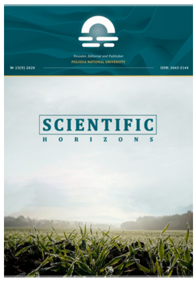
SCIENTIFIC HORIZONS

Journal homepage: https://sciencehorizon.com.ua
Scientific Horizons, 26(5), 56-64



UDC 633.174:631.5
DOI: 10.48077/scihor5.2023.56

Photosynthetic productivity of sorghum (*Sorghum bicolor* L. (Moenh) in the conditions of the Right-Bank Forest-Steppe of Ukraine

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Article's History:
Received: 2.03.2023
Revised: 10.04.2023
Accepted: 3.05.2023

Suggested Citation:
Pravdyva, L., Zatserkovna, N., Vakhniy, S., Khakhula, V., & Hornovska, S. (2023). Photosynthetic productivity of sorghum (Sorghum bicolor L. (Moenh) in the conditions of the Right-Bank Forest-Steppe of Ukraine. *Scientific Horizons*, 26(5), 56-64.

Abstract. Sorghum (*Sorghum bicolor* L. (Moenh) is a technical, food, and fodder crop and can be used for various purposes, given its value, the acreage should be substantially expanded in Ukraine, and the elements of cultivation technology should be thoroughly examined. The purpose of the study was to determine the effect of the growth regulator on the photosynthetic productivity of sorghum in the conditions of the Right-Bank Forest-Steppe of Ukraine. The following methods were used in the study: field, measuring and weighing, mathematical, and statistical. The study was conducted in conditions of unstable moisture in the Right-Bank Forest-Steppe of Ukraine in 2016-2019. Based on the results of the study, it was determined that the use of a plant growth regulator affected photosynthetic productivity, namely, the leaf surface area, photosynthetic potential and net photosynthesis productivity. The

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indicators for the content of chlorophylls changed. Thus, the assimilation area of leaves reached a maximum with seed treatment and spraying of crops and amounted to 8.56 thousand m^2/ha during the tillering period, during the period of stem elongation – 29.6 thousand m^2/ha, during flowering and full ripeness – 40.32 and 4.97 thousand m^2/ha. Net photosynthetic productivity in the control was the lowest – 4.67 g/m^2, the use of a growth regulator on seeds and crops contributed to its increase by 0.27 and 0.79 g/m^2. With the treatment of seeds and crops, the net photosynthetic productivity was the highest and amounted to 6.12 g/m^2. The sum of chlorophylls *a+b* had the highest rates during the tasselling period and, depending on the experiment options, ranged from 4.36 to 5.35. The yield of grain and biomass also varied depending on the use of the preparation, and was the highest in the version with seed treatment and spraying of crops (7.1 and 35.9 t/ha). The close relationship between photosynthetic productivity and the yield of sorghum is also determined. The study can contribute to the widespread use of growth regulators in sorghum crops, ensure the full development of plants, and increase grain yields and biomass

Keywords: leaf surface area; net photosynthesis productivity; chlorophyll content; grain and biomass yield

INTRODUCTION

Among the grain crops grown in Ukraine, sorghum is one of the drought-resistant and highly productive crops. It is important that at high temperatures, plants have the ability to continue the assimilation process.

According to Ortiz *et al.* (2019), Li *et al.* (2021), and Kovalenko *et al.* (2023), sorghum (*Sorghum bicolor* L. (Moenh) is a universal and promising energy culture – it is an agricultural, widely cultivated, and highly productive type C_4 plant. Kolozsvári *et al.* (2022) note that sorghum has substantial photosynthetic efficiency and can produce high grain yields and powerful energy-rich biomass in the short term. According to Davydenko *et al.* (2022) sorghum is currently used as human food, animal feed, an alternative energy source, and for industrial purposes. It ranks fifth after major grain crops and sixth in the world in terms of gross grain yield.

As researchers Alekseev (2021) and Polevyi *et al.* (2020) note, sorghum plants have great potential to adapt to growing conditions, particularly drought, soil salinity, high temperature, etc. Grains with a high starch content are valuable raw materials for the production of bioethanol, and biomass (leaves and stems) of plants can be used as solid fuels. Abreha *et al.* (2022) believe that modern technologies for growing agricultural crops are based on the theory of crop formation as a photosynthetic system and are developed considering biological characteristics, including the type of plant photosynthesis.

Grishchenko *et al.* (2020) state that the yield of crop seeds and biomass depends on the photosynthetic activity of plants, which depends on weather and climatic conditions and cultivation technology. In the first case, the factors are not controlled by humans, in the other – directly depend on their activity. Therefore, the investigation of elements of the technology of growing sorghum, in particular, the effect of the growth regulator on photosynthetic productivity in the conditions of the Right-Bank Forest-Steppe of Ukraine, is a relevant and promising area.

Researchers Davydenko and Rozhkov (2022), note that in agriculture, low-cost crop cultivation technologies are more popular, the elements of which are the use of growth regulators, biologics, microfertilisers, etc. These preparations are economical, their use helps to improve the growth and development of plants and provides a substantial increase in the yield and quality of grown products. The high efficiency of using growth regulators on grain crops is associated with their ability to increase the accumulation of macro- and microelements, increase the concentration of photosynthetic pigments, and, as a result, activate photosynthesis and increase crop productivity. In addition, they allow controlling the duration of individual phases of plant growth and development and also help to correct the state of crops due to unfavourable abiotic conditions.

Studies by Nemahunguni *et al.* (2019), Ngoroyemoto *et al.* (2020), and Gupta *et al.* (2021) proved that plant biostimulants stimulate growth in many plant species under different growing conditions, have a positive effect on photosynthetic pigments, carbohydrates, proteins, and phytohormones. Notably, their effectiveness depends on the method of application, the type of plant, the growth period, etc. According to Mazur *et al.* (2018) and Shevchenko (2017), the use of growth regulators activates the mechanism of immunity, stress resistance, and adaptability of plants. Their use affects the formation of crops with optimal morphostructural and functional indicators.

A study by Shevchenko & Tokmakova (2018), conducted on corn crops in Polissia determined that due to the growth-stimulating properties of the preparation, quantitative and qualitative parameters of the photosynthetic activity of plants increase. Its use for seed and crop treatment increases the leaf surface area by 40% and the net photosynthetic productivity of crops by 63.8%. When treated with plant growth regulators, the accumulation of photosynthetic pigments increases (by 12-24%), while the content of water-soluble sugars decreases by 9.0-17.5%, which indicates the functional activity of the photosynthetic apparatus.

In accordance with this, the purpose of the study was to investigate the effect of the growth regulator on the assimilation surface area, photosynthetic potential, net photosynthetic productivity, and chlorophyll content in sorghum in the conditions of the Right-Bank Forest-Steppe of Ukraine.

MATERIALS AND METHODS

The study was conducted in 2016-2019 at the Bila Tserkva Experimental Station of the Institute of Bioenergy Crops and Sugar Beet of the National Academy of Agrarian Sciences of Ukraine. Soils on which the study was conducted: typical low-humus chernozems. Humus content is 3.5%, total nitrogen – 0.31%, hydrolytic acidity – 2.41 mg-eq., easily hydrolysed nitrogen – 134 mg/kg, phosphorus – 276 mg/kg, potassium – 98 mg/kg, base saturation – 90%. The scheme of the experiment provided for the treatment of seeds and vegetative plants with a growth regulator: factor A (seed treatment) – without treatment (control) and treated seeds with a growth regulator; Factor B (treatment of crops with a growth regulator) – seeds not treated + spraying of crops and seeds treated + spraying of crops with a regulator. The experiment is repeated four times. Area of the sown area is 50 m^2, accounting – 21 m^2. Crops were formed with a row spacing of 45 cm and a density of 200 thousand units/ha, sowing depth – 4-6 cm. According to the scheme, the growth regulator Vermistim was used in the experiment – a preparation made as an extract from vermicompost. It contains a complex of water-soluble fulvic acids, enzymes, vitamins, and phytohormones.

Accounting and monitoring of crops, in particular, determination of leaf surface area, photosynthetic potential, net productivity of photosynthesis, chlorophylls *a* and *b*, were conducted according to the methodology developed at the Institute of Bioenergy Crops and Sugar Beet by Roik *et al.* (2020) and Pravdyva *et al.* (2021). Weather conditions, in particular, temperature and precipitation, had deviations from long-term indicators, but were favourable for growing sorghum in the conditions of the Right-Bank Forest-Steppe of Ukraine. Correlation regression analysis was performed using a PC in Excel programme based on the obtained results.

Statistical analysis. After first undergoing an analysis of variance (ANOVA), all data were analysed with the software SAS (SAS Institute Inc., USA) to determine the statistical substantiality of the treatment effects (P=0.05 or less). Significant differences between individual means were determined using the least significant difference (LSD) test.

RESULTS AND DISCUSSION

Photosynthetic productivity of crops has a substantial impact on the yield of sorghum, which in turn depends on the leaf surface area. The yield of biomass and organic matter also depends on its size. Analysing the results, it was determined that the leaf surface area varied both by the periods of plant growth and development and by the use of a growth regulator. In general, seed and crop treatment increased the leaf surface area by 20-55% compared to the control, depending on the development phase (Table 1).

Table 1. *Effect of the growth regulator on the leaf surface area of sorghum plants (2016-2019)*

Method of preparing seeds for sowing		Leaf surface area, thousand m^2/ha, per phase:			
		tillering	stem elongation	flowering	full ripeness
Seed treatment (factor A)	Without treatment – control	6.83	20.4	33.5	3.19
	Seeds treated with a plant growth regulator	7.92	27.2	36.1	4.12
Crop treatment (Factor B)	Untreated seeds + spraying of crops with a plant growth regulator	8.15	28.6	38.9	4.68
	Seeds treated + spraying of crops with a plant growth regulator	8.56	29.6	40.32	4.97
	$LSD_{0.05}$	0.11	0.98	1.36	0.13

Source: *compiled by the authors*

During the flowering period, the leaf surface area of plants had maximum values, after which it decreased until the grain was fully ripe, and amounted to 33.5 thousand m^2/ha for control, 36.1 thousand m^2/ha for seed treatment with a growth regulator, 38.9 thousand m^2/ha in the version where only crops and 40.32 thousand m^2/ha were sprayed together with the treatment of seeds and crops. The study showed that in the control group, the leaf surface area had the lowest indicators.

The duration of functioning of the resulting area of the assimilation surface of plants is an important condition for ensuring high yields and is expressed by an indicator of photosynthetic potential. This indicator for the growing season gives a general characteristic of the photosynthetic activity of plants and, depending on the growing conditions, varies substantially.

The photosynthetic potential varied depending on the size of the leaf surface area during the growing season. It was the highest in the version where the growth regulator was used on seeds and crops and amounted to 1.31 mln. m^2×days/ha; in the variant where only seeds and crops were treated, it was lower by 3-5%. And the lowest indicator of photosynthetic potential (1.21 mln. m^2×days/ha) was observed in the control group where the growth regulator was not used (Table 2). One of the most important indicators of the photosynthetic potential of plants is the net productivity of photosynthesis, which shows the ratio of the daily growth of dry matter to the area of leaves, that is, the intensity of the assimilation surface of sorghum plants. With the beginning of plant development, the productivity of photosynthesis gradually increased, which reached a maximum on the 65th day after the emergence of seedlings, after which a sharp decrease occurred. It was determined that net productivity depends on the use of a growth regulator, with the highest values obtained in the group where seeds and crops were treated with a growth regulator and amounted to 6.12 g/m^2. In other variants of the experiment, the net photosynthetic productivity decreased to 4.67 g/m^2. Photosynthetic activity of sowing is the basis for the formation of a high yield. The study determined that the use of a growth regulator substantially increases the yield of sorghum. For example, in the group where the growth regulator was used on both seeds and crops, grain yields of 7.1 t/ha and biomass of 35.9 t/ha were achieved. Slightly lower yields of grain and biomass were observed in the variant where only seeds were treated (5.2 and 32.8 t/ha) and where only crops were treated (5.9 and 33.4 t/ha). In the control group, the yield is the lowest – 4.4 and 29.2 t/ha.

Table 2. *Photosynthetic potential, net photosynthetic productivity and yield of sorghum depending on the application of the growth regulator (2016-2019)*

Method of preparing seeds for sowing		Photosynthetic potential, (mln.m^2/ha)×days	Net photosynthetic productivity, g/m^2	Seed yield, t/ha	Biomass yield, t/ha
Seed treatment (factor A)	Without treatment – control	1.21	4.67	4.4	29.2
	Seeds treated with a plant growth regulator	1.24	4.94	5.2	32.8
Crop treatment (factor B)	Untreated seeds + spraying of crops with a plant growth regulator	1.27	5.46	5.9	33.4
	Seeds treated + spraying of crops with a plant growth regulator	1.31	6.12	7.1	35.9
$LSD_{0.05}$		0.04	0.08	0.33	1.45

Source: *compiled by the authors*

The process of photosynthesis that occurs in leaves promotes the absorption of carbon dioxide from the external environment, due to the energy of sunlight and its conversion into chemical energy of organic substances. This function is performed by chlorophyll, which is part of the cellular composition of plant leaves. The total amount of chlorophyll and its concentration in plant leaves is an important physiological parameter. It characterises the potential power of the photosynthetic apparatus depending on the phase of crop development, the reaction of plants to the action of various factors of influence (growth regulator, natural environmental factors, mineral nutrition, etc.) and has a close relationship with the biological productivity of the plant organism. The chlorophyll content in the leaves of sorghum plants gradually increased in the growth and development phases and was maximum in the tasselling phase, and in the waxy and full ripeness phase, it intensively decreased depending on the experiment options.

The results of the study showed a substantial difference in the content of chlorophylls *a* and *b* in the leaves of sorghum plants from the tillering period to full ripeness (Table 3). The growth regulator is of great importance for the formation of chlorophylls in sorghum plants. Thus, the treatment of seeds and crops with a growth regulator, compared to the control option, increased the content of chlorophyll *a* in the phase of tasselling by 18.4% and the content of chlorophyll *b* by 18.8%. When using the preparation only on seeds and only on crops, the content of chlorophyll *a* increased by 3.30 and 6.35%, and chlorophyll *b* – by 5.88 and 13.2%. The lowest number of them was observed in the control group.

***Table 3.** Dynamics of chlorophylls in sorghum plants depending on the use of a growth regulator, mg/g of dry matter (2016-2019)*

Method of preparing seeds for sowing		Phase of plant growth and development:											
		Tillering			Stemming			Tasselling			Full ripeness		
		a	*b*	*a+b*	*a*	*b*	*a+b*	*a*	*b*	*a+b*	*a*	*b*	*a+b*
Seed treatment (factor A)	Without treatment – control	2.70	0.82	3.52	2.93	0.87	3.8	3.24	1.12	4.36	1.54	0.62	2.16
Seed treatment (factor A)	Seeds treated with a plant growth regulator	2.84	0.85	3.69	3.08	0.91	3.99	3.35	1.19	4.54	1.58	0.65	2.23
Crop treatment (factor B)	Untreated seeds + spraying of crops with a plant growth regulator	2.88	0.89	3.77	3.14	0.94	4.08	3.46	1.29	4.75	1.61	0.68	2.29
	Seeds treated + spraying of crops with a plant growth regulator	2.98	0.94	3.92	3.22	0.99	4.21	3.97	1.38	5.35	1.66	0.70	2.36

***Source**: compiled by the authors*

Correlation and regression analysis of data between photosynthetic potential and leaf surface area is represented by a second-order polynomial and the equation has the form $y=0.0012x^2-0.0727x+2.3316$. A strong correlation was established, with the coefficient R=0.9790, and the coefficient of determination $R^2=0.9817$ (Fig. 1a). Between net photosynthetic productivity and the leaf surface area, a strong correlation R=0.9572 was established, and the coefficient of determination $R^2=0.9884$. The correlation-regression relationship is represented by a polynomial second order and the equation has the form $y=0.0309x^2-2.0789x+39.643$ (Fig. 1b).

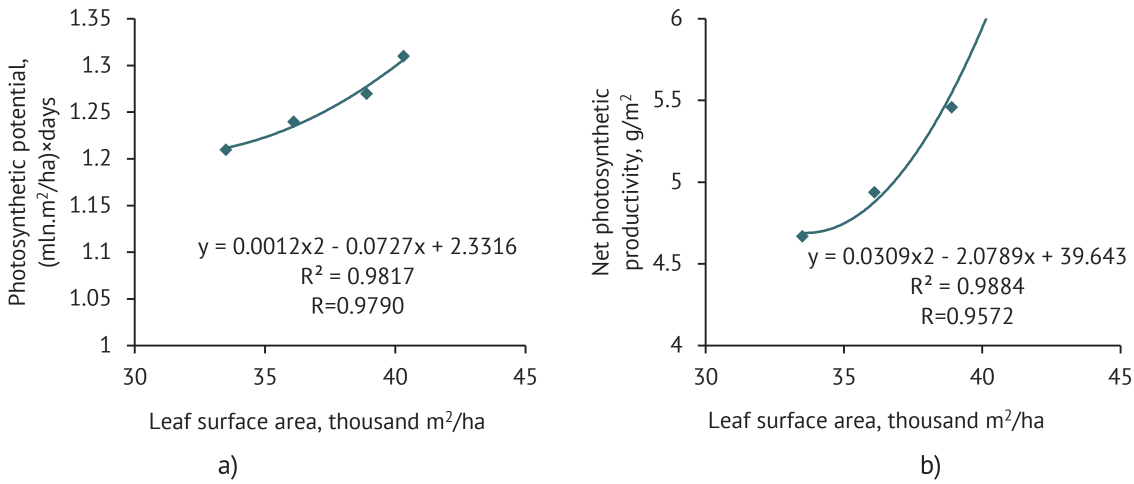
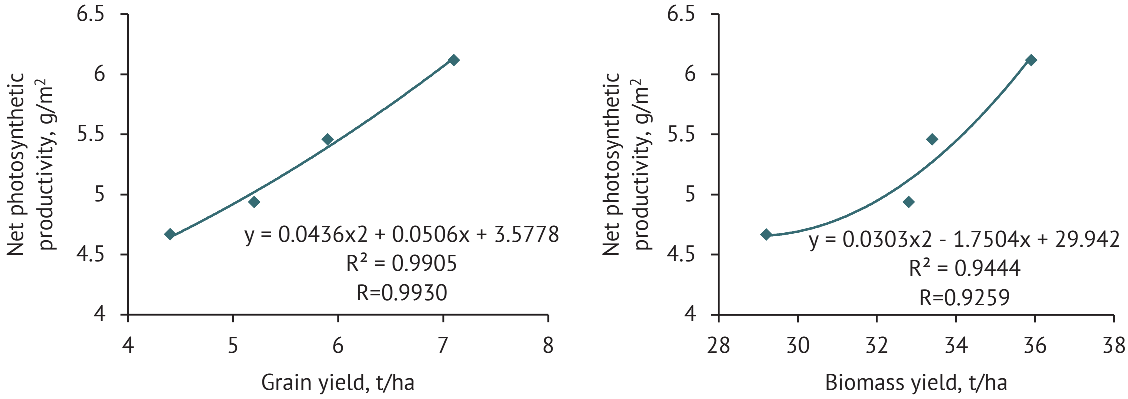


***Figure 1.** Correlation-regression relationship (a) between photosynthetic potential and leaf surface area and (b) between net photosynthetic productivity and leaf surface area*

***Source**: compiled by the authors*

The obtained results showed that with an increase in the net productivity of photosynthetic activity, the yield of sorghum also increased. This is confirmed by correlation and regression analysis, which proved a substantial relationship between net photosynthesis productivity and grain yield and between net photosynthesis productivity and biomass yield (Fig. 2 a, b). The coefficient of determination and correlation was $R^2=0.9905$ and R=0.9930 and $R^2=0.9444$ and R=0.9259. This dependency can also be described a second-order polynomial equation: $y=0.0436x^2+0.0506x+3.5778$ and $y=0.0303x^2-1.7504x+29.942$.



a) b)

Figure 2. *Correlation-regression relationship (a) between net photosynthetic productivity and grain yield and (b) between net photosynthetic productivity and biomass yield*

Source*: compiled by the authors*

The formation of highly productive crops is a complex multi-industry process of regular changes in plant growth and development (Rozhkov & Svyrydova, 2017), which involves a large number of exogenous and endogenous factors that regulate the level of disclosure of the genetic potential of plant productivity. During ontogenesis, genetically determined natural changes occur in plants in stages, which are based on the consistent implementation of the plant development programme. The investigation of the relationship between agrotechnical factors of cultivation will allow managing the production process of sorghum crops.

A study conducted by (Davydenko & Rozhkov, 2022) proved the feasibility of using the growth stimulator Vegestim in cultivating grain sorghum. From the standpoint of agronomic efficiency, the best option was the one in which seeds were treated with this preparation before sowing and two foliar top dressing was conducted – at the beginning of tubing and tasselling. On average, over the years and the examined hybrids of grain sorghum, the yield of sorghum grain in this variant was the highest in the experiment – 5.28 t/ha.

In the studies of Karpenko & Krasnoshtan (2022), it was noted that the most favourable conditions for the formation of the content of pigments in the tissues of grain sorghum leaves are formed with the complex application of Citadel 25 OD, Endophyte L1, and Bioarsenal preparations, accompanied by an increase in the content of chlorophylls a, b, a+b, and carotenoids on average by 7.4-9.1%, 16.0-18.3%, 9.4-11.2%, and 35.5-40.2%, respectively. This indicates that the use of the Citadel 25 OD herbicide in conjunction with the plant growth regulator Endophyt L1 and the biological product Bioarsenal is an effective measure to reduce the negative effect of xenobiotic on the pigment complex of grain sorghum plants.

According to researchers Dyomin *et al.* (2021), it was determined that the variants with complex application of Agrostimulin obtained a substantial increase in the yield of perennial sorghum seeds (1.7 t/ha), which substantially exceeded the control by 0.5 t/ha and other experimental variants (by 0.1-0.2 t/ha). It was also established that the initial rates of interphase periods of growth and development of sorghum plants are reduced by the use of Agrostimulin.

Raid *et al.* (2019) show that the use of growth regulators and microelements substantially impacted the growth, development, and yield of grain sorghum. The improvement of growth parameters with preparations may be a consequence of their role in modifying various physiological and metabolic processes.

A study by Storozhyk *et al.* (2019) indicates that the highest yield of green mass was obtained with a density of 250 thousand plants/ha and seed treatment with the growth stimulator Vympel 2 (0.5 L/t) + foliar top dressing in the tillering phase (0.5 L/ha) when sowing the Dovista hybrid – 98.8 t/ha, which is 5.3 t/ha more than that of the Gulliver hybrid.

Researchers (Titarenko & Karpuk, 2022) determined that when growing a hybrid of sorghum Brigga, the best indicators of energy harvesting with grain were obtained on foliar fertiliser variants with microfertiliser Alpha-Grow-Extra, 2 L/ha in combination with the growth regulator Stimpo-116.72 GJ/ha. And for growing a Yutami sorghum hybrid with seeds on the application of foliar fertiliser with microfertiliser Alpha-Grow-Extra, in combination with both growth regulators, the minimum difference and maximum energy collection were obtained – 134.58 and 134.39 GJ/ha. Lyubich *et al.* (2020) determined that the use of a plant growth regulator positively affects the germination energy and laboratory germination of sorghum and increases them by 4-7% compared to the control option.

Thus, based on the studies conducted by other researchers, growth regulators have a positive effect on the sowing qualities of seeds, plant growth and development, and sorghum productivity. However, the number of studies on the effect of growth regulators on the photosynthetic productivity of grain sorghum is practically nonexistent, so it requires further research.

CONCLUSIONS

Based on the results of the conducted studies, the effect of the pre-sowing treatment of seeds and crops with a plant growth regulator on the photosynthetic productivity of sorghum was established. The obtained data are statistically reliable, relevant, and characteristic for growing in various soil conditions using a growth regulator.

The leaf surface area in the experiment varied depending on the periods of plant development and the use of a growth regulator and reached 40.32 thousand m^2/ha during the flowering period in the variant with the treatment of seeds and crops. The duration of the assimilation surface is expressed by the photosynthetic potential, which ranged from 1.21 to 1.31 mln. m^2/ha×days. On average, the net productivity of photosynthesis increased to 6.12 g/m^2 per day. The highest yield in the experiment was obtained in the following variants: seed treatment + spraying of crops – 7.1 t/ha, seed treatment – 5.1 t/ha, and crop treatment – 5.7 t/ha. Treatment of seeds and crops with a growth regulator, increased the content of chlorophyll *a* by 18.4% and chlorophyll *b* by 18.8%, compared to control.

The results of correlation analysis allowed for establishing the determining factors of influence on the yield of sorghum. It is proved that with high indicators of photosynthetic productivity, the yield of grain and biomass substantially increased, while the correlation coefficient was R=0.9930 and R=0.9259.

In Ukraine, sorghum is poorly examined and sparsely distributed, and, accordingly, requires a detailed investigation of the elements of cultivation technology, namely the use of a growth regulator on seeds and crops, which will contribute to the formation of both grain and high-quality biomass. Growth regulators affect the metabolic and enzymatic processes of plants, ensuring a high intensity of photosynthesis. Currently, sorghum is considered an energy crop, the raw material used for producing ethanol and solid fuels. Therefore, the conducted study is relevant – with proper planning of crops and further use.

ACKNOWLEDGEMENTS

None.

CONFLICT OF INTEREST

None.

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Фотосинтетична продуктивність сорго звичайного двокольорового (*Sorghum bicolor* L. (Moenh) в умовах Правобережного Лісостепу України

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Анотація. Сорго звичайне двокольорове є технічною, продовольчою та кормовою культурою і може бути використане для різноманітних цілей, зважаючи на його цінність, посівні площі повинні бути значно розширені в Україні, а також досконало вивчені елементи технології вирощування. Метою досліджень було визначити вплив регулятора росту на фотосинтетичну продуктивність сорго звичайного двокольорового в умовах Правобережного Лісостепу України. В роботі використовували наступні методи: польовий, вимірювально-ваговий, математично-статистичний. Дослідження проводили в умовах нестійкого зволоження Правобережного Лісостепу України в 2016-2019 рр. За результатами досліджень встановлено, що застосування регулятора росту рослин впливало на фотосинтетичну продуктивність, а саме на площу листкової поверхні, фотосинтетичний потенціал та чисту продуктивність фотосинтезу. Змінювалися показники щодо вмісту хлорофілів. Так, асиміляційна площа листків сягала максимуму з оброблянням насіння та обприскуванням посівів і становила у період кущіння 8,56 тис. м^2/га, у період виходу в трубку – 29,6 тис. м^2/га, у період цвітіння та повної стиглості – 40,32 та 4,97 тис. м^2/га. Чиста продуктивність фотосинтезу на контролі була найменшою – 4,67 г/м^2, застосування регулятора росту на насінні та на посівах сприяло її підвищенню на 0,27 та 0,79 г/м^2. З обробкою насіння і посівів чиста продуктивність фотосинтезу була найвищою і становила 6,12 г/м^2. Сума хлорофілів а+в мала найвищі показники у період викидання волоті і залежно від варіантів досліду була в межах від 4,36 до 5,35. Урожайність зерна та біомаси також варіювала від застосування препарату. І найвищою була у варіанті з обробкою насіння й обприскуванням посівів (7,1 та 35,9 т/га). Також визначено тісноту взаємозв'язків між фотосинтетичною продуктивністю та врожайністю сорго звичайного двокольорового. Наукові дослідження можуть сприяти широкому застосуванню регуляторів росту на посівах сорго, і забезпечити повноцінний розвиток рослин, збільшенню урожайності зерна та біомаси

Ключові слова: площа листкової поверхні; чиста продуктивність фотосинтезу; вміст хлорофілів; урожайність зерна та біомаси