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АНАЛІЗ МЕТОДИЧНИХ ПІДХОДІВ ДО ФОРМУВАННЯ ТАРИФІВ НА ВОДУ ДЛЯ ЗРОШЕННЯ І ТАРИФІВ НА МЕЛІОРАЦІЙНУ ІНФРАСТРУКТУРУ: ДОСВІД КРАЇН-ЧЛЕНІВ ЄС

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USING THE WATER STRESS INDEX FOR TOMATO IRRIGATION CONTROL

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Abstract. The temperature of the leaf surface of plants can be used as an indicator of the agricultural water stress of crops. Since plant temperature is affected by weather factors, it is usually expressed through the crop water stress index (CWSI). To calculate the CWSI, two input parameters must be known: the relationship between plant temperature and solar radiation, and the relationship between plant temperature and the intensity of solar radiation. The experimental and theoretical methods of determining the CWSI, for its values of 0.3 and –2.2. The empirical method of calculating CWSI using the resulting equations is easier to use. The CWSI values obtained for tomatoes in this study are closely correlated with the other irrigation methods.

Key words: water stress index, tomato, subsurface drip irrigation, plant temperature, phystosmonitoring

Relevance of research. Tomato (Solanum lycojersicum L.) is a valuable vegetable crop that is grown for its fruits. About 75% of tomatoes are consumed fresh, and the rest is processed. The sown area in Ukraine is about 80 thousand. hectares, which is 20% of the entire area under vegetable crops [1]. In the south of Ukraine, this is the most common vegetable crop. Tomatoes belong to agricultural crops with a high level of total water consumption: 5.2–5.5 thousand m³/ha and are sensitive to water stress [2; 3]. Accordingly, the determination of the criterion for the appointment of watering tomatoes is an important element for the operational management of the irrigation regime. Today, there are many methods of irrigation [4; 5; 6], one of the criteria for their use is the availability of the necessary tools and qualified personnel. Studies on the determination of CWSI for tomatoes [3; 7–9] and other [10–15] crops conducted abroad indicate that this index is used to assess plant water stress and manage irrigation. Such studies have not yet been conducted in Ukraine. Therefore, the need to conduct research is due to the development of a method of assigning irrigation that does not require expensive tools in order to increase the efficiency and effectiveness of managing the water regime of the soil.

Analysis of recent research and publications. One of the simple and accurate methods of watering, which does not require complex and expensive equipment, is to use the water stress index (crop water stress index – CWSI), which is based on measuring plant and air temperature. In both parameters [3; 10] or leaf temperature sensors [7] can be used to measure plant temperature.

The experimental [16] and theoretical [17; 18] crop water stress index (CWSI) methods can be used to predict irrigation time, was developed in 1981 and has not lost its relevance today [10; 19]. When plants experience water stress, the stomata

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immediately close, transpiration decreases sharply, and the temperature of the leaves rises. To calculate the CWSI, two input parameters must be known that relate the indicators under and without maximum water stress to the water vapor pressure deficit. These basic equations are specific for each culture and locality [8; 9; 16; 19]. Foreign scientists have conducted many studies on determining CWSI for tomatoes [3; 7; 8; 9], cowpea [10], corn [11; 14; 15; 19], sorghum [12], winter wheat [13], pumpkins, soybean, alfalfa [16], eggplant [21; 22], watermelon [23], cotton [24], sweet pepper [25] and concluded that this index accurately assesses the water stress of agricultural crops and can be used as a criterion for irrigation.

The purpose of the study is to determine the value of the water stress index (CWSI) and the basic equations that are necessary for the purpose of watering tomatoes under subsurface drip irrigation in the conditions of the Dneppe Steppe of Ukraine.

Research methods and materials. The study of the water stress index of tomato plants (CWSI) was conducted in 2019 in production conditions on the lands of PE “Organic Systems”. The enterprise is part of the “Agrofusion” group of companies, which specializes in growing tomatoes under drip irrigation in the conditions of the Dneppe Steppe of Ukraine.

To monitor meteorological parameters, an automatic Internet weather station (METOS) from the company “Instruments” [2] was used, which was located directly at the experimental site. The weather station is equipped with sensors for air temperature, humidity, solar radiation, wind speed, and a rain gauge. The temperature of tomato plants was measured with an LT-1z sensor, and the change in stem diameter was measured with an SD-5z sensor, which was connected to a PM-11z pyromonitor from the company “Bio-Instrument S.R.L.” [30]. Sensors for monitoring the physiological state of plants were installed according to methodical instructions [31].

The theoretical and imperial water stress index (CWSI) was calculated using the formula (16-18):

\[
\text{CWSI} = \frac{(T_e - T_a)_{\text{air}} - (T_e - T_a)_{\text{air,max}}}{(T_e - T_a)_{\text{air,max}}} - 1, \quad (1)
\]

where:
- \( T_e \) – temperature of the plant, °C;
- \( T_a \) – air temperature, °C;
- \( (T_e - T_a)_{\text{air}} \) – the temperature difference between CWSI and plant and air temperature was 0.71 and 0.63, respectively (Fig. 1). This result confirms research [13] on winter wheat culture conducted in northern China [13]. The results of the calculations confirm the relationship between CWSI and plant and air temperature. Thus, the correlation coefficients between CWSI and air temperature were 0.71 and 0.64, respectively.

According to the analysis of the daily dynamics of the CWSI, the tendency of this indicator to increase from 0.05 to 0.20 is followed [12; 17; 19]. Thus, after sunrise at 06:00, CWSI was close to “0” on average during the observation period, then, as the intensity of solar radiation increased, CWSI also increased and reached its maximum value (1.08) at 20:00.

The aerodynamic drag \( (r_c) \) needed to calculate the CWSI according to the Jackson method [18] was calculated using the formula [32]:

\[
R_c = \frac{\frac{1}{\gamma} \left( \frac{z}{z_0} \right) \left( \frac{z}{z_0} \right)^{\gamma - 1}}{\left( \frac{1}{\gamma} + \frac{1}{\gamma} \right)^{\gamma - 1}} \left( \frac{z}{z_0} \right)^{\gamma - 1} - 1, \quad (4)
\]

where:
- \( z \) – wind measurement height, m;
- \( d \) – the height of the offset of the zero plane, m;
- \( d = 0.63 h \)
- \( z_0 \) – roughness length, m;
- \( m = 0.13 h \)
- \( u \) – wind measurement height, m;
- \( h \) – the height of the plant, m.

Other parameters of equations 2 and 3 were calculated according to the FAO method 56 [33]. To calculate the slope of the pressure curve of saturated water vapor, \( \lambda \), we used the average temperature of the plant and air (\( T = \frac{T_e + T_a}{2} \)), according to the Jackson method [18].

The Empirical Water Stress Index (CWSI) was calculated using Equation 1, replacing the lower and upper baselines with Equations 5 and 6 [3; 7; 10; 15; 16; 19].

The lower baseline \((T_e - T_a)_{\text{air,ma}}\) was calculated using the empirical method using the formula:

\[
(T_e - T_a)_{\text{air,ma}} = a + b \cdot \text{VPD}, \quad (5)
\]

where:
- \( T_e \) – plant temperature, °C;
- \( T_a \) – air temperature, °C;
- \( \text{VPD} \) – water vapor pressure deficit, kPa;
- \( a \) and \( b \) – different constant coefficients for agricultural crops.

The upper baseline \((T_e - T_a)_{\text{air,ma}}\) was calculated using the empirical method by the formula:

\[
(T_e - T_a)_{\text{air,ma}} = a + b \cdot \text{VPD} \cdot \left[ 1 + \frac{\text{VPD}}{c + \text{VPD}} \right], \quad (6)
\]

where:
- \( \text{VPD} \) – water vapor pressure gradient, kPa;
- \( \lambda \) coefficients and \( b \) obtained from the lower baseline (5); \( \lambda(T_e) - \text{ saturated vapor pressure at air temperature } T_e \) kPa; \( \lambda(T_e + a) - \text{ the saturated vapor pressure at the temperature } T_e + a \) kPa.

\[
\lambda(T_e) = 0.6108 \cdot e^\left(\frac{T_e}{17.28}\right), \quad (7)
\]

\[
\lambda(T_e + a) = 0.6108 \cdot e^\left(\frac{T_e + a}{17.28}\right), \quad (7)
\]

Research results and discussion. The water stress index was calculated for the daylight hours (2 hours after sunrise and 2 hours before sunset) [12]. Research results confirm that CWSI approaches “0” after irrigation and gradually approaches 1 as soil moisture decreases [12]. During the observation period, almost all CWSI values were in the range from 0 to 1. Deviations from this range were observed in the morning and evening, when the CWSI values were less than “0” and more than “1”, respectively (Fig. 1). This result confirms research [13] on winter wheat culture conducted in northern China [13]. The results of the calculations confirm the relationship between CWSI and plant and air temperature. Thus, the correlation coefficients between CWSI and air temperature were 0.71 and 0.64, respectively.

Fig. 1. Daily dynamics of the water stress index of tomato plants.
The correlation coefficient between the water stress index and the intensity of solar radiation was 0.63 (Fig. 2).

For CWSI analysis, the average value of this indicator was taken at 12:00 and 13:00 [13; 16; 18]. Based on the results of calculations, it was established that the average CWSI value of tomato below 0.2 did not decrease against the background of sufficient soil moisture, which was also established by Brazilian scientists [3]. At the beginning of observations (June 10), the value of CWSI was 0.47–0.50. Then, due to precipitation, and, as a result, a decrease in the water vapor pressure deficit, the CWSI decreased to 0.28. After three waterings of 100 m³/ha on June 14–16, the CWSI increased to 0.42, which indicates an insufficient irrigation rate. After increasing the irrigation rate from June 17 to 120 m³/ha, the CWSI index decreased to 0.30, and later to 0.21. From June 17 to July 15, CWSI was in the range of 0.20–0.30, indicating no water stress during this period. The exception was the period from June 26 to 29, when for technical reasons the irrigation rate was reduced to 80–100 m³/ha, and as a result, CWSI increased to 0.32–0.35.

Starting on July 15, the CWSI began to gradually rise from 0.30 to 0.50. This is due to the onset of fruit ripening, an increase in air temperature, and a deficit of water vapor pressure [9], as well as a decrease in the intensity of irrigation. Based on the results of the analysis, a relationship between the irrigation rate and CWSI was established, the correlation coefficient is –0.60. Increasing the irrigation rate reduces CWSI. It is necessary to prescribe irrigation and increase the irrigation rate for a CWSI value of 0.30 (Fig. 3).

The dependence of CWSI on soil moisture is similar to that on the irrigation rate. An increase in the rate of irrigation led to an increase in soil moisture, and as a result, CWSI decreased. Thus, at the highest soil moisture of 80–81 % MMHC (June 24 and July 1), CWSI values were the lowest and amounted to 0.18–0.20. On June 29, soil moisture decreased to 79 % MMHC and CWSI increased to 0.35. The decrease in soil moisture from July 15 to 78 % MMHC led to an increase in CWSI to 0.4. Based on the results of the study, a relationship between soil moisture and CWSI was established, the correlation coefficient is –0.55. A decrease in soil moisture by 2–3 % MMHC increased the CWSI to the threshold values (0.30) for determining the irrigation period (Fig. 4).

The phytomonitoring method is used for operational management of tomato irrigation [4], therefore the established relationship between CWSI and the change in stem diameter confirms that the water stress index can be used to plan tomato irrigation both independently and in combination with other methods. Thus, with an increase in the diameter of the tomato stem, the CWSI decreased and vice versa. The correlation coefficient between CWSI and the change in stem diameter was –0.51 (Fig. 5).

Calculation of CWSI using the empirical method [3; 7; 10; 15; 16; 19] simplifies the use of the technique compared to the theoretical method, which requires more complex calculations. The Empirical Water Stress Index (CWSIE) was calculated using Equation 1 by changing the lower and upper baselines to Dependencies 5 and 6.
To obtain the equation of the lower baseline \((T_c - T_a)_{BL}\), we used the data obtained according to dependencies [2]. Based on the results of the calculations, we obtained the basic equations for determining the CWSI of tomatoes:

\[
(T_c - T_a)_{BL} = -0.842 - 2.591 \times VPD.
\] (8)

\[
(T_c - T_a)_{BL} = -0.842 - 2.591 \times VPG.
\] (9)

According to the obtained equation 8, it was established that with a water vapor pressure deficit of 0.1 to 4.2 kPa, the temperature difference between the plant and the air was from 1.2 to –6.3°C (Fig. 6).

It is possible to use the obtained equation of the lower baseline \((T_c - T_a)_{BL}\) [10; 14; 34] to determine the irrigation of tomatoes. To do this, it is necessary to measure the temperature, the relative humidity of the air, and the temperature of the plant. Then, by substituting the water vapor pressure deficit (VPD) in equation 8, calculate the permissible temperature difference \((T_c - T_a)_{BL}\).

In order to determine the time of watering, it is necessary to compare the temperature difference between the plant and the air \((T_c - T_a)\) measured in the field, with the permissible value \((T_c - T_a)_{BL}\). In this case, three conditions are met:

1. If the value of \((T_c - T_a)\) is greater than \((T_c - T_a)_{BL}\), watering is not required.

2. If the value of \((T_c - T_a)\) is less than \((T_c - T_a)_{BL}\), watering is required.

3. If the value of \((T_c - T_a)\) is approximately equal to \((T_c - T_a)_{BL}\), it is time for watering.

The values obtained by CWSI calculations using the theoretical method are greater than the empirical ones [3; 9; 21]. But regardless of this, there is a close correlation between both methods \((r = 0.92)\), which indicates the possibility of using these methods for the operational planning of watering tomatoes. The empirical method of calculating the CWSI using the resulting equations 8 and 9 is preferred because of its simplicity. It is necessary to prescribe irrigation or increase the irrigation rate using the empirical method of determining CWSI when the value is \(-2.2\) (Fig. 7).

**Conclusions.** The research results confirmed that the water stress index (CWSI) can be used for the operational management of tomato irrigation. The correlation coefficients between CWSI and plant and air temperature were 0.71 and 0.64, respectively. In the morning hours, CWSI was close to “0”, then, as the intensity of solar radiation increased, CWSI also increased and reached its maximum value (1.08) at 20.00. The correlation coefficient between the water stress index and the intensity of solar radiation was 0.63.

The relationship between irrigation rate, soil moisture, and CWSI of tomatoes was established – the correlation coefficient was –0.60 and –0.55, respectively. Increasing the irrigation rate reduced CWSI. It is necessary to prescribe irrigation or increase the irrigation rate for a theoretical CWSI value of 0.30.

The relationship between CWSI and the change in stem diameter was established: as tomato stem diameter increased, CWSI decreased, and vice versa. The correlation coefficient between CWSI and stem diameter change was –0.51.

Theoretical and empirical methods estimate the CWSI equally, and there is a high correlation between these methods \((r = 0.92)\). The empirical method of calculating CWSIE using the resulting equations 8 and 9 is recommended due to its ease of application. It is necessary to prescribe irrigation or increase the irrigation rate using the empirical method of determining CWSIE when a value of –2.2 is reached.

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