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Evaluation of Metrological Characteristics of a Computerized Conductivity Meter of Irrigation Solution Based on the Uncertainty Theory

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ABSTRACT

There is a gap in the research on the metrological characteristics of computerized conductivity meters of industrial greenhouses. To make up for this gap, this paper explores these characteristics of modern computerized conductivity meters for irrigation solution, based on uncertainty theory, instrumental analysis of liquid media, theory of probability and mathematical statistics, etc. The author designed a conductivity meter for irrigation solution based on an analog conductivity sensor for Arduino, and measured output voltage and solution temperature. Based on the measured results, both the basic uncertainties (noise properties of electronic components) and additional uncertainties (solution temperature dynamics) of the computerized tool were evaluated. The results show that the designed conductivity meter has a basic relative uncertainty within ±0.61 %; the relative additional uncertainty could be improved from 10.5 to 3.21 % through piecewise linear approximation of the measured conductivity; the total relative critical uncertainty of conductivity measurement was not more than ±3.82 %. The research findings lay the basis for high-quality online monitoring of irrigation solution when growing greenhouse flora.

1. INTRODUCTION

Nowadays, successful development of the agro-industrial complex in a market economy allows providing state food security, providing the population with high-quality products of domestic production, forming an export potential and a positive image of the state as a producer and exporter of high-quality agricultural products and derivatives. Technological and economic efficiency of cultivation of vegetable crops in industrial greenhouse complexes is determined by the level of their digitalization and automation [1, 2]. In turn, a mandatory procedure for automating technological processes of growing introduced flora is obtaining measurement information on the main parameters of the greenhouse microclimate [3, 4]. One of the most informative and at the same time regulated for compulsory measurement control of microclimate parameters of greenhouses is electrical conductivity of solution [5, 6], since one of the determining factors for increasing yields is optimal adding of nutrients into the solution [7].

At the present stage of development of science and technology, a wide spectrum of research is devoted to solving the problem of automating and digitizing the processes of growing greenhouse crops, the obligatory functional component of which is obtaining measurement information on electrical conductivity of solution [8-10].

The scientific article [6] substantiates the need for continuous instrumental measurements of electrical conductivity of irrigation solution with aggregation of observation results on the mean value and mean square deviation of the results, as well as the location of measurements. In the regulatory documents [11, 12], the allowable ranges for changing electrical conductivity of irrigation solution are justified depending on the type of crops grown and their growing season: for tomatoes – from 2.0 to 4.0 $mS \cdot cm^{-1}$, for cucumbers – from 2.0 to 2.5 $mS \cdot cm^{-1}$.

Research articles [5, 13] present the substantiation of scientific and practical foundations of designing monitoring systems and assessing the quality of irrigation water in greenhouse conditions. Scientific papers [14-18] present the main provisions on creating systems for monitoring parameters of physical environments using budget Arduino microprocessor platforms. Advanced methods of evaluating and analyzing metrological and functional characteristics of sensors used as sensitive elements while designing computerized measurement systems for non-destructive testing of physical environment parameters are substantiated and experimentally proved in the research articles [19-22]. Technical documentation [23] gives a detailed description of the method for determining conversion characteristics of analog sensors of electrical conductivity of liquid media.

Having generalized the existing research results on the design and metrological provision of modern computerized information measurement systems for conductivity of liquid media, we found that most authors focus on the relevance and research intensiveness of problems in this subject area.

Analysis the above-mentioned research articles and regulatory documentation proved that issues of statistical analysis of metrological characteristics of computerized conductivity meters of industrial greenhouses have not been sufficiently investigated.

The purpose of the article is to carry out experimental studies with subsequent statistical analysis of metrological characteristics of modern computerized meters of irrigation solution electrical conductivity. This research will allow us to formulate scientific and applied fundamentals of optimization of developing, designing and implementing high-precision methods and tools for monitoring and managing nutrient dosing regimens for different types and periods of vegetation.

The research subject is evaluation of the main (noise properties of electronic components) and additional (solution temperature dynamics) uncertainties of computerized tools for measuring electrical conductivity of irrigation solution. The object of the research is non-stationary processes and destabilizing factors that have a negative impact on measurement accuracy of electrical conductivity. The obtained research results can be used to substantiate the structural-algorithmic organizations of computerized systems for monitoring parameters of irrigation solution to optimize technological processes of growing greenhouse crops.

Section 2 describes the used research methods and tools, Section 3 explains all scientific and practical findings, Section 4 explains conclusions from the present work and suggestions for future investigations.

2. METHODOLOGY

2.1 Hardware components

A serial analog conductivity measurement sensor for Arduino by DFRobot was chosen as a sensitive element of the conductivity information measurement system [23]. This type of sensor has a built-in signal converter that meets the requirements of hardware and software compatibility with the budget microprocessor platform Arduino Uno. A microprocessor-based temperature measurement module based on the DS18B20 sensor and buffer solutions for sensor calibration are supplied with the sensor. The physical configuration of the sensor with indication of its geometric dimensions is shown in Figure 1, and the connection diagram is shown in Figure 2 [23]. The unit of aggregation and initial digital processing of the results of experimental observations is designed using the Arduino Uno board with the DS1302 real-time clock module and SD expansion cards.

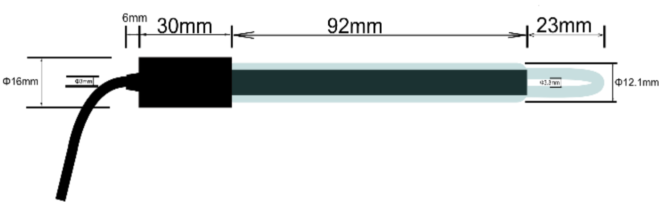


Figure 1. Physical configuration and geometric dimensions

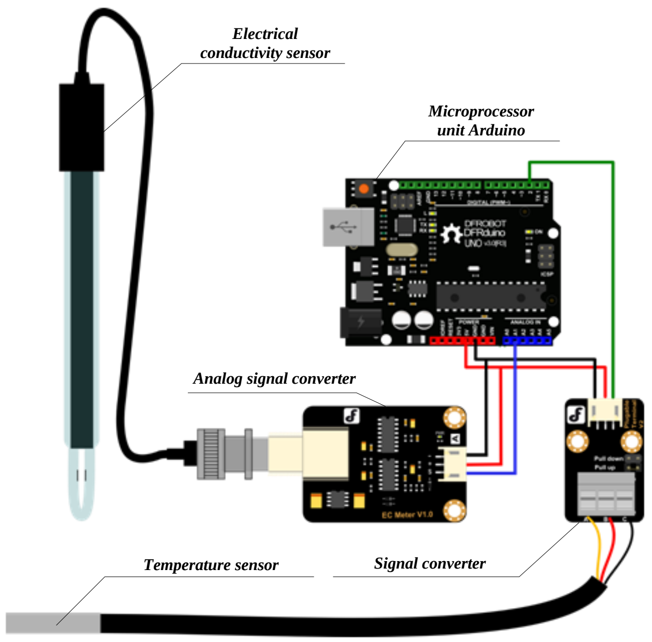


Figure 2. Connection diagram of the sensors

The main specification data of the sensor are presented in Table 1.

Table 1. Specification data of the analog conductivity sensor for Arduino by DFRobot

No	Parameter	Bogey value
1	Supply voltage	+5.0 V
2	Measurement range	from 1.0 to 20.0 mS·cm^{-1}
3	Operating temperature range	from 5.0 to 40.0 °C
4	Relative error	±10.0 %
5	Connection interface	3-pin SMD

Setup and maintenance of temperature points in the operating range from 5 to 35 °C to take the sensor temperature conversion was performed using a standardized thermostat with the operating range from 0 to 80 °C with temperature control resolution of 1.0±0.2 °C.

2.2 Software

In the research of the conductivity meter, certified software was used. The algorithm for using the software is shown in Figure 3.

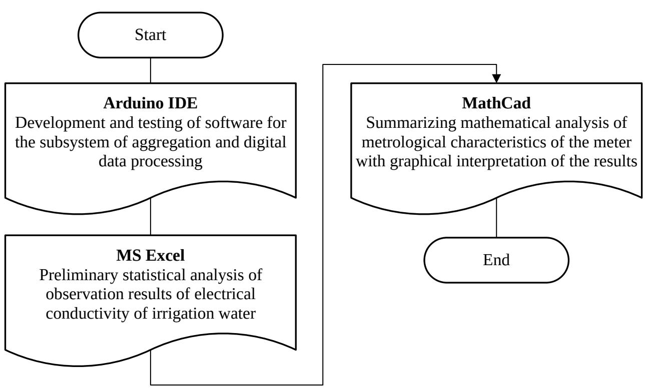


Figure 3. Algorithm for using the software

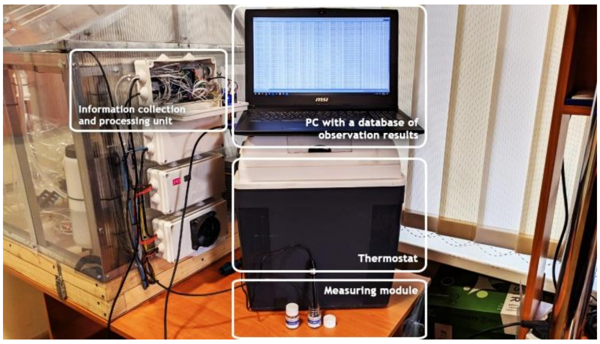
2.3 Experiment technique

The main research results were obtained by using: analysis and design of architectural and algorithmic system organizations; the uncertainty theory; methods of instrumental analysis of liquid media; the theory of probability and mathematical statistics; experiment planning methods; computer analysis of measurement results.

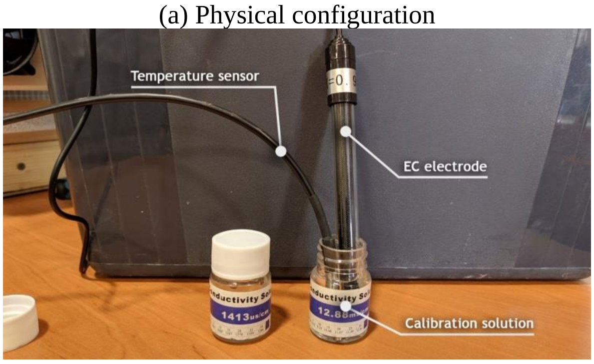
The conducted preliminary research [24, 25], a priori information about the research subject and object [23], and taking into account the condition of minimizing the random component of measurement uncertainty allowed us to establish that three series of measurements should be carried out with identical methods, tools and conditions of experimental tests.

The adopted method of obtaining the metrological characteristics of the conductivity meter is a method of comparison with the control gauge. The time interval for polling the conductivity meter within one observation cycle (at fixed conductivity and temperature) is 5 minutes; the number of points within the specified period is 100. The experiments were performed at nominal values of conductivity of calibration solutions: EC_{min}(T=25 °C)=1.413mS·cm^{-1} and EC_{min}(T=25 °C)=12.88mS·cm^{-1}.

The temperature range of the testis from 5 to 35 °C with a measurement interval of 5.0±0.2 °C. The physical configuration of the test stand for studying the metrological characteristics of the conductivity meter of irrigation solution is shown in Figure 4.



(a) Physical configuration



(b) Measuring part

Figure 4. Photo of the test stand for calibration of the conductivity meter

2.4 Algorithm for quantifying measurement uncertainty

The proposed method for evaluating the metrological characteristics of the designed computerized conductivity meter is based on processing the results of combined measurement with repeated observations. The measured values are output voltage of the conductivity sensor (*Uout*) and the solution temperature (*T*).

The purpose of the experiment was to determine the empirical dependence of the electrical conductivity *EC*=*f*(*Uout*, *T*) in an analytical form, which can be used in the software component of the information measurement system of electrical conductivity in greenhouse conditions. The test was also aimed at evaluating dependence of the components of the measurement uncertainty of electrical conductivity (*EC*) on the noise component of the sensor output voltage (*Uout*) and the destabilizing factor of temperature (*T*).

The method of quantifying parameters of the accuracy of the designed measurement system involved calculating the following indicators [26, 27].

Expected values of the meter output voltages ($\overline{Uout_i}$) were calculated by Eq. (1) for each series of experiments at $EC = \text{const}$ and $T = \text{const}$:

$$\overline{Uout_i} = \frac{1}{N} \cdot \sum_{j=1}^{N} Uout_{i,j}, \tag{1}$$

where, $Uout_{i,j}$ are the results of *j* observations of the sensor output voltages in each of the *i* series, V; *N* is the number of observations in each series.

The arithmetic mean ($\overline{\overline{Uout}}$) of the expected output voltages of the meter ($\overline{Uout_i}$) was calculated by Eq. (2). This estimate was taken as the best for the measured value (*Uout*) at $EC = \text{const}$ and $T = \text{const}$:

$$\overline{\overline{Uout}} = \frac{1}{K} \cdot \sum_{i=1}^{K} \overline{Uout_i}, \tag{2}$$

where, K is the number of groups of observations obtained under the condition of traceability of measurements.

Intra-group dispersions $\left(D_{Uout_i}\right)$ for each series were calculated by Eq. (3) at $EC = \text{const}$ and $T = \text{const}$:

$$D_{Uout_i} = \frac{1}{N-1} \cdot \sum_{j=1}^{N} \left(Uout_{i,j} - \overline{Uout_i} \right)^2. \tag{3}$$

Dispersion $\left(D_{\overline{Uout}}\right)$ of the expected values of the meter output voltage was calculated by Eq. (4) at $EC = \text{const}$ and $T = \text{const}$:

$$D_{\overline{Uout}} = \frac{1}{K-1} \cdot \sum_{j=1}^{K} \left(\overline{Uout_i} - \overline{\overline{Uout}} \right)^2. \tag{4}$$

The hypothesis of the significance of the effect of intergroup dispersion with respect to the intra-group component was tested on the basis of *F*-distribution criterion.

To do this, on the basis of experimental data, the value of the Fisher criterion (F_{ex}) was calculated by Eq. (5):

$$F_{ex} = \frac{S_I^2}{S_{II}^2} = \frac{\frac{N}{K-1} \sum_{i=1}^{K} \left(\overline{Uout_i} - \overline{\overline{Uout}} \right)^2}{\frac{1}{K(N-1)} \sum_{i=1}^{K} \sum_{j=1}^{N} \left(Uout_{i,j} - \overline{\overline{Uout}} \right)^2}, \tag{5}$$

where, S_I and S_{II} are independent estimates of the random distribution of observation results.

Then the condition was checked by Eq. (6):

$$F_{ex} < F_p, \quad (6)$$

where, F_p is the critical value of the Fisher criterion at confidence coefficient P.

The total random uncertainty of conductivity measurement was calculated. If the condition (6) is fulfilled, the existence of intergroup dispersion is refuted and the total mean square deviation of the observation results of the meter output voltage (σ_U) is calculated by Eq. (7):

$$\sigma_U = \sqrt{\frac{(K-1)\cdot S_I^2 + K\cdot(N-1)\cdot S_{II}^2}{K\cdot N\cdot(K\cdot N-1)}}. \quad (7)$$

If the condition (6) is not fulfilled, then the existence of intergroup dispersion is accepted and the total mean square deviation of the observation results of the meter output voltage (σ_U) is calculated by Eq. (8):

$$\sigma_U = \sqrt{\frac{1}{K\cdot(K-1)}\sum_{i=1}^{K}\left(\overline{Uout_i} - \overline{\overline{Uout}}\right)^2}. \quad (8)$$

An estimate of the relative basic random uncertainty of measurement of the meter output signal ($\delta_{EC\,U}$) was made by Eq. (9):

$$\delta_{EC\,U} = \frac{\sigma_U}{\overline{\overline{Uout}}}\cdot 100\%. \quad (9)$$

The critical value of the main relative measurement uncertainty of electrical conductivity, as the maximum value of the series ($\delta_{EC\ U\ max}$).

Methods of numerical regression analysis were used to identify the conversion response of the meter *EC*=*f*(*Uout*, *T*). This characteristic was established as a result of processing compatible measurements of the parameters (*Uout*) and (*T*) at different temperatures in the range from 5 to 35 °C and the values of electrical conductivity of calibration solutions: $EC(T = 25°C)$=1.413 $\mathrm{mScm^{-1}}_{min}$ and $EC(T = 25°C)$=12.88 $\mathrm{mScm^{-1}}_{max}$.

The relative values of additional uncertainty of conductivity measurement were estimated by Eq. (10) in terms of destabilizing effects of temperature ($\delta_{EC\ T}$) in the range from 5 to 35 °C with a measurement interval of 5 °C:

$$\delta_{EC\,T} = \frac{EC(T=25°C) - EC(T_z)}{EC(T=25°C)}\cdot 100\%. \quad (10)$$

where, $EC(T = 25\ °C)$ is the value of electrical conductivity at the nominal solution temperature (25 °C), $\mathrm{mS\cdot cm^{-1}}$; $EC(T_z)$ is the value of electrical conductivity within the operating temperature range, $\mathrm{mS\cdot cm^{-1}}$.

The average ($\delta_{EC\ T\ \mathrm{mean}}$) and critical ($\delta_{EC\ T\ max}$) values of the relative uncertainty of approximation of the electrical conductivity function were calculated by Eq. (11) and Eq. (12), respectively:

$$\delta_{EC\,T\,\mathrm{mean}} = \frac{1}{M}\cdot\sum_{z=1}^{M}\left|\frac{EC_{\mathrm{real}}(T_z) - EC_{\mathrm{meas}}(T_z)}{EC_{\mathrm{real}}(T_z)}\right|\cdot 100\ \%; \quad (11)$$

$$\delta_{EC\,T\,\max} = \max\left(\left|\frac{EC_{\mathrm{real}}(T_z) - EC_{\mathrm{meas}}(T_z)}{EC_{\mathrm{real}}(T_z)}\right|\cdot 100\ \%\right), \quad (12)$$

where, $EC_{\mathrm{real}}(T_z)$ is the actual value of electrical conductivity, $\mathrm{mS\cdot cm^{-1}}$; $EC_{\mathrm{meas}}(T_z)$ is the value of electrical conductivity, obtained by measurements with further approximation, $\mathrm{mS\cdot cm^{-1}}$; T_z is the temperature value from the operating range from 5 to 35 °C with a measurement interval of 5 °C; M is the number of control points from the operating temperature range equal to 7.

The estimation of the relative total critical measurement uncertainty of the electrical conductivity of irrigation solution (δ_{EC}) was performed by Eq. (13):

$$\delta_{EC} = \pm\left|\delta_{EC\,U\,\max} + \delta_{EC\,T\,\max}\right|. \quad (13)$$

where, $\delta_{EC\ U\ max}$ and $\delta_{EC\ T\ max}$ are the critical values of the main and additional relative uncertainties of measurement of electrical conductivity, %.

3. RESUTS AND DISCUSSION

Having conducted the experimental studies of the computerized conductivity meter, we obtained three series of experimental data for nominal values of conductivity of buffer solutions, which are shown in Figure 5,a – for $EC(T = 25°C)$=1.413 $\mathrm{mScm^{-1}}_{min}$ and Figure 5,b – $EC(T = 25°C)$=12.88 $\mathrm{mScm^{-1}}_{max}$.

Also Figures 6,a and 6,b show the dependence of the electrical conductivity of calibration solutions on temperature changes.

Based on the above-mentioned method, according to Eq. (1)-(9), quantitative estimates of the accuracy parameters of the designed measurement system were obtained.

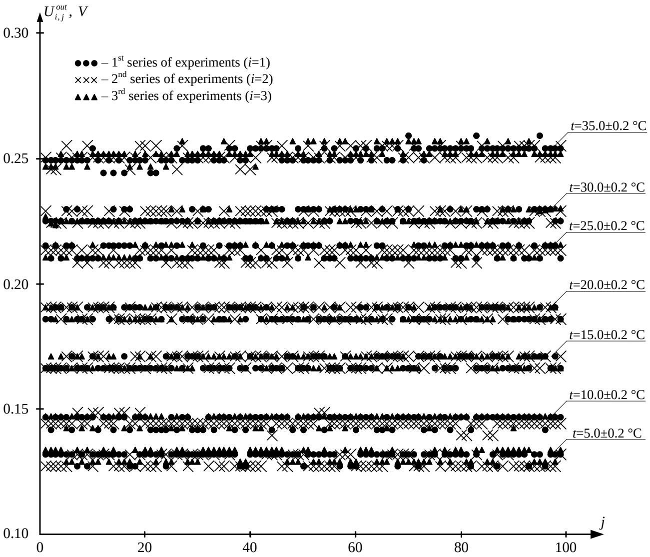
The critical value of the Fisher criterion (F_p) was assumed to be 3.07 [28] with the standard value of the confidence coefficient $P = 0.95$ with the number of degrees of freedom of the averaged intra group dispersion $(i-1) = 2$ and the number of degrees of freedom of the values of intra group dispersion $i\cdot(j-1) = 297$.

Quantitative analysis of the results of statistical processing of the observation results enabled us to determine that the main relative uncertainty of measurement ($\delta_{EC\,U}$) ranges from ±0.07 to ±0.61 %.

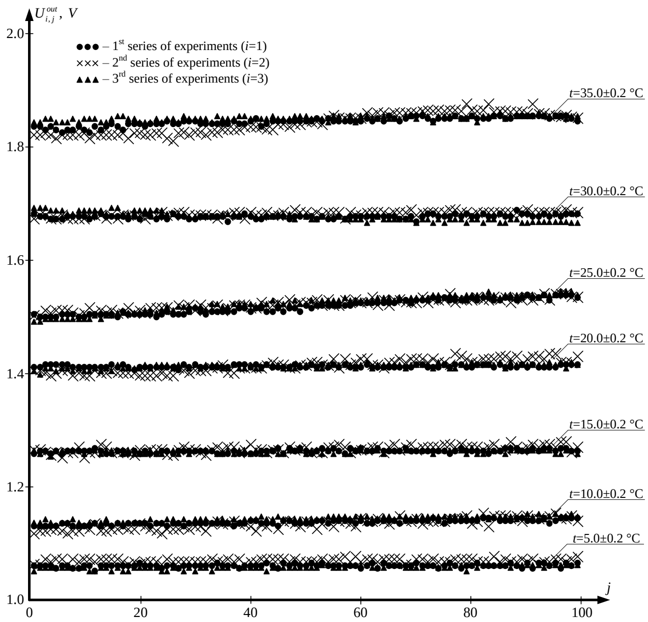
The critical value of the relative measurement uncertainty ($\delta_{EC\,U\,\max}$) is ±0.61 %, which satisfies the regulated requirements for these types of measurement control.

Qualitative analysis of the data presented in Figure 5 allowed us to identify that the uncertainty is digital and is mainly determined by uncertainty of the analog-digital conversion.

Graphical interpretation of the results of combined experimental measurements to obtain calibration characteristics of the conductivity computerized meter of irrigation solution in the form of a family of characteristics is shown in Figure 7.

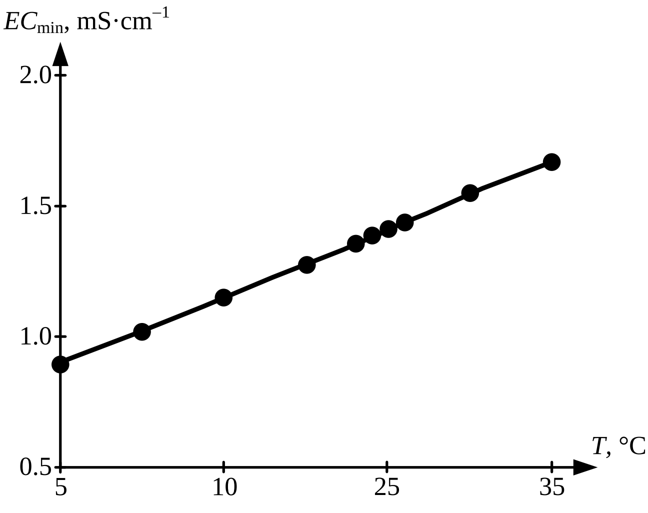


(a) $EC_{\min}\left(T=25°\mathrm{C}\right)=1.413\,\mathrm{mS\cdot cm^{-1}}$

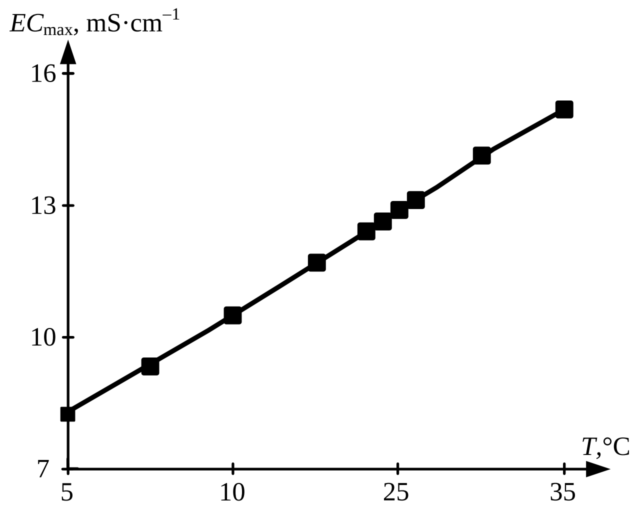


(b) $EC_{\max}\left(T=25°\mathrm{C}\right)=12.88\,\mathrm{mS\cdot cm^{-1}}$

Figure 5. Results of experimental observations



(a) $EC_{\min}\left(T=25°\mathrm{C}\right)=1.413\,\mathrm{mS\cdot cm^{-1}}$



(b) $EC_{\max}\left(T=25°\mathrm{C}\right)=12.88\,\mathrm{mS\cdot cm^{-1}}$

Figure 6. Dependencies of electrical conductivity

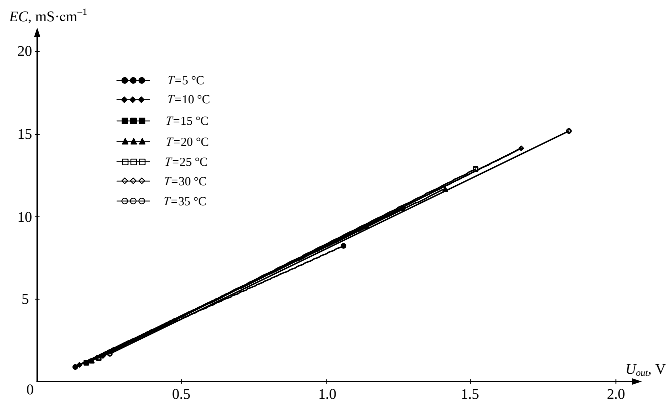


Figure 7. The family of conversion characteristics

Having analyzed the existing calibration method of the conductivity sensor [23], we found that the conversion characteristic was taken at 25 °C at two points: $EC_{\min}=f\left(Uout_{\min}\right)$ and $EC_{\max}=f\left(Uout_{\max}\right)$, therefore, when this function is approximated, a linear dependence (14) is used:

$$EC = a_0 + a_1 \cdot Uout, \qquad (14)$$

where, a_0 and a_1 are additive and multiplicative components of the approximation equation.

Having analyzed the results of the conductivity meter calibration presented in Figure 7, we discovered that with temperature changes, different values of additive (due to the offset of the characteristic relative to the origin along the ordinate axis) and multiplicative (due to the slope ratio of the characteristic) components of the approximation equation of electrical conductivity function (*EC*) to the informative voltage parameter (*Uout*) were observed.

Numerical values of the additive (a_0) and the multiplicative (a_1) components of the approximation equation (14) do not remain constant, but depend on temperature, as shown in Figures 8,a and 8,b. This effect causes an additional uncertainty of the conductivity measurement.

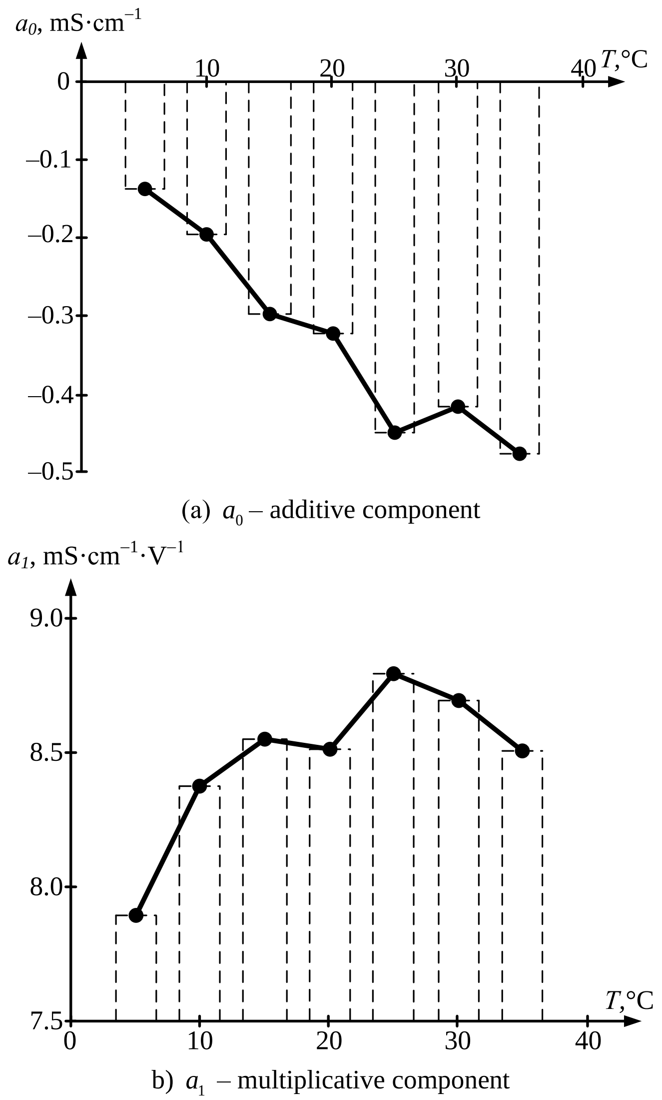


Figure 8. Dependence of approximation coefficients

The dependency analysis presented in Figure 8 and Eq. (10) allowed us to establish that the magnitude of the additional uncertainty of the conductivity measurement reaches 10.5 %, which is 17 times higher than the value of the main uncertainty. Thus, there is a need to improve the existing method of sensor calibration.

We propose to use the method of piecewise linear approximation of the meter conversion function $EC=f(Uout, T)$ in different sub-ranges of temperature change. Thus, having analyzed the measurement results shown in Figures 8,a and 8,b we established that the calibration characteristic of the meter can be approximated by a linear equation in which the approximation coefficients are a function of temperature by Eq. (15):

$$EC = a_0(T) + a_1(T)\cdot Uout. \qquad (15)$$

Based on the results of the regression analysis of the calibration characteristics of the meter, taking into account real-life environment of its operation in greenhouse conditions, it was proposed to divide the temperature range from 5 to 35 °C into the following sub-ranges: from 5 to 10 °C; from 10 to 15 °C; from 15 to 20 °C; from 20 to 25 °C; from 25 to 30 °C; from 30 to 35 °C. Numerical values of the approximation coefficients a_0 and a_1 are assumed to be equal to the arithmetic mean values of these sub-ranges (see Figures 8,a and 8,b). Consequently, the calibration characteristic of the computerized meter becomes a set of functions (16):

$$EC = \begin{cases} -0.166 + 8.135\cdot Uout, \text{ if } 5 \le T \le 10; \\ -0.246 + 8.462\cdot Uout, \text{ if } 10 < T \le 15; \\ -0.310 + 8.529\cdot Uout, \text{ if } 15 < T \le 20; \\ -0.387 + 8.652\cdot Uout, \text{ if } 20 < T \le 25; \\ -0.434 + 8.744\cdot Uout, \text{ if } 25 < T \le 30; \\ -0.447 + 8.601\cdot Uout, \text{ if } 30 < T \le 35. \end{cases} \qquad (16)$$

Having analyzed the results obtained with Eq. (11), we found the average uncertainty approximation value of the measurement results of electrical conductivity of the irrigation solution ($\delta_{EC\,T\,\mathrm{mean}}$), which does not exceed ±1.48 %, and the maximum value ($\delta_{EC\,T\,\max}$) of this uncertainty according to Eq. (12) is not more than ±3.21 %. This allows reducing the additional uncertainty value ($\delta_{EC\,T}$) on average by 5 times. Thus, the value of the total relative critical uncertainty (δ_{EC}) calculated by Eq. (13) does not exceed ±3.82 %, which satisfies the current regulated requirements.

4. CONCLUSIONS

The article solved the topical scientific and practical problem of evaluating the metrological characteristics of modern computerized meters of electrical conductivity of irrigation solution. This made it possible to substantiate the scientific and applied foundations for optimizing procedures of designing, developing and introducing high-quality methods and tools of online monitoring of the quality of irrigation solution when growing greenhouse flora.

The existing results of scientific and practical research on the development of computer-integrated systems for monitoring and quality management of irrigation solution were analyzed and summarized. Scientific and applied provisions for evaluation of the metrological characteristics of conductivity meters were synthesized.

The basic relative uncertainty of the designed conductivity meter was evaluated, which is not more than ±0.61 %. The method of piecewise linear approximation of the result of the combined measurement of electrical conductivity was substantiated, which made it possible to reduce the relative additional uncertainty by 5 times (on average) from 10.5 % to 3.21 %. The total relative critical uncertainty of measurement of electrical conductivity with the designed meter was evaluated; it does not exceed ±3.82 %, which satisfies the current regulated requirements for these types of measurements.

Promising future studies on improving efficiency of computerized electrical conductivity meters for irrigation solution for industrial greenhouses are: conducting experimental tests of the designed measuring device in actual operating conditions in order to confirm the scientific and applied results obtained in laboratory conditions; optimization of the hardware and software configuration of the meter, taking into account geometric and dynamic properties of irrigation systems for greenhouse crops; estimation of investment attractiveness of implementation of the developed information measurement system in industrial greenhouse complexes. Also, the future work would be to use more statistical data for the development of prediction models, which will be analyzed in the cloud side using IoT and Data Mining technologies. And the researches on evaluation of energy and economic performance of the system is necessary to perform in the near future.

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NOMENCLATURE

EC	electrical conductivity, mS·cm^{-1}
T	solution temperature, °C
$Uout$	sensor output voltage, V
$\overline{Uout_i}$	expected values of the meter output voltages, V
$Uout_{i,j}$	results of j observations of the sensor output voltages in each of the i series, V
$\overline{\overline{Uout}}$	the arithmetic mean of the expected output voltages of the meter, V
D_{Uout_i}	intra-group dispersions for each series, V^2
$D_{\overline{Uout}}$	dispersion of the expected values of the meter output voltage, V^2
F_{ex}	the value of the Fisher criterion of experimental data
S_I, S_{II}	independent estimates of the random distribution of observation results
F_p	the critical value of the Fisher criterion
P	confidence coefficient
$EC_{\text{real}}(T_z)$	the actual value of electrical conductivity, mS·cm^{-1}
$EC_{\text{meas}}(T_z)$	the value of electrical conductivity, obtained by measurements with further approximation, mS·cm^{-1}
a_0	additive component of the approximation equation, mS·cm^{-1}
a_1	multiplicative component of the approximation equation, mS·cm^{-1}·V^{-1}

Greek symbols

σ_U	the total mean square deviation of the observation results of the meter output voltage, V
$\delta_{EC\,U}$	the relative basic random uncertainty of measurement of the meter output signal, %
$\delta_{EC\,U\,\max}$	the critical value of the main relative measurement uncertainty of electrical conductivity, %
$\delta_{EC\,T}$	the relative value of additional uncertainty of conductivity measurement in terms of destabilizing effects of temperature, %
δ_{EC}	the total relative critical uncertainty, %

Subscripts

j	the number of observations
i	the nuber of series
N	the number of observations in each series
K	the number of groups of observations obtained under the condition of traceability of measurements
M	the number of control points from the operating temperature range