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EVALUATION OF PRODUCTIVITY AND DROUGHT TOLERANCE OF OIL-SEED FLAX (*Linum usitatissimum* L.) VARIETIES DEPENDING ON THE CONDITIONS OF HUMIDIFICATION AND MINERAL NUTRITION IN THE SOUTH OF UKRAINE

Raisa VOZHEHOVA[1], Vira BOROVYK[1], Vira KONOVALOVA[2], Serhii KOKOVIKHIN[1], Iryna BILIAIEVA[1], Pavlo LYKHOVYD[1], Olena PILIARSKA[1], Iryna BIDNYNA[1]

[1]Institute of Irrigated Agriculture, Naddniprianske, Kherson, Ukraine
[2]Askania State Agricultural Research Station of the Institute of Irrigated Agriculture of NAAS, 40 let Pobedy Street 16, vil. Tavrychanka, Kherson, 74862, Ukraine

Corresponding author email: pavel.likhovid@gmail.com

Abstract

The goal of the study was to determine drought tolerance of varieties of oil-seed flax and to improve its cultivation technology through the optimization of mineral nutrition in dependence on soil humidification with connection to the changes of climate in the South of Ukraine. To achieve the goal we performed three-year field experiment with the crop in regard to the design of the study, and investigated such factors as variety (Evryka, Orfei, Vira), mineral nutrition background (N_0P_0, $N_{45}P_{60}$, $N_{60}P_{60}$, $N_{90}P_{60}$), soil humidification conditions (irrigation, rain-fed). The maximum yields were provided by the variety Evryka (2.36 t ha^{-1}) in the irrigated conditions, and the variety Vira (1.47 t ha^{-1}) in the non-irrigated conditions at the application of $N_{90}P_{60}$. The best yield of oil was provided by the variety Vira (0.97 t ha^{-1} and 0.57 t ha^{-1} with the application of $N_{60}P_{60}$ in the irrigated and non-irrigated conditions, respectively). The main indices of drought tolerance, namely, mean productivity (MP) - 1.30, yield stability index (YSI) - 0.55, yielding index (YI) - 106, stress tolerance index (STI) - 0.47, revealed that the variety Vira was the best one among the studied varieties of oil-seed flax. Multiple linear regression analysis revealed general tendency to the increase in oil-seed yield by 6.431 kg with the increase of irrigation rate by every 1 mm; by 4.548 kg per every 1 kg ha^{-1} of Nitrogen fertilizers; by 1.228 kg per every 1 kg ha^{-1} of Phosphorus fertilizers, respectively.

Key words: *change of climate, cultivation conditions, seed yield, weather conditions, yield of oil.*

INTRODUCTION

In recent years due to the diversification of grain production there is an increase in the sowing areas under the oil crops among which oil-seed flax has a special place. Oil-seed flax (*Linum usitatissimum* L.) is used as a raw material for production of fast-drying oil for chemical industry (Nykter et al., 2006), linoleum, as a food and fodder additive (Bernacchia et al., 2014; Kajla et al., 2015), directly for nutrition and in the form of flour in bakery.

It was determined that flax was known as a fiber and oil plant in the ancient East, and it was introduced in agricultural practice earlier than cotton-plant (Herbig & Maier, 2011; Valamoti, 2011). The earliest findings of the seeds of flax crop are dated 4900-8700 BC (Vaisey-Genser & Morris, 2003; Zohary et al., 2012; Harris, 2014). Other reports certify that oil fiber with the age of nearly 30 thousand years was discovered (Kvavadze et al., 2009). Geography of the findings of flax remnants is very wide. Oil-seed flax could be cultivated in different regions of Ukraine, and it does not concede by the profitability level to other oil crops.

The advantage of oil-seed flax cultivation is, firstly, its drought tolerance that gives an opportunity to obtain yields of 1.2-2.5 t ha^{-1} every year. Secondly, it has a short vegetative period (80-105 days) that allows harvesting of flax in the end of July, and as a result, it is one of the best previous crops for winter cereal crops. Thirdly, tolerance to unfavorable weather and climatic conditions, especially seedlings are tolerant to the spring frosts, and the crop is seed-cast and lodging resistant. Besides, oil-seed flax has easy cultivation technology, does not require application of insecticides and fungicides owing to the absence of specific insects and diseases in the Steppe zone of Ukraine, it is not exigent to soil fertility and could be cultivated without application of fertilizers as an ensuring crop for the occurrence of winter cereals re-sowing.

Drought tolerance is a capacity of plants to endure significant dewatering and overheating maintaining normal growth, development and reproductive capacity. The problem of drought tolerance is actual for many regions of our country and the world because of changes in the parameters of climate to its warming that is accompanied by drought. Scientists believe that oil-seed flax is a good drought-resistant crop (Chekhov et al., 2007; Sheremet et al., 2014). However, some scientists state that notwithstanding biologically caused high drought-tolerance and plasticity, oil-seed flax in the South of Ukraine suffers from the lack of moisture (because of high transpiration coefficient of the crop - 420-690) and is very responsible to irrigation (Gobelyal, 2007; Rudik, 2013). The root system of flax is comparatively poor developed and shallow, but its suction force is very high. Most moisture is used from the soil layer of 0-60 cm (Johnston et al., 2002). The feature of the root system of flax is its unstoppable growth in depth to the end of vegetation. This provides the plants with an opportunity to assimilate moisture after flowering from the deeper soil layers and provides better standing of drought in comparison to other crops. Besides, flax is supposed to be the best option for no-till cropping systems (Lafond et al., 1992).

The maximum yield of seeds is provided by flax when the crop has enough precipitation or irrigation amounts (about 50 mm) during the period from budding to the end of flowering at the moderate temperatures (Zinchenko et al., 2001). The researches proved that in average at the expense of irrigation seed yield of oil-seed flax increases by 34.9%. Flax is very responsive to the application of fertilizers. Strengthening of mineral nutrition ($N_{90}P_{60}K_{60}$) is accompanied by the increase in the yield by 41.0-43.3% (Rudik, 2016).

So, the thoughts of scientists differ, some of them state that flax is a drought-tolerant crop while others convince that oil-seed flax suffers from the lack of humidification in the South of Ukraine.

The aim of our study was to determine the drought tolerance of oil-seed flax varieties and to improve their cultivation technology through the optimization of mineral nutrition in dependence on the soil humidification conditions in Southern region of Ukraine in connection with the global changes of climate.

MATERIALS AND METHODS

The study was carried out at the experimental field of Askania State Agricultural Research Station of the Institute of Irrigated Agriculture of NAAS in 2015-2018. The study was conducted in three replications by using the systematic design. The cultivation technology of oil-seed flax was common for the conditions of the South of Ukraine, excluding the studied factors. The previous crop was winter wheat. Soil tillage was performed by plowing on the depth of 20-22 cm. Application of mineral fertilizers was performed with accordance to the design of the study. The sowing rate of all the studied varieties of the crop was 5 million seeds ha^{-1}. Sowing was conducted by the seed drill “KLEN-1.6”. Four waterings with the rate of 30 mm were carried out during the vegetative period of the crop by the means of an irrigation machine “Zimmatik”. Plant care included the application of herbicide Bazahran (active substance *bentazon*, 480 g L^{-1}) in the dose of 1.0 L ha^{-1} at the height of the crop 3-10 cm, and the application of insecticide Razit (active substances include *imidacloprid*, 140 g L^{-1}, *acetamiprid*, 160 g L^{-1}, *cypermethrin*, 100 g L^{-1}) in the dose of 0.2 L ha^{-1} at the stage of the crop’s young growth. The yield was harvested by using a self-propelled combine “Sampo-130”. The oil content in the seeds was determined by the method of extraction in the apparatus of Soxhlet with accordance to the State Standard DSTU 7577:2014 (Ministry of Agrarian Policy and Food of Ukraine, 2016). Statistical data processing was performed by the means of AgroStat add-in for Microsoft Excel (Ushkarenko et al., 2014). The difference between the variants is significant at the probability level of 95%, and it is proved by the results of multi-factor analysis of variance (ANOVA) test with calculation of the least significant difference (LSD_{05}). Correlation analysis was performed within Microsoft Excel software by the standard methodology of calculations (Ushkarenko et al., 2014). Regression model of the yield depending on irrigation and mineral fertilization was carried out using the multiple regression analysis procedure within Microsoft Excel software.

The soil of the experimental field is dark-chestnut clay-loamy slightly-solonized with the humus content of 2.15-2.30% in the arable layer. The bulk density of the soil layer 0-40 cm is 1.2-1.3 g cm^{-3}, the wilting point in the layer 0-40 cm is 7.8-9.8%, and the water-holding capacity in the soil layer of 0-70 cm is 20.5-22.4%. Groundwater lays deeper than 15 m. The water for irrigation was taken from the Kakhovka irrigation system, which is characterized as suitable for irrigation without limitation.

The study included an investigation of the factors: A - humidification regime (with or without irrigation); B - varieties of oil-seed flax (Evryka, Orfei, Vira); C - mineral nutrition background (N_0P_0, $N_{45}P_{60}$, $N_{60}P_{60}$, $N_{90}P_{60}$).

Evryka is a variety of linseed flax recommended for cultivation in the zones of Forest-Steppe, Steppe, Polissya. The plants are characterized with high tolerance to lodging, seed falling, capsules cracking, moderate tolerance to diseases. The height of the plants is 57-62 cm, the stem is round with the diameter of 3-4 mm. The duration of period of vegetation is 81 days. 1000 seed weight is 7-8 g. The variety is included in the State Register of Plants and Varieties of Ukraine since 2004.

Orfei is a variety of oil-seed flax with high drought and lodging tolerance. Potential productivity of the plants is high. The height of the plants is 52-55 cm. The duration of period of vegetation is 84-86 days. 1000 seed weight is 7-9 g, the oil content in the seeds is about 44.8%. The variety is included in the State Register of Plants and Varieties of Ukraine since 2002.

Vira is an oil-seed flax variety with high tolerance to lodging and seed falling. The duration of period of vegetation is 83 days. The yield of oil is nearly 1.10 t ha^{-1}. The variety is included in the State Register of Plants and Varieties of Ukraine since 2009.

The methods used in the study - field method for the determination of the dependence of the studied object from anthropogenic factors and seed productivity, analytical method for the estimation of the crop cultivation conditions, statistical method for the calculations and evaluation of the significance of the obtained results.

Drought tolerance was determined by the index of stress tolerance (TOL) as the difference between the yield in stress (Ys) and non-stress (Yp) conditions, and between the mean productivity (MP) of Ys and Yp (Rosielle & Hamblin, 1981) by using the following formulas:

$TOL = Y - Ys$

$MP = (Yp+Ys)/2$

where: *Yp* is the yield in the optimum conditions; *Ys* is the yield in the drought stress conditions.

We also calculated the index of drought stress susceptibility (DSI), which characterizes the level of susceptibility of the genotype to different stress factors, especially – drought (Fisher & Maurer, 1978), and the index of stress tolerance (STI) by using the formulas:

$DSI = (1 - Y/Yp)/D$

$D = 1 - X/Xp$

$STI = (Yp \times Ys)/Ypm^2$

where: *Y* is the yield in the drought conditions; *Yp* is the yield in the optimum conditions; *D* is the intensity of drought; *X* and *Xp* is the level of yield of all the varieties under the influence of drought and without it, respectively; *D* value usually fluctuates within 0 - 1.

We also used geometrically mean productivity of the yield of the studied varieties to evaluate their drought tolerance (GMP) (Yücel & Mart, 2014) by the following equation:

$GMP = \sqrt{Yp \times Ys}$

where: *Yp* is the yield in the optimum conditions; *Ys* is the yield in the drought stress conditions.

The index of yield stability (YSI) and the index of yield in the stress conditions were calculated by the ratio of the stress-influenced yield to the mean yield of the studied variety (Bouslama & Schapaugh, 1984; Gavuzzi et al., 1997):

$YSI = Ys/Yp$

where: *Yp* is the yield in the optimum conditions; *Ys* is the yield in the drought stress conditions.

RESULTS AND DISCUSSIONS

General feature of the climate of southern Steppe zone is insufficient amount of precipitation, low relative air humidity, frequent dry-winds, warm autumn and winter, and prolonged period without frosts. The climate of the South of Ukraine is continental, hot, dry. We used the data of observations of Kherson agrometeorological station, which have been carried out since 1882, to evaluate the weather conditions of the years of the study (Table 1).

Meteorological conditions of 2016 were the most favorable for the growth and development of oil-seed flax plants both in the irrigated and non-irrigated conditions. During the period of March, April and May 130.1 mm of precipitation was fixed. The maximum amount of rainfall was observed in the III decade of April and I decade of May - 78.4 mm. There was 65.9 mm of precipitation in June. This amount surpassed the long-term mean norm 1.5 times (65.9 mm in comparison to 46.0 mm) but it was still insufficient for the formation of high yield of the crop in the rain-fed conditions. July was characterized by very low amount of rainfall (only 20 mm) that had no considerable effect on the oil-seed flax crop in the end of its vegetation.

Table 1. Weather conditions during the period of vegetation of the studied oil-seed flax varieties, average for 2016-2018

Month	Index	Years of the study			Average air temperature, °C	Average sum of precipitation, mm	Long-term mean indices
		2016	2017	2018			
March	Average daily temperature, °C	6.1	4.5	1.5	4.0	-	2.2
	Precipitation, mm	25.3	10.2	35.1	-	23.5	26.0
April	Average daily temperature, °C	12.4	7.6	12.9	10.9	-	9.6
	Precipitation, mm	41.7	81.8	2.7	-	42.1	28.0
May	Average daily temperature, °C	15.9	13.9	19.5	16.4	-	15.6
	Precipitation, mm	63.1	25.8	13.0	-	33.9	38.0
June	Average daily temperature, °C	21.5	19.7	22.4	21.2	-	20.0
	Precipitation, mm	65.9	8.0	23.0	-	32.3	46.0
July	Average daily temperature, °C	23.9	21.9	24.1	23.3	-	22.4
	Precipitation, mm	20.0	80.0	61.5	-	53.8	42.0
August	Average daily temperature, °C	24.6	22.9	25.0	24.2	-	21.6
	Precipitation, mm	88.5	33.0	15.0	-	45.5	35.0
September	Average daily temperature, °C	17.4	18.6	18.7	18.2	-	16.4
	Precipitation, mm	28.2	32.0	14.0	-	24.7	28.0
October	Average daily temperature, °C	8.5	7.1	10.5	8.7	-	9.6
	Precipitation, mm	46.3	49.3	21.0	-	38.7	26.0

Table 2. Field seedling rate and plant height of the oil-seed flax varieties depending on the application of mineral fertilizers at the irrigated and rain-fed conditions, average for 2016-2018

Humidification conditions	Variety	Mineral nutrition background	Plant height, cm	Field seedling rate, %	Plant density, million ha^{-1}
Irrigation	Evryka	Control (N_0 P_0)	55.8	90	4.5
		N_{45} P_{60}	57.4	90	4.5
		N_{60} P_{60}	60.3	90	4.5
		N_{90} P_{60}	61.3	91	4.5
	Orfei	Control (N_0 P_0)	59.9	92	4.6
		N_{45} P_{60}	62.3	91	4.5
		N_{60} P_{60}	63.1	93	4.6
		N_{90} P_{60}	64.8	92	4.6
	Vira	Control (N_0 P_0)	57.2	95	4.7
		N_{45} P_{60}	58.6	95	4.8
		N_{60} P_{60}	59.7	95	4.7
		N_{90} P_{60}	63.2	95	4.8
Rain-fed	Evryka	Control (N_0 P_0)	46.5	96	4.3
		N_{45} P_{60}	47.5	86	4.3
		N_{60} P_{60}	48.8	86	4.4
		N_{90} P_{60}	51.3	87	4.3
	Orfei	Control (N_0 P_0)	47.5	87	4.4
		N_{45} P_{60}	49.0	89	4.5
		N_{60} P_{60}	50.1	90	4.5
		N_{90} P_{60}	50.7	89	4.5
	Vira	Control (N_0 P_0)	46.5	90	4.6
		N_{45} P_{60}	48.8	92	4.6
		N_{60} P_{60}	49.8	92	4.6
		N_{90} P_{60}	50.6	92	4.6
LSD_{05}		Factor A	0.34	1.65	0.12
		Factor B	0.28	0.96	0.13
		Factor C	0.40	0.97	0.08

Beginning of the spring of 2017 was in usual terms. During March, April and May 117.8 mm of rainfall came to the experimental field, 81.8 mm of them - in April. April was humid but comparatively cold: temperature regime of April and May was lower than the long-term mean norm by 1.7-2.0ºC, and on 19th of April there was snow-cover of 15-20 cm and temperature decreased to 0ºC that negatively affected the plants of oil-seed flax and caused the stagnation of their growth. The 3rd decade of May was characterized by the by the gradual increase of mean daily air temperature.

The spring of 2018 was late. Snow-cover was on the ground until the end of March. Such weather provided good storage of productive moisture in the soil (up to 200 mm). Mean daily temperatures from April began to increase, and at the beginning of May reached the values of 25-35ºC. May was very hot with low rainfall amount (13 mm against 38 mm as the long-term mean norm). The absence of moisture accompanied by the enormously high temperatures in 2018 had a negative effect on the yield of the crop in the non-irrigated conditions (Table 4). The yields on the fertilized plots in the irrigated conditions fluctuated within 2.18-2.48 t ha^{-1}, and in the rain-fed conditions it was just about 0.79-1.00 t ha^{-1}, or 1,39-1,48 t ha^{-1} lower.

The analysis of weather conditions showed that 2016 was the most favorable year for the growth and development of oil-seed flax: 379 mm of productive moisture came into the soil during the vegetative period of the crop. The level of moisture income was slightly lower in 2017 - 320 mm, and considerably lower in 2018 - just 185 mm. We should mention that 2018 was very dry year even for the conditions of the arid Steppe zone.

The results of the three-year study testified that the plants of oil-seed flax differed by their height within the variety in dependence on the dose of fertilizers applied and conditions of soil humidification.

The difference on the fertilized variants in the irrigated conditions between the lowest and the highest plant was: at the variety Evryka - 3.9 cm, Orfei - 2.5 cm, Vira - 4.6 cm, respectively. With the increase of Nitrogen fertilizer dose the height of the plants increased. The maximum plant height was observed on the variants with the application of $N_{90}P_{60}$ (61.3-63.2 cm). The above-mentioned difference in the height of the plants was diminished in the variants with no irrigation, and it was 3.8, 1.7, 1.8 cm for the varieties Evryka, Orfei and Vira, respectively. However, the tendency regarding the fertilization saved: the highest plants were on the plots with $N_{90}P_{60}$ - 50.6-51.3 cm (Table 2).

Humidification conditions significantly affected the formation of the plant height of oil-seed flax. The plants were in average 10 cm higher in the irrigated conditions than in the rain-fed ones.

The best indices of field seedling and plant density were observed at the plants of the variety Vira with the indices of 95% and 4.8 million of plants ha^{-1} in the irrigated conditions, and 92% and 4.6 million of plants ha^{-1} in the rain-fed conditions, respectively. The variety Orfei had worse indices of seedling rate and plant density (93% and 4.6 million of plants ha^{-1} in the irrigated conditions, and 89% and 4.5 million of plants ha^{-1} in the non-irrigated conditions, respectively), and the variety Evryka had the worst indices of 91% and 4.5 million of plants ha^{-1} in the irrigated conditions, and 87% and 4.3 million of plants ha^{-1} in the rain-fed conditions, respectively. Almost the same tendency of the seed seedling was observed in the conditions of laboratory.

The conditions of cultivation affected significantly on the formation of the elements of the crop productivity (Table 3). The maximum number of capsules (18.0) and seeds (160.5) per plant had the plants of the variety Vira at the application of $N_{90}P_{60}$ in the irrigated conditions. However, the highest weight of seeds per plant (1.28 g) with the 1000 seeds weight of 9.06 g was obtained from the plants of the variety Evryka at the application of $N_{90}P_{60}$. The maximum 1000 seeds weight both in the irrigated (8.94-9.06 g) and rain-fed (7.90-8.05 g) conditions was formed by the plants of the oil-seed flax variety Evryka. The varieties Vira and Orfei performed better in the non-irrigated cultivation conditions. More capsules (11.5) and seeds (102.2) per plant were formed at the variety Vira, and weight of seeds per plant was more at the variety Orfei (0.60 g) at the application of $N_{90}P_{60}$ at the expense of higher 1000 seeds weight - 6.35 g.

Table 3. Productivity of the varieties of oil-seed flax depending on the studied factors, average for 2016-2018

Humidification conditions	Variety	Mineral nutrition background	Number of capsules per plant	Number of seeds per plant	Weight of seeds per plant	1000 seeds weight
Irrigation	Evryka	Control (N_0 P_0)	10.9	92.6	0.81	8.94
		N_{45} P_{60}	13.9	120.6	1.06	9.10
		N_{60} P_{60}	16.0	138.7	1.23	9.15
		N_{90} P_{60}	17.0	147.8	1.28	9.06
	Orfei	Control (N_0 P_0)	10.9	95.7	0.66	7.00
		N_{45} P_{60}	13.5	119.9	0.82	7.04
		N_{60} P_{60}	15.7	140.5	0.98	7.05
		N_{90} P_{60}	16.4	146.3	1.04	7.18
	Vira	Control (N_0 P_0)	13.8	122.5	0.80	6.57
		N_{45} P_{60}	16.1	143.4	0.94	6.59
		N_{60} P_{60}	17.0	152.5	1.01	6.67
		N_{90} P_{60}	18.0	160.5	1.05	6.64
Rain-fed	Evryka	Control (N_0 P_0)	6.4	52.5	0.41	7.90
		N_{45} P_{60}	7.7	64.6	0.50	8.04
		N_{60} P_{60}	8.2	69.2	0.55	8.12
		N_{90} P_{60}	8.6	72.5	0.57	8.05
	Orfei	Control (N_0 P_0)	8.7	75.4	0.47	6.23
		N_{45} P_{60}	9.7	85.6	0.53	6.32
		N_{60} P_{60}	10.2	90.6	0.56	6.31
		N_{90} P_{60}	10.8	96.8	0.60	6.35
	Vira	Control (N_0 P_0)	9.2	81.9	0.48	5.91
		N_{45} P_{60}	10.6	94.7	0.54	5.84
		N_{60} P_{60}	10.8	98.0	0.56	5.87
		N_{90} P_{60}	11.5	102.2	0.59	5.96
LSD_{05}		Factor A	0.53	1.77	0.01	0.09
		Factor B	0.42	2.82	0.02	0.05
		Factor C	0.62	3.29	0.02	0.06

The results of correlation analysis allowed determination of relationships between the yield of oil-seed flax and the studied factors. There were determined close direct inter-connections between the yields of oil-seed flax varieties and the number of capsules, the number of seeds, the weight of seeds per plant, independently from the conditions of humidification and fertilizers' doses. The calculated coefficients pointed out that the productivity of oil-seed flax is determined by the number of capsules and seeds per plant, together with the weight of seeds per plant differently for the studied varieties: for Evryka r = 0.82, for Vira r = 0.80 in the irrigated conditions, and for Evryka r = 0.91, for Orfei r = 0.95 in the non-irrigated conditions, independently on the application of mineral fertilizers. The increase of yield caused the decrease in 1000 seeds weight of the variety Vira, that is proved by the coefficient of correlation value r = 0.27. This fact could be explained by the higher density of this variety in comparison to the other in the rain-fed conditions.

Yield formation is a difficult process that is genetically and environmentally determined. Obtaining high yields depends on the heat, moisture, and nutritive elements income to plants (Table 4).

The results of the study testify that the yield of oil-seed flax increases with the increase of the Nitrogen supply. The maximum yield of seeds of the variety Evryka (2.36 t ha^{-1}) was obtained in the irrigated conditions at the application of $N_{90}P_{60}$. The maximum yield of oil-seed flax in the rain-fed conditions was provided by the varieties Vira (1.47 t ha^{-1}) and Orfei (1.45 t ha^{-1}) at the application of $N_{90}P_{60}$. The differences between the variants with application of $N_{60}P_{60}$ and $N_{90}P_{60}$ were insignificant at $p < 0.05$.

The decrease in the dose of fertilizers application had a negative effect on the yield of the crop both in the irrigated and non-irrigated conditions, independently on the variety. The lowest yield in the study was obtained at the control (non-fertilized) variant with the variety Evryka under the rain-fed conditions of humidification - 0.99 t ha^{-1}. Application of $N_{90}P_{60}$ provided the yield at the level of 1.33 t ha^{-1} that is by 0.14 t ha^{-1} lower than of the variety Vira at the same conditions of cultivation.

Our study proved that the variety played significant role on the oil content in oil-seed flax seeds (Table 5).

The highest oil content of 47.4% was obtained at the oil-seed flax variety Vira in the irrigated conditions on the plots with the application rate of mineral fertilizers $N_{90}P_{60}$, when the yield of oil was 0.97 t ha^{-1}. In the rain-fed conditions this variety also provided the highest oil content of 46.0% with the yield of oil 0.57 t ha[1] under the application of $N_{60}P_{60}$.

The economic efficiency of the crop cultivation is represented in the Table 6.

Table 4. Yields of oil-seed flax varieties in dependence on the conditions of soil humidification and mineral nutrition background, average for 2016-2018

Humidification conditions (Factor A)	Variety (Factor B)	Mineral nutrition background (Factor C)	Yield of seeds, t ha^{-1}			Average yield of seeds for 2016-2018, t ha^{-1}
			2016	2017	2018	
Irrigation	Evryka	Control (N_0 P_0)	1.48	1.77	1.86	1.70
		N_{45} P_{60}	1.76	2.04	2.39	2.06
		N_{60} P_{60}	1.99	2.28	2.42	2.23
		N_{90} P_{60}	2.19	2.41	2.48	2.36
	Orfei	Control (N_0 P_0)	1.44	1.74	1.71	1.63
		N_{45} P_{60}	1.76	1.98	2.18	1.97
		N_{60} P_{60}	1.93	2.19	2.25	2.12
		N_{90} P_{60}	2.11	2.33	2.29	2.24
	Vira	Control (N_0 P_0)	1.43	1.83	1.69	1.65
		N_{45} P_{60}	1.78	2.24	2.18	2.06
		N_{60} P_{60}	1.94	2.37	2.20	2.17
		N_{90} P_{60}	2.13	2.49	2.27	2.29
Rain-fed	Evryka	Control (N_0 P_0)	1.25	1.02	0.71	0.99
		N_{45} P_{60}	1.56	1.19	0.84	1.20
		N_{60} P_{60}	1.74	1.27	0.86	1.29
		N_{90} P_{60}	1.88	1.33	0.79	1.33
	Orfei	Control (N_0 P_0)	1.29	1.15	0.73	1.06
		N_{45} P_{60}	1.58	1.31	0.91	1.27
		N_{60} P_{60}	1.76	1.39	0.96	1.37
		N_{90} P_{60}	1.92	1.48	0.96	1.45
	Vira	Control (N_0 P_0)	1.35	1.20	0.78	1.11
		N_{45} P_{60}	1.59	1.34	0.94	1.29
		N_{60} P_{60}	1.76	1.41	1.00	1.39
		N_{90} P_{60}	1.96	1.49	0.97	1.47
LSD_{05}		Factor A	0.04	0.03	0.10	0.06
		Factor B	0.02	0.02	0.10	0.09
		Factor C	0.01	0.02	0.11	0.08

Table 5. Effect of different doses of mineral fertilizers and soil humidification on the qualitative indices of oil-seed flax oil, average for 2016-2018

Humidification conditions (Factor A)	Variety (Factor B)	Mineral nutrition background (Factor C)	Oil content, %	Yield of oil, t ha^{-1}
Irrigation	Evryka	Control (N_0P_0)	43.3	0.66
		$N_{45}P_{60}$	43.9	0.80
		$N_{60}P_{60}$	44.8	0.89
		$N_{90}P_{60}$	45.0	0.94
	Orfei	Control (N_0P_0)	45.1	0.65
		$N_{45}P_{60}$	45.2	0.79
		$N_{60}P_{60}$	46.4	0.88
		$N_{90}P_{60}$	46.2	0.92
	Vira	Control (N_0P_0)	45.2	0.66
		$N_{45}P_{60}$	45.1	0.83
		$N_{60}P_{60}$	46.1	0.89
		$N_{90}P_{60}$	47.4	0.97
Rain-fed	Evryka	Control (N_0P_0)	43.5	0.38
		$N_{45}P_{60}$	43.2	0.46
		$N_{60}P_{60}$	43.7	0.51
		$N_{90}P_{60}$	43.6	0.52
	Orfei	Control (N_0P_0)	42.0	0.40
		$N_{45}P_{60}$	44.9	0.51
		$N_{60}P_{60}$	45.0	0.55
		$N_{90}P_{60}$	44.7	0.58
	Vira	Control (N_0P_0)	42.8	0.42
		$N_{45}P_{60}$	45.7	0.52
		$N_{60}P_{60}$	46.0	0.57
		$N_{90}P_{60}$	45.3	0.59
LSD_{05}		Factor A	0.30	0.065
		Factor B	0.20	0.025
		Factor C	0.27	0.017

Table 6. Economic efficiency of oil-seed flax cultivation depending on the variety, soil humidification and mineral nutrition, average for 2016-2018 (currency exchange rate applied in the calculations is 1 USD = 26.00 UAH)

Humidification conditions (Factor A)	Variety (Factor B)	Mineral nutrition background (Factor C)	Value of production, USD ha^{-1}	Expenditures, USD ha^{-1}	Profit, USD ha^{-1}	Profitability, %
Irrigation	Evryka	Control (N_0P_0)	784.62	250.35	534.27	213
		$N_{45}P_{60}$	950.77	307.12	643.65	210
		$N_{60}P_{60}$	1029.23	367.62	661.62	180
		$N_{90}P_{60}$	1089.23	389.19	700.04	180
	Orfei	Control (N_0P_0)	752.31	268.27	484.04	180
		$N_{45}P_{60}$	909.23	325.77	583.46	179
		$N_{60}P_{60}$	978.46	384.73	593.73	154
		$N_{90}P_{60}$	1033.85	410.12	623.73	152
	Vira	Control (N_0P_0)	761.54	260.19	501.35	193
		$N_{45}P_{60}$	950.77	317.69	633.08	199
		$N_{60}P_{60}$	1001.54	376.65	624.88	166
		$N_{90}P_{60}$	1056.92	402.04	654.88	163
Rain-fed	Evryka	Control (N_0P_0)	456.92	207.62	249.31	120
		$N_{45}P_{60}$	553.85	265.00	288.85	109
		$N_{60}P_{60}$	595.38	270.12	325.27	120
		$N_{90}P_{60}$	613.85	310.85	303.00	97
	Orfei	Control (N_0P_0)	489.23	209.38	279.85	134
		$N_{45}P_{60}$	586.15	266.77	319.38	120
		$N_{60}P_{60}$	632.31	275.73	356.58	129
		$N_{90}P_{60}$	669.23	312.65	356.58	114
	Vira	Control (N_0P_0)	512.31	201.31	311.00	154
		$N_{45}P_{60}$	595.38	258.73	336.65	130
		$N_{60}P_{60}$	641.54	267.69	373.85	140
		$N_{90}P_{60}$	678.46	307.08	371.38	121

The best performance in the irrigated conditions was provided by the variety Evryka, which formed the maximum yield of 2.36 t ha^{-1} with the highest profit of 700.04 USD ha^{-1} under the application of mineral fertilizers in the dose $N_{90}P_{60}$.

The profitability level was 180%. However, the best yield of oil was provided by the variety Vira (47.4% or 0.97 t ha^{-1}).

It was determined that the variety Vira is the best one for cultivation in the rain-fed conditions of the South of Ukraine. This variety provided the yield of 1.39 t ha^{-1} at the application of $N_{60}P_{60}$ with the highest profit (373.85 USD ha^{-1}) and profitability (140%). The oil content of this variety was 46.0%, and the yield of oil was 0.57 t ha^{-1}. At the same time, the control variant provided profitability of 154% with the yield of oil just 42.8%.

It was also discovered that cultivation of oil-seed flax in the irrigated conditions provided the increase of seed yield in average by 41% or 0.97 t ha^{-1}.

Evaluation of drought tolerance of the studied varieties of oil-seed flax was performed through the calculation of the corresponding indices that consider the level of yield losses in drought conditions in comparison to optimal conditions. These indices show both tolerance and susceptibility of the varieties to drought (Bouslama & Schapaugh, 1984; Rudik, 2013). The reaction of genotypes to drought was performed by the yielding index (Zinchenko et al., 2001). Mathematical processing and calculation of the above-mentioned indices significantly simplifies the process of drought tolerance assessment (Vus et al., 2017).

The main indices of drought tolerance, namely, mean productivity (MP) - 1.30, yield stability index (YSI) - 0.55, yielding index (YI) - 106, stress tolerance index (STI) - 0.47, revealed that the variety Vira was the best one among the studied varieties of oil-seed flax (Table 7).

Table 7. Comparison of the indices of drought tolerance of the studied varieties of oil-seed flax, average for 2016-2018

Variety	DSI	TOL	MP	YSI	YI	STI	GMP
Evryka	1.09	0.81	1.21	0.50	92	0.39	1.13
Orfei	0.98	0.75	1.27	0.54	102	0.44	1.21
Vira	0.96	0.75	1.30	0.55	106	0.47	1.24

Note: DSI - drought susceptability index; TOL - index of tolerance to drought; MP - mean productivity; YSI - yield stability index; YI - yielding index; STI - stress tolerance index; GMP - geometrically mean productivity.

Drought tolerance is an important quality of oil-seed flax, especially, in the modern conditions of the changes in regional and global climate (Lykhovyd, 2018) and modern challenges, which arose due to the lack of freshwater for irrigation needs (Vozhehova et al., 2018).
Multiple linear regression analysis revealed general tendency to the increase in oil-seed yield by 6.431 kg with the increase of irrigation rate by every 1 mm; by 4.548 kg per every 1 kg ha^{-1} of Nitrogen fertilizers; by 1.228 kg per every 1 kg ha^{-1} of Phosphorus fertilizers, respectively.
The results of ANOVA are represented in the Table 8, and the results of regression analysis are provided in the Table 9.

Table 8. ANOVA results for multiple regression analysis of oil-seed flax seed yield depending on humidification conditions and mineral fertilizers

	Degrees of freedom	Sum of squares	Mean squares	F	F significance
Regression	3	4.411	1.470	241.785	7.07×10^{-16}
Residuals	20	0.122	0.006		
Total	23	4.533			

Table 9. Regression statistics for the analysis of oil-seed flax yield depending on humidification conditions and mineral fertilizers

	Coefficients	Standard errors	t-statistics	P-value
Y-interception	0.970833	0.035594	27.27499	2.70×10^{-17}
Imput X1	0.006431	0.000265	24.23844	2.68×10^{-16}
Input X2	0.004548	0.000982	4.628643	0.000162
Input X3	0.001685	0.001228	1.371629	0.185372

Note: Y - yield, t ha^{-1}; Input X 1 - irrigation rate, mm; Input X 2 - Nitrogen fertilizer dose, kg ha^{-1}; Input X 3 - Phosphorus fertilizer dose, kg ha^{-1}.

Table 10. Approximation of the regression model of oil-seed falx yield depending on humidification conditions and mineral fertilizers

Input X1 (irrigation rate, mm)	Input X2 (Nitrogen dose, kg ha^{-1})	Input X3 (Phosphorus dose, kg ha^{-1})	True yields, t ha^{-1}	Modeled yields, t ha^{-1}	Residuals (modeled-true), t ha^{-1}
0	0	0	0.99	0.97	-0.02
0	45	60	1.20	1.28	0.08
0	60	60	1.29	1.34	0.05
0	90	60	1.33	1.48	0.15
0	0	0	1.06	0.97	-0.09
0	45	60	1.27	1.28	0.01
0	60	60	1.37	1.34	-0.03
0	90	60	1.45	1.48	0.03
0	0	0	1.11	0.97	-0.14
0	45	60	1.29	1.28	-0.01
0	60	60	1.39	1.34	-0.05
0	90	60	1.47	1.48	0.01
120	0	0	1.70	1.74	0.04
120	45	60	2.06	2.05	-0.01
120	60	60	2.23	2.12	-0.11
120	90	60	2.36	2.25	-0.11
120	0	0	1.63	1.74	0.11
120	45	60	1.97	2.05	0.08
120	60	60	2.12	2.12	0
120	90	60	2.24	2.25	0.01
120	0	0	1.65	1.74	0.09
120	45	60	2.06	2.05	-0.01
120	60	60	2.17	2.12	-0.05
120	90	60	2.29	2.25	-0.04

The equation of oil-seed yield depending on the studied factors looks like $Y = 0.970833 + 0.006431 \times X1 + 0.004548 \times X2 + 0.001685 \times X3$.
The values of regression statistics, namely: multiple coefficient of regression R - 0.9865; square coefficient of regression R^2 - 0.9732; normalized R^2 - 0.9691; standard error - 0.0779 testify about high accuracy of the developed model, which was also proved by its approximation, showing a slight amplitude of residuals not exceeding 0.15 t ha^{-1} with average error of modeling averaging to 3.71% (Table 10).
The results of regression analysis explain peculiarities of the crop productivity formation and point out a great importance of irrigation for oil-seed flax production in the South of Ukraine. It was also determined that the least effect on the crop yield is associated with application of Phosphorus fertilizers, and

Nitrogen had a moderate level of the impact on the yield.

Nowadays, linseed flax is cultivated in 64 countries of the world, and the areas under the crop are increasing. And yield of the crop is highly different in different regions of the world, and even through the European countries (D'Antuono & Rossini, 2006). One of the main oil-seed and fiber flax producers is the United Kingdom, where the crop is cultivated both as a fiber and oil crop to provide the maximum economic efficiency and benefits of the production (Foster et al., 1998). It was suggested that oil-seed flax has a potential to become the third main oil crop in the world production, standing in the one row with rape and sunflower (Diepenbrock, 2001). And European countries in general and Ukraine are one of the most important areas of the world linseed production. That is why it is so important to conduct comprehensive investigation regarding the crop productivity.

It was evaluated that the maximum potential yield of oil-seed flax seeds at the level of 4.5-5.0 t ha^{-1} could be obtained under the following combination of cultivation conditions: the density of plants 6-7 million of plants ha^{-1}, number of capsules per stem 15-22, number of seeds per capsule 8-9, 1000 seeds weight 5.5-6.0 g, dry weight herbage biomass yield of 9.0-10.0 t ha^{-1} (Candrakova & Bakula, 2001). It is believed that plant density and number of capsules per plant have the greatest effect on the yield of oil-seed flax (Zajac et al., 2012). This presumption was proved by our results that testified about the fact that the yield of seeds had close connection with the number of capsules and seeds per plant, together with the weight of seeds per plant, according to the results of correlation analysis. Besides, the study conducted in Turkey reports about the same tendency: the highest close direct positive influence on the yield of linseed was provided by the number of capsules per plant with r value of 0.797 (Copur et al., 2006). However, earlier work by Zajac et al. (2005) reports that linseed yield is dependent mostly on the growing season conditions and features of the cultivated genotype of the crop. The study conducted by Al-Doori (2012) reports about significant dependence of linseed yield on the date of sowing and variety (genotype). It is evident that right chosen varieties for concrete climatic conditions provide the best productivity that was also certified by the results of our study, where the variety Evryka was the number one in the irrigated conditions, and the variety Vira - in the rain-fed conditions, respectively. Additionally, the comprehensive study in regard to the response of oil-seed flax on different technological options discovered that the seed yield is significantly affected by the dose of Nitrogen applied (the best variant was with 100% supply of the crop with this element accordingly to the results of the soil test) and plant density (should be higher than 300 plants m^{-2}) with no significant effect of sowing date on the crop productivity (Lafond et al., 2008). It was stated that the optimum date of sowing is highly dependent on the latitude of the crop cultivation with the general tendency of better sowing later in the North, and earlier sowing in the South. The studied by Lafond et al. (2008) cultivars did not show significant difference in the yield. But Gallardo et al. (2014) agree with us, namely, they also report about significant dependence of seed yield and linseed oil quality on the variety. Besides, they proved that delayed sowing of the crop in Argentina should not be practiced.

The results of Berti et al. (2009) agree with ours in the point of the reaction of oil-seed flax to mineral fertilization with Nitrogen and Phosphorus. They also proved significant increase in the seed yield with the increase of Nitrogen supply; however, they used enormously high rates of this nutritive element of 200 kg ha^{-1} that is not environmentally friendly in our opinion. The results of another study discovered that the application of $N_{60}P_{40}S_{30}$ significantly increased the yield of flax on the loam and sandy loam soils (Aulakh et al., 1989). The deficiency of Nitrogen results in considerable decrease of oil-seed flax yield and yield components, therefore, artificial Nitrogen supply is an irreplaceable element of the crop cultivation (Hocking & Pinkerton, 1991).

Besides the factors studied in current research, there are a number of other important technological factors of oil-seed flax productivity regulation, namely: sowing depth and preparation of the seedbed (Couture et al., 2004); row spacing of the crop (Kocjan Acko &

Trdan, 2008); fertilization with macro (NPK) and micronutrients (Berti et al., 2009). Thereby, further scientific researches are required to create a comprehensive image of oil-seed flax response to different agricultural treatments in different environmental conditions, considering soil and climate factor of the crop productivity (Dillman, 1943).

CONCLUSIONS

The maximum yields of seeds were provided by the oil-seed flax variety Evryka (2.36 t ha^{-1}) in the irrigated conditions, and the variety Vira (1.47 t ha^{-1}) in the non-irrigated conditions at the application of $N_{90}P_{60}$. The best yield of oil was provided by the variety Vira (0.97 t ha^{-1} and 0.57 t ha^{-1} with the application of $N_{60}P_{60}$ in the irrigated and non-irrigated conditions, respectively). The variety Vira has the highest drought tolerance among the studied varieties of oil-seed flax. By the means of statistical yield analysis, it was revealed that the strongest effect on the crop yield is caused by irrigation, and the least - by Phosphorus fertilization. Mineral nutrition must be adjusted with accordance to the field fertility level with taking into account humidification conditions. The main regularity is: Nitrogen supply of the crop should be strengthened at the irrigated conditions, and the crop should not be over-fertilized with Nitrogen in the rain-fed conditions, especially, if the genotype of the cultivated variety is not drought tolerant enough.

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