensor.

Parameter, units	The value specified by the manufacturer
Power supply voltage, V	From 3.5 to 5.5
Operating temperature range, °C	From –55 to 125
Relative error of temperature measurement, %	±0.5
Conversion time, ms	750

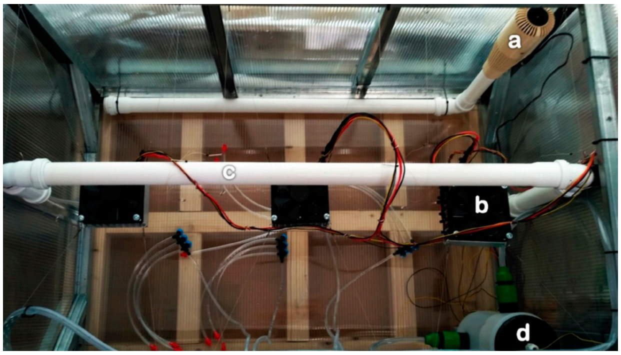

Figure 2: Photo of the technical implementation of the laboratory greenhouse heating system (**a** – heating subsystem; **b** – artificial lighting subsystem; **c** – air humidification subsystem; and **d** – drip irrigation subsystem).

data, the transient stage is not shown; measurements are taken during the first 20 sec. The E_v measurement has been performed in the range from 4,470 to 96,850 lx, which corresponds to E_e illumination in terms of the energy system (Vovna et al., 2018) from 15 to 325 W·m^{-2}. Figure 7 shows the graphs of the illumination for the three measurement series: 4,470, 44,700, and 89,400 lx, which correspond to the values E_e: 15, 150, and 300 W·m^{-2}, respectively. The values of illumination (see Figure 7) are used to evaluate the metrological characteristics of the measuring channel of effective illumination, based on the GY-302 module of the BH1750FVI photodiode (Light intensity Sensor Module GY-30 BH1750FVI, 2018).

Figures 8, 9 and 10 show the results of the illumination changes: 4,470, 44,700, and 89,400 lx, respectively. These values are measured by GY-302 BH1750FVI illumination sensor and Benetech GM1020 luxmeter.

Table 9. Technical specifications of the heating element of the greenhouse heating system.

Parameter, unit.	Mode A	Mode A
Heating element power, W	165	330
Output air temperature, °C	40±5	55±6
Productivity, m^3·sec^{-1}	3·10^{-3}	6.3·10^{-3}
Energy efficiency of the heating element, kW·h^{-1}	0.17	0.33

When analyzing the obtained dependences, it has been found out that the results of illumination measuring for the GY-302 BH1750FVI sensor contain both random and systematic components of the error. To reduce the value of the random component of the illumination measurement error, the results of $\overline{E}_{v\,\mathrm{ref}}$ and $\overline{E}_{v\,\mathrm{meas}}$ observations (Matula et al., 2016; Weisstein, 2018) have been averaged:

$$\overline{E}_{v\,\mathrm{ref}} = \frac{1}{n}\times\sum_{i=1}^{n} E_{v\,\mathrm{ref}\,i};\quad \overline{E}_{v\,\mathrm{meas}} = \frac{1}{n}\times\sum_{i=1}^{n} E_{v\,\mathrm{meas}\,i}, \tag{2}$$

where E_v ref $_i$, lx and E_v meas $_i$, lx – observation results obtained by means of the standard Benetech GM1020 luxmeter and the GY-302 BH1750FVI illumination sensor under investigation.

To eliminate the systematic error, we have measured the illumination of the GY-302 BH1750FVI sensor under study and the standard Benetech GM1020 luxmeter in the range from 4,470 to 96,850 lx, which corresponds to E_e illumination from 15 to 325 W·m^{-2}. The results of the research are presented in Figure 11, where the illumination measurement results obtained by GY-302 BH-1750FVI sensor and standard values obtained by Benetech GM1020 luxmeter have been compared in one coordinate system. In Figure 11, *a* and *b* are the nominal and real characteristics when comparing the measurement results of GY-302 BH1750FVI sensor with those of the standard Benetech GM1020 luxmeter.

When analyzing the results of measuring the illumination with GY-302 BH1750FVI sensor and a standard Benetech GM1020 luxmeter, it has been found that there is a systematic error component in the GY-302 BH1750FVI sensor results. This component is multiplicative in nature. To estimate its value, the relative error in illumination measuring has been calculated (Matula et al., 2016; Weisstein, 2018):

$$\delta_{Ev} = \frac{\overline{E}_{v\,\mathrm{ref}} - \overline{E}_{v\,\mathrm{meas}}}{\overline{E}_{v\,\mathrm{ref}}}\cdot 100, \tag{3}$$

where $\overline{E}_{v\,\mathrm{ref}}$, lx and $\overline{E}_{v\,\mathrm{meas}}$, lx – averaged illumination values measured by the Benetech GM1020 luxmeter and the GY-302 BH1750FVI sensor.

The change in the value of the relative error in illumination measuring of the GY-302 BH1750FVI sensor due to its measured value is shown in Figure 12.

When analyzing the dependence of the change in the relative error in illumination measuring on its measured value (see Figure 12), it has been found that in the initial part of the GY-302 BH1750FVI sensor conversion characteristics in the range of illumi-

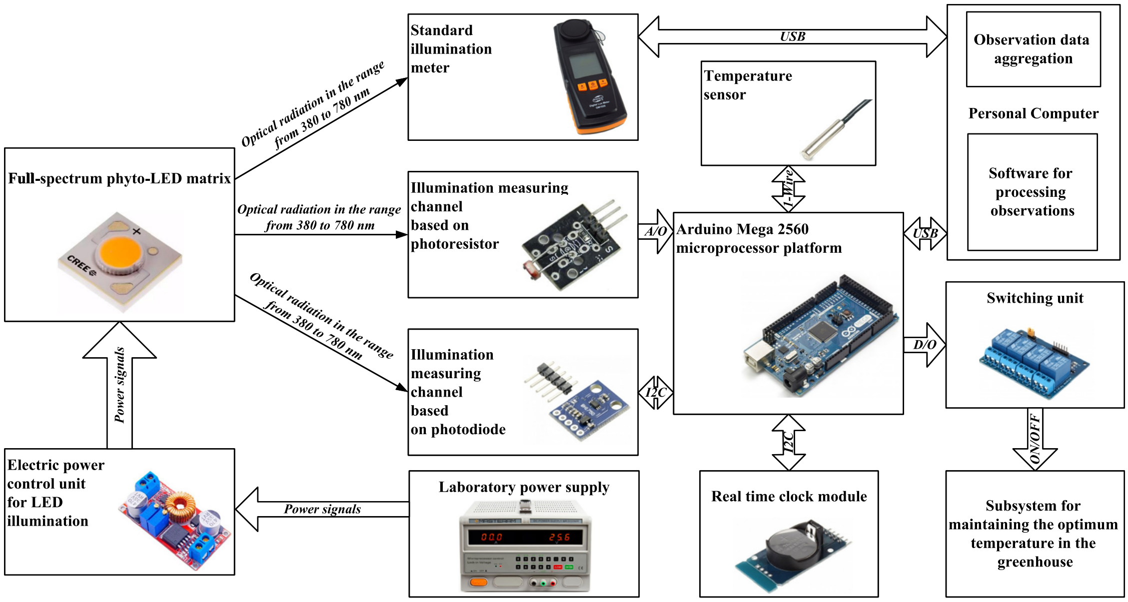

Figure 3: Block diagram of the implementation of the method for evaluating the metrological characteristics of illumination sensors.

nation measurement from 4,470 to 29,800 lx, the error is from $\delta_{Ev\ min} = -7.8\%$ to $\delta_{Ev\ max} = -18.8\%$. When increasing the value of the measured illumination from 29,800 to 96,850 lx, the value of the relative measurement error ranges from –11.9 to –13.8%. Moreover, in the specified range, the relative error is oscillating in vicinity of $\delta_{Ev\ system} = -12.7\%$. This is the value of the systematic error of illumination measuring by the GY-302 BH1750FVI sensor. To eliminate the systematic component of the illumination measurement error, taking into account its multiplicative nature, a linear calibration equation has been used:

$$E_{v\ \text{calibr}} = k \cdot E_{v\ \text{real}}, \qquad (4)$$

where $E_{v\ \text{real}}$, lx – the measured illumination value of the GY-302 BH1750FVI sensor; $E_{v\ \text{calibr}}$, lx – the illumination value after calibration; k – the calibration coefficient, the value of which is 0.889; this value has been established experimentally while studying the GY-302 BH1750FVI sensor.

To assess the effectiveness of applying the linear calibration Equation (4) to the GY-302 BH1750FVI sensor, the illumination measurement results (see Figure 13) obtained by the GY-302 BH1750FVI sensor during its calibration and those of the Benetech GM1020 luxmeter have been compared graphically.

Having analyzed the graphical dependence (see Figure 13), we have found that the linear calibration Equation (4) almost completely eliminates the systematic component of the measurement error of the GY-302 BH1750FVI illumination sensor. For the quantitative evaluation of the reduction in the value of the systematic error during illumination measuring by means of the calibration Equation (4), the change in the relative error of illumination measuring calculated by the Equation (3) due to its measured value has been established (see Figure 14).

A comparative analysis of the dependence of the change in the relative illumination measurement error of the GY-302 BH1750FVI sensor on its measured value (see Figure 14) has shown that by using the calibration Equation (4), it has become possible to reduce the value of the systematic illumination measurement error by 127 times from $\delta_{Ev\ system} = 12.7\%$ to $\delta_{Rv\ system} = 0.1\%$ in the range from 29,800 to 96,850 lx. When using the calibration equation in the initial part of the GY-302 BH1750FVI sensor conversion characteristics, the value of the error is reduced by 3.5 times from $\delta_{Ev\ max} = 18.8\%$ to $\delta_{Ev\ max\ calibr} = 5.4\%$ in the measurement range from 4,470 to 29,800 lx. Having conducted studies involving the developed recommendations, we will be able to improve the metrological characteristics of the effective illumination meter by using the GY-302 BH1750FVI sensor and its calibration equation, which will allow measuring in the range from 4,470 to 29,800 lx with the relative error of not more than 5.4%. In the range from 29,800 to 96,850 lx it will not be more than 1.0%.

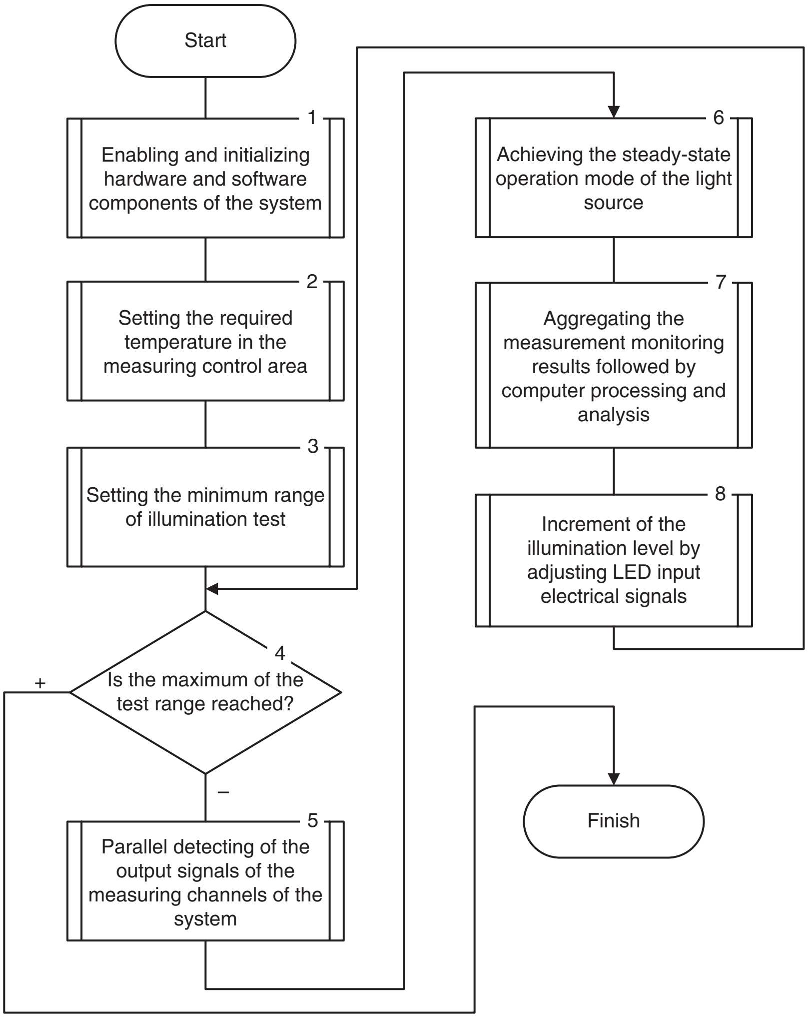

Figure 4: Algorithm for conducting laboratory tests of the system under study.

Figure 5: Photo of the laboratory computerized greenhouse.

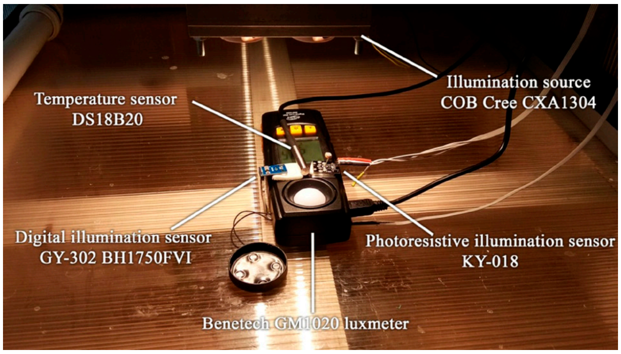

Figure 6: Physical configuration of the setup for recording the conversion characteristics of the illumination sensors under testing.

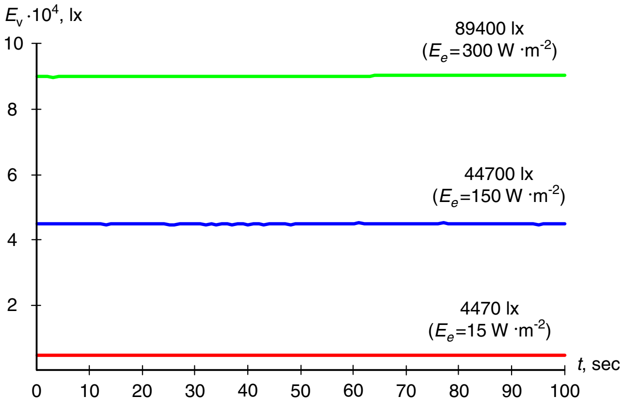

Figure 7: Illumination change measured by means of standard Benetech GM1020 luxmeter.

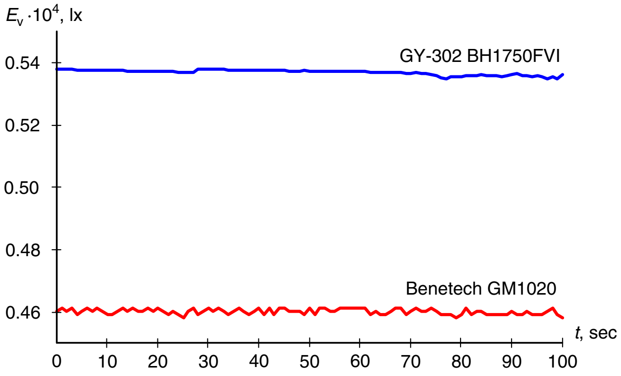

Figure 8: Illumination measurement results for 4,470 lx (15 W·m^{-2}).

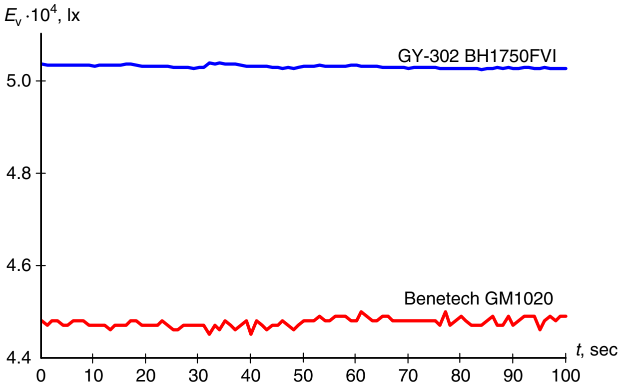

Figure 9: Illumination measurement results for 44,700 lx (150 W·m^{-2}).

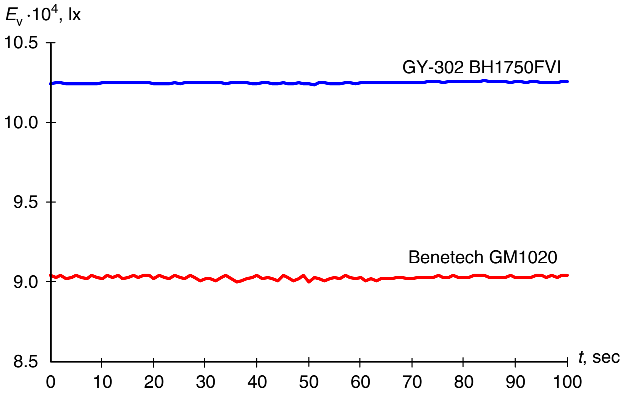

Figure 10: Illumination measurement results for 89,400 lx (300 W·m^{-2}).

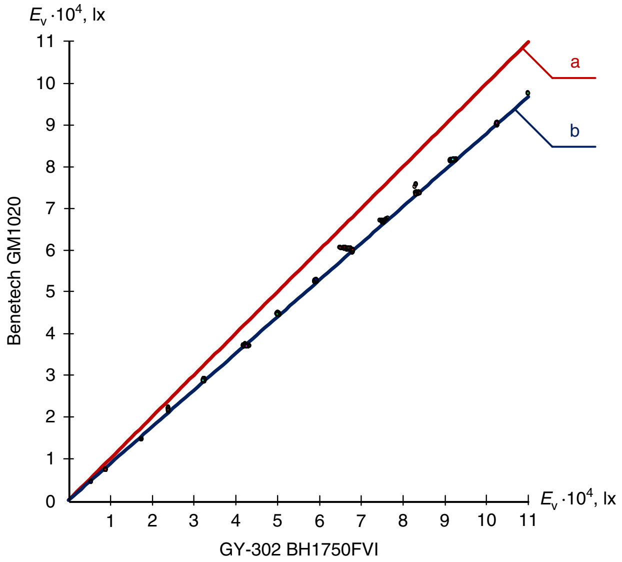

Figure 11: Graphic comparison of the illumination measurement results obtained by GY-302 BH1750FVI sensor with those of the standard luxmeter Benetech GM1020.

Research findings of the measuring channel of effective illumination, designed on the basis of KY-018 module

Having analyzed the technical characteristics of VT83N1 photoresistor of KY-018 module, we have found that by using this photoresistor the developed measuring channel of effective illumination will allow measurements in the working range from 10 to 10^4 lx with a relative error of no more than ±10%. Experimen-

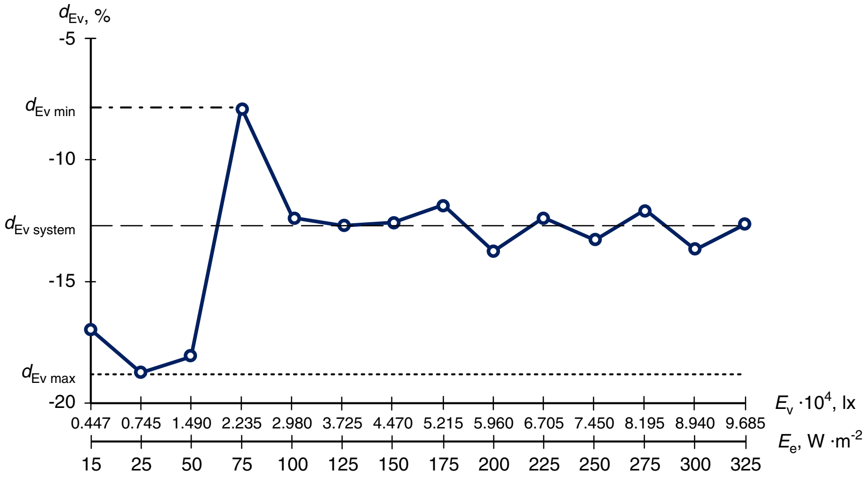

Figure 12: The change in the relative error of illumination measurement of the GY-302 BH1750FVI sensor due to its measured value.

tal studies of the measuring channel of effective illumination based on VT83N1 photoresistor of KY-018 module (KY-018 Photoresistor Module, 2018) have been performed at an ambient temperature of (20±0.5)°C. To check the metrological characteristics of the measuring channel, experimental studies have been carried out in the range of illumination measuring from 4,470 to 96,850 lx. The change in VT83N1 photoresistor resistance due to illumination in the indicated range is shown in Figure 15. Benetech GM1020 luxmeter has been used as a standard illumination measuring tool.

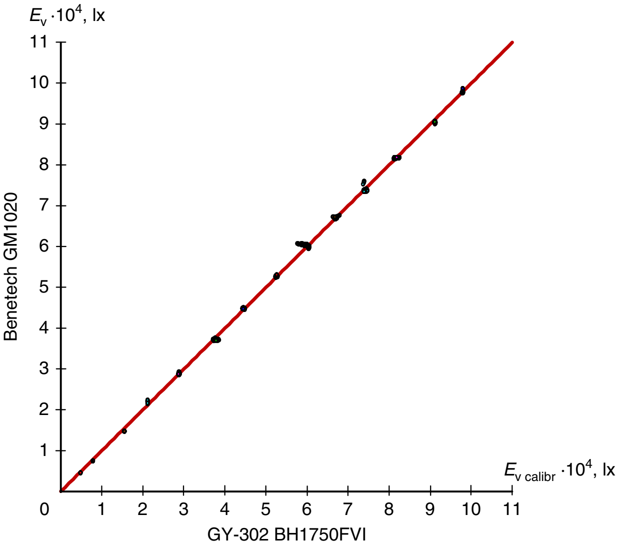

Figure 13: Graphic comparison of the illumination measurement results obtained by the GY-302 BH1750FVI sensor with those of the standard luxmeter of the Benetech GM1020 type by means of the linear calibration equation.

Having analyzed the results of experimental studies (see Figure 15), it has been established that it is potentially possible to make measurements of the illumination with VT83N1 photoresistor of the KY-018 module up to 30,000 lx. When illumination increases by more than 30,000 lx, the change in resistance of VT83N1 photoresistor of KY-018 module becomes almost indistinguishable and is oscillating in vicinity of 330 Ohm. For a qualitative evaluation of the error value in the range from 10 to 30,000 lx, the change in resistance of VT83N1 photoresistor of KY-018 module due to the illumination has been approximated by the equation:

$$R = R_0 \cdot \left(\exp\left(-\alpha_R \times E_v\right) + \beta_R\right), \tag{5}$$

where R – Ohm is the change in resistance of VT83N1 photoresistor of KY-018 module; R_0 – Ohm is the resistance of VT83N1 photoresistor taking into account the conversion characteristic form (β_R), the values of which are determined experimentally with the minimum illumination of the photoresistor and make up $R_0 = 528$ Ohm and $\beta_R = 0.682$; α_R, lx^{-1} is the damping decrement of the conversion characteristic, the value of which is determined upon approximation and is $\alpha_R = 22^{1}0^{-5}$ lx^{-1}.

Approximated conversion characteristics of VT83N1 photoresistor of KY-018 module due to illumination changes up to 30,000 lx and the results of experimental studies are shown in Figure 16. In the indicated illumination range, the relative error of approximation of the conversion characteristics by the Equation (5) due to illumination changes to 30,000 lx does not exceed 1.5%, which fully meets the require-

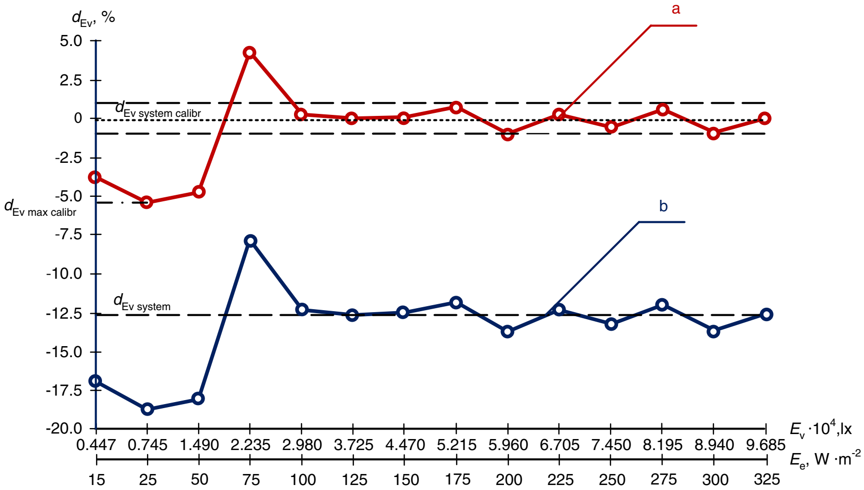

Figure 14: The change in the relative error of the GY-302 BH1750FVI sensor from its measured value before (b) and after using the calibration equation (a).

ments for the development of the measuring channel of effective illumination for industrial applications.

To quantify the real measurement range of VT83N1 photoresistor of KY-018 module, the illumination measurement results (see Figure 17) obtained by means of VT83N1 photoresistor of KY-018 module during its calibration and those of the standard Benetech GM1020 luxmeter have been graphically compared.

Having analyzed the characteristics (see Figure 17), it has been found that the results of illumination measurements by means of VT83N1 photoresistor and those of the standard Benetech GM1020 luxmeter correlate with each other up to 20,000 lx. With an increase of illumination from 20,000 to 30,000 lx, there is a significant increase in measurement error. For a quantitative evaluation of the metrological characteristics of the measuring channel of effective illumination, built on the basis of VT83N1 photoresistor (KY-018 Photoresistor Module, 2018), the relative error of illumination measuring is calculated by means of the Equation (3) due to its measured value. This dependence is shown in Figure 18.

When analyzing the dependence of the change in the relative illumination measurement error by VT83N1 photoresistor of KY-018 module on its measured value (see Figure 18), it was found that in the measurement range from 10 to 10,000 lx, which is regulated by the technical characteristics of VT83N1 photoresistor of KY-018 module (KY-018 Photoresistor Module, 2018), the value of the basic error does not exceed ±1.5%. This result is 6.7 times less than the value of the relative measurement error specified in the technical characteristics of VT83N1 photoresistor of KY-018 module, which is not more than ±10%.

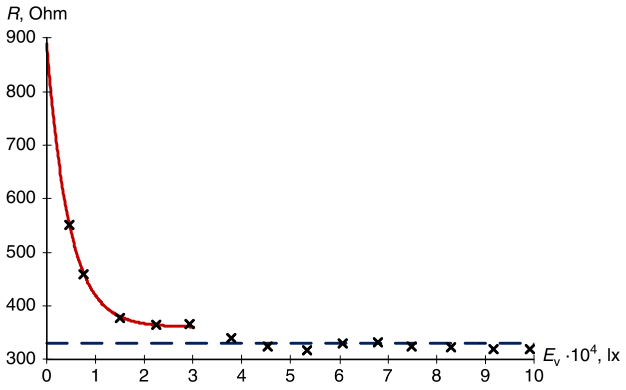

Figure 15: Resistance change of KY-018 VT83N1 module due to illumination.

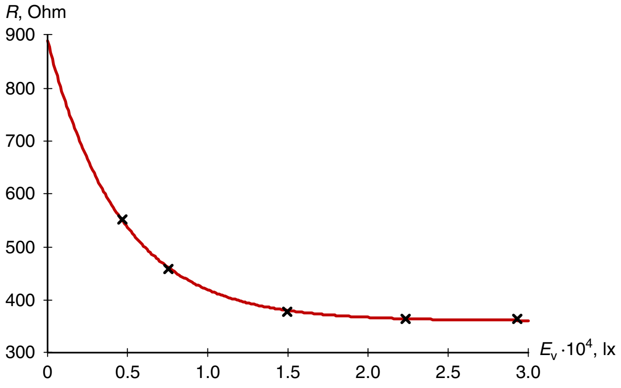

Figure 16: Conversion characteristics of KY-018 module due to illumination change to 30,000 lx.

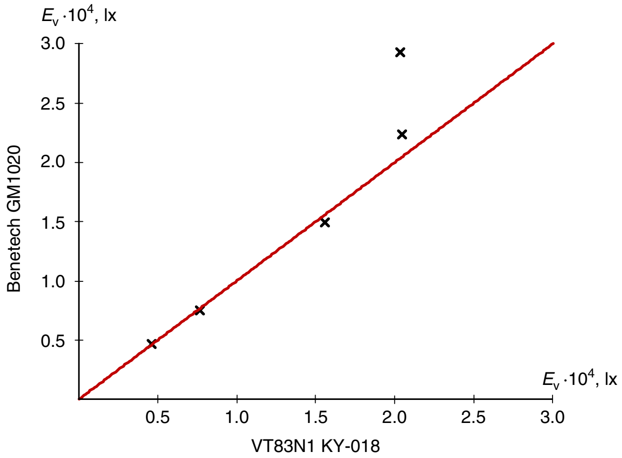

Figure 17: Graphic comparison of the illumination measurement results obtained by VT83N1 photoresistor of KY-018 module with those of the standard Benetech GM1020 luxmeter.

When extending the range of illumination measuring of VT83N1 photoresistor to 22,000 lx, the value of the relative error increases to ±10%, and with an increase to 30,000 lx it exceeds ±30%. Experimental studies of VT83N1 photoresistor of KY-018 module allow us to establish the real measurement range from 10 to 22,000 lx, in which the relative measurement error does not exceed ±10%.

Promising research areas

The main promising areas for future research on the metrological provision of modern computerized means of metrical monitoring and controlling the effective illumination of industrial greenhouse complexes are:

- evaluating the dynamic component of the total error and the efficiency parameter of measuring the effective illumination in the visible optical range in the conditions of protected cultivation;
- establishing the patterns of influence of the temperature dynamics of the cultivation area on the metrological characteristics of computerized means of effective illumination measuring;
- extrapolating the results of experimental tests of illumination sensors on real protected horticulture facilities;
- optimizing the structural-algorithmic organization of a computerized information-measuring system for monitoring and controlling effective illumination under greenhouse conditions; and
- substantiating the scientific and practical foundations of the influence of the intensity and spectral composition of the artificial lighting system on the qualitative and quantitative growth indicators of greenhouse crops.

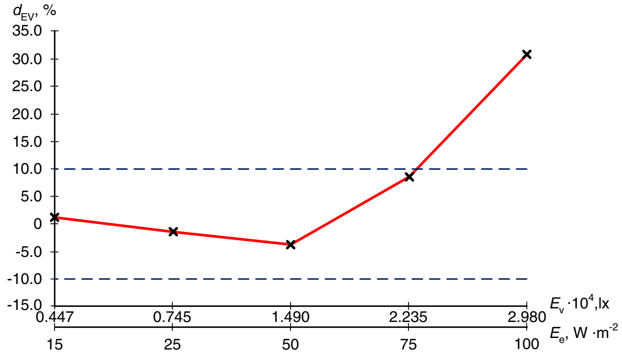

Figure 18: The change in the relative illumination measurement error by means of VT83N1 photoresistor of KY-018 module due to its measured value.

Discussion

As a result of the research, a relevant scientific and applied problem has been solved regarding the evaluation and analysis of metrological and functional characteristics of serial sensors of effective illumination in the visible optical range. This made it possible to substantiate the scientific and practical bases for improving the effectiveness of the systems for metrical monitoring and controlling the illumination of crops.

The results of theoretical and experimental studies can be used as the basis for the development of agrotechnical methods of increasing the pace, volume and quality of cultivated products under protected cultivation conditions.

Conclusions

The main results of the paper are:

- Current scientific findings on the influence of illumination parameters on the efficiency of growing greenhouse crops have been critically analyzed and logically generalized.
- Scientific and applied approaches have been justified and the means for obtaining the conversion and evaluation characteristics of metrological specifications of the serial low-cost

sensors of the effective illumination of the greenhouse cultivation area have been technically implemented.

- A linear calibration equation for the effective illumination measuring channel has been established based on the GY-302 BH1750FVI sensor; its use in the measuring channel reduces the basic relative error of the illumination measurement by 127 times from $\delta_{Ev\ system} = 12.7\%$ to $\delta_{Ev\ system\ calibr} = 0.1\%$ in the range from 29,800 to 96,850 lx and by 3.5 times from $\delta_{Ev\ max} = 18.8\%$ to $\delta_{Ev\ max\ calibr} = 5.4\%$ in the range from 4,470 to 29,800 lx.
- The real measurement range of VT83N1 photoresistor of KY-018 module is established – from 10 to 22,000 lx, where the relative measurement error does not exceed ±10%, in comparison with the regulated range from 10 to 10,000 lx specified in the technical characteristics, with the same value of error.
- Promising directions for future research on the metrological provision of modern computerized means of metrical monitoring and controlling effective illumination of industrial greenhouse complexes are justified.

Notations

Nomenclature

k_l	Linear similarity constant
h_{real}	Height of the standard all-year greenhouse
a_{real}	Length of the standard all-year greenhouse
b_{real}	Width of the standard all-year greenhouse
h_{model}	Height of the designed model of the automated greenhouse
a_{model}	Length of the designed model of the automated greenhouse
b_{model}	Width of the designed model of the automated greenhouse
E_v	Effective illumination
E_c	Illumination in terms of the energy system
$\overline{E}_{v\ ref}$	Result measurement of the standard Benetech GM1020 luxmeter
$\overline{E}_{v\ means}$	Result measurement of the GY-302 BH1750FVI illumination sensor under investigation
$E_{v\ ref\ i}$	Results observations of the standard Benetech GM1020 luxmeter
$E_{v\ meas\ i}$	Result observations of the GY-302 BH1750FVI illumination sensor under investigation
δ_{Ev}	Relative error in illumination measuring
$E_{v\ calibr}$	Illumination value after calibration
k	Calibration coefficient
$E_{v\ real}$	Measured illumination value of the GY-302 BH1750FVI sensor
$\delta_{Ev\ system}$	Systematic illumination measurement error
$\delta_{Ev\ system\ calibr}$	Systematic illumination measurement error after calibration
R	Photoresistor resistance
R_c	Resistance of VT83N1 photoresistor taking into account the conversion characteristic.

Greek Symbols

β_R	Conversion characteristic form
α_R	Damping decrement of the conversion characteristic

Abbreviations

AC	Alternating Current
CRI	Colour Rendering Index
DC	Direct Current
LED	Light Emitting Diode
PAR	Parabolic Aluminized Reflector
SHEE	State Higher Educational Establishment
USB	Universal Serial Bus

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