AGRICULTURAL UNIVERSITY - PLOVDIV

FACULTY OF HORTICULTURE WITH VITICULTURE
DEPARTMENT OF MELIORATIONS, LAND REGULATION AND AGROPHYSICS

NADYA STOYANOVA HRISTOVA

REGULATED IRRIGATION REGIME

ABSTRACT

of the dissertation for awarding educational and scientific degree „Doctor“ in the scientific specialty „Meliorations“, professional field 6.1. Crop Science

Scientific supervisor:

Assoc. Prof. Dr. Rossitza Meranzova

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The dissertation is written on 142 pages and contains 46 tables and 49 figures. The cited literature includes 226 sources, of which: 28 are in Cyrillic and 198 in Latin.

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I. INTRODUCTION

It is undisputed that under climate change, irrigation is a major factor and an effective means of limiting or preventing the stress impact of drought on agricultural crops.

A regulated irrigation regime or regime in water deficit conditions is one way to increase the efficiency of water use, thereby obtaining higher yields per unit of irrigation water, plants are exposed to a certain level of water stress during a certain stage of their development or throughout the growing season.

Modern methods of micro irrigation, and in particular - drip irrigation and micro sprinkler, have proven their effectiveness in irrigation practice, contributing to more economical and rational use of water resources. Tracking changes in soil moisture is one of the main elements in the application of a regulated irrigation regime, tailored to the specifics of the plant and the need for the economical use of water.

As a result of the change in air temperature and water resources, it is expected that in the coming years, the most vulnerable will be the spring agricultural crops, especially those grown on non-irrigated areas, as well as those that develop a large leaf surface and their root system is shallowly located, such as lettuce.

In Bulgaria, the cultivation of lettuce in the spring and autumn-winter periods is very popular, both in open areas and in cultivation facilities. It is known that it is one of the crops that are most sensitive and susceptible to water stress. In our country, no research has been carried out on the irrigation regime of lettuce, as well as the influence of water deficit on its productivity, and the culture's response to water stress conditions. This necessitated the development of the present topic to determine and propose in practice the appropriate irrigation technique that would lead to the most justified irrigation regime of lettuce from an economic and agronomic point of view.

II. GOAL AND TASKS

The present study aims to optimize the irrigation regime, with drip irrigation and micro sprinkler, on productivity, evapotranspiration, the parameters of the "Water - yield" relationship, as well as the economic efficiency of its application on the "*Winter Butterhead*" salad variety.

To achieve the goal, the following tasks have been developed:

1. Establishing the parameters of the irrigation regime, by reducing the irrigation rates, with drip irrigation and micro sprinkler

2. Study of the influence of the tested irrigation regimes on the values and dynamics of changes in evapotranspiration during drip irrigation and micro sprinkler, as well as its relationship with the reference evapotranspiration, temperature, and air saturation deficit with water vapor through biophysical coefficients
3. Study the impact of the tested irrigation regimes and the corresponding irrigation technique on the yield
4. Study of the dependencies "Yield - Irrigation rate" and "Yield - Evapotranspiration", with the relevant irrigation technique
5. Study of the dependence "Yield - Leaf area index" and derivation of a formula for forecasting the yield
6. Evaluation of the economic efficiency of the applied irrigation regimes, through micro-irrigation techniques in growing lettuce outdoors

III. MATERIALS AND METHODS

1. Object, scheme of placing the experience and irrigation technique

The experiment was conducted during the period 2020-2021, in the Educational and Experimental Field of the Agricultural University, Plovdiv. Experimental work was carried out with lettuce, the variety "*Winter Butterhead*". The plants are planted on a wide flat bed in a four-row strip, according to the scheme 70+30+30+30+30 x 20 cm, food area - 0.06 m^2. The size of the experimental plots is 5 m^2, and the vintage plots are 3 m. Two parallel one-factor experiments were conducted with two irrigation techniques for micro-irrigation - drip and micro sprinkler, with the same irrigation options.

For the drip irrigation system, irrigation thin-walled single-season pipelines, type Dual Drip 17/16.1, were used. The distance between the drippers, 0.2 m, was chosen with a view to the optimal water supply to the plants in the given planting scheme. The nominal flow rate is 2.2 l/h at a working pressure of 0.8 bar. Two irrigation pipelines are placed in each bed.

The micro sprinkler system was implemented with micro sprinkler devices with a diameter of 3.5 m, working pressure of 2 bar, and flow rates of 90 l/h and 45 l/h. Due to the location of the beds, it was necessary to use two types of micro sprinklers with a spreading angle of 180° and 90°. The location of both the irrigation and the distribution pipeline is one-sided along the length of the beds. Each of the variants, both in drip irrigation and in micro sprinkler, is individually supplied.

2. Variants of the study

To establish the influence of the irrigation regime on the growing up and productivity of the tested lettuce variety, the following options were implemented in three repetitions for both irrigation techniques:

V1 – irrigation with 100% of the irrigation rate m (100% m), - control 1, also called optimal;

V2 – irrigation with 80% of the irrigation rate m (80% m);

V3 – irrigation with 60% of the irrigation rate m (60% m);

V4 – non-irrigation - control 2.

The time for irrigation and the volume of the irrigation rates for both irrigation techniques were determined based on the level of soil moisture. Pre-irrigation soil moisture was assumed to be 85-90% of FC (Field Capacity) for the 0.2 m layer. Variants V2 and V3 were irrigated at the same time as variant V1, but with a reduction in irrigation rates through the duration of irrigation. The irrigation rate for variant V1 - irrigation with 100% of the irrigation rate m is calculated according to the following formula:

$$\mathbf{m = 10.H. (\delta^{FC} - \delta^{av}) \quad (mm)}$$

where:

m – irrigation rate, mm;

H – depth of the active soil layer, m;

δ^{FC} и δ^{av} – volumetric soil moisture at FC and available volumetric soil moisture, %.

3. Soil moisture tracking with EU-5 capacitive sensors

Soil moisture is monitored within 1-3 days, in all variants, with the EC-5 capacitive sensors, which were previously calibrated for the experimental conditions. A standard procedure was used to calibrate sensors, type ECH2O, in laboratory and field conditions. The simple general model is given by the equation:

$$\mathbf{Y = aX+b,}$$

where:

b - constant, intercept of the linear regression line ;

a – the slope of the regression line;

Y – volumetric soil moisture;

X – volumetric moisture sensor report.

The following two equations have been established for the specific soil type:

laboratory	**Y=0.819x - 0.0626**	$R^2 = 0.9819$	(1)
on a field	**Y=0.893x - 0.0795**	$R^2 = 0.9429$	(2)

4. Yield. Relationship „Yield – Irrigation rate“

4.1 Yield

The yield data by variants and years, for both irrigation techniques, were processed by analysis of variance, using the program product "BIOSTAT" and "ANOVA", and the ranks of evidence were established.

4.2 Relationship „Yield – Irrigation rate“

The parameters of the relationship "Yield - irrigation rate" for both irrigation techniques were established using the formulas below, and the data were processed by the method of least squares using the software product "YIELD".

- ✓ *Regression given by quadratic equation :*

$$\mathbf{Y = ax^2 + bx + c},$$

where:

Y – relative yield;

X – relative irrigation rate;

c - a constant that indicates the amount of relative yield under non-irrigated conditions

- ✓ *Davidov formula*:

$$\mathbf{Y = 1 - (1 - Yc).(1 - X)^n},$$

where:

Y – relative yield;

Yc – relative yield in case of non-irrigated option;

X – relative irrigation rate;

n – degree index

5. Evapotranspiration. Relationship „Yield – Evapotranspiration“. Biophysical coefficients

5.1 Evapotranspiration

Evapotranspiration is calculated for the 0.2 m layer using the water balance equation:

$$\mathbf{ET = W_i - W_f + \Sigma m_i + N} \qquad \mathbf{(mm)}$$

where:

W_i и W_f – initial and final water supply, mm;

Σm_i – the sum of irrigation rates for the period, mm;

N – the amount of usable rainfall, mm.

Income from deepening the root system and income from the capillary rise of groundwater are not accounted for in the calculations. According to Crafty's method, the usability of the fallen precipitation was determined. The total, decadal, and midnight ET values were determined for all variants and for both irrigation techniques, as well as the relative share of the components that form it - initial water supply, irrigation rate, and vegetation precipitation.

The reference evapotranspiration ET_0 values were obtained from an automatic weather station located near the place of the experiment. The Penman-Monteith formula is used to calculate reference evapotranspiration :

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)},$$

where:

ET_0 – the reference evapotranspiration (mm.day^{-1});

R_n – the net radiation on the grass surface (MJ.m^2.day^{-1});

G – heat flow from the soil (MJ.m^2.day^{-1});

T – the average daily air temperature at 2 m height (^{0}C);

u_2 – wind speed at 2 m height (m.s^{-1});

e_s – saturated water vapor pressure (КPa);

e_a – actual water vapor pressure (КPa);

(e_s – e_a) – the deficit of saturated water vapor pressure (КPa);

Δ – the slope of the water vapor pressure curve (КPa. ^{0}C^{-1});

γ – psychometric constant (KPa. $^{0}C^{-1}$).

5.2 Relationship „Yield – Evapotranspiration“

The parameters were established using the formulas presented below in the text, and the data were processed using the "YIELD" program.

- ✓ *FAO formula – linear relationship between yield and total evapotranspiration*:

$$\frac{Y}{Yo} = 1 - Kc\left[1 - \frac{ET}{ETo}\right]$$

where:

Y – yield under reduced irrigation;

Yo – yield under optimal irrigation;

ET – evapotranspiration at yield Y;

ETo - evapotranspiration at yield Yo;

Kc – coefficient of the yield.

- ✓ *Davidov's formula – a degree dependence between yield and total evapotranspiration:*

$$\frac{Y}{Yo} = 1 - A\left(1 - \frac{ET}{ETo}\right)^{N}$$

where:

A – coefficient of the yield;

N – exponent

- ✓ *Davidov's formula - a two degree relationship between yield and total evapotranspiration*:

$$\frac{Y}{Yo} = \left[1 - \left(1 - \frac{\mathrm{ET}}{\mathrm{ETo}}\right)^{N}\right]^{M}$$

where:

N – exponent for the growing season;

M – graduated indicator dependent on culture.

5.3 Biophysical coefficients

Based on the real and reference evapotranspiration, as well as the sum of the average nightly air temperature and the sum of the air humidity deficit, the following biophysical coefficients have been determined in decadal values:

- ✓ *Z* – the coefficient represents the ratio of ET for a certain period time to the sum of the average daytime air temperature ∑T° for the same period. Calculated by dependency:

$$\mathbf{ET = Z \,. \sum T^{\circ}}$$

- ✓ *Кс* – coefficient of culture depending on reference (ETo) and real evapotranspiration (ET), calculated by the formula:

$$\mathbf{ET = Кс \,. ETo}$$

- ✓ *R* – the coefficient represents the ratio of ET to the sum of air humidity deficit ∑D , calculated by the formula:

$$\mathbf{ET = R \,. \sum D}$$

6. Leaf Area(LA) and Leaf Area Index (LAI*)*

The determination of the leaf area of one plant was carried out using a planimeter, model KR92N. The mass of the whole plant and the mass of the fresh and dry leaves was also recorded, and regression relationships were derived. The measurements were made at the time of harvesting, at the end of the growing season of the crop for 15 plants of each variant, and with the corresponding irrigation technique.

The determination of the Leaf Area Index is calculated according to the formula:

$$\boldsymbol{LAI = \frac{LA}{A}}$$

where,

LA – leaf area, cm^2;

A – agricultural area, cm^2.

7. Economical analysis

To assess the economic effect of the applied irrigation regime, the following indicators are defined:

- Average sales price - BGN/kg;
- Cost - BGN/kg;
- Total income - BGN/da;
- General expenses - BGN/da;

- Total income (profit) - BGN/da;
- Rate of return – the ratio of total income to material costs, %;
- Rate of profitability - the ratio of profit to total costs, %.

IV. SOIL - CLIMATE CONDITIONS

The soil-climatic conditions of a given region are essential for normal vegetative development of the plants, as well as for obtaining high yields with excellent product quality. They are also a determining factor for drawing up and applying an irrigation regime.

1. Characteristics of the soil and the water source

The soil on which the experiment was conducted is the alluvial - meadow. The content of physical clay is 24%, which characterizes it as slightly sandy-clayey. The soil reaction is moderately alkaline, with a pH value of 8.26. The content of humus in the soil is high - 3.81%, according to the classifications for the humus stock of soils in Bulgaria. According to the requirements of salad plants, the soil on which the experiment was conducted is suitable for their cultivation. An exception is the soil reaction, for which pH = 6.0 - 6.8 is recommended as optimal. The bulk density for the 0-0.20 m layer is $\alpha = 1.59$ (t/m^3). The gravity soil moisture at FC for the above-mentioned soil layer is $\delta g = 25.28\%$, and the volume $\delta v = 40.2\%$.

A chemical analysis of the water from the water source was also carried out to determine some of its characteristics. The calculated value of the SAR indicator is 1,550 meq/l, which indicates that the water is suitable for irrigation (at < 3 meq/l).

2. Climatic characteristic

The main indicators of the climate, which have a significant impact on the development of plants and the need to provide water through irrigation, are precipitation, temperature, and relative humidity of the air. In the period of the two-year study, these indicators differed significantly, both in terms of distribution and value.

2.1. Precipitation diring the vegetation period

About vegetation precipitation, it was found that 2020 is an average-wet year with a security of precipitation P = 29%, and 2021 is an average-dry year with a security of precipitation P = 67.7%. The amount of precipitation during the growing season of 2020 is

100.8 mm, with 43.75% of them having precipitation of less than 4 mm, from an ameliorative point of view this rainfall is considered to be ineffective, and 56.25% are over 4 mm. In 2021, the amount of precipitation during the growing season is 45.4 mm, with 63.63% of them having precipitation less than 4 mm, and only 36.37% having more than 4 mm.

2.2. Air temperature

In 2020, the sum of the air temperatures during the growing season is 676.1°C, with a security P = 70.9%, which characterizes it as average - cool, while in 2021 it is 705.7°C, with a security of air temperature P = 38.7%, which defines it as medium-warm.

2.3. Air humidity

The sum of the air saturation deficit during the vegetation period of the first year is D = 178.03 Hpa, and for the second it is in the amount of D = 273.89 Hpa, with a security of air saturation deficit P = 87.1% for 2020, and P = 29% for 2021 According to this parameter, the first experimental year is characterized as wet, and the second as moderately dry.

2.4. Dryness index

According to de Marton's classification, the first experimental year is defined as semi-dry with an index of IDM = 12.1, and the second as dry IDM = 4.8, which in turn means that irrigation is a mandatory agrotechnical practice.

V. RESULTS

1. Irrigation regime

At the start of the experiment, after planting the seedlings, the soil was brought to moisture at FC (Field Capacity) in all variants, including the non-irrigated one, by giving an equalizing watering. In the first experimental year, the realized irrigation rates are as follows: - for the 100% variant m – 61 mm; 80% m – 48.8 mm and 60% m – 36.6 mm, with drip irrigation, and with micro sprinkler, respectively - 100% m – 67 mm; 80% m – 53.6 mm and 60% m – 40.2 mm. In the second trial year, the applied irrigation rate for drip irrigation was respectively: for the 100% variant m – 105 mm; 80% m – 84 mm, and 60% m – 63 mm, and for micro sprinkler - the 100% m – 110 mm variant; 80% m – 88 mm and 60% m – 66 mm. Table 1 presents the average values of the number of irrigations, the average net irrigation rate, and total irrigation rate, by variants for the two experimental years - respectively for drip irrigation and micro sprinkler.

Table 1.

Number of irrigations, average irrigation, and total irrigation rate in drip irrigation and micro sprinkler, by variants, for the experimental period

Вариант	Drip irrigation			Micro sprinkler		
	100% m	80% m	60% m	100% m	80% m	60% m
M, mm	83,0	66,4	49,8	88,5	70,8	53,1
The average number of waterings	8,5	8,5	8,5	8,5	8,5	8,5
m, mm	9,8	7,8	5,9	10,4	8,3	6,2

2. Yields

The average yield data presented in table 2 by variants and years, with both irrigation techniques, show that for the conditions of the experiment, the regulated irrigation regime has a significant impact on the productivity of lettuce, variety "*Winter Butterhead*".

Table 2.

Impact of drip irrigation and micro sprinkler on average lettuce yield 2020 - 2021

2020-2021	**Drip irrigation**				**Micro sprinkler**			
		Compared to variant 100%m				**Compared to variant 100%m**		
Variant	***Yield kg/da***	***Y +/-***	***%***	***Proof of difference***	***Yield kg/da***	***Y +/-***	***%***	***Proof of difference***
100% m	5672	St	100	St	5757	St	100	St
80% m	4853	-819	85,6	***	4963	-794	86,2	*
60% m	4384	-1288	77,3	***	4481	-1276	77,8	**
non-irrigated	1390	-4282	24,5	***	1390	-4367	24,1	***
	GD at P: 5%=243,9 kg/da; 1%=369,5 kg/da; 0,1%=593,9 kg/da;				GD at P: 5%=589 kg/da; 1%=892,3 kg/da; 0,1%=1434,4 kg/da;			

The productivity of lettuce under non-irrigated conditions is mainly determined by the amount and distribution of rainfall during its growing season. On average for the research period, the yield obtained in the variant in which no irrigation was implemented was 1390 kg/da. The additional yield established as a result of the regulated irrigation regime is significantly different from that under non-irrigated conditions, and this difference is presented in table 3.

Table 3.

Additional yield in drip irrigation and micro sprinkler on average for 2020 - 2021

2020-2021	**Drip irrigation**				**Micro sprinkler**			
		Compared to the non-irrigated variant				**Compared to the non-irrigated variant**		
Variant	***Yield kg/da***	***Y +/-***	***%***	***Proof of difference***	***Yield kg/da***	***Y +/-***	***%***	***Proof of difference***
100% m	5672	4282	408,03	***	5757	4367	414,3	***
80% m	4853	3463	349,1	***	4963	3573	357,1	***
60% m	4384	2994	315,4	***	4481	3091	322,5	***
non-irrigated	1390	St	100,0	St	1390	St	100,0	St
	GD at P: 5%=243,9 kg/da; 1%=369,5 kg/da; 0,1%=593,9 kg/da;				GD at P: 5%=589 kg/da; 1%=892,3 kg/da; 0,1%=1434,4 kg/da;			

The increase in yield by drip irrigation variants is as follows: in the 100% m variant – 408.03%; 80% m – 349.1% and 60% m – 315.4%, and at micro sprinkler, respectively: 100% m – 414.3%; 80% m - 357.1% and 60% m - 322.5%. It was statistically proven that even the supply of a smaller irrigation rate than the maximum leads to a significant increase in lettuce yield, compared to the non-irrigated option. The plants respond to the supplied amounts of water and regardless of the reduction of the irrigation rate by up to 40%, a decrease in the yield of approximately 23-26% is reported for both micro-irrigation techniques. The yield obtained under non-irrigated conditions is lower than that under irrigated conditions by 315 to 414 %.

3. Productivity of the irrigation norm and yield losses depending on the applied regulated irrigation regime

From the results presented in Tables 4 and 5, it can be summarized that with drip irrigation, the greatest additional yield at the consumption of 1 mm of water, the highest productivity of the irrigation rate is obtained with the variant 60% m – 62.2 kg/m³, and with micro sprinkler – 59.5 kg/m³. With almost equal values is the productivity in the variants 100% m – 53.3 kg/m³, 80% m – 53.1 kg/m³ in drip irrigation, and by micro sprinkler 100% m –50.5 kg/m³, 80% m – 51 kg/m³. On average for the two years, yield losses in the 80% and 60% m variants, as well as the no-irrigation option, are - 14.5%, 22.7% and 75.5% - for drip irrigation, and micro sprinkler, respectively - 13.8 %, 22.1% and 75.9%.

Table 4.

Productivity of the irrigation rate and yield losses as a result of the water deficit on average for the year 2020 - 2021 with drip irrigation

Variant	Total yield	Additional yield		Yield losses		Irrigation rate		Productivity of the irrigation rate
	kg/da	kg/da	%	kg/da	%	mm	%	kg/m³
100%m	5672	4282	487,2	St.	St.	83	100	53,3
80%m	4853	3463	419,3	-819	85,5	66,4	80	53,1
60%m	4384	2994	370,0	-1288	77,3	49,8	60	62,2
non-irrigated	1390	St.	St.	-4282	24,5	0	-	-

Table 5.

Productivity of the irrigation rate and yield losses as a result of the water deficit on average for the year 2020 - 2021 with micro sprinkler

Variant	Total yield	Additional yield		Yield losses		Irrigation rate		Productivity of the irrigation rate
	kg/da	kg/da	%	kg/da	%	mm	%	kg/m³
100%m	5757	4367,5	495,1	St.	St.	88,5	100	50,5
80%m	4963	3573,5	429,5	-794	86,2	70,8	80	51,0
60%m	4481	3091,5	380,0	-1276	77,9	53,1	60	59,5
non-irrigated	1390	St.	St.	- 4367	24,1	-	-	-

The application of a differentiated irrigation regime through a micro-irrigation system leads to a change in the efficiency of the irrigation rate. This change is in the range of 15 to 18% and shows that regardless of the magnitude of the reduction in water volumes and the technique by which this reduction is achieved, the efficiency is of this order.

4. Relationship „Yield – Irrigation rate“

The dependence is determined based on the data on the relative yield and the relative irrigation rate. By the method of the least squares, with the help of the program product "YIELD", the parameters of the ralationship are determined according to the formulas presented in the methodical part, both for drip irrigation and micro sprinkler.

4.1 Relationship „Yield – Irrigation rate" at drip irrigation

Establishing the relationship "Yield - Irrigation norm" for lettuce grown in conditions of water deficit is necessary to analyze the effectiveness of applying an irrigation regime, the way of its realization, and forecasting the potential yields of the crop under similar conditions.

The raw data needed to calculate dependence are presented in Table 6, both by year and averaged over the study period.

Table 6.

Initial data for establishing the relationship "Water - Yield" at drip irrigation

Year	Variant	Y kg/da	ΔY kg/da	$\frac{Y}{Yo}$	$\frac{\Delta Y}{\Delta Yo}$	$\frac{M}{M_0}$
2020	100% m	5573	3634	1	1	1
	80% m	4693	2754	0,842096	0,757843	0,8
	60% m	4500	2561	0,807465	0,704733	0,6
	non-irrigated	1939	0	0,347928	0	0
2021	100% m	5770	4930	1	1	1
	80% m	5012	4172	0,868631	0,846247	0,8
	60% m	4267	3427	0,739515	0,695132	0,6
	non-irrigated	840	0	0,145581	0	0
average	100% m	5672	4282	1	1	1
	80% m	4853	3463	0,855594	0,808734	0,8
	60% m	4384	2994	0,7729	0,699206	0,6
	non-irrigated	1390	0	0,244997	0	0

**Y – Yield; ΔY – Additional yield; Y/Y_0 – relative total yield; $\Delta Y/\Delta Y_0$ – relative-additional yield; M/M_0 – relative irrigation norm*

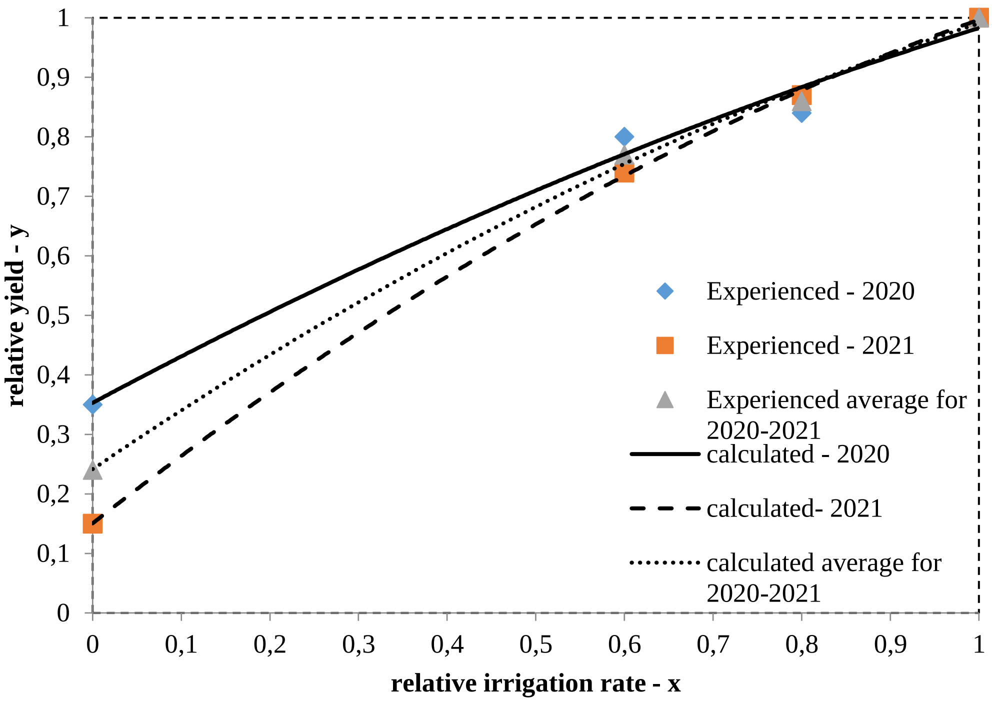
4.1.1 Relationship "Total yield - Irrigation rate" at the drip irrigation, expressed by the regression equation - $y = ax^2 + bx + c$

The relationship "Total yield - irrigation rate" was established by regression analysis of the experimental data using the software product "Microsoft Office Excel". The obtained results by year and averaged over the experimental period are presented graphically in Figure 1, and the derived equations and coefficient of determination values are presented in Table 7.

Convex parabolas expressed by an equation of the second degree ($y = ax^2 + bx + c$) very accurately express the dependence, approximating the experimental data with a very high coefficient of determination $R^2 > 0.99$, both by years and averaged over the experimental period (Table 7).

Figure 1.

Relationship "Total yield - irrigation rate" according to the equation - $y = ax^2+bx+c$, with drip irrigation



According to the obtained curves, with a rate of 80-85% m, the yield can reach 90-95% of the maximum for the corresponding year. On average for the experimental period, when irrigating salad plants with 50% m, 78% of the maximum yield can be reached. Using the resulting quadratic equation, it can be predicted that even with an increase in the irrigation rate by 50% of the average maximum, the yield will increase by 18%, which from the point of view of efficient use of water is not recommended.

Table 7.

Parameters of the relationship "Total yield - irrigation rate" according to the equation: $y = ax^2 + bx + c$, in drip irrigation

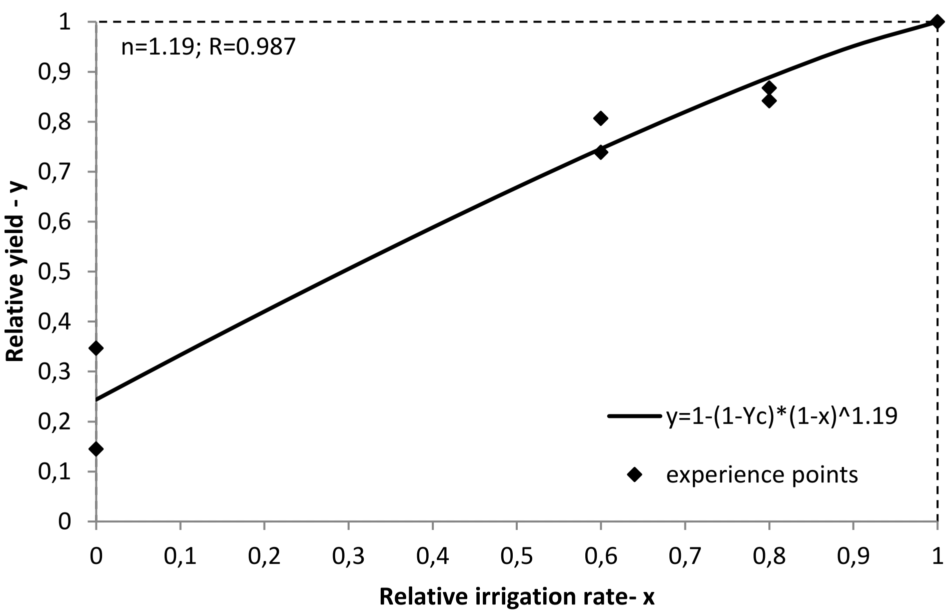
Year	$y = ax^2 + bx + c$	R^2
2020	$y = -0{,}1678x^2 + 0{,}7975x + 0{,}3529$	0,987
2021	$y = -0{,}2645x^2 + 1{,}0137x + 0{,}2415$	0,997
Average	$y = -0{,}3177x^2 + 1{,}1638x + 0{,}1506$	0,999

4.1.2 Relationship "Total yield - irrigation rate" in drip irrigation, expressed by Davidov's formula – $y = 1-(1-Y_c)(1-x)^n$

The relationship between the total yield and the irrigation rate, averaged over the experimental period, determined by Davydov's one-step formula is presented in Figure 2. Graphically, the relationship is described by a curve representing a convex parabola that averages the experimental points at a power indicator n = 1.19, and a very high correlation coefficient R = 0.987. According to the obtained curve, when 80-85% of the optimal rate (100% m) is realized, a yield of 90-95% of the maximum can be obtained.

Figure 2.

The relationship "Relative yield - relative irrigation rate", expressed by Davidov's formula $y = 1-(1-Yc)(1-x)^n$, with drip irrigation



4.2 Relationship „Yield – Irrigation rate“ at micro sprinkler

Table 8 presents the input data needed to calculate the dependency.

Table 8.

Initial data for establishing the relationship "Water - Yield" at micro sprinkler

Year	Variant	Y kg/da	ΔY kg/da	$\frac{Y}{Yo}$	$\frac{\Delta Y}{\Delta Yo}$	$\frac{M}{M_0}$
2020	100% m	5640	3702	1	1	1
	80% m	4783	2845	0,84805	0,768504	0,8
	60% m	4547	2609	0,806206	0,704754	0,6
	non-irrigated	1938	0	0,343617	0	0
2021	100% m	5873	5033	1	1	1
	80% m	5142	4302	0,875532	0,854759	0,8
	60% m	4414	3574	0,751575	0,710113	0,6
	non-irrigated	840	0	0,143027	0	0
average	100% m	5757	4367,5	1	1	1
	80% m	4963	3573,5	0,862069	0,818203	0,8
	60% m	4481	3091,5	0,778338	0,707842	0,6
	non-irrigated	1389	0	0,241292	0	0

**Y – Yield; ΔY – Additional yield; Y/Y_0 – relative total yield; $\Delta Y/\Delta Y_0$ – relative-additional yield; M/M_0 – relative irrigation norm*

4.2.1 Relationship "Total yield - Irrigation rate" at the micro sprinkler, expressed by the regression equation – $y = ax^2 + bx + c$

As mentioned in the case of drip irrigation, here also the relationship "Total yield - irrigation rate" was established by regression analysis of the experimental data by years and an average of the experimental period, presented in Figure 3. The derived equations and coefficients of determination are presented in Table 9.

Graphically, the dependence both by years and on average for the experimental period is expressed by curves, convex parabolas subject to the equation – $y = ax^2 + bx + c$, and the same approximates the experimental data with a very high coefficient of determination – for the year 2020 – $R^2 = 0.989$; for 2021 – $R^2 = 0.996$; average for the experimental period – $R^2 = 0.999$ (Table 9).

According to the curves describing the dependence when realizing a rate of 80% m, the yield obtained is 90% of the maximum.

Figure 3.

Relationship "Total yield - irrigation rate " according to the equation – $y = ax^2+bx+c$, with micro sprinkler

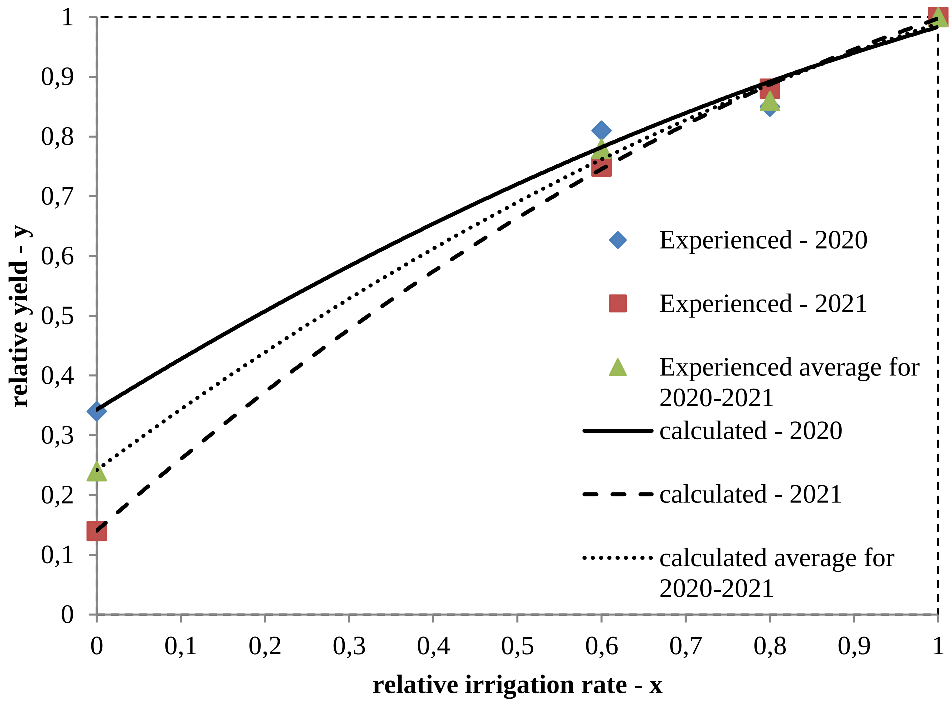


Table 9.

Parameters of the relationship "Total yield - irrigation rate " according to the equation: $y = ax^2 + bx + c$, in micro sprinkler

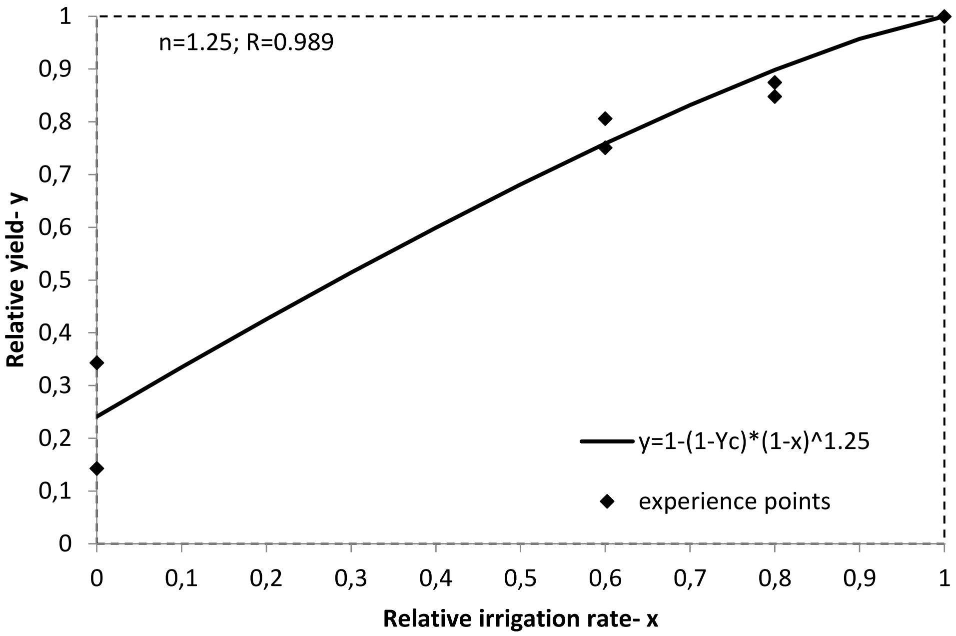
Year	$y = ax^2 + bx + c$	R^2
2020	$y = -0{,}2293x^2 + 0{,}8698x + 0{,}3428$	0,989
2021	$y = -0{,}2983x^2 + 1{,}0456x + 0{,}2418$	0,996
Average	$y = -0{,}3791x^2 + 1{,}236x + 0{,}1404$	0,999

4.2.2 Relationship "Total yield - irrigation rate " in micro sprinkler, expressed by Davidov's one-step formula – $y = 1-(1-Y_c)(1-x)^n$

The convex parabola presented in Figure 4 averages the experimental points very well at a exponent n = 1.25 and a very high correlation coefficient R = 0.989. According to the obtained curve, the yield can reach 90-95% of the maximum, only at a rate of 90% m.

Figure 4.

The relationship "Relative yield - relative irrigation rate ", expressed by Davidov's one-step formula $y = 1-(1-Yc)(1-x)^n$, with micro sprinkler



The productivity of the lettuce, as it was already proven, is largely influenced by the applied irrigation regime. It is also confirmed by the derived dependencies for the relationship between the relative decrease in yield compared to the relative decrease in the irrigation rate. The derived dependence, which is expressed by an equation of the second degree, allows predicting the possible reduction of the yield when supplying smaller amounts of water compared to those defined as maximum.

5. Evapotranspiration

5.1 Influence of regulated irrigation regime on total and daily mean evapotranspiration values

Maximum ET, averaged over the experimental period, was obtained for the 100% m treatments under both irrigation techniques. In the non-irrigated variant, there was a decrease in the cumulative ET by 38.7% and 42.4% under drip irrigation and micro sprinkler, respectively (Table 10). The application of a regulated irrigation regime with irrigation rates of 60% and 80% m, resulted in a decrease in the water consumption of lettuce plants. By reducing the irrigation rate by 20% of the optimum rate, a reduction of only 7.2% was achieved with drip irrigation and 9.8% with micro sprinkler. The resulting reduction in the cumulative ET for the 60% m drip-irrigated variant was 20.7% and 22.9% for the micro sprinkler variant, respectively, with almost the same percentage reduction (22.7% for drip irrigation and 22.1% for micro sprinkler) in yield losses for the respective irrigation technique.

Table 10.

Total evapotranspiration of lettuce by drip irrigation and micro sprinkler variants on average for 2020 - 2021

2020-2021	**Drip irrigation**				**Micro sprinkler**			
	Variants				**Variants**			
Indicators	**100% m**	**80% m**	**60% m**	**non-irrigated**	**100% m**	**80% m**	**60% m**	**non-irrigated**
ET, mm	108,6	100,8	86,1	66,6	115,6	104,3	89,1	66,6
Compared to variant 100% m, %	100	92,8	79,3	61,3	100	90,2	77,1	57,6
Compared to the non-irrigated variant, %	163,2	151,5	129,4	100	173,6	156,6	133,9	100,0

5.2 Average day/night movement of ET

The averaged values for the two experimental years, graphically presented in Figures 5 and 6, show that in the second ten days of May, the daily average evapotranspiration values under both irrigation techniques reached their maximum.

This same period is characterized by an intensive growth of the leaf rosette and the turning of the heads of lettuce plants. The mean daily ET values for the optimally irrigated variants were 3,25 mm and 3,35 mm for drip irrigation and micro sprinkler, respectively. The 80% m treatments had the corresponding maximum daily mean ET values of 2.95 mm and 2.85 mm under drip irrigation and micro sprinkler, and the 60% m treatments had 2.6

mm and 2.55 mm, respectively. The maximum daily mean ET value for the non-irrigated variant was 2.15 mm.

Figure 5.
Average day/night movement of ET in 2020-2021 at drip irrigation

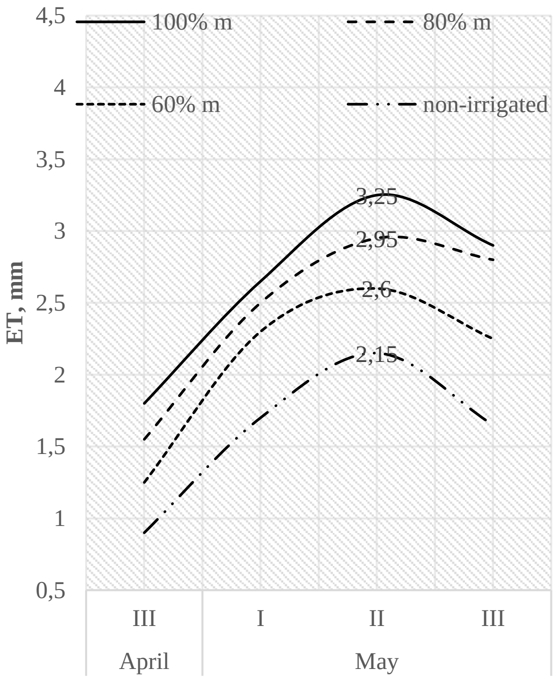
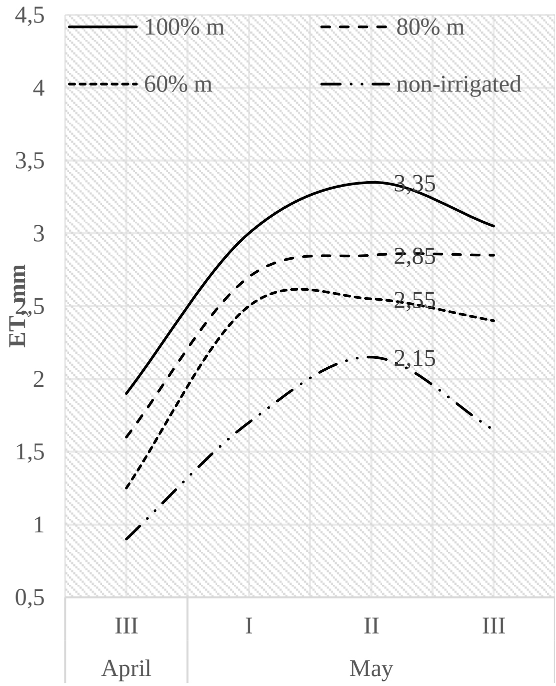


Figure 6.
Average day/night movement of ET in 2020-2021 at micro sprinkler



5.3 Mean decadal course of ET expressed by regression equations under drip irrigation, averaged over the experimental period

The results obtained by regression analysis of the experimental data by variance for the average decadal run of ET, averaged over the study period, are presented graphically in Figure 7, and the derived equations and coefficients of determination (R^2) are plotted in Table 11.

Graphically, the decadal mean course of ET during the growing season of the crop, by variant, is expressed by curved, convex parabolas expressed by a second-degree equation of the form: $y = ax^2+bx+c$ (Figure 7). These approximate the experimental data with a very high coefficient of determination (Table 11).

Figure 7.

The average decadal trend of ET under drip irrigation

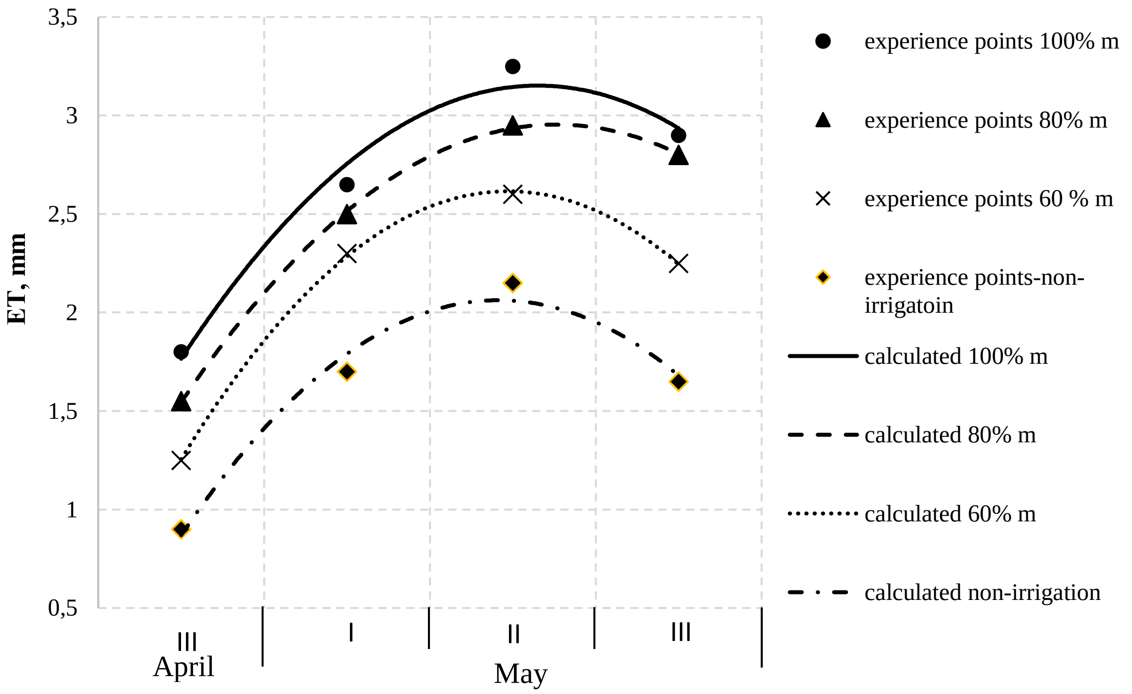


Table 11.

Regression equations and coefficients of determination for drip irrigation by variants averaged over 2020-2021

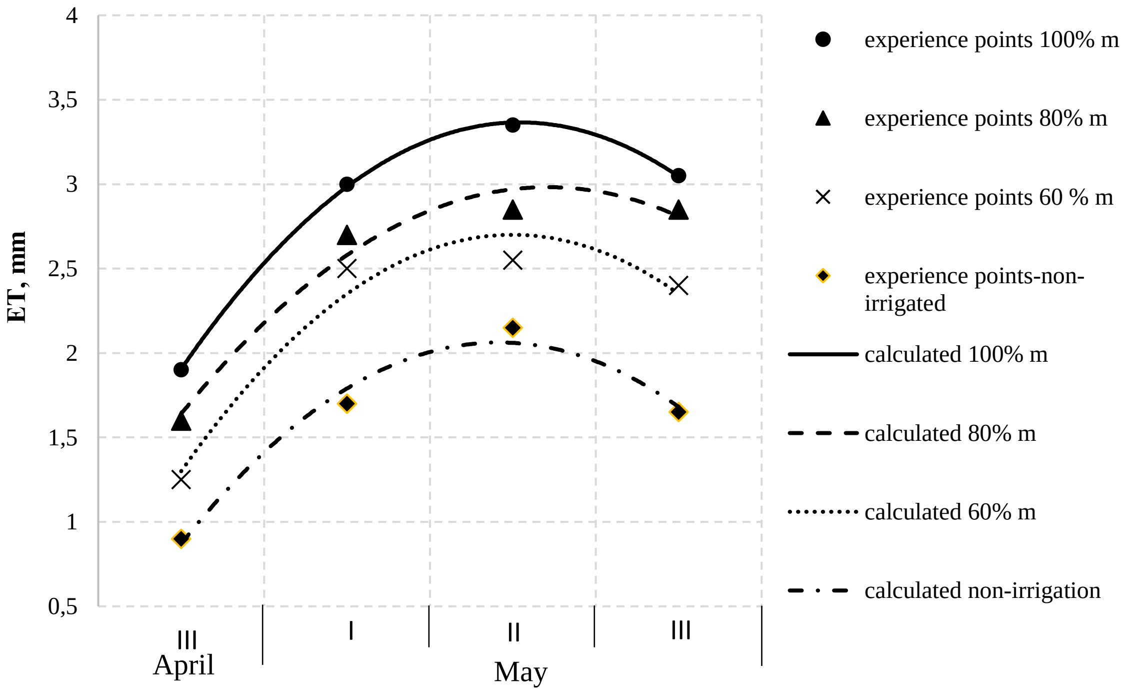
Variant	Regression of type: $y = ax^2+bx+c$	R^2
100% m	$y = -0,3x^2+1,89x+0,175$	0,979
80% m	$y = -0,275x^2+1,795x+0,025$	0,999
60% m	$y = -0,35x^2+2,08x-0,475$	0,999
non-irrigation	$y = -0,325x^2+1,895x-0,7$	0,978

5.4 Mean decadal course of ET expressed by regression equations under micro sprinkler, averaged over the experimental period

As with drip irrigation, the results obtained by regression analysis of the experimental data, by variant, are presented graphically in Figure 8 and the derived equations and coefficients of determination (R^2) in Table 12.

Figure 8.

Average decadal trend of ET under microsprinkler



The mean decadal course of ET during the growing season of a crop, expressed by curved, convex parabolas expressed by a quadratic equation of the form: $y = ax^2 + bx + c$, describes very well the variation of water use of lettuce plants by variants (Figure 8). As the same approximates the experimental data with a very high coefficient of determination, in the 100% m variant it is R^2=0.999; followed by the 80% m variant - R^2=0.971; 60% m - R^2=0.957 and the non-irrigated variant - R^2=0.978 (Table 12).

Table 12.

Regression equations and coefficients of determination for micro sprinkler by variants averaged over 2020-2021

Variant	Regression of type: $y = ax^2+bx+c$	R^2
100% m	$y = -0,35x^2+2,13x+0,125$	0,999
80% m	$y = -0,275x^2+1,765x+0,15$	0,971
60% m	$y = -0,35x^2+2,1x-0,45$	0,957
non-irrigation	$y = -0,325x^2+1,895x-0,7$	0,978

5.5 Formation of ET

The formation of evapotranspiration depends on the climatic characteristics of a given year, as well as on the irrigation regime applied and the specific crop.

Table 13 and Table 14 present the elements (water storage - W, usable precipitation – N, and irrigation norm - M), forming the evapotranspiration of lettuce for the 0-20 m layer.

Table 13.

Formation of ET under drip irrigation

	Variants		*ET*	*W*	*N*	*M*
2020	***100%m***	mm	106,6	4	41,6	61
		%	100	3,8	39,0	57,2
	80%m	mm	96,4	3,8	43,8	48,8
		%	100	3,9	45,4	50,6
	60%m	mm	86,7	3,5	46,6	36,6
		%	100	4,0	53,7	42,2
	non-irrigated	mm	69,6	7	62,6	-
		%	100	10,1	89,9	
2021	***100%m***	mm	110,6	3	2,6	105
		%	100	2,7	2,4	94,9
	80%m	mm	105,2	3,3	17,9	84
		%	100	3,1	17,0	79,8
	60%m	mm	85,5	2,8	19,7	63
		%	100	3,3	23,0	73,7
	non-irrigated	mm	63,5	22,1	41,4	-
		%	100	34,8	65,2	

Table 14.

Formation of ET under micro sprinkler

	Variants		*ET*	*W*	*N*	*M*
2020	***100%m***	mm	113,2	4,2	42	67
		%	100	3,7	37,1	59,2
	80%m	mm	101,8	3,9	44,3	53,6
		%	100	3,8	43,5	52,7
	60%m	mm	89,4	3,5	45,7	40,2
		%	100	3,9	51,1	45,0
	non-irrigated	mm	69,6	7	62,6	-
		%	100	10,1	89,9	
2021	***100%m***	mm	117,9	4,1	3,8	110
		%	100	3,5	3,2	93,3
	80%m	mm	106,7	3,9	14,8	88
		%	100	3,7	13,9	82,5
	60%m	mm	88,8	3,5	19,3	66
		%	100	3,9	21,7	74,3
	non-irrigated	mm	63,5	22,1	41,4	-
		%	100	34,8	65,2	

In the first and second experimental years, under the optimally irrigated treatments, irrigation rates played a major role in shaping evapotranspiration under both irrigation techniques (Tables 13 and 14).

In percentage, it occupies 57.2% and 94.9% in 2020 and 2021 under drip irrigation, and 59.2% and 93.3% under micro sprinkler, respectively. This significant difference can be explained in terms of rainfall availability during the growing season, with 2020 characterized as moderately wet and 2021 as moderately dry. The percentage of usable rainfall in the first year is 39% for drip irrigation and 2.4% in the second year, and 37.1% and 3.2% for micro sprinkler. The participation of water storage in both irrigation techniques is minimal, with 3.8% in drip irrigation and 3.7% in micro sprinkler in 2020, and 2.7% and 3.5% in 2021, respectively.

When reducing by 20% the rates compared to the optimal variant - 100% m, in both irrigation techniques, the trend is maintained as in percentage terms a higher share in the formation of ET is occupied by the irrigation rate. For drip irrigation it is 50.6% for 2020 and 79.8% for 2021, for micro sprinkler it is 52.7% and 82.5% respectively. Under this option, there is an increase in usable rainfall approaching the irrigation rates in percentage - 45.4% in the first year for drip irrigation and 43.5% for micro sprinkler. In the second year, the proportion of usable rainfall was comparatively lower than in the first year, at 17% for drip irrigation and 13.9% for micro sprinkler. There is a slight increase in the share of water storage in drip irrigation in 2020 which is 3.9% and in micro sprinkler 3.8%, and in 2021 3.1% and 3.7% respectively (Table 13 and 14).

In the 60% m variant, in the first experimental year, usable rainfall had a higher impact on ET formation under both irrigation techniques. In drip irrigation, it was 53.7% and in micro sprinkler 51.1%, followed by irrigation rate 42.2% and 45%, respectively, and the participation of water reserve was 4% and 3.9%. In the second crop year, the rainfall was double that of the first crop year, so the irrigation rate dominated the ET formation. In drip irrigation, the percentage share was 73.7% and in micro sprinkler 74.3%. Usable rainfall in drip irrigation and micro sprinkler occupied respectively - 23% and 21.7%, and water storage - 3.3% and 3.9% (Tables 13 and 14).

In the non-irrigated option, ET formation is entirely due to usable vegetation precipitation. In the first year they occupy 89.9% and in the second year 65.2%, with the participation of the water stock being 10.1% and 34.8%, respectively (Tables 13 and 14).

5.6 Productivity of ET

The ET productivity is the ratio of the yield obtained per unit area when 1 mm of water is used. Table 15 presents the data needed to calculate this indicator, averaged over the experimental period.

On average over the experimental period, the highest ET productivity was obtained under drip irrigation, 52.22 kg/m^3 when 100% m was realized. The 60% m variant in both irrigation techniques, reported almost equal productivity, respectively for drip irrigation -

50.9 kg/m^3, for micro sprinkler - 50.28 kg/m^3. The productivity of the 80% m variant was very similar on average over the experimental years, 48.16 kg/m^3 for drip irrigation; 47.59 kg/m^3 for micro sprinkler, respectively. The lowest productivity was calculated for the non-irrigated variant (Table 15).

Table 15.

ET productivity under drip irrigation and micro-irrigation averaged over the experimental period

2020-2021	Drip irrigation				Micro sprinkler			
	Variants				*Variants*			
	100% m	*80% m*	*60% m*	*non-irrigated*	*100% m*	*80% m*	*60% m*	*non-irrigated*
Yield, (kg/da)	5672	4853	4384	1390	5757	4963	4481	1390
ET, (mm)	108,6	100,8	86,1	66,55	115,55	104,25	89,1	66,55
Productivity of ET (kg/m³)	52,22	48,16	50,90	20,54	49,82	47,59	50,28	20,54

6. Relationship „Yield – ET"

To establish the impact of water stress conditions created by the applied irrigation regimes with a reduction in irrigation rates, the „Yield-Evapotranspiration" relationship was investigated.

6.1 Drip irrigation

Table 16 presents the initial data for yield and total ET in drip irrigation, with the help of which the relationship "Yield - ET" was established. With the program product "YIELD", the experimental data for relative yield and relative ET were processed by the method of the least squares. The optimal variant – 100% m, where the highest yield was obtained, was accepted as a unit.

Table 16.

Baseline data for the "Yield - ET" relationship in drip irrigation

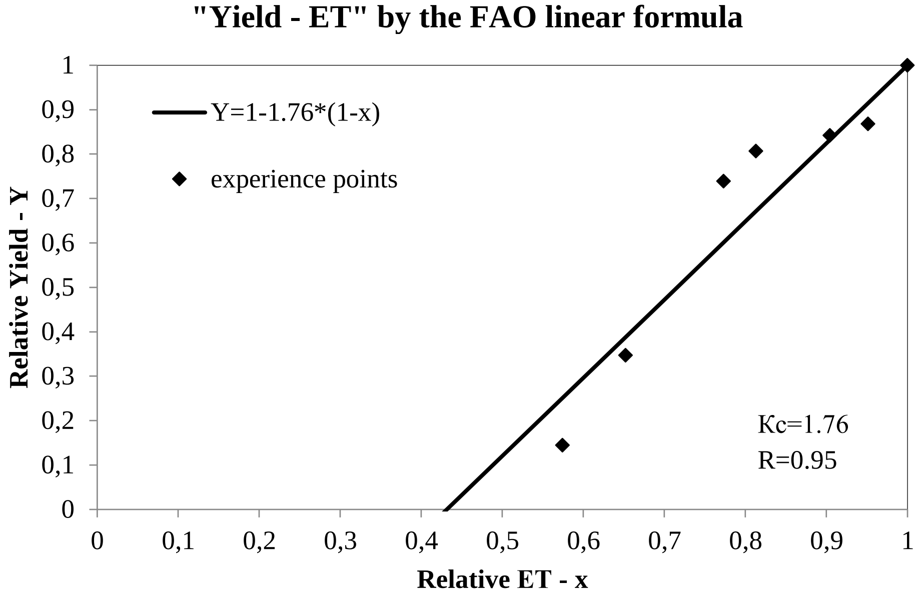
Year	*Variant*	*Y* kg/da	$\frac{Y}{Yo}$	*ET, mm*	$\frac{ET}{ETo}$
2020	*100%m*	5573	1	106,6	1
	80%m	4693	0,84	96,4	0,90
	60%m	4500	0,81	86,7	0,81
	non-irrigated	1939	0,35	69,6	0,65
2021	*100%m*	5770	1	110,6	1,00
	80%m	5012	0,87	105,2	0,95
	60%m	4267	0,74	85,5	0,77
	non-irrigated	840	0,15	63,5	0,57
average	*100%m*	5672	1,00	108,6	1,00
	80%m	4853	0,86	100,8	0,93
	60%m	4384	0,77	86,1	0,79
	non-irrigated	1390	0,24	66,55	0,61

**Y – yield; Y/Y_0 – relative total yield; ET – total evapotranspiration; ET/ET_0 – relative total evapotranspiration*

6.1.1 Relationship "Yield - ET" in drip irrigation, using the FAO formula

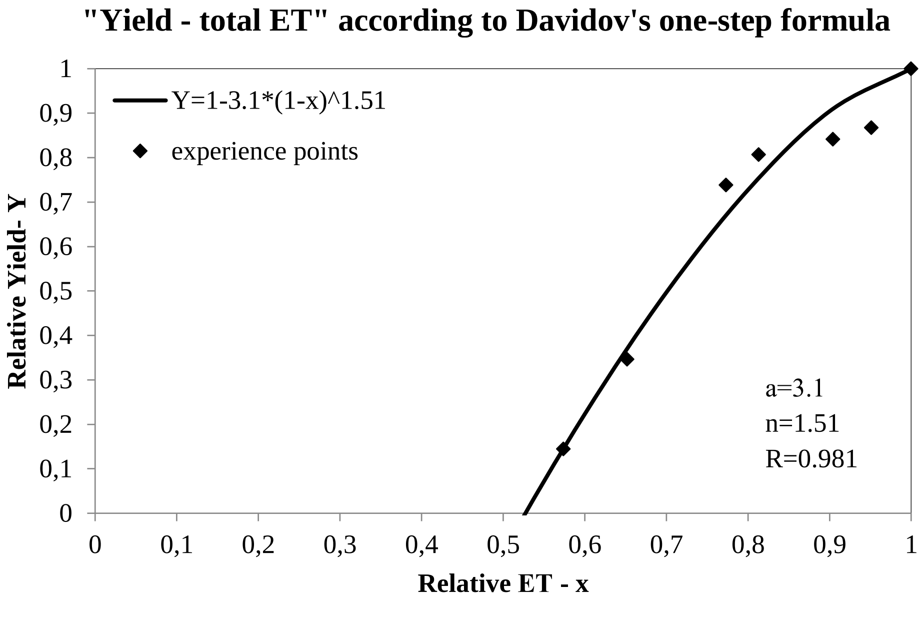
Figure 9 presents the summary experimental data, both by year and average experimental period, averaged with the FAO linear function. The yield coefficient is Ks = 1.76, which means that to obtain some, even minimal yield, the water consumption must be about 40-45%, compared to the maximum, and in this particular case it is compared to the reported highest values of ET in the optimal option – 100% m. The correlation coefficient is very high R = 0.95.

Figure 9.



6.1.2 Relationship "Yield - ET" under drip irrigation, according to Davidov's one-step formula

Figure 10.



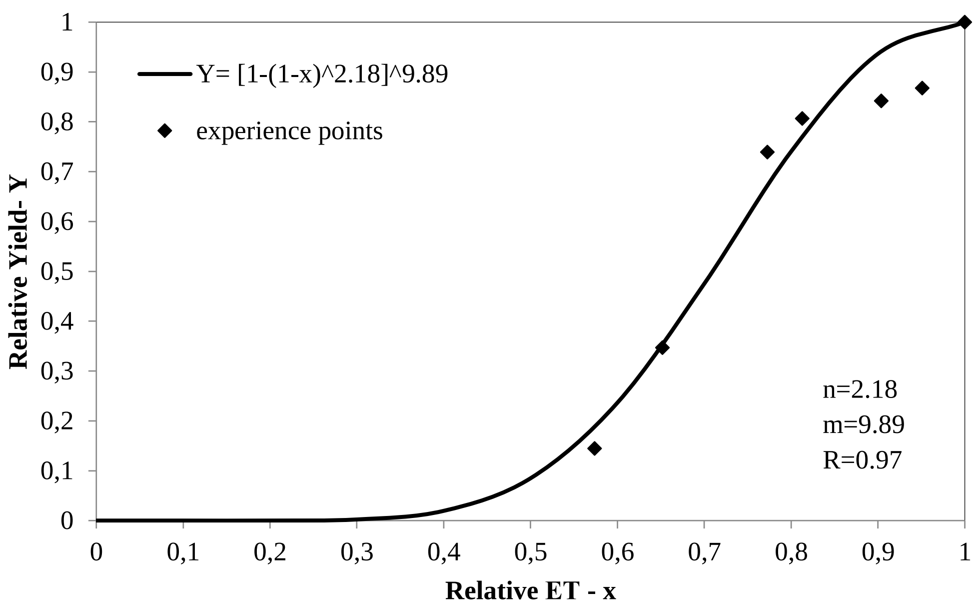
Graphically, the dependence is expressed through a parabola, which makes it possible to predict what the yield would be at a specific value of ET. The yield coefficient obtained from the formula is – a=3.1, and the exponent – n=1.51 and a very high correlation coefficient R=0.981 (Figure 10). With the dependence obtained in this way, minimum yield can be obtained at values above 50-55% of the maximum water consumption.

6.1.3 „Yield-total ET“ relationship for drip irrigation, using Davidov's two-step formula

The formula was used to calculate the degree indices n=2.18, and m=9.89, again obtaining a high correlation coefficient R=0.97. The results are graphically depicted in Figure 11, represented by an S-shaped curve that accounts for the smooth change in relative yield with increasing relative total evapotranspiration.

Figure 11.

"Yield - ET" according to Davidov's two-step formula



The highest correlation coefficient was obtained when yield and ET data for lettuce were analyzed using Davidov's one-step formula.

6.2 Micro sprinkler

The dependence on the micro sprinkler was also determined based on the relative yield and relative ET data, again using the YIELD software presented in Table 17. The optimal variant, 100% m, was taken as the unit, which gave the highest yield.

Table 17.

Baseline data for the "Yield - ET" relationship in micro sprinkler

Year	*Variant*	*Y* kg/da	$\frac{Y}{Yo}$	*ET, mm*	$\frac{ET}{ETo}$
2020	*100%*	5640	1	113,2	1
	80%	4783	0,85	101,8	0,90
	60%	4547	0,81	89,4	0,79
	non-irrigated	1938	0,34	69,6	0,61
2021	*100%*	5873	1	117,9	1
	80%	5142	0,88	106,7	0,91
	60%	4414	0,75	88,8	0,75
	non-irrigated	840	0,14	63,5	0,54
average	*100%*	5757	1	115,6	1
	80%	4963	0,86	104,3	0,90
	60%	4481	0,78	89,1	0,77
	non-irrigated	1389	0,24	66,6	0,58

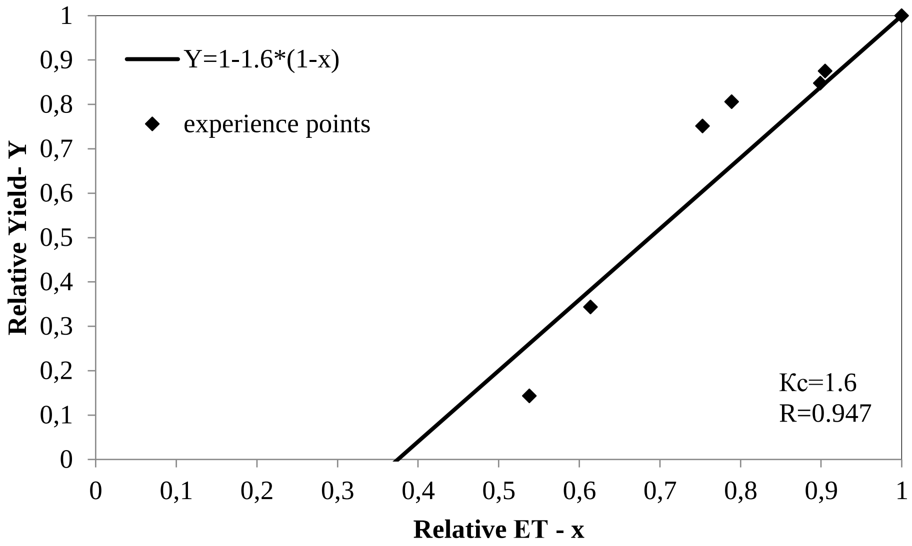
**Y – yield; Y/Y_0 – relative total yield; ET – total evapotranspiration; ET/ET_0 – relative total evapotranspiration*

6.2.1 Relationship "Yield - ET" in micro sprinkler, using the FAO formula

Graphically, the linear dependence of FAO, under micro sprinker is plotted in Figure 12, with averaged data both by year and averaged over the experimental period. The resulting yield coefficient is Kc = 1.6, with a high correlation coefficient of R = 0.947. In contrast to drip irrigation, from the results obtained with micro sprinker, it can be reported that to obtain a minimum yield, the total ET must be in the range of 35-40%, relative to the maximum.

Figure 12.

"Yield - total ET" by the FAO linear formula

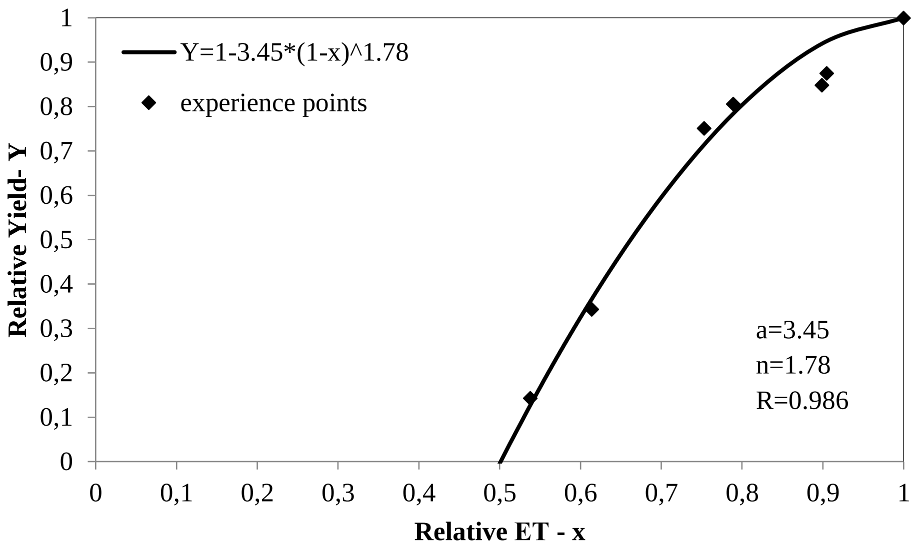


6.2.2 Relationship "Yield - total ET" under micro sprinker, according to Davidov's one-step formula

Figure 13 shows the relationship between relative yield and relative total ET, again using the averaged data as in the FAO formula, but calculated using Davidov's one-step formula. Graphically, the relationship is expressed by a parabola. The yield coefficient obtained from the formula is a=3.45, with a step-index of n=1.78 and a very high correlation coefficient of R=0.986, indicating that 50% of the maximum water consumption is required to obtain the minimum yield.

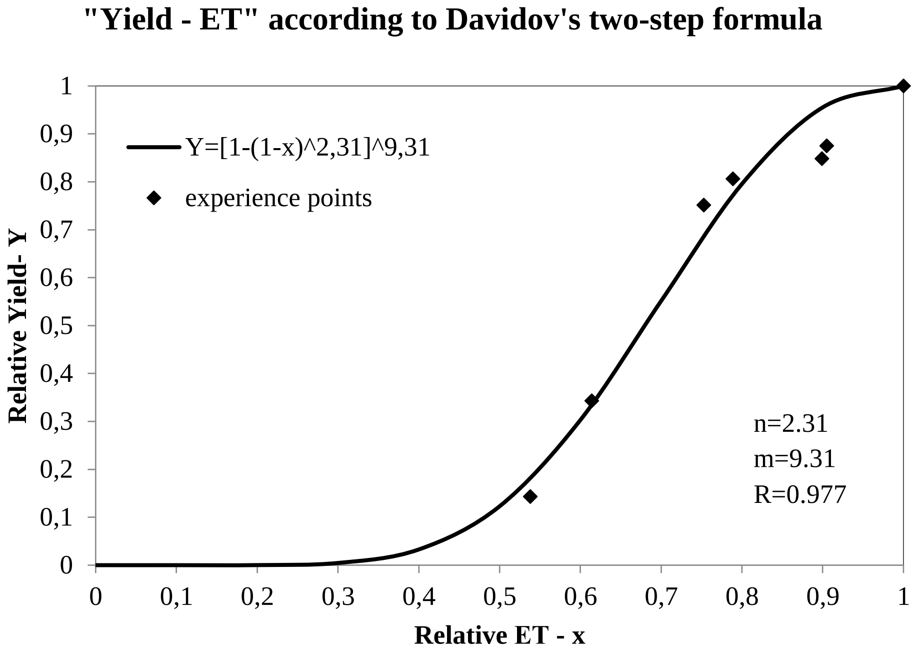
Figure 13.

"Yield - total ET" according to Davidov's one-step formula



6.2.3 „Yield - ET“ relationship for micro sprinker, using Davidov's two-step formula

Figure 14.



The same experimental data used in the previous formulas were processed using Davidov's two-step formula. The degree indices n=2.31, and m=9.31, with a high correlation coefficient R=0.977 were calculated. The results are graphically plotted with an S-shaped curve presented in Figure 14, accounting for the variation of relative yield with change in relative total ET, which increases the accuracy of the approximation.

7. Biophysical coefficients

7.1 Values of the biophysical coefficient Z

The biophysical coefficient Z also referred to as the total water use coefficient was determined based on the actual evapotranspiration of the crop grown and the temperature sume during the growing season.

The variation of the actual ET, respectively for drip irrigation and micro sprinkler, during the growing season is also reflected in the obtained averaged values of the biophysical Z factor, graphically presented in Figures 15 and 16.

Figure 15.
Value of the biophysical coefficient Z, averaged over the experimental period, under drip irrigation

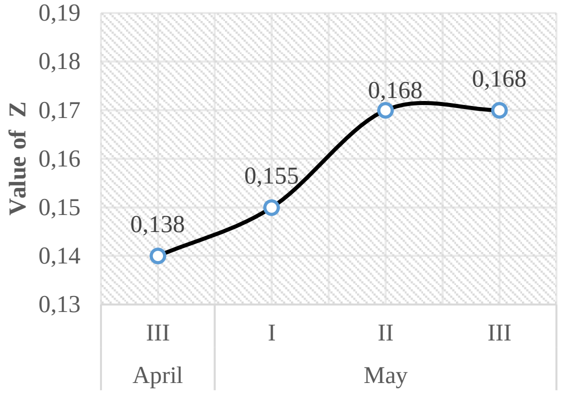
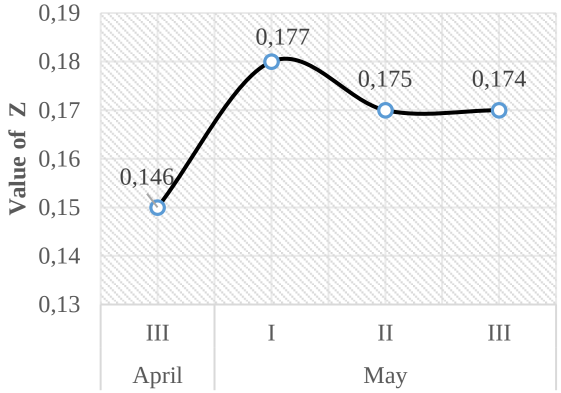


Figure 16.
Value of the biophysical coefficient Z, averaged over the experimental period, under micro sprinkler



7.2 Values of the biophysical coefficient R

The deficiency of air saturation with water vapor is an important and determining factor in the course of evapotranspiration. Using the coefficient R, many authors recommend it for the indirect determination of ET.

The dynamics of the air-water vapor saturation deficit during the experimental years, irrespective of the irrigation technique, is reflected in the averaged values of the R factor presented in Figures 17 and 18.

Figure 17.
Value of the biophysical coefficient R, averaged over ten days over the experimental period, under drip irrigation

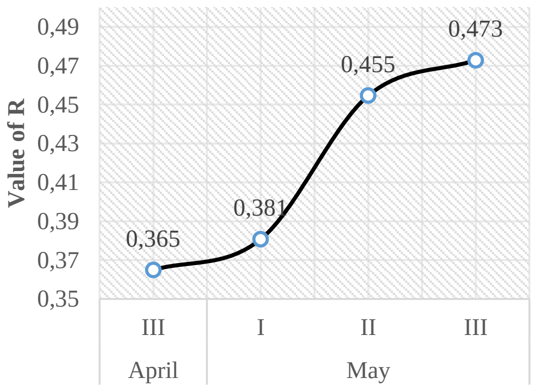
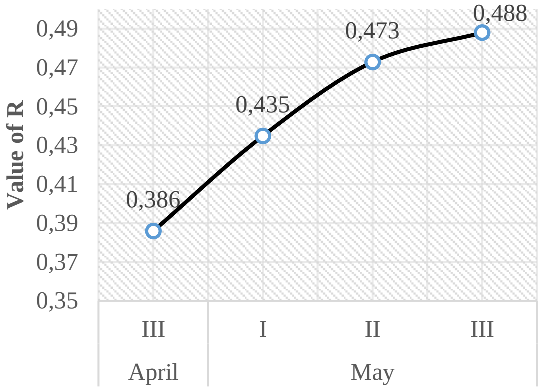


Figure 18.
Value of the biophysical coefficient R, averaged over ten days over the experimental period, under drip irrigation micro sprinkler



7.3 Values of the biophysical coefficient Kc

Evapotranspiration (ETo) is an indicator of the evaporative power of the atmosphere and is calculated for a crop table that reflects the potential of the medium to evaporate water according to the climatic conditions during the growing season.

On average over the experimental period, the increase in the Kc coefficient during the growing season is presented in Figures 19 and 20, reaching maximum values in the second ten days of May, 1.31 and 1.355 for drip irrigation and micro sprinkler, respectively. From the analysis, it can be concluded that crop water use is crucial in forming the values of the Kc coefficient.

Figure 19.
Value of the biophysical coefficient Kc, averaged over ten days over the experimental period, under drip irrigation

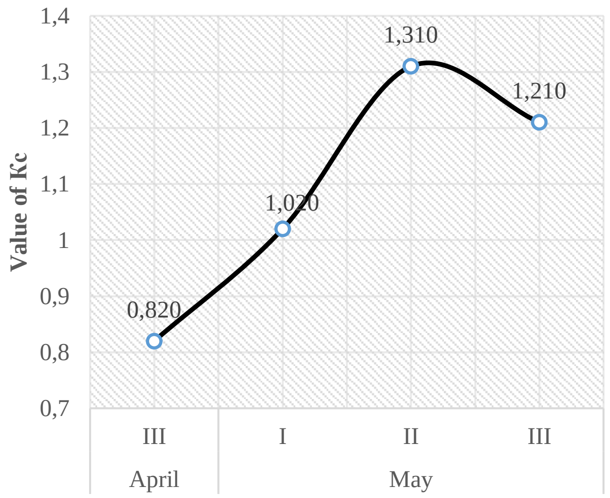
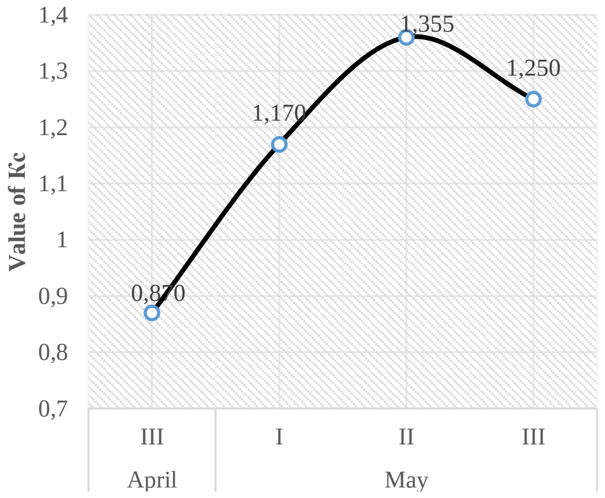


Figure 20.
Value of the biophysical coefficient Kc, averaged over ten days over the experimental period, under micro sprinkler



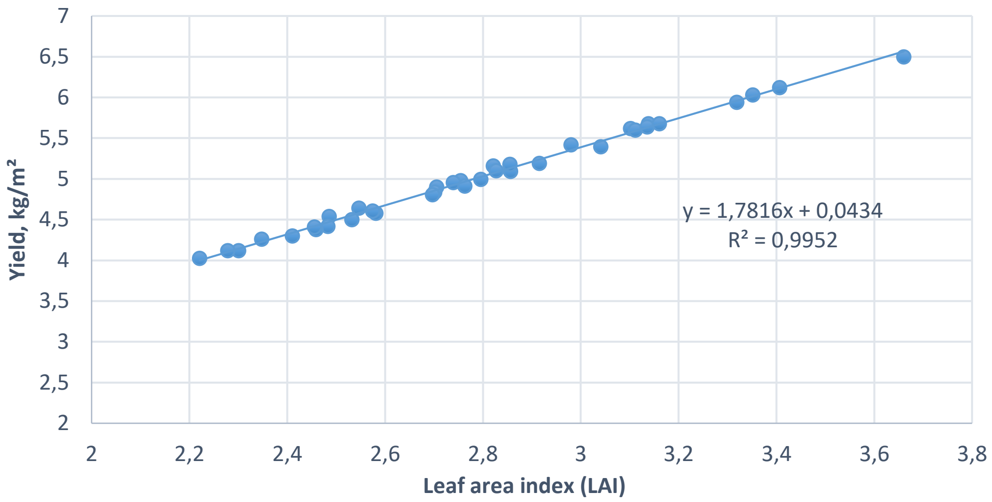
8. Influence of the regulated irrigation regime on leaf area (LA) and leaf area index

Using all the experimental data across treatments, years, and irrigation techniques, a relationship between leaf area index (LAI) and yield was derived and presented in Figure 21.

The latter is best expressed by a linear equation of the form y=1.7816x+0.434, with a very high coefficient of determination (R^2=0.995), where *x* is LAI and *y* is yield. Using the equation from the graph, one can predict the yield depending on how the foliage develops and what the LAI value is, and the accuracy is very high.

Figure 21.

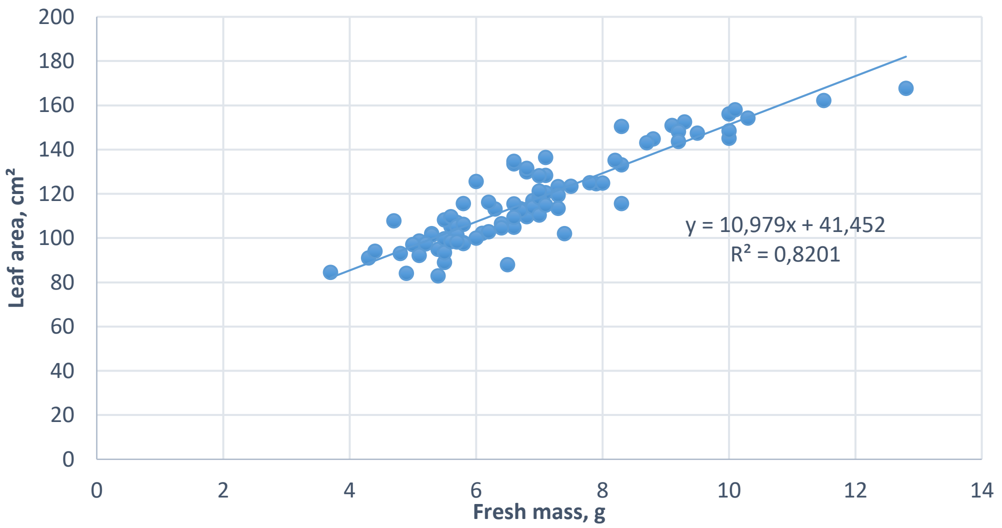
Relationship between LAI and yield



In the course of the processing and analysis of the experimental data, some useful dependencies were also identified for practice, which would facilitate the procedures related to the establishment of some indicators. For example, leaf area recording is important for obtaining information on photosynthetic performance and general plant condition, but at the same time, it is a complex and labor-intensive process. For this purpose, a relationship has been established that allows for a quick and easy determination of the leaf area (LA) of lettuce based on leaf mass data. According to the results, the mass of fresh leaves (Figure 22), as well as that of dry leaves (Figure 23) can be used.

Figure 22.

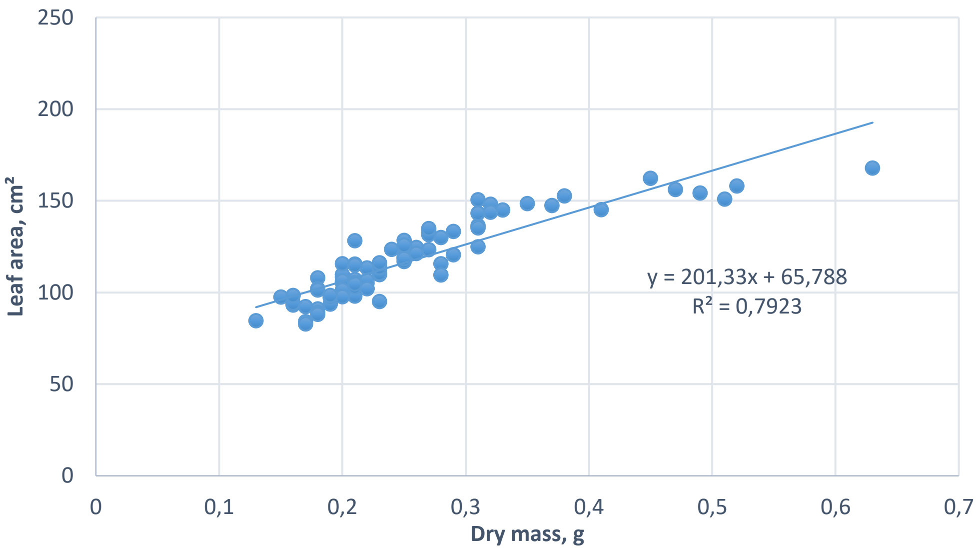
Relationship between LA and fresh leaf mass



In both cases, the relationship is linear on average at $R^2 \geq 0.8$, which means that their usability is equivalent. However, preference should be given to fresh foliage dependence as it removes the need to dry the leaves. This in turn saves a lot of time and energy costs.

Figure 23.

Relationship between LA and dry leaf mass



9. Economic analysis

One of the most important aspects of conducting a regulated irrigation regime in lettuce is to evaluate its economic efficiency, that is which irrigation options under the respective irrigation technique are profitable, cost-effective, and profitable.

The results obtained for the yield averaged over the experimental period under drip irrigation and micro sprinkler allow an economic evaluation to be presented under different irrigation options.

The most important indicators (total revenue, total costs, total income (profit), cost, rate of return, rate of profitability) characterizing the economic efficiency when using the respective irrigation technique are presented in Tables 18 and 19.

Table 18.

Economic results of regulated irrigation regime with drip irrigation of lettuce - average over the study period

Variants	100%	80%	60%	non-irrigation
Yield, кg/da	5672	4853	4384	1390
Average price, BGN/кg	1,60	1,60	1,60	1,60
Total revenue, BGN/da	9075,20	7764,80	7014,40	2224,00
Total costs, BGN/da	4350,8	4346,6	4342,5	4330
Cost, BGN/кg	0,77	0,90	0,99	3,12
Rate of profitability, %	108,6	78,6	61,5	-48,6
Rate of return, %	130,4	111,7	101,0	32,1
Total income (profit), BGN/da	4724,4	3418,2	2671,9	-2106,0

Table 19.

Economic results of regulated irrigation regime with micro sprinkler of lettuce - average over the study period

Variants	100%	80%	60%	non-irrigation
Yield, кg/da	5757	4963	4481	1390
Average price, BGN/кg	1,60	1,60	1,60	1,60
Total revenue, BGN/da	9211,2	7940,8	7169,6	2224
Total costs, BGN/da	4352,1	4347,7	4343,3	4330
Cost, BGN/кg	0,76	0,88	0,97	3,12
Rate of profitability, %	111,6	82,6	65,1	-48,6
Rate of return, %	132,3	114,2	103,2	32,1
Total income (profit), BGN/da	4859,1	3593,1	2826,3	-2106

VI. CONCLUSIONS

1. The application of a regulated irrigation regime in the lettuce, cultivar „*Winter Butterhead*“, by two micro irrigation techniques, showed that the highest yields were obtained at 100% m and maintaining high soil moisture. To achieve this, depending on the climatic conditions, it is recommended to irrigate every 2-3 days during the spring period at an irrigation rate of 8-10 mm. This option also provides the best economic results.

2. Reducing irrigation rates lowers the productivity of lettuce plants. Irrigation carried out at irrigation rates of 80 and 60% m reduced crop yield by 14.4% and 22.7%, on average, under drip irrigation and 13.8% and 22.2%, respectively, under micro sprinkler. From an economic point of view, it can be recommended that irrigation should be carried out at a rate of 80% m, in a condition of limited water resources, with a rate of return of 111.7% for drip irrigation and 114.2% for micro sprinkler.

3. It is not economically viable to grow lettuce under non-irrigated conditions as, depending on the degree of drought, yield losses are significant compared to options where 100% of the required irrigation rate is provided.

4. The irrigation rate productivity of the optimally irrigated variants of the two irrigation techniques is very close, almost equal to those irrigated with 80% m. The highest irrigation rate productivity, averaged over the experimental period, was found for the 60% m variant, 62.2 kg/m^3 for drip irrigation, and 59.5% kg/m^3 for micro sprinkler, respectively.

5. The „Yield-irrigation rate“ relationship has a high coefficient of determination, on average over the experimental period for both micro-irrigation techniques R^2=0.99. Expressed by Davidov's degree formula, graphically the relationship "Yield-Irrigation rate ", is expressed by a convex parabola with degree n=1.19 and correlation coefficient R=0.987, for drip irrigation, and micro sprinkler: n=1.25 and R=0.989.

6. Under the experimental conditions, the optimally irrigated variants of the tested lettuce cultivar also consumed the highest amounts of water, respectively, the drip irrigation consumed an average of 108.6 mm and the micro sprinkler 115.6 mm. The implementation of lower irrigation rates compared to the optimum adopted under drip irrigation reduced the water consumption of the crop, in the 80% m variant the reduction of ET was 7.2%, and in the 60% m - 20.7%. Under micro sprinkler, ET values were 9.8% and 22.9%, respectively.

7. The highest daily crop water use was recorded in the second decade of May, coinciding with the intense growth of lettuce plants. Maximum values of daily mean ET were found in the 100% m variant, 3.25 mm in drip irrigation and 3.35 mm in micro sprinkler, respectively, and minimum in the non-irrigated variant - 2.15 mm.

8. The involvement of irrigation rate predominated and dominated the formation of ET, especially in the variants irrigated with 100% and 80% m. In the variant with a 40% irrigation rate reduction, this participation ranged from 42.2% to 73.7% under drip irrigation and from 45% to 74.3% under micro sprinkler.

9. The highest ET productivity in drip irrigation was recorded in the 100% m variant - 52.2 kg/m^3, while in micro sprinkler it was found in the 60% m variant - 50.28 kg/m^3. It was lowest under non-irrigated conditions.

10. The „Yield-ET“ relationship is best represented by the one-step Davidov's formula, graphically expressed by a curve, with a degree-index of n=1.51, a yield coefficient of a=3.1, and a high correlation coefficient of R=0.981 for drip irrigation; n=1.78, a yield coefficient of a=3.45, and a high correlation coefficient of R=0.986 for micro sprinkler, respectively. Yield coefficients calculated using the FAO linear formula identified lettuce as sensitive to water deficit (Kc=1.76 under drip irrigation and Kc=1.6 under microsprinkler).

11. Although drip irrigation realized lower water volumes during the lettuce growing season, yields were about 1.5% lower compared to micro sprinkler. Higher irrigation water productivity values of 4.7% to 5.3% and higher evapotranspiration productivity values of 1.2% to 4.8% were obtained with this irrigation method, making it more economical in terms of irrigation water use efficiency compared to micro sprinkler.

12. It is recommended to use the biophysical coefficient Z, established based on temperature sum and evapotranspiration, to indirectly determine the ET of lettuce plants under both irrigation techniques.

13. The found linear relationship y=1.7816x+0.434, between yield and leaf area index, can be used to predict the yield of lettuce.

SCIENTIFIC AND SCIENTIFIC-APPLIED CONTRIBUTIONS

1. For the first time in Bulgaria, the influence of a regulated irrigation regime with two micro-irrigation techniques (drip irrigation and micro sprinkler) on the productivity of lettuce cultivar "*Winter Butterhead*" was investigated with practically applicable results.
2. Established were elements of the regulated irrigation regime, under the respective irrigation technique, and the crop response to its application, in years with different rainfall availability.
3. The parameters of the dependence "Yield-irrigation rate " and "Yield-ET" are determined by existing mathematical models, under the respective irrigation technique.
4. The sensitivity of lettuce to water deficit was determined, using the FAO formula and the one-step formula of Davidov’s, crop coefficient, under two micro-irrigation techniques.
5. Biophysical coefficients of ET of lettuce - R, Z, and Kc were calculated. It is recommended to use the biophysical coefficient Z, for indirect determination of ET of lettuce plants under both irrigation techniques.
6. Correlations between fresh weight, leaf area, leaf area index, and yield were established which can be used to predict the expected yield of lettuce.
7. The economic efficiency of the application of a regulated irrigation regime in two micro-irrigation techniques was determined.

LIST WITH SCIENTIFIC PAPERS IN RELATION TO THE DISSERTATION

1. Hristova, N., & Meranzova, R. (2022). Yield of Lettuce Grown in Conditions of Water Deficit. *Journal of Mountain Agriculture on the Balkans* , Vol. 25, Issue 3, pp. 268–280. ISSN 1311-0489 (Print), ISSN 2367-8364 (Online).
2. Hristova, N., Meranzova, R., & Dimov, K. (2021). Establishing the Evapotranspiration of Lettuce, with Differentiated Irrigation Regime. *Journal of Mountain Agriculture on the Balkans,* Vol. 24, Issue 5, pp. 396–407. ISSN1311-0489 (Print), ISSN 2367-836 (Online).
3. Hristova, N., Meranzova, R., & Dimov, K. (2021). Influence of Water Quality on the Weight of Lettuce, Maritima Variety. *Journal of Mountain Agriculture on the Balkans,* Vol. 24, Issue 4, pp. 411–428. ISSN1311-0489 (Print), ISSN 2367-836 (Online).