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Features of photosynthetic activity and water consumption of safflower

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Abstract

Safflower is a heat-loving and very drought-resistant short-day plant that could be well adapted to dry climate conditions. The aim of the experiment was to establish the influence of mineral fertilisers and growth regulators on the leaf surface area, net photosynthesis productivity, and safflower yield in the conditions of the Southern Steppe of Ukraine. The three-factorial experiment was conducted between 2017 and 2019. The soil of the experimental site was ordinary medium-strength and low-humus chernozem. For the experiment, the following factors were selected: (*Carthamus tinctorius* L.) cultivars (factor A) 'Zhyvchyk' and 'Dobrynya'; application of mineral fertilisers (factor B): without fertilisers (control), $N_{60}P_{50}$ for main tillage, and P_{50} for main tillage + N_{60} before sowing (P_{50} + N_{60}); application of growth regulators (factor C): without growth regulators (control), growth regulators Rost-koncentrat + Chelatin oil, Chelatin forte + Chelatin mono boron, Chelatin mono boron + Chelatin phosphorus-potassium, and Chelatin phosphorus-potassium + Chelatin multimix + Chelatin mono boron. The experimental data revealed that with the increase in total water consumption and net photosynthesis productivity the yield of each cultivar increased in direct proportion. The yield of 'Zhyvchyk' was higher than that of 'Dobrynya'.

Keywords: *Carthamus tinctorius*, mineral fertilisers, leaf surface area, growth regulators, total net photosynthesis productivity.

Introduction

Safflower (*Carthamus tinctorius* L.) is a heat-loving and very drought-resistant short-day plant, well adapted to the dry continental climate. This plant is especially heat-demanding during the flowering and ripening growth stages (GS). Safflower belongs to the same family as sunflower and is positioned as an alternative to it. The biological features of this culture and its adaptive potential correspond to the arid conditions of the Southern Steppe of Ukraine. This plant is resistant to weeds and does not die even in heavy contamination (Shevchenko et al., 2017). Like any culture, safflower requires consideration of biological characteristics and compliance with the elements of technology of its cultivation.

In Ukraine, there are no clear production recommendations on the timing and methods of sowing, seeding rates, application of mineral fertilisers, etc. Currently, these aspects are actively studied at the Institute of Oilseeds of the National Academy of Agrarian Sciences of Ukraine, Kherson State Agrarian University, Askaniiska State Agricultural Research Station of the Institute of Irrigated Agriculture of the National Academy of Agrarian Sciences of Ukraine and research and production firm "Dryada". By joint efforts, new cultivars adapted to zonal conditions have been created, and separate elements of culture cultivation technology have been developed.

Conducted scientific research and the accumulated experience of producers testify that the yield of dye safflower in the Southern Steppe of Ukraine can reach 1.5–1.8 t ha^{-1} (Lazer etal., 2012). For increasing yield and improving quality of safflower, agronomic requirements for cultivation, which are based on biological and physiological characteristics of this culture, are of primary importance (Yermakov, Polyakov, 2013).

The level of consumption of safflower nutrients depends on many factors related to the climatic conditions of the Southern Steppe of Ukraine and the genetic characteristics of cultivars. For the formation of one tonne of seeds and the corresponding amount of vegetative mass, safflower uses 30–35 kg N, 20–25 kg P, and 35–45 kg K. An important biological feature of safflower is the ability of the root system to absorb micro- and macroelements from sparingly soluble soil compounds. Therefore, despite poor or saline soils, safflower provides itself with sufficient nitrogen, phosphorus, and potassium to form the biological mass. In the Southern Steppe of Ukraine, even on low-yielding soils, safflower crops are generally in good condition and do not require the application of potassium fertilisers, neither in simple or complex mineral forms (Abbadi, Gerendás, 2012).

As a drought-resistant crop, safflower has proven itself well suited for the climatic conditions of the Southern Steppe of Ukraine. To reveal its biological potential on unproductive soils of this zone, it is necessary to add additional missing micronutrients – growth regulators. There are two most common ways to use growth regulators: pre-sowing seed treatment and spraying vegetative plants. Under the conditions of a balanced ratio of all factors and the optimal value of other factors, growth regulators can increase the productivity of crops by 15–30%. In terms of efficiency, the hectare rate of growth regulators is equated to the effect of mineral fertilisers at the level of N:P:K 25 kg ha^{-1}, etc. (Solonenko, 2019). One of studies shows that a balanced continuous use of fertilisers, either alone or in combination with organic manures, is necessary for sustaining higher yield of safflower (Meshram et al., 2019).

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In the agrocenosis, the relationship between plants is volatile, and it depends on many factors. The main task of obtaining high yield involves creating such a crop that can most fully explore the possibilities of photosynthetic activity of plants in the agrocenosis; this can be achieved by creating favourable conditions for plant growth and development (Turgut, 2015). The issue of increasing plant yield is directly related to the fact that the parameters of their formation are determined by both the potential of the culture and external factors, primarily the level of cultivation technology (Ivanchenko, Belikina, 2021).

The largest accumulation (90–95%) of dry crop mass occurs through photosynthesis in the leaves (Pashchenko, 2009). According to Nichiporovich (1966), the optimal leaf surface area should range around 40,000–50,000 m^2 ha^{-1}. The process of the formation of leaf surface area over 60,000 m^2 ha^{-1} is a negative phenomenon, as normal exchange of gas and light in crops is disturbed and thus the net photosynthesis productivity (NPP) is reduced. To obtain a high yield, it is not enough to form a large area of the assimilation surface and, having received it, it is impossible to guarantee a high crop yield.

A quite important indicator of photosynthetic activity in crops is NPP, which characterises the intensity of accumulation of dry crop biomass during the day per 1 m^2 of leaf surface of plants. Indicators of NPP, which have values of 3–4 g m^{-2} per day, should be considered satisfactory, 4–6 – good, and more than 6 g of dry matter weight per 1 m^2 of leaf surface area per day – very good. In the experiments of Musinov et al. (2014), the leaf surface area was formed at the level of 9.37–17.04 thousand m^2 ha^{-1} on average over the years of the experiment. Application of mineral fertilisers significantly affected the increase in the leaf surface area, the photosynthetic potential and yield of dry biomass, and, to a lesser extent, the value of NPP and photosynthetic active radiation (PAR) use ratio (Musinov et al., 2014).

According to the research by Khomina (2015), growth regulator Agroemistim-extra had the most pronounced effect on the leaf surface area for safflower dye: when processing seeds, the area of the leaf surface was 32,600 m^2 ha^{-1}, and when spraying vegetative plants, it was 31,200 m^2 ha^{-1}. These values exceeded the treatment without growth regulators (control), 2300 and 1000 m^2 ha^{-1}, respectively. According to Solonenko (2019), the maximum parameters of the leaf apparatus of dye safflower, both in terms of years and of the average over the years of the experiment, were on the treatments of the two-lane method of sowing: for 'Lagidny', the average of leaf surface area was 30.4 m^2 ha^{-1}, and for 'Sonyachny' it was 29.6 m^2 ha^{-1}. The photosynthetic potential of agrocenoses of dye safflower for 'Lagidny' ranged from 813,800 to 886,400 m^2 days ha^{-1}, and for 'Sonyachny' it was 796,200–860,000 m^2 days ha^{-1}. Average values of photosynthetic potential over the experimental years of 944,200–967,100 m^2 days ha^{-1} indicate its increase by spraying crops with Regoplant by 12.6–12.7% compared to the treatment without growth regulators (Solonenko, 2019).

Fedorchuk and Filipov (2013) found that the photosynthetic apparatus reached its maximum size during the flowering GS at the early sowing period and averaged 37,800–35,900 m^2 ha^{-1}, exceeding the late period by 1.5–1.6 times. At the late sowing period, NPP was 28.4% lower than at the early period. The timing of sowing had an impact on the dynamics of the accumulation of air-dry mass of both plants and in general. Plants sown between 21 and 30 of March had the highest indicators: full ripeness of seeds, corresponding to 29.9–38.9 g per plant during the flowering GS, while at the stalking GS this parameter was 11% lower.

According to Kshnikatkina et al. (2019), the largest leaf surface area of safflower was formed during the flowering GS of 22.9–26.8 thousand m^2 ha^{-1}. Net photosynthetic productivity varied from 1.98 to 2.55 million m^2 ha^{-1}; the highest NPP was observed in 2018 and 2016 and was equal to 2.95 and 2.99 g m^{-2} day^{-1}, respectively.

The aim of the research was to establish the influence of mineral fertilisers and growth regulators on the leaf surface area, net photosynthesis productivity (NPP) and safflower yield in the conditions of the Southern Steppe of Ukraine.

Materials and methods

The experiment was conducted between 2017 and 2019 in the fields of the Institute of Oilseed Crops of the National Academy of Agrarian Sciences of Ukraine. The soil of the experimental site was ordinary medium-strength and low-humus chernozem with humus content in the arable 0–30 cm layer of 3.5% (according to the State Standard of Ukraine 4362:2004), available nitrogen (N) 72–85 mg kg^{-1} (State Standard of Ukraine 4115:2002), mobile phosphorus (P_2O_5) 96–103 mg kg^{-1} (State Standard of Ukraine 4115:2002), mobile potassium (K_2O) 152–169 mg kg^{-1} of soil (State Standard of Ukraine 4115:2002), pH_{H2O} 6.5–7.0 of the soil solution (State Standard of Ukraine 4362:2004).

In 2017, 2018, and 2019, the agrometeorological conditions for the safflower growing seasons (April–August) differed from the average long-term indicators (Figure 1). The amount of precipitation from March to August was 196.1 mm in 2017, 208.0 mm in 2018, and 315.3 mm in 2019, against the average annual indicator of 269.0 mm. The average temperature for the April–August period was 20.3°C in 2017, 22.2°C in 2018, and 20.7°C in 2019, against the average of 17.6°C. Thus, 2017 turned out to be the driest year, the amount of precipitation was by 72.9 mm lower than the average annual indicator. At the same time, the average temperature exceeded the long-term average by 2.7°C. It was even hotter in 2018, with average temperatures higher by 4.6°C. Precipitation during the growing season fell by 61 mm than the average long-term indicator. For safflower cultivation, the most favourable year was 2019 with precipitation exceeding the annual average by 46.3 mm. Temperature readings were 3.1°C higher than average annual values.

Safflower was sown with seeder KLEN-4,2 (Vektor-R Ltd., Ukraine) between 1 and 10 of April with a sowing rate of 240,000 similar seeds per hectare. The row spacing was 70 cm, the distance between plants in the row – 6 cm. The main tillage system was mouldboard ploughing. The following experimental factors were selected: cultivars (factor A): 'Zhyvchyk' and 'Dobrynya'; application of mineral fertilisers (factor B): without fertilisers (control), $N_{60}P_{50}$ for main tillage, and P_{50} for main tillage + N_{60} before sowing (P_{50} + N_{60}); application of growth regulators (factor C): without growth regulators (control), growth regulators Rost-koncentrat + Chelatin oil, Chelatin forte + Chelatin mono boron, Chelatin mono boron + Chelatin phosphorus-potassium, and Chelatin phosphorus-potassium +

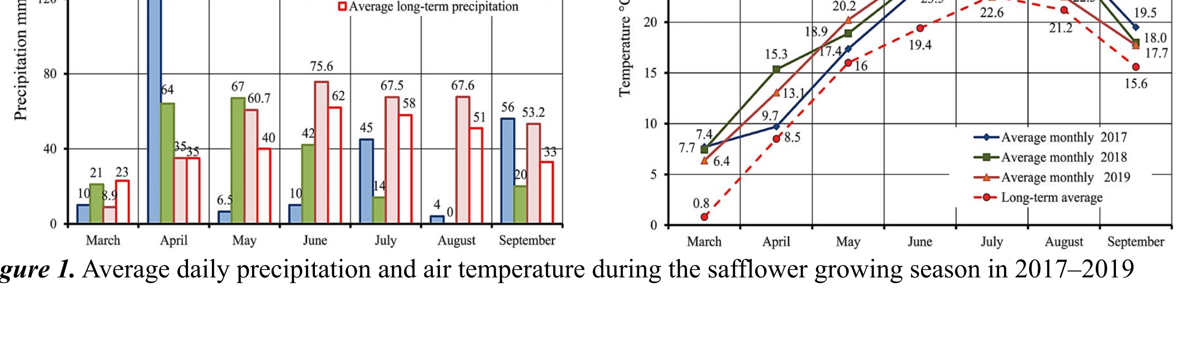


Figure 1. Average daily precipitation and air temperature during the safflower growing season in 2017–2019

Chelatin multimix + Chelatin mono boron. Plants were treated at the growth stage (GS) of 6–10 leaves on the scale of BBCH codes 14–19 (Meier, 2003). Sowing dates: 30 March 2017, 6 April 2018, and 8 April 2019; maturity dates: 12 August 2017, 8 August 2018, and 6 August 2019. To control weeds during the growing season of the crop, two inter-row treatments were carried out: the 1st at the 8–10 leaves GS to a depth of 6–8 cm, and the 2nd after two weeks to a depth of 8–10 cm.

Characteristics of safflower (Carthamus tinctorius L.) cultivars. 'Zhyvchyk' (in the Register of Plant Varieties of Ukraine since 2010): duration of the growing season 130–135 days, plant height 90–95 cm, oil content in seeds 32%, weight of 1000 seeds 40–45 g, yield in the south of Ukraine 1.9 t ha^{-1}; 'Dobrynya' (in the Register of Plant Varieties of Ukraine since 2016): duration of the growing season 110–120 days, plant height 87–100 cm, oil content in seeds 31%, weight of 1000 seeds 38–43 g, yield in the south of Ukraine 1.7–1.9 t ha^{-1} (http://imk.zp.ua/index.php/kataloh-sortiv-ta-hibrydiv/saflor).

Description of plant growth regulators. Rost-koncentrat is a complex organo-mineral fertiliser based on potassium humate, enriched with macronutrients nitrogen, phosphorus, potassium and a full set of microelements in chelated form. Chelatin oil is a concentrated micronutrient fertiliser containing trace elements in an innovative chelate complex, which includes copper, potassium, boron, and zinc. Chelatin forte is a highly effective environmentally-friendly micro fertiliser in a biologically active form based on chelates of microelements: copper, zinc, bromine, molybdenum, and cobalt. Chelatin mono boron is a special fertiliser with trace elements in an innovative chelate complex with a high boron content. Chelatin phosphorus-potassium is a liquid fertiliser with a balanced complex of phosphorus and potassium. Chelatin multimix is a chelated fertiliser with a complex of macro- and microelements, which consists of nitrogen, phosphorus, potassium, sulphur, copper, zinc, boron, iron, magnesium, manganese, cobalt, and molybdenum (https://kisson-agro.com.ua/produkcya/dobriva/mneraln/).

For determining the dry matter weight (DMW), plants were selected (by cutting at the soil level) according to the development (budding, flowering, and physiological ripeness) GS in each treatment in the amount of five pieces. Subsequently, they were dried at a temperature of 105°C for 4 h. Harvesting was carried out on a plot of land using a selection harvester Wintersteiger Classic (Wintersteiger AG, Austria) with a seed moisture content of 10–12%.

Setting up experiments, conducting research and statistical analysis was carried out in accordance with generally accepted methods of field experiments in agriculture and crop production (Dospekhov, 1985).

The leaf surface area was determined at three safflower development GS: budding, flowering, and physiological ripeness. The leaf surface area was determined in the following steps: (1) selecting five random plants from each site, (2) separating the leaves from the plant, (3) leaf scanning on a scanner Canon CanoScan LIDE 300 with a resolution of 1200 pixels according to the RGB colour model, (4) saving files in .jpg format, (5) conversing colour model of the received files to bitmap image using the software package Adobe Photoshop, (6) calculating the number of black pixels on the bitmap image using the software package JmageJ (Shevchenko, Aliev, 2018; Aliiev, 2020), (7) calculating the leaf surface area by entering the calibration coefficients using the software package Excel, and (8) averaging the value of the leaf surface area.

NPP was calculated by the formula (Nichiporovich, 1966):

$$NPP = \frac{W_2 - W_1}{0.5(L_2 + L_1)n} \quad (1),$$

where NPP is net photosynthesis productivity, g m^{-2} day^{-1}; W_1 and W_2 – dry biomass of the crop sample at the beginning and end of the accounting period, g; $0.5(L_1 + L_2)$ – average working leaf area for this period, m^2; n – the number of days.

TNPP was determined according to the formula proposed by the authors:

$$TNPP = NPP_1 \times N_1 + NPP_2 \times N_2 + NPP_3 \times N_3 \quad (2),$$

where TNPP is total net photosynthesis productivity, g m^{-2}; N – the duration of the growing season, days; indices 1, 2 and 3 correspond to the seedling–budding, budding–flowering, and flowering–maturity stages.

The moisture content in the 0–100 cm soil layer was determined by weight. For this purpose, samples were taken with an AM-16 drill in layers, every 10 cm in triplicate before sowing and at harvest. The total water consumption (Q) of the crop was calculated by the formula (Dospekhov, 1985):

$$\sum Q = W_0 - W_k + 0.75 \sum O \quad (3),$$

where W_0 is the moisture content before sowing, mm; W_k – the moisture content during harvesting, mm; 0.75 – precipitation utilisation factor; ∑O – the amount of precipitation during the growing season, mm.

The water consumption ratio was determined by the formula (Dospekhov, 1985):

$$K_Q = \frac{\sum Q}{Y} \quad (4),$$

where K_Q is the water consumption ratio, m^3 t^{-1}; Q – total water consumption of the crop, mm; Y – yield, t ha^{-1}.

Statistical analysis was performed using software Statistica (StatSoft Inc., USA).

Results and discussion

Investigation of the leaf surface area of one safflower plant revealed the effect of mineral fertilisers and growth regulators on its performance. Values of the leaf surface area of both safflower cultivars during the seedling–budding GS were in the range of 0.035–0.040 m^2. At the same time, a slight effect of additional nutrition on the leaf surface area of one plant of each cultivar was noted. In treatments with the application of mineral fertilisers and growth regulators, the leaf surface area increased by 0.001–0.004 m^2 in relation to the treatment without growth regulators (control) (Table 1).

Statistical analysis of the experimental data is shown in Table 2.

The leaf surface area at the budding–flowering GS was in the range of 0.089–0.101 m^2 for 'Zhyvchyk' and 0.093–0.105 m^2 for 'Dobrynya'. After mineral fertilisation, the leaf surface area for the main application of $N_{60}P_{50}$ increased by 0.006–0.008 m^2 for 'Zhyvchyk' and by 0.007–0.008 m^2 for 'Dobrynya', and with the application of $P_{50} + N_{60}$ by 0.005–0.009 and 0.006–0.008 m^2, respectively. For 'Zhyvchyk', after the application of growth regulators to seedlings, the leaf surface area in the treatment without mineral fertilisers increased by 0.001–0.005 m^2, in the treatment with fertiliser application – by 0.003–0.004 m^2. For 'Dobrynya', under the treatment without growth regulators (control), the leaf surface area increased by 0.002–0.004 m^2, when applying $N_{60}P_{50}$ – by 0.003–0.005 m^2, and with $P_{50} + N_{60}$ – by 0.004–0.005 m^2.

The leaf surface area for one plant of both cultivars at the flowering–maturity GS decreased compared to the budding–flowering GS and was equal to 0.054–0.062 m^2. The application of $N_{60}P_{50}$ during the main tillage led to an increase in leaf surface area by 0.004–0.005 m^2 for 'Zhyvchyk' and 0.003–0.005 m^2 for 'Dobrynya'; when $P_{50} + N_{60}$ was applied, the leaf surface area increased by 0.003–0.005 m^2 for both cultivars in comparison with the treatment without growth regulators. The use of growth regulators with the background without fertilisers (control) and with the main application of $N_{60}P_{50}$ increased the leaf surface area by 0.001–0.003 m^2 for both cultivars, and the application of $P_{50} + N_{60}$ – by 0.002–0.003 m^2 for 'Zhyvchyk' and by 0.003 m^2 for 'Dobrynya'.

Analysis of statistical data (Table 1) showed that the greatest impact on the leaf surface area had the application of mineral fertilisers (71.61%) and growth regulators (9.69%). Varietal difference of the leaf surface area was practically not observed (the influence of the factor was 2.44%). The smallest significant difference of factors was 0.001 m^2.

DMW of one plant increased under the influence of additional nutrition: to a greater extent from mineral fertilisers and to a lesser extent from growth regulators. DMW of one plant at the germination–budding GS was 5.61–6.16 g for 'Zhyvchyk' and 5.33–5.91 g for 'Dobrynya'. After the mineral fertilisation during the germination–budding GS, DMW of one

Table 1. Influence of the application of mineral fertilisers and growth regulators on photosynthetic activity of safflower plants growth stages in the Southern Steppe of Ukraine (2017–2019)

Application of mineral fertilisers (B) No need to list things known from textbooks	Application of growth regulators (C)	Leaf surface area of 1 plant m^2			Dry matter weight of 1 plant g			NPP $g\ m^{-2}\ day^{-1}$			TNPP $g\ m^{-2}$
		seedling–budding	budding–flowering	flowering–maturity	seedling–budding	budding–flowering	flowering–maturity	seedling–budding	budding–flowering	flowering–maturity	
Cultivar (A)		'Zhyvchyk'									
Without fertilisers (control)	1	0.035	0.089	0.054	5.61	8.15	10.85	4.07	3.28	4.76	479.1
	2	0.037	0.093	0.057	5.96	8.64	11.53	4.17	3.34	4.78	456.9
	3	0.035	0.090	0.055	5.87	8.51	11.34	4.26	3.41	4.89	467.0
	4	0.036	0.092	0.056	5.93	8.61	11.47	4.23	3.39	4.85	463.6
	5	0.037	0.094	0.057	5.91	8.57	11.42	4.10	3.30	4.73	460.4
$N_{60}P_{50}$ main tillage	1	0.038	0.097	0.059	6.04	8.77	11.67	4.07	3.26	4.67	446.2
	2	0.040	0.101	0.062	6.16	8.93	11.91	3.99	3.20	4.56	436.7
	3	0.038	0.097	0.059	6.02	8.74	11.63	4.03	3.24	4.63	442.4
	4	0.039	0.100	0.061	6.16	8.95	11.90	4.01	3.24	4.63	441.6
	5	0.039	0.100	0.061	6.08	8.82	11.73	4.00	3.20	4.56	441.7
P_{50} main tillage + N_{60} before sowing	1	0.038	0.096	0.058	6.00	8.71	11.57	4.04	3.27	4.69	450.8
	2	0.039	0.100	0.061	6.10	8.85	11.78	3.98	3.20	4.57	441.3
	3	0.039	0.099	0.060	6.03	8.75	11.64	4.00	3.19	4.55	445.5
	4	0.039	0.099	0.060	6.15	8.93	11.87	4.04	3.26	4.65	444.1
	5	0.039	0.099	0.060	6.09	8.84	11.76	4.04	3.22	4.61	441.3
Cultivar (A)		'Dobrynya'									
Without fertilisers (control)	1	0.035	0.093	0.055	5.33	7.73	10.29	3.94	2.99	4.43	454.5
	2	0.036	0.097	0.057	5.52	8.02	10.68	3.90	2.98	4.41	438.4
	3	0.036	0.095	0.056	5.36	7.78	10.35	3.85	2.96	4.37	442.8
	4	0.036	0.097	0.058	5.56	8.07	10.74	3.92	2.98	4.41	439.2
	5	0.036	0.096	0.057	5.43	7.88	10.48	3.86	2.96	4.40	444.6
$N_{60}P_{50}$ main tillage	1	0.037	0.100	0.059	5.74	8.32	11.11	3.99	3.01	4.46	427.2
	2	0.039	0.104	0.061	5.83	8.45	11.28	3.84	2.94	4.34	418.7
	3	0.038	0.103	0.061	5.77	8.35	11.17	3.86	2.93	4.34	414.9
	4	0.039	0.105	0.062	5.91	8.58	11.45	3.86	2.94	4.36	416.0
	5	0.038	0.103	0.060	5.84	8.46	11.30	3.92	2.97	4.42	421.7
P_{50} main tillage + N_{60} before sowing	1	0.037	0.099	0.058	5.71	8.28	11.04	3.96	3.02	4.49	427.6
	2	0.039	0.104	0.061	5.80	8.41	11.23	3.81	2.91	4.32	420.2
	3	0.038	0.103	0.061	5.71	8.29	11.03	3.82	2.91	4.29	419.2
	4	0.039	0.103	0.061	5.76	8.36	11.15	3.83	2.93	4.34	422.4
	5	0.039	0.104	0.061	5.80	8.42	11.23	3.82	2.93	4.34	422.0

1 – without growth regulators (control), 2 – Rost-koncentrat (1.0 L ha^{-1}) + Chelatin oil (1.5 L ha^{-1}), 3 – Chelatin forte (1.0 L ha^{-1}) + Chelatine mono boron (1.0 L ha^{-1}), 4 – Chelatine mono boron (1.0 L ha^{-1}) + Chelatine phosphorus-potassium (1.0 L ha^{-1}), 5 – Chelatine phosphorus-potassium (0.5 L ha^{-1}) + Chelatin multimix (0.5 L ha^{-1}) + chelatine mono boron (0.5 L ha^{-1}); NPP – net photosynthesis productivity, TNPP – total net photosynthesis productivity

plant increased by 0.15–0.43 g with the application of $N_{60}P_{50}$ for 'Zhyvchyk' and by 0.31–0.41 g for 'Dobrynya'; with application of P_{50} + N_{60} – by 0.14–0.39 and 0.20–0.38 g, respectively. The application of growth regulators increased the DMW under treatment without fertilisers by 0.26–0.35 g for 'Zhyvchyk' and by 0.03–0.23 g for 'Dobrynya'; with the application of $N_{60}P_{50}$ – by 0.04–0.12 g and 0.03–0.17 g, and with the application of P_{50} + N_{60} – by 0.03–0.15 g and 0.05–0.09 g, respectively.

DMW of one plant at the budding–flowering GS was 8.15–8.95 g for 'Zhyvchyk' and 7.73–8.58 g for 'Dobrynya'. The application of $N_{60}P_{50}$ led to weight gain of 0.23–0.62 g for 'Zhyvchyk' and 0.43–0.59 g for 'Dobrynya', with the application of P_{50} + N_{60} – by 0.21–0.56 and 0.39–0.55 g, respectively. The influence of growth regulators was more noticeable in the treatment without fertilisers: the DMW increased by 0.36–0.49 g for 'Zhyvchyk' and by 0.05–0.29 g for 'Dobrynya'; in the treatment with the application of $N_{60}P_{50}$, the DMW increased by 0.05–0.18 g for 'Zhyvchyk' and by 0.03–0.26 g for 'Dobrynya'; in the treatment with P_{50} + N_{60} application – by 0.04–0.22 and 0.01–0.14 g, respectively.

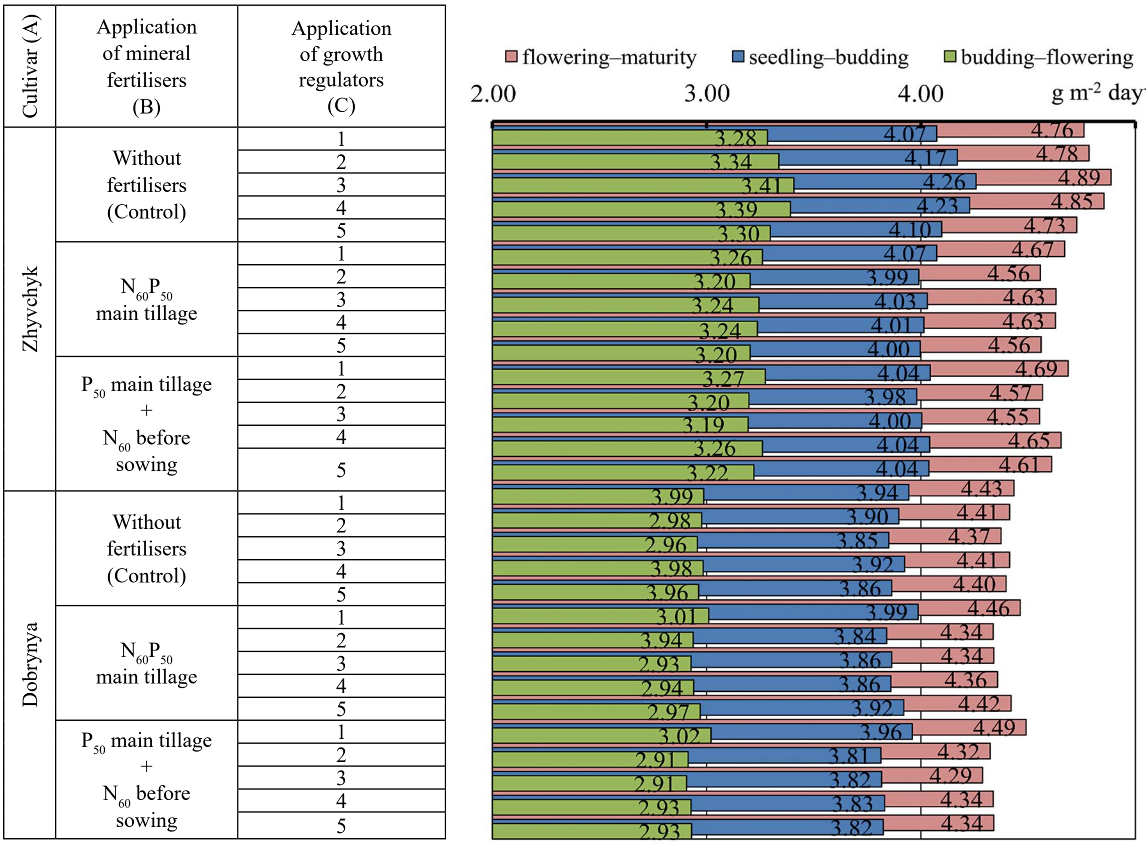
The highest values of DMW of one plant were observed during the flowering–maturity GS: these indicators were in the range for 'Zhyvchyk' of 10.85–11.91 g and for 'Dobrynya' 10.29–11.45 g. The application of $N_{60}P_{50}$ led to increase of DMW by 0.29–0.82 g for 'Zhyvchyk' and by 0.6–0.82 g for 'Dobrynya', and the application of P_{50} + N_{60} – by 0.25–0.72 and 0.41–0.75 g, respectively, in comparison with control treatment. After the application of growth regulators under the treatment without fertilisers, DMW increased by 0.54–0.73 g for 'Zhyvchyk' and by 0.06–0.45 g for 'Dobrynya', against the background of P_{50} + N_{60} – by 0.06–0.24 and 0.06–0.34 g, and against the background of P_{50} + N_{60} – by 0.07–0.21 and 0.11–0.19 g, respectively.

Analysis of statistical data (Table 1) showed that the DMW was influenced by all factors: the influence of the cultivar was 44.46%, of mineral fertilisers – 36.13%, and of growth regulators – 10.17%. According to Fisher's criterion, not pairwise interaction of factors was observed. The smallest significant difference for the main factors was equal to 0.03 m^2.

According to the results of the three-year experiment, change in the indicators of NPP of safflower, depending on mineral fertilisers and growth regulators, has been established. Thus, at the budding GS, indicators were in the range of 3.99–4.10 g m^{-2} day^{-1} for 'Zhyvchyk' and 3.81–3.99 g m^{-2} day^{-1} for 'Dobrynya'. During the budding–flowering GS, under the influence of additional mineral nutrition, the leaf surface area of one plant increased, which led to a slight darkening of part of the leaves and, as a result, a decrease in the intensity of photosynthesis. Accordingly, the indicators of NPP also decreased in comparison with the budding GS and were equal to 3.19–3.41 g m^{-2} day^{-1} for 'Zhyvchyk' and 2.91–3.02 g m^{-2} day^{-1} for 'Dobrynya'. At the same time, the highest NPP (3.28–3.41 and 2.96–2.99 g m^{-2} day^{-1}, respectively) was in control treatment without fertilisers. Against the background of mineral fertilisers, NPP decreased by 0.01–0.17 g m^{-2} day^{-1} for 'Zhyvchyk' and by 0.02–0.05 g m^{-2} day^{-1} for 'Dobrynya'. The highest indicators of NPP for 'Zhyvchyk' and 'Dobrynya' were observed at the flowering–maturity GS: 4.55–4.89 and 4.32–4.49 g m^{-2} day^{-1}, respectively (Figure 2).

According to the research data of other studies (Pandey, Sharma, 1996; Kubsad, Mallapur, 2003; Sayyad et al., 2009; Turgut, 2015) and comparison with the obtained results, it was found that the maximum yield of safflower can be formed by crops with optimal leaf surface area. It is important that it grows rapidly to the maximum value and stays at the achieved level for a long time without a sharp decrease until the end of the growing season absorbing solar radiation as much as possible.

The indicator of the TNPP, relative to the cultivars of safflower, was higher in 'Zhyvchyk' and, depending on the



Explanation of treatments under Table 1

Figure 2. Influence mineral fertilisers and growth regulators on net photosynthesis productivity (NPP) of safflower cultivars in the Southern Steppe of Ukraine (2017–2019)

treatment of the application of growth regulators, was 456.9–479.1 g m^{-2} in control treatment without fertilisers against the background of the main application of $N_{60}P_{50}$ 436.7–446.2 g m^{-2} and against the background of a separate application of P_{50} + N_{60} 441.3–450.8 g m^{-2}. For 'Dobrynya', these indicators were equal to 438.4–454.5, 414.9–427.2, and 419.2–427.6 g m^{-2}, respectively.

Analysis of statistical data (Table 2) showed that the indicators of NPP were most influenced by the cultivar (52.50%) and the application of mineral fertilisers (27.95%). In turn, the application of growth regulators had almost no effect (2.08%) on the NPP. According to Fisher's criterion, not pairwise interaction of factors was observed. The smallest significant difference for the main factors was equal to 0.04 g m^{-2} day^{-1}.

Table 2. Influence of factors: cultivar (A), application of mineral fertilisers (B), and growth regulators (C), on photosynthetic activity of safflower plants in the Southern Steppe of Ukraine (2017–2019)

Factor	Leaf surface area of 1 plant m²				Dry matter weight of 1 plant g				NPP g m^{-2} day^{-1}			
	Fisher's criterion		LSD_{05}	Influence of factor %	Fisher's criterion		LSD_{05}	Influence of factor %	Fisher's criterion		LSD_{05}	Influence of factor %
	F	F_{05}			*F*	F_{05}			*F*	F_{05}		
A	5.51	4.17	0.001	2.44	309	4.17	0.03	44.46	138	4.17	0.04	52.50
B	80.7	3.32	0.001	71.61	125	3.32	0.03	36.13	36	3.32	0.04	27.95
C	5.46	2.69	0.001	9.69	17.7	2.69	0.03	10.17	1.37	2.69	0.04	2.08
A × B	0.33	3.32	0.0004	0.29	5.30	3.32	0.008	1.52	1.65	3.32	0.01	1.25
A × C	0.76	2.69	0.0003	1.35	0.68	2.69	0.007	0.39	1.06	2.69	0.01	1.60
B × C	0.37	2.27	0.0004	1.31	2.62	2.27	0.007	3.01	1.09	2.27	0.01	3.29
A × B × C	0.46	2.27	0.0002	1.62	1.14	2.27	0.0003	1.30	1.26	2.27	0.005	3.81
Error	–		–	13.3	–		–	4.31	–	–		11.3

NPP – net photosynthesis productivity; *F* – calculated value, F_{05} – at 5% significance level (table value)

Depending on the background of mineral nutrition and the treatment of the application of growth regulators, the yield level was in the range of 1.46–1.71 t ha^{-1} for 'Zhyvchyk' and of 1.55–1.85 t ha^{-1} for 'Dobrynya' (Table 3, Figure 3). The increase from the application of mineral fertilisers was equal to 0.11–0.17 t ha^{-1} for 'Zhyvchyk' and 0.17–0.22 t ha^{-1} for 'Dobrynya'. Depending on the treatment of the application of regulators, the yield of safflower increased by 0.05–0.12 t ha^{-1} for 'Zhyvchyk' and by 0.03–0.11 t ha^{-1} for 'Dobrynya'. The highest yield of 'Zhyvchyk' (1.71 and 1.70 t ha^{-1}) and of 'Dobrynya' (1.84 and 1.85 t ha^{-1}) was obtained against the background of $N_{60}P_{50}$ mineral fertilisers under the main tillage with the application of Rost-koncentrat + Chelatin oil and Chelatin mono boron + Chelatine phosphorus-potassium, respectively.

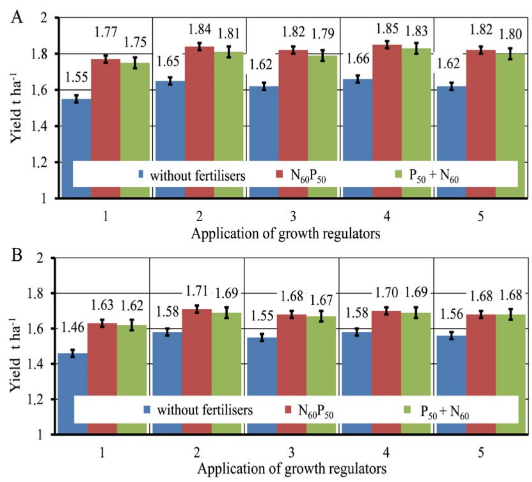
According to statistical data analysis (Table 4), the yield was most affected by the cultivar (factor A) – 38.83% and the application of mineral fertilisers (factor B) – 35.19%. The smallest significant difference of the main factors was 0.01–0.02 t ha^{-1}.

Comparing the results of our own experiment with other studies (Nabipour et al., 2007), it can be concluded that the nature of the change in yield and its growth were the same. However, the difference was in the varietal characteristics of safflower, soil, and agrotechnological conditions. Thus, irrigation results in a greater increase in yield, by almost 15%. The application of growth regulators compensates for it, as proved in our experiment.

Table 3. Influence of the application of mineral fertilisers and growth regulators on yield of safflower cultivars in the Southern Steppe of Ukraine (2017–2019)

Cultivar (A)	Application of mineral fertilisers (B)	Application of growth regulators (C)	Yield t ha^{-1}	Extra yield t ha^{-1}: effect of fertilisers	Extra yield t ha^{-1}: effect of growth regulators
Zhyvchyk	Without fertilisers (control)	1	1.46	–	–
		2	1.58	–	0.12
		3	1.55	–	0.09
		4	1.58	–	0.12
		5	1.56	–	0.10
	$N_{60}P_{50}$ main tillage	1	1.63	0.17	–
		2	1.71	0.13	0.08
		3	1.68	0.12	0.05
		4	1.70	0.11	0.07
		5	1.68	0.12	0.05
	P_{50} main tillage + N_{60} before sowing	1	1.62	0.15	–
		2	1.69	0.11	0.07
		3	1.67	0.12	0.06
		4	1.69	0.11	0.08
		5	1.68	0.12	0.07
Dobrynya	Without fertilisers (control)	1	1.55	–	–
		2	1.65	–	0.10
		3	1.62	–	0.07
		4	1.66	–	0.11
		5	1.62	–	0.07
	$N_{60}P_{50}$ main tillage	1	1.77	0.22	–
		2	1.84	0.19	0.07
		3	1.82	0.20	0.05
		4	1.85	0.19	0.08
		5	1.82	0.20	0.05
	P_{50} main tillage + N_{60} before sowing	1	1.75	0.20	–
		2	1.81	0.17	0.06
		3	1.79	0.17	0.03
		4	1.83	0.17	0.07
		5	1.80	0.18	0.05

Explanation of treatments under Table 1



Explanation of treatments under Table 1

Figure 3. Influence of mineral fertilisers and growth regulators on yield of safflower cultivars 'Zhyvchyk' (A) and 'Dobrynya' (B) in the Southern Steppe of Ukraine (2017–2019)

The results of three-year experiment showed that the moisture content at the end of the growing season in the 0–100 cm soil layer for 'Zhyvchyk' was 148.6–155.8 mm and for 'Dobrynya' 144.6–152.7 mm. Total water consumption of the crop varied depending on the application of mineral fertilisers and growth regulators: the lowest values for both cultivars were observed in the control treatment and were equal to 241.4 mm for 'Zhyvchyk' and 244.5 mm for 'Dobrynya'. After applying fertilisers, water consumption increased with different growth regulators for both cultivars: for 'Zhyvchyk', it was 2.7–5.0 mm on the background of $N_{60}P_{50}$ application and 2.3–4.1 mm on the background of P_{50} + N_{60}; for 'Dobrynya', it was 3.2–5.6 mm on the background of $N_{60}P_{50}$ application and 3.3–5.1 mm on the background of P_{50} + N_{60}. The application of growth regulators also led to an increase in the total water consumption of the crop: for 'Zhyvchyk', it was 2.2–3.8 mm in the absence of mineral fertilisers, 0.7–2.2 mm on the background of $N_{60}P_{50}$ application, 1.6–2.8 mm on the background of P_{50} + N_{60}; for 'Dobrynya', it was 3.0–4.4 mm in the absence of mineral fertilisers, 0.9–2.5 mm on the background of $N_{60}P_{50}$ application, and 1.9–3.0 mm on the background of P_{50} + N_{60}.

To determine the effect of nitrogen fertilisation on yield, yield components, chlorophyll content, photosynthetic characteristics, and water use efficiency of safflower grown under rainfed conditions, a two-year field experiment was conducted (Dordas, Sioulas, 2007). In comparison with the results of our experiment, it can be argued that not only nitrogen fertilisers affected the yield, chlorophyll content, and water consumption of the crop. These indicators also significantly influence phosphorus fertilisers and various growth regulators containing microfertilisers.

Table 4. Influence of mineral fertilisers (B) and growth regulators (C) on yield of safflower cultivars (A) in the Southern Steppe of Ukraine (2017–2019)

Factor	Yield t ha^{-1}: Fisher's criterion F	Fisher's criterion F_{05}	LSD$_{05}$	Influence of factor %
A	143.7	4.00	0.01-0.02	38.83
B	65.1	3.15	0.01-0.02	35.19
C	4.82	2.53	0.02-0.03	5.21
A × B	7.33	3.15	0.02-0.03	3.96
A × C	0.26	2.53	0.03-0.04	0.28
B × C	0.15	2.10	0.04-0.05	0.32
A × B × C	0.04	2.10	0.05-0.06	0.08
Error	–	–	–	16.21

F – calculated value; F_{05} – at 5% significance level (table value)

The objective of the research (Anicésio et al., 2018) was to evaluate the chlorophyll index, biometric characteristics, and water use efficiency of safflowers grown under different nitrogen and potassium rates and controlled soil water capacity. In contrast to the above, the results of our experiment were obtained in the field which took into account agrometeorological conditions. Thus, the results of our experiment supplemented the results of the obtained patterns of influence of mineral fertilisers and growth regulators on yield, photosynthetic activity, and total water consumption of the crop.

After comparing and approximating the total water consumption (Q) of the crop (mm), the indicator of the TNPP (g m^{-2}) with the yield (Y) (t ha^{-1}) was used to calculate the linear equations with the software package Wolfram Mathematica:

for the cultivar 'Zhyvchyk':

$$\begin{cases} Y = 4.316514 - 0.0059{+}8234\ TNPP, \\ Y = -7.12483 + 0.0355181\ Q; \end{cases}$$

for the cultivar 'Dobrynya':

$$\begin{cases} Y = 5.15{+}678 - 0.00807751\ TNPP, \\ Y = -8.432384 + 0.0404083\ Q. \end{cases}$$

They are presented in the form of systems (Table 5, Figure 4). The level of yield of safflower cultivars depends on the total water consumption of the crop and the TNPP (Figure 4). Thus, with the increase of total water consumption and NPP, the yield increased in direct proportion, because the yield was determined by the amount of moisture spent on its formation and the duration of the growing period in general and growth stage in particular. At the same time, while maintaining this dependence, the yield of 'Zhyvchyk' was higher than those of 'Dobrynya', which was related to the genetic potential of each cultivar.

The obtained dependences can be explained by the fact that an increase in the leaf surface area, the degree of its actual development enhances the efficiency of photosynthetic activity (Table 5, Figure 4). This leads to an increase in the yield of safflower. The second factor was the presence of moisture and the efficiency of its water absorption, which also led to increased yield. If the resources of moisture and nutrition are insufficient, then the main factor limiting the yield of plants is the insufficient development of the leaf surface and low productivity in poor soils.

As the general conclusion of current experiment, it should be emphasised that at this stage, safflower is a rare, niche crop in Ukraine. However, according to its biological characteristics, it is well suited to the arid conditions of the Southern Steppe of Ukraine. This oilseed crop is capable of forming a high and stable yield, which makes it an alternative to sunflower, as confirmed by the studies of other Ukrainian scientists (Lazer et al., 2012; Fedorchuk, Filipov, 2013; Khomina, 2015; Solonenko, 2019). To increase the yield of safflower, scientifically based use of mineral fertilisers and growth regulators is important. Optimisation of these elements of cultivation technology contributes to a more rational consumption of soil moisture, an increase in the assimilation surface of leaves, and their effective work to improve crop productivity.

Table 5. Influence of additional nutrition on water consumption by safflower cultivars in the Southern Steppe of Ukraine (2017–2019)

Cultivar (A)	Application of mineral fertilisers (B)	Application of growth regulators (C)	Moisture content in 0–100 cm soil layer at the end of the growing season mm	Total water consumption (Q) of the crop mm	Yield (Y) t ha^{-1}	Water consumption ratio (K_Q) m^3 t^{-1}
Zhyvchyk	Without fertilisers (control)	1	155.8	241.4	1.46	1653
		2	152.4	244.8	1.58	1549
		3	153.6	243.6	1.55	1572
		4	152.0	245.2	1.58	1552
		5	153.0	244.2	1.56	1565
	$N_{60}P_{50}$ main tillage	1	150.8	246.4	1.63	1512
		2	149.4	247.8	1.71	1449
		3	150.1	247.1	1.68	1471
		4	149.3	247.9	1.70	1458
		5	148.6	248.6	1.68	1480
	P_{50} main tillage + N_{60} before sowing	1	151.7	245.5	1.62	1515
		2	148.9	248.3	1.69	1469
		3	150.1	247.1	1.67	1480
		4	149.7	247.5	1.69	1464
		5	149.2	248.0	1.68	1476
Dobrynya	Without fertilisers (control)	1	152.7	244.5	1.55	1577
		2	148.3	248.9	1.65	1508
		3	149.7	247.5	1.62	1528
		4	148.4	248.8	1.66	1499
		5	148.9	248.3	1.62	1533
	$N_{60}P_{50}$ main tillage	1	147.1	250.1	1.77	1413
		2	145.1	252.1	1.84	1370
		3	146.2	251.0	1.82	1379
		4	144.6	252.6	1.85	1365
		5	145.4	251.8	1.82	1384
	P_{50} main tillage + N_{60} before sowing	1	147.6	249.6	1.75	1426
		2	145.0	252.2	1.81	1393
		3	145.7	251.5	1.79	1405
		4	144.6	252.6	1.83	1380
		5	145.6	251.6	1.80	1398

Explanation of treatments under Table 1

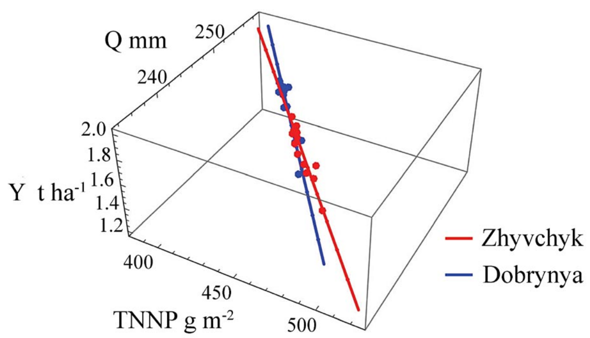


Figure 4. Dependence of yield (Y) of safflower cultivars 'Zhyvchyk' (red line) and 'Dobrynya' (blue line) on total water consumption (Q) of the crop and total net photosynthesis productivity (TNPP)

Conclusions

It was found that the application of mineral fertilisers and growth regulators in the conditions of the Southern Steppe of Ukraine led to a more efficient use of moisture, an increase in the leaf surface area of safflower plants, an increase in the overall net photosynthesis productivity (NPP), and formation of a higher yield. The results of the obtained experimental data allowed us to formulate the following conclusions:

1. The highest indices of NPP: 4.55–4.89 g m^{-2} day^{-1} for the 'Zhyvchyk' and 4.29–4.49 g m^{-2} day^{-1} for the 'Dobrynya', were observed during the flowering–ripening GS.
2. The highest values of the leaf surface area: 0.089–0.101 m^2 for 'Zhyvchyk' and 0.093–0.105 m^2 for 'Dobrynya', were observed during the budding-flowering GS for the treatments with the use of fertilisers; for NPP, it was observed during the flowering–maturity stage for the treatments without fertilisers and amounted to 4.55–4.89 g m^{-2} day^{-1} for 'Zhyvchyk' and 4.29–4.49 g m^{-2} day^{-1} for 'Dobrynya'.

3. Treatment of crops with growth regulators against the background of the application of mineral fertilisers led to an increase in the indicators of plant productivity elements and the overall level of yield of safflower cultivars. The highest yields were obtained in variants with an application of fertilisers $N_{60}P_{50}$ for the main tillage with the use of growth regulators Rost-concentrate + Chelatin oil and Chelatin mono boron + Chelatin phosphorus-potassium, and they amounted to 1.71 and 1.70 t ha^{-1} for 'Zhyvchyk' and 1.84 and 1.85 t ha^{-1} for 'Dobrynya'.

4. The obtained linear correlations showed the relationship between total water consumption (Q) of the crop (mm), the total net photosynthesis productivity (TNPP) (g m^{-2}) and the yield (Y) (t ha^{-1}). With the increase of total water consumption and NPP, the yield increased in direct proportion. If this dependence is maintained, the yield of 'Zhyvchyk' was higher than those of 'Dobrynya', which was related to the genetic potential of each cultivar.

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Dažinio dygmino fotosintezės aktyvumas ir vandens suvartojimas Ukrainos pietinėse stepėse

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Santrauka

Dygminas yra šilumą mėgstantis ir labai atsparus trumpos dienos augalas, galintis gerai prisitaikyti sauso klimato sąlygomis. Eksperimento tikslas – nustatyti mineralinių trąšų ir augimo reguliatorių įtaką lapų paviršiaus plotui, grynajam fotosintezės produktyvumui ir dygminų derliui Ukrainos pietinių stepių sąlygomis. Trijų veiksnių eksperimentas vykdytas 2017–2019 m. Eksperimento vietos dirvožemis – paprastasis vidutinio sunkumo ir mažai humusingas juodžemis. Eksperimento veiksniai: dažinio dygmino (*Carthamus tinctorius* L.) veislės (A veiksnys) 'Zhyvchyk' ir 'Dobrynya'; tręšimas mineralinėmis trąšomis (B veiksnys): be trąšų (kontrolinis variantas), $N_{60}P_{50}$ pagrindiniam žemės dirbimui, ir P_{50} pagrindiniam dirbimui + N_{60} prieš sėją (P_{50} + N_{60}); tręšimas augimo reguliatoriais (C veiksnys): be augimo reguliatorių (kontrolinis variantas), augimo reguliatoriai Rost-koncentrat + chelatino aliejus, Chelatin forte + Chelatin mono boron, Chelatin mono boron + Chelatin phosphorus-potassium ir Chelatin phosphorus-potassium + Chelatin multimix + Chelatin mono boron. Eksperimento rezultatai parodė, kad didėjant suminiam vandens suvartojimui ir grynajam fotosintezės produktyvumui, abiejų veislių dygminų derlius didėjo tiesiogiai proporcingai; derlius buvo didesnis veislės 'Zhyvchyk' nei 'Dobrynya' dygminų.

Reikšminiai žodžiai: *Carthamus tinctorius*, mineralinės trąšos, lapų paviršiaus plotas, augimo reguliatoriai, bendrasis grynasis fotosintezės produktyvumas.