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Determination of the actual evapotranspiration of tomatoes by calculation methods.

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Goal. *To determine the actual evapotranspiration of seedling tomatoes by calculation methods and, based on the obtained results, propose the optimal water regime of the soil depending on the phases of plant development.* ***Methods.*** *Short-term field methods, generally accepted analytical and statistical methods of experimental data processing.* ***Results.*** *Calculation of the actual evapotranspiration of tomatoes (ETf) by various methods confirmed that the process took place mainly from 7 to 8 p.m. and during that time 95 – 96% of the daily amount of moisture evaporated. The maximum values of actual and reference (ETo) evapotranspiration — 1.44 – 1.97 mm/h and 0.94 mm/h — were recorded from 12 to 3 p.m., and the minimum values — after sunset. The reaction of plants to changes in environmental factors was monitored. Thus, with a deficit of air vapor pressure of 5.2 mb, the speed of sap ascent through the xylem was 0.9 rel. units, and ETf depending on the method used — 4.4 – 6.6 mm/day. With a deficit of air vapor pressure of 16.2 mb, the speed of sap ascent through the xylem decreased to 0.5 v. units, and ETf, depending on the method used, increased to 9.6 – 14.2 mm/ day. The correlation coefficient between the speed of sap movement through the xylem and ETf was 0.68 – 0.71. Under average meteorological conditions and the use of the Penman – Monteit, Monteit, and Budyko methods, the MARE error was 8%, 19, and 28%, respectively; in the case of adverse meteorological conditions and the use of the Penman – Monteit, and Monteit methods, it increased to 48 – 49%, and in the case of Budyko's method, it almost did not change and amounted to 27%. The analysis of the daily dynamics of tomato evapotranspiration showed that all the selected methods responded equally to changes in climatic parameters. The errors of MARE and RMSE of determination of ETf by phases of tomato development were calculated. On average, during the growing season, the used methods gave a MARE error of 16.2 – 19.7% (good accuracy of ET determination), and RMSE — 2.0 – 2.3 mm. The smallest errors were observed using the Penman – Monteit method, and the largest — using the Monteit method. With the application of the specified calculation methods, the coefficients of tomato culture Ks were also calculated. On* *average, during the growing season, the MARE error, depending on the method, was 13.3 – 17.4%, and the RMSE error was 0.29 – 0.30.* ***Conclusions.*** *Based on the research results, the possibility of using the combined Penman-Monteit equation, Monteit, and Budyko equations to determine the actual evapotranspiration of seedling tomatoes without using additional coefficients was confirmed. It was found that under unfavorable meteorological conditions, calculation methods did not take into account the protective effect of the plant, and therefore overestimated the actual value of ETf by 30 – 60%. Comprehensive statistical analysis confirmed the good accuracy of ETf and Ks determination by the selected methods: the MARE error during the growing season was within 10 – 20%, and the RMSE error was 2.0 – 2.3 mm and 0.29 – 0.30, respectively.*

Keywords: culture coefficient, xylem, air vapor pressure deficit, Penman-Monteit method, Monteit method, Budyko method.

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Tomatoes (*Solanum lycopersicom L.*) are a widespread vegetable crop, about 75% of its fruits are consumed fresh, and the others are sent for processing. According to the FAO, in the world tomatoes occupy the first place among vegetable crops in terms of cultivation area and it reaches about 4 million hectares [1]. In Ukraine, tomatoes are grown in an area of about 80,000 hectares, which is 20% of all land under vegetable cultivation [2]. 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 of 5-5.5 thousand m^3/ha [3], they are also demanding on the water regime of the soil, especially during the period of mass fruiting. When growing tomatoes, soil moisture must be maintained at a level not lower than 80% of the minimal water capacity of the soil. Lack of moisture, as well as waterlogging, negatively affects the growth and development of plants and significantly reduces the yield [4].

Quite a number of methods are used to determine watering regimes [5]. Calculation methods that take into account various meteorological factors are widely used to manage the water regime of the soil [6]. The theoretical basis for the application of calculation methods is that the evapotranspiration of agricultural crops with sufficient soil moisture depends on the biological characteristics of the plant and the influence of physical factors of evaporation [7, 8]. The use of modern equipment for measuring meteorological factors [9] and physiological parameters of plants [10] with an interval of one hour or less makes it possible to use complex calculation methods that take into account a significant number of meteorological elements and biological features of plants [7, 11, 12]. Methods that first determine the potential evapotranspiration, and then, using various coefficients, the actual one, have become the most widespread. The accuracy of such methods depends on the established coefficients. There are also calculation methods that make it possible to determine the actual evapotranspiration of agricultural crops without using additional coefficients [13-18].

The purpose of the research is to determine the actual evapotranspiration of seedling tomatoes by calculation methods and, on the basis of the obtained data, to form the optimal water regime of the soil in accordance with the phases of growth and development of the crop under conditions of climate change.

Research materials and methods. Field experimental research was carried out during 2019-2021 in production conditions on the lands of PE "Organic Systems", which is part of the group of companies "Agrofusion" (Baltazarovka village, Chaplynka district, Kherson region, a subzone of the Dry Steppe, 46°40'N 33°35' E).

The soil of the research and production site is dark chestnut with low humus (1.7-1.9%), the soil moisture content for the 0-50 cm soil layer is 25.8% of the completely dry soil, and the bulk density is 1.35 g/cm^3. Water intake for irrigation was carried out from the Chaplynka Canal (Chaplynka irrigation system, feeding from the North Crimean Canal, water from the Dnipro River). The experiments were carried out using an early-ripening Melman F1 Organic tomato hybrid for combine harvesting, which was grown in an organic farming system. The planting scheme is 1.50×0.25 m. Subsoil drip irrigation was used for irrigation, the depth of laying irrigation pipelines is 0.25 m. The iMetos IMT 300 automatic Internet meteorological station [19] from the "Pessl Instruments" company [9] to monitor meteorological parameters during the research located directly on the site was used. The weather station is equipped with sensors for air temperature, air humidity, solar radiation, wind speed, and a rain gauge. The temperature of tomato plants was measured with an LT-1z sensor, and the relative speed of xylem sap flow was measured with an SF-4z sensor, which were connected to a PM-11z phytomonitor from the "Bio-Instrument S.R.L." company. [10].

The accuracy of determining the actual evapotranspiration of tomatoes was studied by four methods:

1. Using the combined Penman-Monteith equation, which can be used to calculate the actual evapotranspiration of any crop for specific surface and aerodynamic resistance [7].

$$ET = \frac{1}{\lambda} \cdot \frac{\Delta(R_n - G) + \rho_{ar} \cdot C_p \cdot \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma \cdot \left[1 + \frac{r_c}{r_a}\right]}, \textit{ mm/hour} \quad (1)$$

where Δ – the gradient of the vapor pressure curve, kPa/°C; R_n – pure radiation on the surface of plants, MJ/m^2·h; G – soil heat flow density, MJ/m^2·h; ρ_{ar} – air density at constant pressure, kg/m^3; Cp – specific heat capacity of air at constant pressure, Cp=1.013·10^{-3} MJ/kg·°C; e_s – saturated air vapor pressure, kPa; e_a – actual air vapor pressure, kPa; γ – psychometric constant, kPa/°C; r_a – aerodynamic resistance, c/m; r_c – resistance of the total surface of the plant, r_c =45 c/m [8]; λ – latent heat of evaporation, λ=2.45 MJ/kg.

2. 2. Using the equation D.L. Monteith, which is derived from the energy balance of vegetation [8].

$$ET = \frac{1}{\lambda} \cdot \frac{\rho_{ar} \cdot C_p \cdot (e_C^* - e_A)}{\gamma \cdot (r_a + r_c)},\ mm/hour \tag{2}$$

where ρ_{ar} – air density at constant pressure, kg/m^3; Cp – specific heat capacity of air at constant pressure, Cp=1013 J/kg·°C; e^*c – saturated air vapor pressure at plant temperature, Pa; e_A – actual air vapor pressure, Pa; γ – psychometric constant, Pa/°C. r_a – aerodynamic resistance, c/m; r_c – resistance of the total surface of the plant, r_c =45 c/m [8]; λ – latent heat of evaporation, λ=680.55 W/kg.

3. Using the heat balance equation of M.I. Budyko for an optimally moistened surface [11].

$$ET = \rho_{ar} \cdot D \cdot (e_s - e_a) \cdot 60,\ mm/hour \tag{3}$$

where ρ_{ar} – air density at constant pressure, g/cm^3; D – coefficient of external diffusion, D=0.60 cm/s [11]; e_s – pressure of saturated air vapor at the temperature of the evaporating surface, mb; e_a – actual air vapor pressure, mb; 60 is the conversion factor from minutes to hours.

4. Using the Penman-Monteith method for the reference surface [12]

$ETc = ET_0 \cdot Kc$, *mm*

$$ET_0 = \frac{0{,}408\Delta(R_n - G) + \gamma \frac{37}{T_{hr}+273} u_2 (e_s(T_{hr}) - e_a)}{\Delta + \gamma(1 + 0{,}34u_2)},\ \text{mm/hour} \tag{4}$$

where Rn – pure radiation on the plant surface, MJ/m^2·h; G – soil heat flow density, MJ/m^2·h; T_{hr} – hourly air temperature at a height of 2 m, °C; u_2 – wind speed at a height of 2 m, m/s; $e_s(T_{hr})$ – pressure of saturated air vapor at air temperature, kPa; e_a – actual air vapor pressure, kPa; Δ – gradient of the steam pressure curve, kPa/°C; γ – psychometric constant, kPa/°C; Kc – coefficient of tomato culture [21].

Aerodynamic resistance (r_a) was calculated according to the formula [21]:

$$\mathrm{r_a} = \frac{4{,}72 \cdot \left(\ln\left(\frac{\mathrm{z-d}}{\mathrm{z_0}}\right)\right)^2}{1 + 0{,}54\mathrm{u}} \tag{5}$$

where z – height of the wind measurement, m; d – height of the offset of the zero plane, m; d≈0.63h; z_0 – roughness length, m; z_0≈0.13h; u – wind speed, m; h – height of the plant, m.

Other parameters included in formulas (1)-(4) were calculated according to the methodology of FAO Irrigation and Drainage Paper No. 56 [12].

To assess the accuracy of calculations of the actual amount of evapotranspiration, the average absolute percentage error of MARE (Mean Absolute Percent Error) and root mean square error (RMSE) were determined [22].

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{ETc-ET}{ETc}\right| \qquad (6)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(ETc-ET)^2} \qquad (7)$$

where *ETc* – tomato evapotranspiration calculated by the Penman-Monteith method for the reference surface (accepted by us as a standard); *ET* – evapotranspiration is calculated according to methods (1)-(3).

Research results and discussion. Selected calculation methods provide an opportunity to calculate ET_f in 1-hour increments and, due to this, to investigate in sufficient detail the influence of various meteorological factors on ET_f of tomatoes. In turn, monitoring the temperature of the leaf and the rate of sap flow through the xylem makes it possible to monitor the reaction of the plant to changes in environmental factors. Calculations of ET_f using the selected methods confirm the results of previous studies by scientists of the Institute of Water Problems and Land Reclamation of NAAS [23] about the daily dynamics of water consumption of tomatoes, in particular, that 95-96% of daily water consumption occurs from 7 a.m. to 8 p.m. The maximum ET_f value was fixed between 12 to 3 pm, and the minimum was after sunset. Thus, on June 8, the maximum ET_f value of tomato was observed at 1 p.m. and, depending on the method used and was 0.63-0.78 mm/h, at night this process almost stopped. On June 12, the maximum ET_f value of tomato was observed at 3 p.m. and, depending on the method was 1.94-1.29 mm/h, and the minimum value was 0.01-0.23 mm/h. The maximum value of ET_0 on these days was 0.53 and 0.84 mm/h, respectively (Fig. 1).

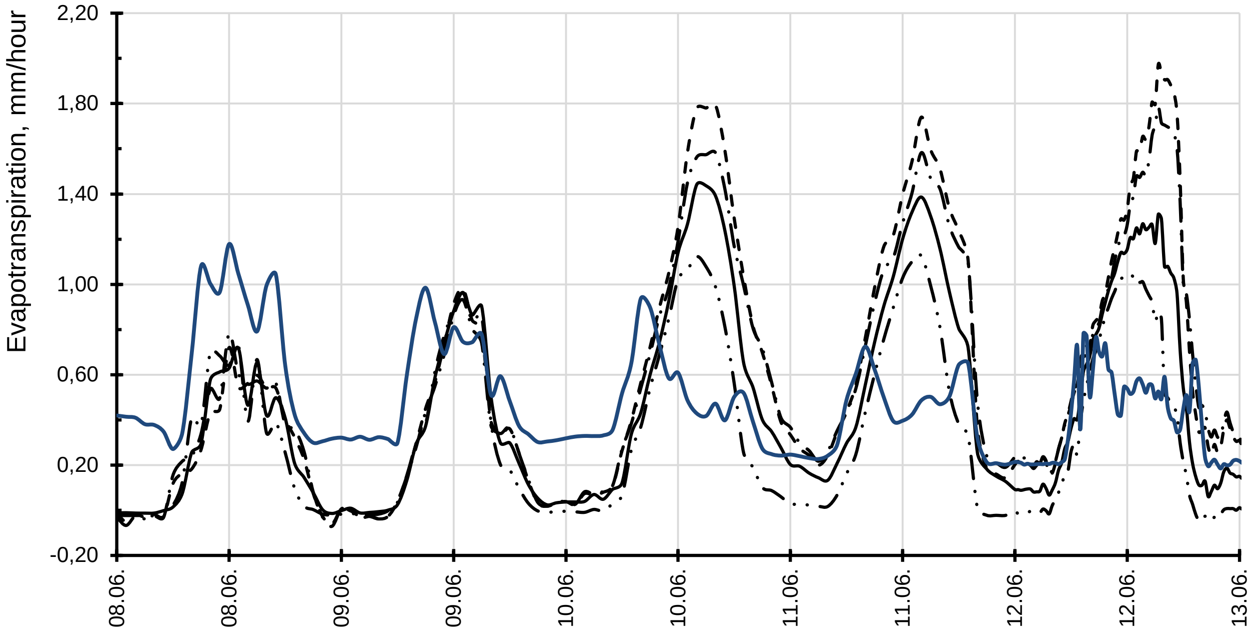

Fig. 1. Hourly dynamics of tomato evapotranspiration, mm/hour, determined in 2019 using various methods: —— – Penman-Monteith; - - - – Monteith; — · — – Budyko; — · · – – Penman-Monteith for the reference surface; (—— – Sap movement along the xylem, rel. unit)

For the average meteorological conditions of June, which were observed on June 8-9 (Table 1), ET_f of tomato was within 4.4-6.6 mm/day and depending on the method of calculation. During this period, the rate of sap flow through the xylem was 0.9 relative units, and the average air vapor pressure deficit and ET_0 were 5.2 mb and 5.1 mm, respectively. With the increase in meteorological indicators on June 10-12, ET of tomato increased to 9.6-14.2 mm/day depending on the research method used. The average deficit of air vapor pressure and ET_0 increased by 3.1 and 1.6 times, respectively, and the speed of sap flow through the xylem under such meteorological conditions decreased to 0.5 relative units. The response of plants to changes in environmental factors is monitored: with an average daily air vapor pressure deficit of 5.2 mb, the transpiration of tomato plants is not limited, which is confirmed by the speed of sap movement through the xylem at level 1, and the absence of midday stomatal depression. The average daily temperature of the plant was at the same level as the air temperature, and the maximum temperature was 0.5 °C higher than the air temperature. With an average daily vapor pressure deficit of 16.2 mb, the protective mechanism of moisture conservation by plants is observed, transpiration decreases [8], which is confirmed by a decrease in the rate of sap movement through the xylem to 0.5 relative units and the presence of midday stomatal depression (Fig. 1). The average daily and maximum temperature of the plant during this period was 0.4 °C lower than the air temperature.

Correlation coefficients between the calculation method (Penman–Monteith, Monteith, Budyko) and the speed of sap flow through the xylem were 0.68, 0.71, and 0.69, respectively. Under the average meteorological conditions observed on June 8-9, the MARE errors in the case of using the Penman–Monteith, Monteith, and Budyko methods are 8%, 19%, and 28%, respectively. And under unfavorable meteorological conditions on June 10-12, the MARE errors using the Penman–Monteith and Monteith methods increased and amounted to 48% and 49%, respectively. For the Budyko method, the MARE error almost did not change and amounted to 27%. The obtained results indicate that under unfavorable meteorological conditions, calculation methods do not take into account the protective effect of the plant, and therefore overestimate the actual ET by 30-60%. This feature must be taken into account when determining watering regimes using calculation methods.

1. Meteorological indicators used to calculate the actual evapotranspiration of tomatoes (2019)

Date	Air temperature, °C		Plant temperature, °C		Water vapor pressure deficit, mb		Flow of sap through the xylem, rel. unit	Intensity of solar radiation, MJ/m²·day	ET_0, mm
	aver.	max	aver.	max	aver.	max			
June, 8,9	22,5	28,5	22,6	29,0	5,2	22,8	0,9	27,1	5,1
June, 10-12	25,4	33,4	25,0	33,0	16,2	42,6	0,5	32,6	8,0
June, 26-28	24,1	31,5	23,8	31,1	16,7	34,6	0,6	32,1	7,0
July, 8	20,9	27,2	20,7	26,7	2,7	12,8	0,7	9,7	1,5

Analysis of the daily dynamics of tomato evapotranspiration shows that all selected methods react almost equally to changes in climatic parameters. Thus, during the observation period, the largest ET_f was observed on June 26-28 and was 12.1 mm/day using the Penman-Monteith method, 16.4 mm/day using the Monteith method, 16.4 mm/day using the Budyko method, but 14.2 mm/day using the reference Penman-Monteith method. During the cool and rainy weather observed on July 8, ET_f using all methods decreased to minimum values and amounted to 2.1 mm/day for the Penman–Monteith method, 2.5 mm/day for the Monteith method, 2.4 mm/day for the Budyko method but 3.2 mm/day for reference Penman-Monteith method (Fig. 2).

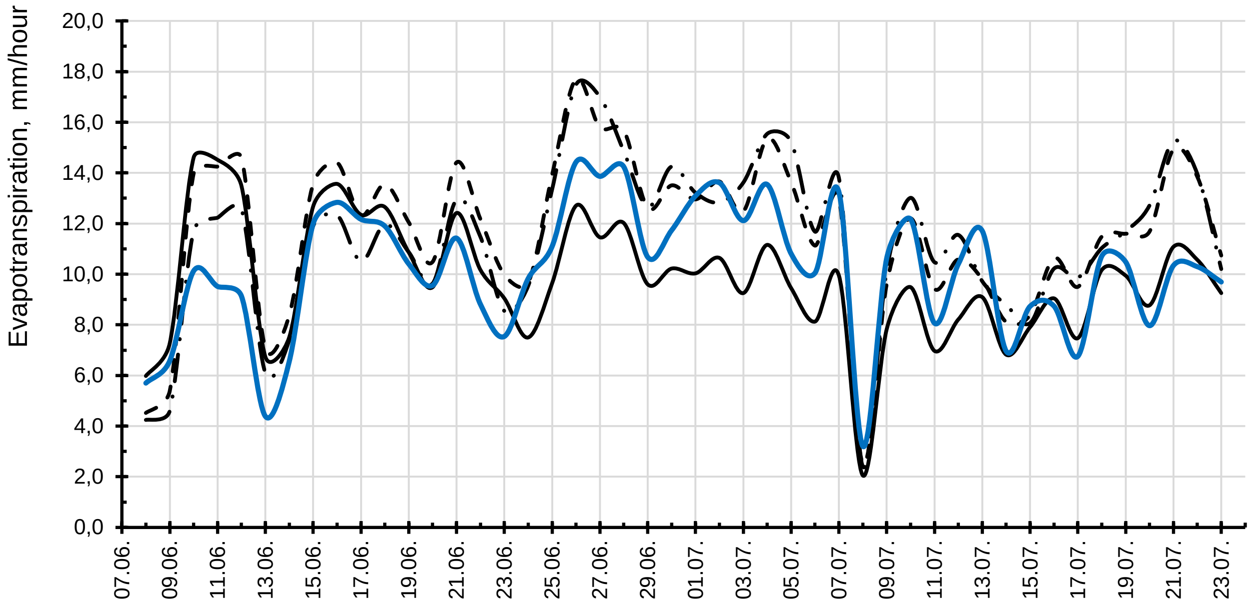

Fig. 2. The daily dynamics of tomato evapotranspiration, determined in 2019 using different methods, mm/day: —— – *Penman-Monteith;* - - - –– *Monteith;* —·— – *Budyko;* ▬ – *Penman-Monteith for reference surface.*

The result of the analysis of the errors in the determination of tomato evapotranspiration by development phases showed that the errors of MARE when using the combined method of Penman-Monteith in the phases of tomato development "flowering – beginning of fruiting" and "beginning of fruiting – fruiting" were 18.5 and 19.5%

(this corresponds to good accuracy of ET_f determination), and the RMSE errors for these stages of tomato development was 2.2 and 2.3 mm, respectively. In the "fruit filling – technical ripeness" phase, the MARE error decreased to 6% (this corresponds to the high accuracy of ET_f determination), and the RMSE was equal to 0.6 mm. In the case of ET_f determination by the Monteith method, the MARE errors in the phases "flowering – beginning of fruit formation" and "fruit filling – technical ripeness" were 27.4 and 23.7% (corresponding to the unsatisfactory accuracy of ET_f determination), and the RMSE errors in these phases of tomato development were 2.7 and 2.5 mm. In the phase "beginning of fruit formation – filling of fruits", the errors of MARE and RMSE in the case of using the Monteith method decreased and, respectively, amounted to 11.5% (satisfactory accuracy of determination) and 1.6 mm. According to the determination of ET_f by the Budyko method, the errors of MARE in the phase "flowering – beginning of fruit formation" and "beginning of fruit formation – fruit filling" were 16.9 and 15.0 % (satisfactory accuracy), and the RMSE errors in these phases of tomato development were 1.7 and 2.0 mm. In the "fruit filling – technical ripeness" phase, the MARE and RMSE errors using the Budyko method increased and amounted to 25.9% (satisfactory accuracy of determination) and 2.8 mm, respectively. On average, during the growing season, the MARE error for all selected methods was at the level of 16.2-19.7% (good accuracy of ET_f determination), and the RMSE was 2.0-2.3 mm. The smallest errors were observed when using the Penman-Monteith method, and the largest – the Monteith method (Table 2).

2. Errors in determining evapotranspiration using different calculation methods (2019)

Phase of tomato development	Indicator	Method			
		Penman–Monteith	Monteith	Budyko	$ET_c=ET_o \cdot K_c$
"Flowering – Beginning of fruiting"	ET, mm	173,3	181,1	159,1	148,6
	MAPE, %	18,5	27,4	16,9	-
	RMSE, mm	2,2	2,7	1,7	-
"Beginning of fruiting – Pouring fruit"	ET, mm	185,4	245,2	252,4	228,5
	MAPE, %	19,5	11,5	15,0	-
	RMSE, mm	2,3	1,6	2,0	-
"Pouring fruit – Technical maturity"	ET, mm	91,0	110,9	111,8	90,7
	MAPE, %	6,0	23,7	25,9	-
	RMSE, mm	0,6	2,5	2,8	-
"Flowering – Technical maturity"	ET, mm	449,8	537,3	523,3	467,8
	MAPE, %	16,2	19,7	18,0	-
	RMSE, mm	2,0	2,3	2,1	-

3. Coefficients of tomato Kc, in different phases of its development (2019)

Phase of tomato development	**Method**			**Kc**
	Penman–	**Monteith**	**Budyko**	

	Monteith			
"Flowering – Beginning of fruiting"	1,72	1,76	1,55	1,43
"Beginning of fruiting – Pouring fruit"	1,68	2,21	2,28	2,08
"Pouring fruit – Technical maturity"	1,90	2,32	2,35	1,89
Error: MAPE RMSE	13,3 0,29	17,4 0,32	14,1 0,30	- -

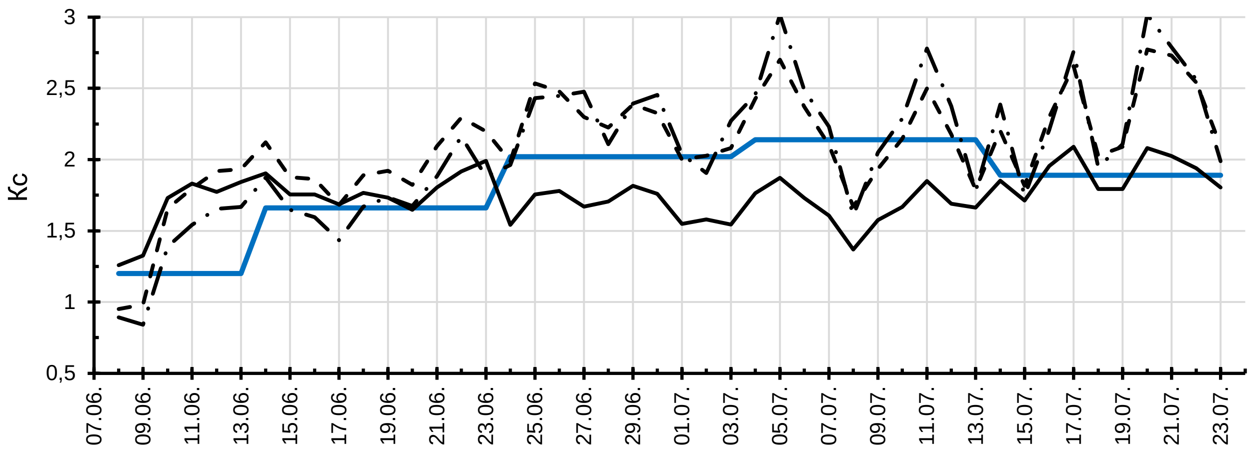

Fig. 3. The dynamics of tomato coefficients Kc, determined in 2019 using different methods:: ——– *Penman-Monteith;* – – – –– *Monteith;* —·— – *Budyko;* —— – *Penman-Monteith for reference surface.*

Analysis of the daily dynamics of tomato evapotranspiration and errors confirm the possibility of using the selected calculation methods to determine actual tomato evapotranspiration without using additional culture coefficients. In order to increase the accuracy of ET_f determination by the selected methods, in further studies, it is necessary to clarify the resistance value of the total surface of tomato plants (*rc*) in the case of applying the combined Penman-Monteith equation and the Monteith equation, as well as the external diffusion coefficient (*D*) in the case of applying the Budyko equation.

Using the specified methods, coefficients of tomato culture were calculated as the ratio of calculated evapotranspiration to reference evapotranspiration $Kc=ET_f/ET_0$, and compared with Kc. For comparison, the value of Kc of tomato was taken from previous studies [20]. For the phase of tomato development "flowering – beginning of fruiting", the coefficients obtained using the Penman-Monteith and Monteith methods were 0.29 and 0.33, respectively, and the coefficients obtained for this phase of development were 0.12 higher when using the Budyko method plants in previous studies. In the phase of development "beginning of fruit formation – filling of fruits", the coefficients obtained using the Monteith and Budyko methods exceeded Kc by 0.13 and 0.20, respectively, and for the Penman-Monteith method, on the contrary, the obtained coefficient was 0.4 lower than Kc. In the phase of tomato development "fruit filling – technical ripeness", the coefficient obtained using the Penman-Monteith method was equal to Kc, and when using the Monteith and Budyko methods, it exceeded it by 0.43 and 0.46, respectively.

On average, during the growing season, the MARE errors in determining the coefficient of tomato culture, depending on the research method used, were 13.3-17.4%, which corresponds to the good accuracy of the calculation of this indicator [22]. The RMSE errors were within 0.29-0.30.

Fig. 3 compares the values of Kc tomato coefficients obtained using different methods. As you can see, they are quite close, which is also confirmed by the MARE and RMSE errors (Table 3). A good correlation of the obtained coefficients is one of the indirect methods of proving their sufficient reliability [11].

Conclusions The research results confirmed the possibility of using the combined Penman-Monteith equation, Monteith and Budyko equations to determine the actual evapotranspiration of seedling tomatoes without using additional coefficients. However, under unfavorable meteorological conditions, the calculation methods do not take into account the protective effect of the plant, which explains the overestimated value of the actual ETf by 30-60%. The conducted comprehensive statistical analysis confirmed the good accuracy of determination of ETf and Kc by the selected methods: the error of MARE during the growing season was 16.2-18.0 and 13.3-17.4%, respectively, which corresponds to the good accuracy of determination of these indicators. The RMSE error was 2.0–2.9 and 0.29–0.30 mm, respectively.

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