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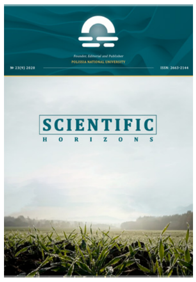

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Sorghum (*Sorghum bicolour* (L.) Moench) growth and development features under the influence of growth regulator

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Abstract. There has been a growing interest in growing sorghum (*Sorghum bicolor* L. (Moenh) as a bioenergy crop, as it can be used to produce biofuels (ethyl alcohol) and solid fuels (pellets and briquettes from the above-ground mass). Sorghum grain is characterised by a high starch content of up to 80%. The research topic is relevant but poorly understood. The research aims to study the effect of growth regulators on the growth and development of sorghum in the conditions of the Right-Bank Forest-

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Steppe of Ukraine. The following research methods were used: field, measuring and weighing, mathematical and statistical. The study presents the results of research for 2016-2019, where the influence of elements of cultivation technology on the peculiarities of the formation of biometric parameters was studied. plant growth regulator had an impact on field germination, vegetation period, biometric indicators of plant growth, and leaf area. The closeness of the correlations of the studied indicators was established, and a correlation-regression analysis of the data was carried out, which showed a strong correlation between the growing season and plant height, where the coefficient was R=0.9264, and the coefficient of determination R^2=0.9864. There was also a strong relationship between stem diameter and plant height, where the correlation coefficient was R=0.9767 and the coefficient of determination was R^2=0.954. The conducted studies confirm the feasibility of using a growth regulator that improves plant development and will contribute to increasing the yield and quality of grain and biomass of sorghum. The obtained results of the research give grounds to believe that growth regulators contribute to the production of environmentally friendly products and are components of environmentally friendly and energy-saving cultivation technology

Keywords: sorghum; growth regulator; seed quality parameters; vegetation period; biometric parameters; leaf area; correlation

INTRODUCTION

Establishing the feasibility of using a growth regulator by treating seeds and spraying sorghum crops to ensure high yields and quality of grain and biomass as raw material for biofuel production determines the research relevance. Following R. Saxena *et al.* (2018), R. Ortiz-Cruz *et al.* (2020) and S. Rajini *et al.* (2020) sorghum (*Sorghum bicolour* (L.) Moench) is a cereal crop belonging to the Poaceae family, originating in Africa, and domesticated 3-5 thousand years ago. According to D. Fuller & C. Stevens (2018), and B. Pandian *et al.* (2022), sorghum can withstand a variety of environmental conditions, including low soil fertility, high temperatures, and insufficient rainfall. It is cultivated primarily in semi-arid areas of Africa and Asia, where it is used for human consumption and is a staple food for local populations.

K. Aregawi *et al.* (2022), P. Espitia-Hernández *et al.* (2022) and Q. Yang *et al.* (2022) note that sorghum is the fifth most important grain crop in the world after wheat, rice, corn and barley. In some regions, it is replacing maize due to its high yields and resistance to drought and heat. As noted by B. Pandian *et al.* (2022), it is a short-day crop that uses moisture and precipitation efficiently, resumes growth after a long dry period, and generates high productivity, which means that sorghum can be grown in arid areas and the face of climate change.

Following C. Mundia *et al.* (2019) and T. Begna (2021a, b) sorghum is used as food, feed, fodder and fuel, so it has new market needs in the world. M. Nurmet *et al.* (2019) note that the world is facing the problem of depletion of conventional fossil fuel sources and a forecast of a doubling of energy demand within a decade, thus raising concerns about unreliable energy supply in the future. J. Dahlberg (2019), L. Pravdyva (2021) and L. Pravdyva *et al.* (2022) found that sorghum is an energy crop, as it can be used for the production of bioethanol (ethyl alcohol) and solid fuel: the aboveground mass is used to produce briquettes and pellets. Therefore, given the versatility of sorghum use, it is relevant and integral to study the elements of cultivation technology, in particular, an important element that affects the formation of many processes of growth, development and productivity of the crop is the use of growth regulators.

According to T. Makoveichuk *et al.* (2018), one of the ways to solve this problem is to use biologically active substances in modern crop cultivation technologies that can regulate plant growth processes and protect them from abiotic and biotic stresses. Plant growth and development regulators are synthetic and natural organic chemicals that are biologically active, even in small quantities, and cause changes in the physiological and biochemical processes of plants. According to A. Panfilova *et al.* (2019), biological products stimulate the growth and development of agricultural plants, increase resistance to stress and disease, and provide balanced nutrition. This effect is achieved by live bacteria converting insoluble compounds into available forms, providing nitrogen nutrition, and protecting plants from bacterial and fungal diseases. V. Hamaiunova *et al.* (2019) argue that the use of mineral fertilisers and growth regulators in cereal crop cultivation technologies helps to optimise plant nutrition throughout the growing season. Plant growth stimulants increase the intensity of metabolic and growth processes in plants, resulting in increased crop productivity and improved product quality.

The research aims to determine the effect of the growth regulator on the quality of sorghum seeds, the duration of the growing season, biometric parameters, and correlation in the conditions of the Right-Bank Forest-Steppe of Ukraine.

MATERIALS AND METHODS

The research was carried out in 2016-2019 at the Bila Tserkva Experimental Breeding Station of the Institute of Bioenergy Crops and Sugar Beet of the National Academy of Agrarian Sciences of Ukraine – the Right-Bank Forest-Steppe zone of Ukraine. The research scheme envisages a two-factor experiment: seed treatment (factor A) and treatment of crops with a growth regulator (Factor B) (Table 1).

Table 1. *Study plan*

Factor A: Seed treatment	Factor B: Treatment of crops with a growth regulator
1. No treatment – control (water)	1. Untreated seeds + spraying of crops with a regulator
2. Seeds treated with a regulator	2. Treated seeds + and spraying of crops with a regulator

Source: *compiled by the author*

The area of the sowing plot is 50 m^2, the accounting plot is 25 m^2, and the replication of the experiment is four times. The plots were arranged by the method of systematic replication: in each replication, the experimental variants were placed in the plots sequentially. Sowing of seeds was carried out at a depth of 4-6 cm, row spacing of 45 cm, and density of 200 thousand seeds/ha. Following the methodology of M. Roik *et al.* (2020) and L. Pravdyva *et al.* (2021), crops were recorded and monitored. To establish the peculiarities of growth and development of sorghum plants, the following were determined: laboratory and field germination of seeds, duration of the growing season from emergence to full maturity; and biometric parameters.

The soil of the experimental site is typical deep low-humus chernozem of coarse-dusty medium loamy granulometric composition. Magnesium and calcium carbonates occur at a depth of 55-65 cm. The topsoil (0-30 cm) contains about 17% of silt particles and 46-54% of coarse dust. The terrain is flat, with a groundwater table of 8 m. The agrophysical and agrochemical properties of the arable (0-30 cm) soil layer are characterised by the following indicators: humus – 3.5%, total nitrogen – 0.31%; hydrolytic acidity – 2.41 mg-eq; easily hydrolysed nitrogen (N) – 134 mg, P_2O_5 – 276 mg, K_2O – 98 mg per 1000 g of soil. The degree of saturation with bases is 90%.

Weather conditions in the years of study during the growing season were characterised by minor deviations with an excess of long-term indicators (Figs. 1, 2). In 2016, the average air temperature during the growing season was 17.9°C, which is 2.48°C higher than the average long-term indicators. In 2017, the average air temperature was 17.2°C, which exceeded the long-term average by 1.85°C. In 2018 and 2019, the average air temperature for the growing season exceeded the long-term average by 2.91 and 1.83°C.

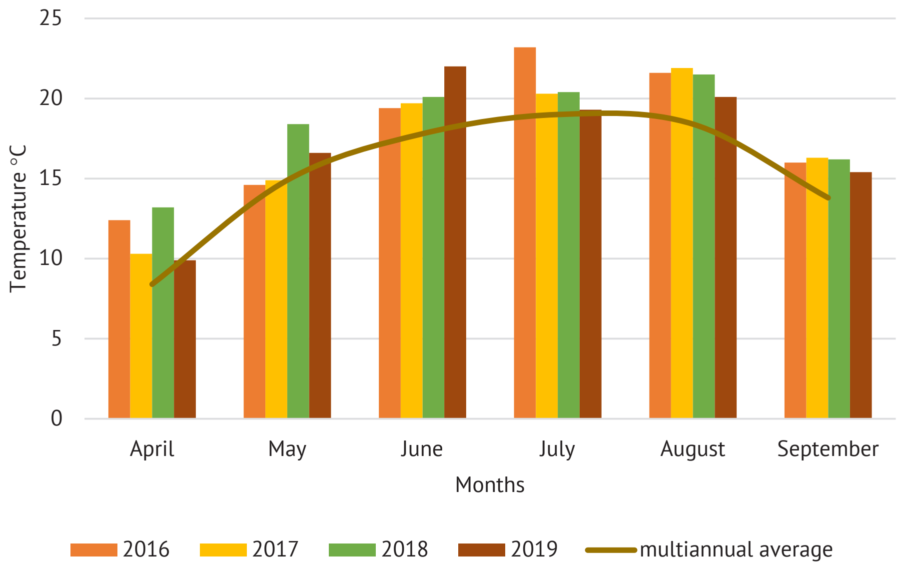

Figure 1. *Air temperature during the growing season in 2016-2019*

The amount of precipitation was uneven across months and below the long-term average. In 2016, during the growing season, the amount of precipitation was 102.6 mm less than the long-term average. In 2017, the amount of precipitation was 186.8 mm, which is 159.2 mm less than the long-term average. In 2018-2019, the amount of precipitation was 84.8 and 72.7 mm less than the long-term average.

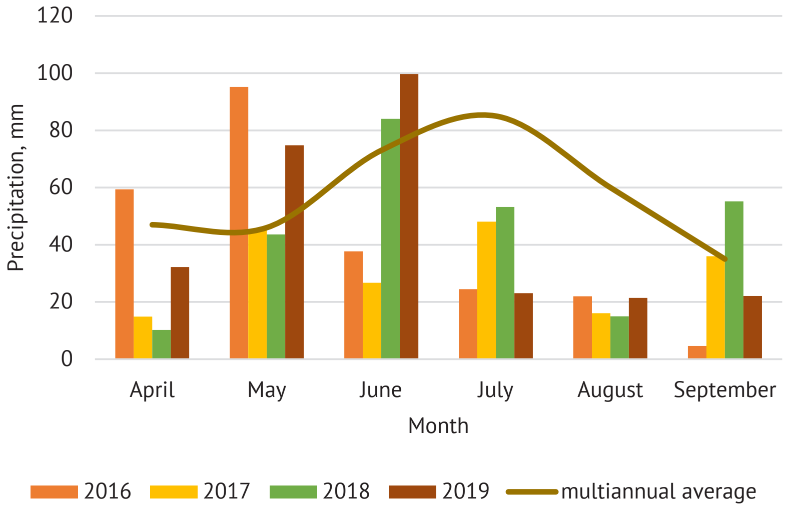

Figure 2. *Precipitations during the growing season in 2016-2019*

However, for the cultivation of sorghum, the soil and climatic conditions were typical of the conditions of the research and favourable for the cultivation of this crop. The experiment used the growth regulator Vermistim, a complex preparation made as an extract from vermicompost obtained through vermiculture as a product of worms' vital activity after they process organic waste. It consists of a wide range of organic and mineral substances, including humates, fulvic acids, and strains of beneficial soil organisms in dissolved and active form. The complex of organic substances also includes regulatory, micro, and macro elements, vitamins, and phytohormones.

Statistical analysis. To determine the statistical significance of the treatment effects (P=0.05 or less), after first undergoing an analysis of variance (ANOVA), all data were analysed with the software SAS (SAS Institute Inc., USA). Significant differences between individual means were determined using the least significant difference (LSD) test. Correlation and regression analysis was carried out using a PC in Excel based on the research results.

RESULTS AND DISCUSSION

Analysing the research results, it was found that sorghum responds positively to the treatment of seeds and crops with a growth regulator. Thus, the germination energy and laboratory germination of seeds were 93.4 and 97.8%, which is 2.3 and 3.2% less than the control (seed treatment with water). Field germination was slightly lower than the laboratory germination and amounted to 87.2% in the variant without treatment with the growth regulator, 91.5% in the variant where only seeds were treated with the preparation, 87.4% in the variant with untreated seeds but sprayed crops, and 90.8% with seed and crop treatment (Table 2). The use of a growth regulator provided a significant increase in field germination of sorghum seeds.

Table 2. *Quality indicators of common sorghum seeds depending on the method of seed preparation for sowing (average for 2016-2019)*

Seed quality metrics	Seed treatment		Treatment of crops with a growth regulator	
	No treatment – control (water)	Seeds treated with a regulator	Untreated seeds + spraying of crops with a regulator	Treated seeds + and spraying of crops with a regulator
Seed germination energy, %	91.1	93.4	–	–
Laboratory germination of seeds, %	94.6	97.8	–	–
Field germination of seeds, %	87.2	91.5	87.4	90.8
$LSD_{0.5}$ (seed germination energy) - 1.30				
$LSD_{0.5}$ (seed laboratory similarity) - 0.39				
$LSD_{0.5}$ (seed field similarity) - 0.84				

Source: *compiled by the author*

The duration of the growing season varied depending on the use of the plant growth regulator (Fig. 3). It was proved that seed treatment and spraying of crops reduced the vegetation period of plants to 92 days, while in the untreated variant, the period from germination to full maturity was 105 days.

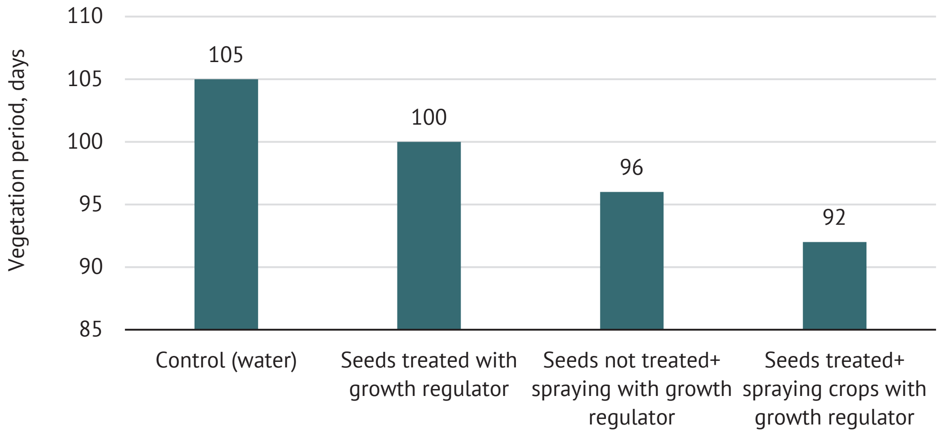

Figure 3. *Duration of the growing season of sorghum depending on the method of seed preparation for sowing (average for 2016-2019)*

The use of the growth regulator significantly improved the biometric parameters of the studied plants and the crop as a whole (Table 3). The lowest indicators were obtained in the variant where the growth regulator was not used (control), with a plant height of 118.6 cm, stem diameter of 1.4 cm, tillering and plant weight of 1.8 pcs/plant and 88.2 g. In the variant where only seeds and sowings were treated, the height of plants was on average 2.0-4.2 cm higher, the diameter was 1.5 cm, the number of tillers was up to 2.0 per plant, and the average plant weight was 2.1 and 3.6 g higher. The highest indicators of plant growth and development were observed in the variant where both seeds and crops were treated: plant height significantly increased – 130.2 cm, diameter – 1.7 cm, plants bushy – 2.5 pieces/plant and plant weight – 93.5 g.

Table 3. *Biometric indices of growth and development of sorghum plants depending on the method of seed preparation for sowing (average for 2016-2019)*

Seed sowing treatment method		Indicator for the harvest period			
		Plant height, cm	**Stem diameter, cm**	**Bushiness of plants, pcs./plant**	**Plant mass, g**
Seed treatment (Factor A)	No treatment – control	118.6	1.4	1.8	88.2
	Seeds treated with a plant growth stimulant	120.4	1.5	2.0	90.3
Crop treatment (Factor B)	Untreated seeds + spraying of crops with a plant growth stimulant	122.8	1.5	2.0	91.8
	Treated seeds + and spraying of crops with a plant growth stimulant	130.2	1.7	2.5	93.5
$LSD_{0.5}$		1.39	0.20	0.28	1.30

Source: *compiled by the author*

The use of a growth regulator provided an increase in the area of the assimilative apparatus of plants (Table 4), and, accordingly, photosynthetic activity. The growth of leaf surface area in sorghum plants occurred from germination to flowering, where the maximum values of the assimilation surface area were obtained. Thus, in the variant without the use of a growth regulator, the leaf surface area was 20.4 thousand m^2/ha. Seed treatment and the use of a growth regulator on sorghum crops increased the leaf surface area by 2.6 and 5.4 thousand m^2/ha. In the variant where seeds and crops were treated, the assimilation surface area reached a maximum and amounted to 40.32 thousand m^2/ha.

Table 4. Influence of growth regulator on the change of leaf surface area of sorghum, thousand m²/ha, (average for 2016-2019)

Seed sowing treatment method		Leaf area, thousand m²/ha, per phase:			
		bushing	tube exit	blooming	maturity
Seed treatment (Factor A)	No treatment – control	6.83	20.4	33.5	3.19
	Seeds treated with a plant growth stimulant	7.92	27.2	36.1	4.12
Crop treatment (Factor B)	Untreated seeds + spraying of crops with a plant growth stimulant	8.15	28.6	38.9	4.68
	Treated seeds + and spraying of crops with a plant growth stimulant	8.56	29.6	40.32	4.97
	$LSD_{0.5}$	0.11	0.98	1.36	0.13

Source: *compiled by the author*

The correlation and regression analysis of the data between the growing season and plant height is represented by a second-order polynomial and the equation is *y = 0.0831x2 – 17.229x + 1011.7*. A strong correlation was found, with the coefficient being R=0.9264 and the coefficient of determination R^2=0.9864 (Fig. 4).

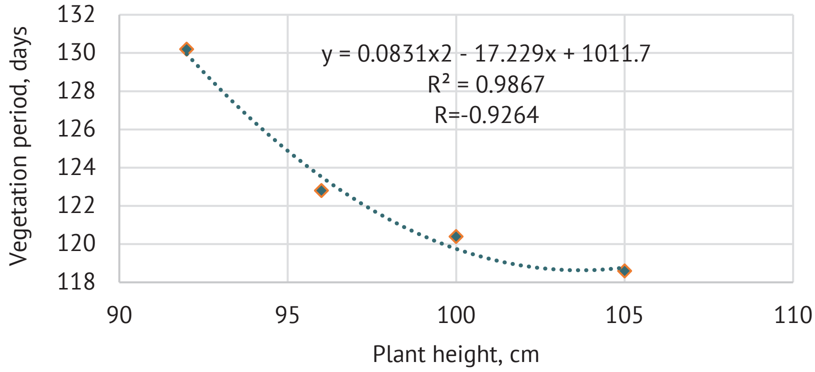

Figure 4. *Correlation and regression relationship between the growing season and plant height (average for 2016-2019)*

Source: *compiled by the author*

Correlation and regression analysis of the data showed a strong linear correlation between stem diameter and plant height, with the equation *y = 0.0241x – 1.4396* (Fig. 5). The correlation coefficient was R=0.9767 and the coefficient of determination was R^2=0.954.

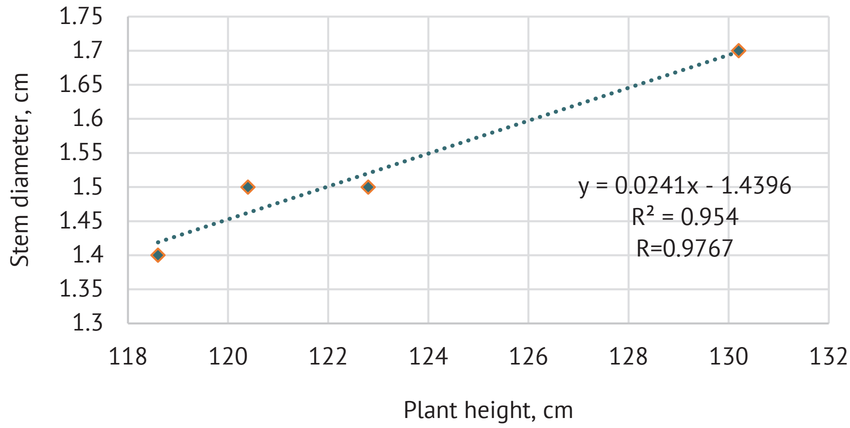

Figure 5. *Correlation and regression relationship between stem diameter and plant height (average for 2016-2019)*

Source: *compiled by the author*

When studying correlations, two main questions arise: the closeness and the shape of the relationship.

Special statistical methods called correlation are used to measure the strength and shape of the relationship. The data in Table 5 show that there are strong correlations associated with biometric traits of sorghum, depending on the use of plant growth regulators.

Table 5. *Correlation matrix (Pearson)*

Biometric parameters	Plant height, cm	Stem diameter, cm	Bushiness of plants, pcs./plant	Plant mass, g	Leaf area, thousand m^2/ha (tillering)	Leaf surface area, thousand m^2/ha (tube yield)	Leaf area, thousand m^2/ha (flowering)	Leaf area, thousand m^2/ha (full maturity)
Plant height, cm	1	0.972	0.980	0.928	0.827	0.738	0.890	0.842
Stem diameter, cm	0.972	1	0.972	0.923	0.869	0.788	0.868	0.848
Bushiness of plants, pcs./plant	0.980	0.972	1	0.904	0.837	0.748	0.847	0.818
Plant mass, g	0.928	0.923	0.904	1	0.966	0.927	0.991	0.982
Leaf area, thousand m^2/ha (tillering)	0.827	0.869	0.837	0.966	1	0.989	0.847	0.985
Leaf surface area, thousand m^2/ha (tube yield)	0.738	0.788	0.748	0.927	0.989	1	0.928	0.973
Leaf area, thousand m^2/ha (flowering)	0.890	0.868	0.847	0.991	0.847	0.928	1	0.988
Leaf area, thousand m^2/ha (full maturity)	0.842	0.848	0.818	0.982	0.985	0.973	0.988	1

Note: *Significant correlation at $p < 0.05$*
Source: *compiled by the author*

The correlation calculation shows that the most important indicators that will influence the formation of crop productivity are plant weight, leaf area, height, and tillering. Figure 6 shows a sorghum trial plot. The plants are in the waxy ripeness phase (third decade of August). Area where seeds and crops were treated with a growth regulator.

Figure 6. *Sorghum in the experimental plots*

Source: *authors' photo*

It is worth noting that during the vegetation period, natural genetically determined changes occurred in sorghum plants under the influence of the growth regulator, which was reflected in the consistent development of plants and crops in general. Research by T. Asami & Y. Nakagawa (2018) has shown that plants treated with growth regulators suffer less from unfavourable environments and unstable weather conditions. Growth regulators promote the formation of nutrients that enhance the enzymatic activity of plant cells and the development of stimulatory connections by the plant itself. As a result, the permeability of the root cell membrane increases, and the absorption of mineral nutrients from the soil solution by plants improves. The use of growth regulators accelerates the absorption of oxygen and the process of photosynthesis. Accordingly, the photosynthetic activity of agrocenoses and crop yields increase.

According to M. Szczepanek (2018), the high efficiency of growth regulators on cereals is associated with their ability to increase the accumulation of macro- and microelements, the concentration of photosynthetic pigments and, as a result, to activate photosynthesis and increase crop productivity. In addition, growth regulators help to control the duration of certain stages of plant growth and development and also contribute to the correction of crop conditions under the influence of adverse abiotic factors.

Observations of V. Lyubich *et al.* (2020) show that the use of a plant growth regulator affects the germination energy and laboratory germination of sorghum seeds, increasing it by 4-7% compared to the control variant. L. Storozhyk *et al.* (2020) show that the sowing qualities of sugar sorghum of the studied varieties and hybrid decrease even with short-term storage of grain. The laboratory germination rate after 1 year of storage of sugar sorghum is 80-81%, germination energy – 6-67% without the use of biological products. The use of the biological product Phytocide P increased the quality indicators to 83-87% and 73-75%, respectively. Laboratory germination of ≥50% ensures storage of sugar sorghum grain for 4 years. The germination energy is 47-54%, depending on the variety. Treatment of grain with biological products can extend the storage period to 6 years with a germination energy of 50-54%. It is optimal to use the Medovyi variety for the production of sugar sorghum seeds, which have the highest sowing properties with the treatment of grain with a biological product. The laboratory germination rate is 65-87%, and the germination energy is 54-75%, depending on the storage period.

According to O. Prysiazhniuk *et al.* (2022), foliar application of a plant growth regulator at microstage 21 (BBCH) contributed to faster development of sorghum plants and increased grain yield of sorghum varieties (0.19 t/ha of Odesskyi 205 and 0.12 t/ha of Lan 59) compared to application at stage III (Kuperman). S. Dhaliwal *et al.* (2020) argue that the use of growth regulators at the optimal time helps to avoid plant stress caused by unfavourable growing conditions during critical growth stages.

According to the research of Dyomin *et al.* (2021), the use of the product was found to be detected at the initial stages of plant ontogeny and did not affect the rate of seed ripening in the panicle. Changes in the duration of the interphase periods (sowing-seedlings, seedlings-bush, bush-emergence into the tube) mainly depended on the method of application of the preparation. However, the periods of panicle ejection-flowering and flowering-seed ripening were not affected by the experimental variants. At the same time, the total duration of the growing season of perennial sorghum varied depending on the factor under study: in the context of the experimental variants, it ranged from 122 to 132 days. That is, the use of "Agrostimulin" in pre-sowing seed preparation reduces this period by 5 days, treatment during the growing season – by 6 days, and the combined use of these measures – by 10 days.

Thus, based on the conducted research, it should be noted that the use of plant growth regulators on seeds and crops of sorghum allows for a reduction in the rates of fertiliser and pesticide application. It also has a positive effect on the quality and biometric parameters of seeds, which was confirmed by correlation analysis. However, the issue of using growth regulators on sorghum crops requires further study, as there is virtually no information on such studies.

CONCLUSIONS

The results of the research are statistically significant, and the elements of the cultivation technology studied are likely to be used for growing other varieties in different soil and climatic conditions. The results of the research showed that the use of the growth regulator changed the quality indicators of sorghum seeds, namely seed treatment and spraying of crops increased germination energy and laboratory and field germination by 2.3, 3.2 and 4.3% compared to the control. The duration of the growing season without seed and crop treatment was 105 days, while with treatment it was reduced by 13 days.

It was proved that the use of the growth regulator significantly increases biometric parameters: plant height – up to 130.2 cm, stem diameter – up to 1.7 cm, increase in productive stems – up to 2.5 pieces per plant and plant weight – up to 93.5 g. The leaf surface area, depending on the period of development, in the variant where seeds and crops were treated, reached a maximum and ranged from 8.56 to 40.32 thousand m^2/ha: the smallest was in the period of full ripeness – 4.97 thousand m^2/ha in the same experiment.

A close correlation was established between the studied parameters of plant growth and development, which have a significant impact on the yield of sorghum as an energy crop. Given the significant effectiveness of growth regulator application in studies to improve grain and biomass productivity of sorghum and considering climate change, namely, increasing temperature and decreasing precipitation, the study of the effectiveness of growth regulators in sorghum crops is a relevant and promising area of research. Sorghum is considered as a bioenergy crop, so it is worth investigating the use of plant growth regulators in combination with other elements of cultivation technology, which will determine the correct planning of crops and processing in the future.

ACKNOWLEDGEMENTS

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CONFLICT OF INTEREST

None.

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Особливості росту та розвитку сорго (*Sorghum bicolor* (L.) Moench) за дії регулятора росту

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Анотація. Останнім часом зростає інтерес до вирощування сорго звичайного двокольорового як біоенергетичної культури, так як його можна використовувати для виробництва біопалива (етиловий спирт) та твердого палива (пелетів та брикетів із надземної маси). Зерно сорго характеризується високим вмістом крохмалю – до 80 %. Тема досліджень актуальна, але маловивчена. Мета досліджень полягала у вивченні впливу регулятора росту на ріст та розвиток сорго звичайного двокольорового в умовах Правобережного Лісостепу України. Використовувались такі методи досліджень: польовий, вимірювально-ваговий, математично-статистичний. У статті наведено результати досліджень за 2016-2019 роки, де вивчали вплив елементів технології вирощування на особливості формування біометричних показників. Досліджено, що застосування регулятора росту рослин впливало на польову схожість, вегетаційний період, біометричні показники росту рослин, площу листкової поверхні. Встановлено тісноту кореляційних зв'язків досліджуваних показників, та проведено кореляційнорегресійний аналіз даних, який показав сильну кореляцію між вегетаційним періодом і висотою рослин, де коефіцієнт склав R=0,9264, а коефіцієнт детермінації R^2=0,9864. А також сильний зв'язок між діаметром стебла та висотою рослин, де коефіцієнт кореляції склав R=0,9767, а коефіцієнт детермінації відповідно становив R^2=0,954. Проведені дослідження підтверджують доцільність застосування регулятора росту, що покращує розвиток рослин і сприятиме підвищенню урожайності та якості зерна і біомаси сорго звичайного двокольорового. Отримані результати досліджень дають підстави вважати, що регулятори росту сприяють отриманню екологічно чистої продукції та виступають складовими екологічно чистої та енергозберігаючої технології вирощування

Ключові слова: сорго звичайне двокольорове; регулятор росту; якісні показники насіння; вегетаційний період; біометричні показники; площа листкової поверхні; кореляція