The Criterion of the Effective Use of Energy Resources While Producing Plant Products of Specified Quality

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Abstract

A new criterion for efficient use of energy resources, the essence of which is to minimize the difference between the relative indicators of phytoclimatic life support and phyto-development of plants, is proposed for use in automation systems implemented in protected ground facilities. It minimizes energy costs, while ensuring a specified quality of plants and products, and takes into account the phases of plant development.

Keywords

energy efficient control system, energy resources, phytomonitoring, mathematical modeling, greenhouse facilities, product quality monitoring, control strategies.

1. Introduction

At present, specialized studies have not established links between energy consumption and the state of the biological component of the object in protected ground facilities, which are characterized by the spatial distribution of technological parameters and indicators of plant quality. This is not taken into account in the development of principles for the construction and operation of energy-flow automation systems in spatially distributed facilities – greenhouse facilities for the production of products of specified quality.

Rational regulation of the microclimate in the greenhouse provides 90% of the crop [1]. The main components of the microclimate are temperature, light, CO_2 level in the greenhouse and relative humidity. The maximum level of productivity is achieved by reducing plant stress and ensuring an optimal balance of all factors. The condition of the plant and development are evidenced by uniform flowering, fruiting (generativeness) and leaf formation and development of the root system (vegetativeness) [2, 3].

There also arises a need to develop the criterion of the effective use of energy resources, the essence of which is to minimize the difference between the relative indicators of phytoclimatic life support and phyto-development of plants. The use of the above-mentioned criterion in automation systems for the control of energy flows in protected ground facilities for the cultivation of plant products ensures the minimization of energy costs and the predetermined quality of plant products, taking into account the phases of plant development.

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2. Problem Statement

The purpose of this paper is to develop a criterion for the efficient use of energy resources by the control system in an industrial greenhouse, which will increase the energy efficiency of plant production, while ensuring its specified quality.

3. Research Methods

The assessment of the quality of tomatoes grown in protected ground facilities, both based on the traditional differential and integrated methods, does not solve the problem successfully, because there is a need to take into account plant development at different phases.

It is proposed to define phytometric parameters of plant development in a non-contact manner. In the recognition system, the image is processed and entered into the data bank, where it is stored in the control unit, subjected to wavelet analysis, determination and comparison of the coefficients of mathematical decomposition with the database for determination of plant phytometric parameters [3, 20].

Phytometry criterion *Fk* is characterised by a large number of indicators of plant development in different plant phases, which have different measurement scales. We use the following correspondence to bring them to one scale of quality assessment of plant development:

$$Fk = f(K_1, K_2, \ldots K_n), \quad (1)$$

where K_1, K_2,…K_n – individual indicators of plant development quality at different phases.

In general, the definition of quality indicators of plant development will be presented as [2, 4]:

$$K = \sum_{j=1}^{T}\left(A_j \cdot \sum_{i=1}^{H_j}(a_i \cdot k_i)\right) = \sum_{j=1}^{T}\left(A_j \cdot G_{jg}\right), \quad (2)$$

where T – number of groups of tomato quality indicators; H – the number of quality indicators in the *j* group; ai – weighting factor of the *i* property; k_i – relative *i* quality indicator; G_{jg} – the level of quality of the *j* group of indicators (0≤Gjg≤1); A_j – the weight parameter of the *j* group of tomato quality indicators.

Based on the use of the principles of qualimetry [5] we obtained complex indicators for assessing the quality of plant development (K_1-K_n) on the atmospheric temperature Θ and solar radiation L. The following regression equations were derived from the studies:

- formation by a plant of quantity of flowers in an inflorescence:

$$K_1(\Theta, L)=-0{,}05417+0{,}0375\cdot\Theta-{,}55843\cdot L-0{,}00225\cdot L\cdot\Theta^2+0{,}066563\cdot L\cdot\Theta+0{,}11419\cdot L^2--0{,}01188\cdot L^2\cdot\Theta+0{,}000339\cdot L^2\cdot\Theta^2; \quad (3)$$

- formation by the plant of the number of fruits on the branch:

$$K_2(\Theta, L)=0{,}24375-0{,}03125\cdot\Theta-0{,}00203\cdot L-0{,}00013\cdot L\cdot\Theta^2+0{,}014219\cdot L\cdot\Theta+ +0{,}020176\cdot L^2--0{,}00194\cdot L^2\cdot\Theta+0{,}0000181\cdot L^2\cdot\Theta^2; \quad (4)$$

- the average weight of the fruit:

$$K_3(\Theta, L)=1{,}79762-0{,}08929\cdot\Theta-1{,}1082\cdot L--0{,}0012\cdot L\cdot\Theta^2+0{,}084598\cdot L\cdot\Theta+0{,}102193\cdot L^2--0{,}00625\cdot L^2\cdot\Theta+0{,}0000658\cdot L^2\cdot\Theta^2; \quad (5)$$

- the weight gain of the fruit:

$$K_4(\Theta, L)=0{,}211504+0{,}01404\cdot\Theta-0{,}39973\cdot L-0{,}00051\cdot L\cdot\Theta^2+0{,}023981\cdot L\cdot\Theta+ +0{,}027996\cdot L^2--0{,}00039\cdot L^2\cdot\Theta+0{,}0000093\cdot L^2\cdot\Theta^2 \quad (6)$$

Assessment of the quality of plant development by the integral dependence of indicators with the same weighting factor of 0.25 made it possible to obtain the dependence of the phytometry criterion of plant development quality on the influence of average daily atmospheric temperature and light intensity (Fig. 1):

$$Fk\,(\Theta, L)=0{,}517645 - 0{,}01491\cdot\Theta - 0{,}49627\cdot L -0{,}00099\cdot L\cdot\Theta^2 + 0{,}045348\cdot L\cdot\Theta + 0{,}063845\cdot L^2- 0{,}00488\cdot L^2\cdot\Theta + 0{,}000103\cdot L^2\cdot\Theta^2 \quad (7)$$

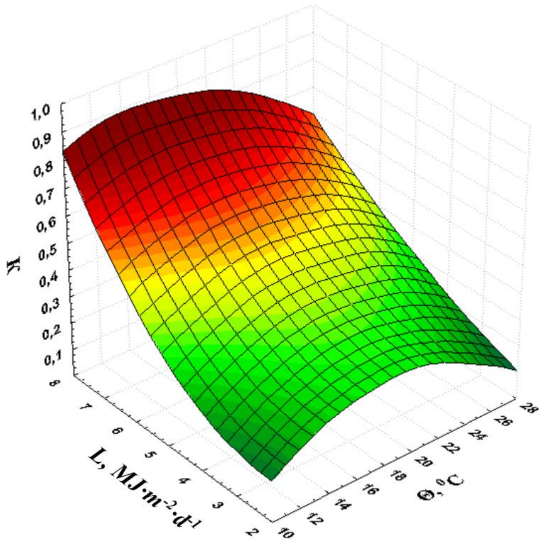

Figure 1: Dependence of phytometric criterion on average daily atmospheric temperature and light intensity

Using phytometry criterion, we determine the level of plant development during its growing season. Maintaining the maximum level of development will allow to form the maximum yield in plants at the initial stage. At the temperatures of 15 - 24ºC in the greenhouse we may observe the best formation of the plant yield (the number of flowers in the inflorescence, the number of fruits on the branch, the average weight of the fruit, the weight gain of the fruit).

To improve plant development, production conditions must be maintained, during which temperatures measured at different points in the greenhouse will be evaluated and compared. The control of technological parameters of the microclimate during plant growing is based on the measured phytometric parameters of the plant, which allows to assess the development of plants by introducing a phytotemperature criterion to assess the condition of the plant [6, 20].

The phytotemperature criterion *Fk* for estimating the development of a plant and its temperature environment evaluates the part of the heat coming from the heat carrier of the greenhouse heating system for heating the plant and the environment around it [6]. Description of experimental data was performed using a standard technique based on the least square method. Thus, the regression equation was obtained explicitly:

$$Fk(\Theta_p, \Theta) = -4{,}96 + 0{,}059\cdot\Theta_p - 0{,}243\cdot\Theta + 0{,}027\cdot\Theta_p\cdot\Theta + 0{,}0031\cdot\Theta_p - 0{,}0091\cdot\Theta - -0{,}0175\cdot\Theta_p^2 - 0{,}0175\cdot\Theta^2 \qquad (8)$$

To ensure the technological requirements for growing quality plant products in the greenhouse, it is proposed to assess the temperature of plants (Θ_p) and the atmosphere of the greenhouse (Θ) based on the use of phytotemperature criteria for assessing plant development (Fig. 2).

According to the analysis of research materials, it is established that the use of phytotemperature criterion makes it possible to obtain the maximum yield from the plant. As a result, from one bush we get less than 160 grams of weight gain per day, because at the temperatures of 17 - 22ºC the plant receives insufficient energy for better development and the increase is 5.2 - 6 grams, and at temperatures above 25ºC the increase in yield will be less than 6 g per hour.

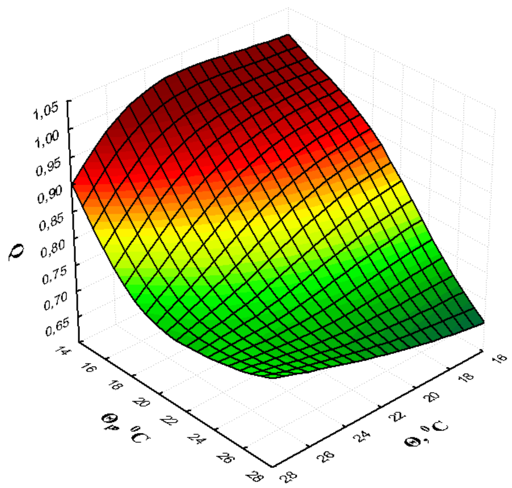

Figure 2: Dependence of phytotemperature criterion on atmospheric and plant temperatures

To determine the indicator of plant life support (*Fk*), we use the following algorithm on the entire area of the greenhouse. Let $\tilde{v}_{ij}(\tilde{t}_{jk})$ – the value of the indicator of the life support of the plant, determined on the *i* row of the *j* place at the corresponding total intensity of solar radiation $(\tilde{t}_{jk})$, where $i=\overline{1,n}$;$j=\overline{1,n}$; n – number of rows; k – the measurement number in the row ($k=\overline{1,K_j}$); K_j – the number of measured plant life support factors in the *j* place; ($j=\overline{1,m}$); m – the number of measurements.

We interpolate discrete dependences $\tilde{v}_{ij}(\tilde{t}_{jk})$ by splines:

$$V_{ij}(t)\ \ (i=\overline{1,n};\ j=\overline{1,m}), \qquad (9)$$

where $t \in [t_{\min}, t_{\max}]$; $t_{\min} = \max_{j=1,m} t_{j1}$; $t_{\max} = \min_{j=1,m} t_{jK_j}$ are respectively the lowest and highest value of the total intensity of solar radiation, for which the life support of the plant was determined during the measurement period.

We choose on the interval of $t \in [t_{\min}, t_{\max}]$ N evenly spaced nodes tk $(k = \overline{1,N})$. Let us calculate the values of splines (9) at these points:

$$v_{ij}(t_k) \;\; (i = \overline{1,n};\; j = \overline{1,m};\; k = \overline{1,N}) \qquad (10)$$

These values describe the *Fk* for all rows and places with the same total intensity of solar radiation. The value of the indicator for the entire area of the greenhouse (10) is presented in (Fig. 3).

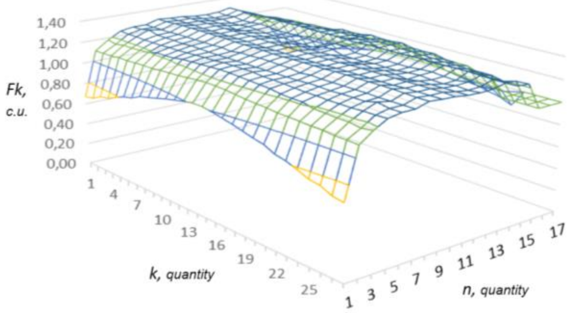

Figure 3: The value of the phytoclimatic indicator of plant life support over the entire area of the greenhouse

Given that φ_i, λ_i – are coordinates of the *i* row, we will determine the coordinates of the center of all rows:

$$\bar{\varphi} = n^{-1}\sum_{i=1}^{n}\varphi_i \,,\; \bar{\lambda} = n^{-1}\sum_{i=1}^{n}\lambda_i . \qquad (11)$$

Taking into account the zones of similarity in the distribution of microclimate parameters, we determine the distances between the rows relative to their central row, describing the spatial density of the rows in which the measurements were made:

$$r_i = \sqrt{(\bar{\varphi} - \varphi_i)^2 + (\bar{\lambda} - \lambda_i)^2} \;\; (i = \overline{1,n}). \qquad (12)$$

Values inverse to distances r_i $(i = \overline{1,n})$, make sense of weighted averaging coefficients $\tilde{w}_i = 1/r_i$ $(i = \overline{1,n})$.

Let us determine the average value $\tilde{v}_{ij}(\tilde{t}_{jk})$ in the rows:

$$\bar{v}_j(t_k) = \sum_{i=1}^{n} w_j v_{ij}(t_k) \;\; (j = \overline{1,m};\; k = \overline{1,N}). \qquad (13)$$

Graphs of the average value of the phytoclimatic indicator of plant life in rows (13) are shown in (Fig. 4).

The average value of the plant life support over the entire area of the greenhouse is determined by the expression:

$$\bar{v}(t_k) = n^{-1}\sum_{i=1}^{n}\bar{v}_i(t_k) \;\; (k = \overline{1,N}). \qquad (14)$$

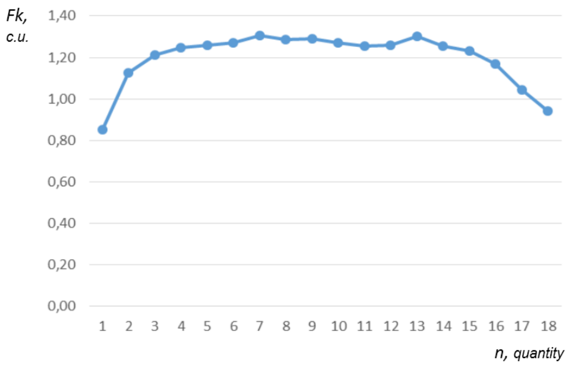

Figure 4: The average value of the phytoclimatic indicator of plant life support in rows

The average value of the plant life support over the entire area *Fk* = 1.2 indicates an excessive level of plant life support parameters.

According to the considered algorithm we will determine the value of phytometric criterion (*Fm*), phytotemperature criterion (*Ft*) and their average value – phytodevelopment index (*Fp*) by rows (Fig. 5), which will allow to establish the level of plant development and crop quality [7].

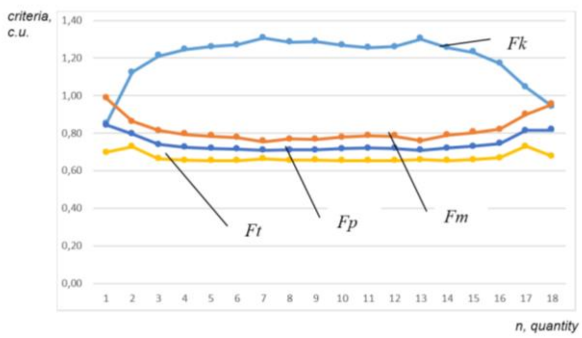

Figure 5: Dependence of change of average value of an indicator of plant life support, phytometric and phytotemperature criteria on all area in rows

It was found that the average value of phytoclimatic index is *Fk=1,2*, of phytometric criterion is *Fm=0,82*, of phytotemperature criterion is *Ft=0,67* and their average value of phytodevelopment index is *Fp=0,74* on the whole area of the greenhouse.

Exceedance in the value of the *Fk>1* indicator shows an excessive level of parameters of plant life support established by agrotechnology, respectively, and the overuse of energy carriers for their provision. The value of *Fp<1* indicates insufficient levels of plant development and quality of plant products in the greenhouse. Obtaining quality products with minimal consumption of energy resources is possible provided that the criterion of efficient use of energy resources for the production of plant products of a specified quality is minimized (Fig. 6):

$$R = Fk - Fp \rightarrow min. \tag{18}$$

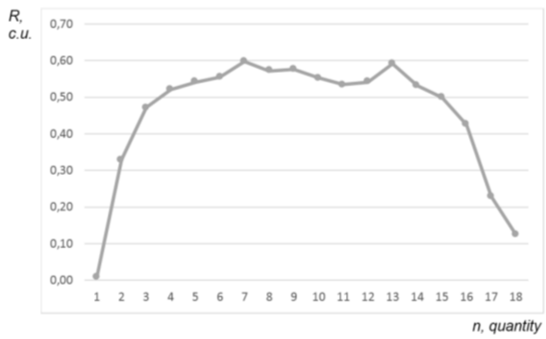

Figure 6: Criterion of efficient use of energy resources during the production of plant products of specified quality

The strategy of effective control is to reduce the standard deviation between the phytoclimatic indicator of plant life support and the value of phyto-development, when its increase indicates inefficient energy consumption by the existing control system of plant production technology of a specified quality.

4. Conclusions

1. The authors offer to introduce the following components into the algorithm of operation of the control system:

- phytometric criterion, which is characterized by a significant number of indicators of plant development in its various phases, namely flowering, fruit formation and harvest; assessment of the quality of plant development will be carried out using the integrated dependence of indicators. The use of phytometry criterion determines the level of plant development during its growing season, and its strict observance allows to form the maximum yield of plants at the initial stage;

- phytotemperature criterion for assessing the state of development of the plant, which creates conditions for obtaining the maximum yield of tomatoes; analysis of changes in plant temperature and atmospheric temperature in a greenhouse equipped with an automatic air temperature control system proves the need to use the proposed criterion.

2. To assess the conditions of plant development in the greenhouse the authors used phytoclimatic indicator of plant life support and assessment of the plant itself – the indicator of phyto-development, which allows to determine the level of plant development and crop quality. Exceedance of phytoclimatic value over 1 has been found to indicate an excessive level of plant life support from established agro-technology, and, respectively, an overexpenditure of energy resources spent on their provision. The value of the indicator of phyto-development less than 1 indicates the insufficiently possible level of plant development and the quality of plant products. It has been established that obtaining quality products with a minimum consumption of energy resources is possible provided that the criterion of efficient use of energy resources is minimized, when the average growth of the greenhouse to 46% indicates inefficient energy consumption of existing control systems.

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