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Comparative analysis of the influence of biologically active substances on photosynthetic productivity of *Sorghum Saccharatum*

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Abstract

This study investigates the effects of biologically active substances and varying doses of nitrogen-phosphorus fertilizers on the photosynthetic activity and quality indicators of two sweet sorghum varieties ("Kazakhstanskoye 20" and "Sazhen") and was conducted on heavy loamy sierozems in Southern Kazakhstan's arid zone. The experimental design included applications of three biostimulants combined with different doses of nitrogen-phosphorus. The complex application of biostimulants and mineral fertilizers significantly enhanced plant development, resulting in increased leaf surface area by 36-76% and photosynthetic potential by 60-112%. The maximum photosynthesis productivity (3.65 g/m²) was achieved when treating seeds with Potassium Humate combined with $N_{90}P_{90}$ fertilization. Treatment with biostimulants and fertilizers improved the chemical composition and nutritional value of green mass, elevating crude protein content to 12.42% for "Kazakhstanskoe 20" and 12.31% for "Sazhen" varieties. The highest digestible protein content per feed unit (96.5 g and 95.6 g, respectively) was observed with Potassium Humate treatment against the $N_{90}P_{90}$ background. Strong correlations (r = 0.83-0.98) were established between photosynthetic activity indices and sweet sorghum green mass yield. The combined application of biostimulants, particularly Potassium Humate, with optimal nitrogen-phosphorus fertilization ($N_{90}P_{90}$) significantly enhances the photosynthetic performance and nutritional quality of sweet sorghum varieties in the arid conditions of Southern Kazakhstan.

Keywords: Biologically active substances, leaf area, photosynthetically active radiation, photosynthetic activity, sweet sorghum.

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1. Introduction.

Sweet sorghum is a valuable forage crop with high drought resistance, heat resistance, and the ability to form a significant yield of green mass in conditions of unstable moisture [1, 2]. Sweet sorghum (Sorghum saccharatum) belongs to the family of grasses (cereals) and is one of the oldest agricultural crops cultivated by humans. The history of its cultivation dates back more than 5,000 years, and the center of origin is considered to be Africa, more precisely, the territory of modern Ethiopia and Sudan [3, 4]. Due to its high adaptive capacity, sweet sorghum has spread widely throughout the world and is currently cultivated in more than 100 countries on five continents. According to FAO [5], sweet sorghum ranks fifth in the world in terms of cultivated area among grain crops after wheat, rice, corn, and barley. In Kazakhstan, especially in its southern regions, there is a steady trend towards expanding the area under this crop, which is due to the growing demand for high-quality feed and increasing climate aridization [6, 7].

In the arid regions of Kazakhstan, the cultivation of sugar sorghum is of particular importance for solving the problem of providing livestock with high-quality feed [8]. In recent decades, drought periods have become more frequent in the south of Kazakhstan, making the cultivation of traditional forage crops less effective. Under these conditions, the role of drought-resistant crops increases, among which sugar sorghum occupies a leading place due to its biological characteristics. In addition, the green mass of sugar sorghum has a high nutritional value, contains a significant amount of protein, sugars and other nutrients, which makes it a promising crop for forage production [9]. The basis for the formation of the yield of agricultural crops is the photosynthetic activity of plants. The intensity of photosynthesis and the productivity of agricultural crops largely depend on the size of the assimilation surface of the leaves, the duration and efficiency of its work [10]. According to Nichiporovich [11], the optimal leaf area for most agricultural crops is 40-50 thousand m²/ha, which creates the most favorable conditions for absorbing solar energy and forming high yields. To achieve such indicators, it is necessary to create optimal conditions for plant growth and development.

Effective implementation of the photosynthetic potential of plants is possible only with the optimization of growing conditions, including the use of biologically active substances and mineral fertilizers [12, 13]. In our previous studies, Mathur et al. [14] it was found that the combined use of biostimulants and mineral fertilizers contributes to an increase in field germination of seeds, an increase in the survival of plants for harvesting and a significant increase in the yield of green mass of sugar sorghum. However, the mechanisms of the influence of these factors on the photosynthetic activity of plants and the quality indicators of green mass require further study.

The complex application of biologically active substances and mineral fertilizers can have a synergistic effect, enhancing the effect of each factor and promoting a more complete realization of the potential productivity of plants [15]. However, the mechanisms of this interaction and its impact on the photosynthetic activity and quality indicators of sugar sorghum in the conditions of the arid zone of Kazakhstan have not been sufficiently studied. Despite the existing studies on this problem, the issues of the complex influence of biologically active substances and mineral fertilizers on the photosynthetic activity and quality indicators of sugar sorghum in the conditions of the arid zone of Kazakhstan require further study. In this regard, the purpose of our research was to study the effect of various biostimulants and doses of mineral fertilizers on the photosynthetic productivity and the qualitative composition of the green mass of sugar sorghum varieties in the conditions of Southern Kazakhstan.

2. Materials and Methods

Field studies were conducted over three years on the experimental plot of the Research Institute "Ecology and Biotechnology" at the South Kazakhstan University named after M. Auezov. The soil of the experimental plot is heavy loamy gray soil with a humus content in the arable layer of 0.98%. The subjects of the research were two varieties of sweet sorghum - "Kazakhstanskoe 20" and "Sazhen".

Sorghum variety "Kazakhstanskoe 20" was created through individual selection. It is a mid-season variety with a vegetation period of 115-117 days. The variety has weak bush growth, with the number of aboveground nodes ranging from 8 to 12. The thickness of the stem is between 1.5 and 1.89 cm, and the leaves are long, measuring 50-60 cm in length and 5-6 cm in width. The height of the plant ranges from 2 to 2.5 meters, and the color of the grain is light brown. The average grain yield over 3 years is 67.0 c/ha, with a yield of 64.0 c/ha, and the density of standing when sowing is 18.7 plants per linear meter. This variety is not significantly affected by diseases and pests. The weight of 1,000 grains is 19.2 g, and the stem contains up to 19.2% sugar. Manufacturer: JSC "Kazakh Research Institute of Agriculture and Plant Growing". Sorghum variety "Sazhen" has an average dry matter yield in the 6th region of 80.0 c/ha, which is 2.7 c/ha higher than the average standard, with seeds yielding 22.9 c/ha. In the Central Black Earth Region, the increase in dry matter yield was 37%, with an average yield of 128.5 c/ha. It exhibits high lodging resistance and drought resistance at the standard level. In field conditions, it was slightly affected by bacterial spotting. Manufacturer: OOO 'AGROPLAZMA'

The effect of three biologically active substances was studied: Celeste Top (10 l/t), Gumi 20 (0.5 l/t) and Potassium Humate (1.0 kg/t), as well as their combinations with three doses of mineral fertilizers: $N_{30}P_{30}$, $N_{60}P_{60}$ and $N_{90}P_{90}$.

Celeste Top is a complex insectofungicidal seed treatment with a growth-stimulating effect, containing thiamethoxam, fludioxonil, and difenoconazole. It protects seeds and seedlings from a wide range of pests and diseases and also stimulates the growth and development of plants due to the presence of components with physiological activity in its composition [16].

Gumi 20 is a complex biostimulant based on humic acids, enriched with microelements and containing bioactive components isolated from organic raw materials. It has a pronounced growth-stimulating, immunomodulatory, and anti-stress effect, increasing plant resistance to drought, frost, salinization, and other unfavorable factors [17].

Potassium humate is one of the most effective humic preparations, containing a high concentration of humic acids (up to 80%) and enriched with potassium and microelements. It has a pronounced growth-stimulating and adaptogenic effect, increases plant resistance to unfavorable environmental factors and promotes a more complete realization of the genetic potential of varieties and hybrids [18]. The experiment was laid out according to a two-factor scheme in fourfold replication: factor A - biologically active substances (no treatment, Celeste Top, Gumi 20, Potassium Humate); factor B - doses of mineral fertilizers (no fertilizers, $N_{30}P_{30}$, $N_{60}P_{60}$, $N_{90}P_{90}$). The plot area is 50 m², the accounting area is 25 m². The location of the plots is randomized.

The agricultural technology in the experiment was generally accepted for the zone. Sowing was carried out in wide rows (70 cm between rows) with a seeding rate of 300 thousand viable seeds per hectare. The seeds were treated with biologically active substances before sowing according to the recommended rates. Mineral fertilizers were applied fractionally: phosphorus - 100% under the main treatment, nitrogen - 50% under the main treatment and 50% in top dressing. During the growing season, the dynamics of leaf area growth were determined using the cutting method, photosynthetic potential (PP), net productivity of photosynthesis (NPP) and the coefficient of PAR use (CP PAR) using generally accepted methods [6, 7]. Leaf area was determined in the main phases of plant development (tillering, tube elongation, panicle emergence). The green mass yield was recorded in the panicle emergence phase using the method of continuous harvesting of the plot area followed by weighing. The chemical composition and nutritional value of the green mass were determined using standard methods [19]. Statistical processing of the research results was performed using the method of dispersion and correlation-regression analysis using the Statistica 10.0 program.

3. Research Results and Their Discussion

3.1. Photosynthetic Activity of Sugar Sorghum Plants

The results of the studies showed that the photosynthetic activity of sugar sorghum plants significantly depended on the use of biologically active substances and mineral fertilizers (Table 1).

Table 1.
Photosynthetic activity of sweet sorghum depending on biologically active substances and mineral fertilizers.

Variant	Leaf area (max). thousand m²/ha	FP. million m² day/ha	NPF. g/m²	PHA efficiency. %	Dry matter. t/ha
Without treatment with biologically active substances					
Without fertilizers (control)	28.0	1.147	2.65	1.1	6.2
$N_{60}P_{60}$	38.0	1.593	2.78	1.3	7.1
$N_{90}P_{90}$	41.0	1.742	3.48	1.5	7.6
Treatment Celeste Top					
Without fertilizers (control)	30.1	1.162	2.72	1.4	6.6
$N_{60}P_{60}$	41.5	2.000	3.41	1.9	7.2
$N_{90}P_{90}$	44.0	2.105	3.55	2.0	8.0
Treatment Gumi 20					
Without fertilizers (control)	31.4	1.270	2.81	1.7	6.8
$N_{60}P_{60}$	42.1	2.060	3.44	2.2	7.7
$N_{90}P_{90}$	46.0	2.240	3.57	2.4	8.2
Treatment with Potassium Humate					
Without fertilizers (control)	31.7	1.383	3.10	2.0	7.0
$N_{60}P_{60}$	47.6	2.324	3.52	2.5	8.4
$N_{90}P_{90}$	49.4	2.431	3.65	2.6	8.6

Analysis of the obtained data showed that seed treatment with biologically active substances increased the leaf surface area of sugar sorghum plants by 7.5-13.2% compared to the control. The use of mineral fertilizers also contributed to an increase in the assimilation surface of plants: against the background of $N_{60}P_{60}$ - by 35.7-50.2%, and against the background of $N_{90}P_{90}$ - by 46.4-55.2% compared to the unfertilized control.

The largest leaf area (49.4 thousand m²/ha) was noted when treating seeds with Potassium Humate against the background of $N_{90}P_{90}$, which was 76.4% higher than the control variant. A similar pattern was observed for other indicators of photosynthetic activity of sugar sorghum plants. The photosynthetic potential of crops, characterizing the duration of the leaf apparatus, varied from 1.147 to 2.431 million m² days/ha, depending on the experimental variant. The maximum PP values were noted when treating seeds with Potassium Humate against the background of $N_{90}P_{90}$ application, which was 2.1 times higher than the control variant.

The net productivity of photosynthesis, showing the amount of dry matter synthesized in the process of photosynthesis by a unit of leaf surface per day, varied from 2.65 to 3.65 g/m² depending on the experimental variant. The highest NPP values (3.65 g/m²) were obtained when treating seeds with Potassium Humate against the background of $N_{90}P_{90}$ application. The coefficient of PAR utilization, characterizing the efficiency of solar energy conversion into organic matter by plants, varied from 1.1 to 2.6% depending on the experimental variant. The maximum values of PAR efficiency (2.6%) were noted when treating seeds with Potassium Humate against the background of $N_{90}P_{90}$ application, which was 2.4 times higher than the control variant.

The accumulation of dry matter by sugar sorghum plants also depended on the use of biologically active substances and mineral fertilizers. The highest amount of dry matter (8.6 t/ha) was obtained when treating seeds with Potassium Humate against the background of $N_{90}P_{90}$ application, which was 38.7% higher than the control variant.

The results of the correlation analysis showed a close relationship between the leaf area and the yield of green mass of sugar sorghum (r = 0.94-0.97), as well as between the photosynthetic potential and the yield (r = 0.88-0.93). This indicates that the photosynthetic activity of plants is one of the main factors determining the productivity of sugar sorghum.

Analysis of the dynamics of the leaf area during the growing season (Table 2) showed that it reached its maximum values in the panicle emergence phase, after which there was a slight decrease in the leaf surface.

Table 2.
Dynamics of the leaf area of sugar sorghum during the growing season, depending on biologically active substances and mineral fertilizers, thousand m²/ha.

Variant	Decade of Vegetation						
	April. III	**May. I**	**May. II**	**May. III**	**June. I**	**June. II**	**June. III**
Without treatment with biologically active substances							
Without fertilizers (control)	7.3	11.0	26.3	28.2	23.0	12.3	8.2
$N_{60}P_{60}$	12.2	24.1	40.0	44.3	33.4	25.2	14.3
$N_{90}P_{90}$	14.1	27.4	42.0	47.2	36.3	30.1	17.8
Treatment with Potassium Humate							
Without fertilizers (control)	8.2	15.5	24.7	29.5	24.1	13.4	11.3
$N_{60}P_{60}$	15.6	24.5	36.2	44.6	34.1	28.4	14.6
$N_{90}P_{90}$	18.8	29.4	44.9	48.5	39.8	30.8	19.4

The largest leaf surface area in the panicle emergence phase (48.5 thousand m²/ha) was noted when treating seeds with Potassium Humate against the background of $N_{90}P_{90}$ application, which was 72.0% higher than the control variant.

The coefficient of PAR use also changed during the growing season (Table 3), reaching maximum values in the panicle emergence phase.

Table 3.
Efficiency of incoming PAR in sugar sorghum crops depending on biologically active substances and mineral fertilizers (average for 2018-2020), %.

Variant	Decade of Vegetation							Due vegetation
	April. III	**May. I**	**May. II**	**May. III**	**June. I**	**June. II**	**June. III**	
Without treatment with biologically active substances								
Without fertilizers (control)	0.2	0.6	0.7	1.5	1.3	0.6	0.5	0.7
$N_{60}P_{60}$	0.3	1.4	2.1	3.4	3.0	1.2	0.8	1.3
$N_{90}P_{90}$	0.6	1.6	2.2	3.7	3.1	1.7	0.9	1.5
Treatment with Potassium Humate								
Without fertilizers (control)	0.5	1.3	1.7	2.5	2.2	1.3	0.8	1.3
$N_{60}P_{60}$	0.8	2.3	2.8	4.5	4.1	2.3	1.5	2.5
$N_{90}P_{90}$	1.0	2.4	3.1	4.7	4.2	2.3	1.6	2.6

The highest efficiency of PAR in the panicle emergence phase (4.7%) was observed when treating seeds with Potassium Humate with $N_{90}P_{90}$, which was 3.1 times higher than the control variant. Over the entire growing season, the maximum efficiency of PAR (2.6%) was also obtained when treating seeds with Potassium Humate with $N_{90}P_{90}$.

3.2. Qualitative Composition of the Green Mass of Sugar Sorghum

Complex use of biologically active substances and mineral fertilizers had a positive effect on the chemical composition and nutritional value of the green mass of sugar sorghum (Table 4).

Table 4.
Chemical composition and nutritional value of the green mass of sugar sorghum depending on biologically active substances and mineral fertilizers.

Variant	Chemical composition. %	Content in 1 kg of dry matter g	Content of digestible protein in one feed unit.
	Protein	feed units	
Variety "Kazakhstanskoe 20"			
Without treatment with biologically active substances			
Without fertilizers (control)	10.89	0.60	86.4
$N_{60}P_{60}$	10.94	0.61	89.4
$N_{90}P_{90}$	11.08	0.61	90.3
Treatment Celeste Top			
Without fertilizers (control)	10.92	0.62	91.0
$N_{60}P_{60}$	11.01	0.66	92.2
$N_{90}P_{90}$	11.20	0.64	94.7
Treatment Gumi 20			
Without fertilizers (control)	10.94	0.64	91.2
$N_{60}P_{60}$	11.13	0.68	92.5
$N_{90}P_{90}$	11.27	0.67	94.9
Treatment with Potassium Humate			
Without fertilizers (control)	10.99	0.65	91.5
$N_{60}P_{60}$	11.16	0.72	93.1
$N_{90}P_{90}$	12.42	0.70	96.5
Variety "Sazhen"			
Without treatment with biologically active substances			
Without fertilizers (control)	10.85	0.58	84.2
$N_{60}P_{60}$	10.92	0.62	88.7
$N_{90}P_{90}$	11.05	0.62	89.4
Treatment Celeste Top			
Без удобрений	10.91	0.61	90.1
$N_{60}P_{60}$	11.01	0.66	91.2
$N_{90}P_{90}$	11.21	0.67	93.5
Treatment Gumi 20			
Без удобрений	10.92	0.62	90.3
$N_{60}P_{60}$	11.11	0.68	91.7
$N_{90}P_{90}$	11.23	0.68	93.9
Treatment with Potassium Humate			
Without fertilizers (control)	10.93	0.65	90.6
$N_{60}P_{60}$	11.22	0.71	92.3
$N_{90}P_{90}$	12.31	0.70	95.6

The crude protein content in the dry mass of sweet sorghum of the Kazakhstan 20 variety varied from 10.89 to 12.42% depending on the experimental variant. The highest protein content (12.42%) was observed when treating seeds with Potassium Humate against the background of $N_{90}P_{90}$ application, which was 1.53 percentage points higher than the control variant.

In the Sazhen variety, the crude protein content varied from 10.85 to 12.31%. The maximum value (12.31%) was also obtained when treating seeds with Potassium Humate against the background of $N_{90}P_{90}$ application, which was 1.46 percentage points higher than the control variant. The content of feed units in 1 kg of dry matter for the Kazakhstanskoe 20 variety varied from 0.60 to 0.72, and for the Sazhen variety, from 0.58 to 0.71, depending on the experimental variant. The highest values (0.72 and 0.71, respectively) were noted when treating seeds with Potassium Humate against the background of $N_{60}P_{60}$ application. An important indicator of feed quality is the content of digestible protein in one feed unit. For the Kazakhstanskoe 20 variety, this indicator varied from 86.4 to 96.5 g, and for the Sazhen variety, from 84.2 to 95.6 g, depending on the experimental variant. The highest values (96.5 and 95.6 g, respectively) were obtained when treating seeds with Potassium Humate against the background of $N_{90}P_{90}$ application, which exceeded the control variant by 10.1-11.4 g.

According to zootechnical standards, for full feeding of cattle, 1 feed unit should contain at least 105-110 g of digestible protein. In our studies, this indicator was below the optimal level, but significantly exceeded the control variant with the complex use of biologically active substances and mineral fertilizers.

The complex use of biologically active substances and mineral fertilizers also contributed to an increase in the yield of feed units and digestible protein per hectare of crops (Table 5).

Table 5.
Output of feed units and digestible protein with the complex use of biologically active substances and mineral fertilizers.

Variant	Yield. T/Ha	
	Feed Units	Digestible Protein
Variety "Kazakhstanskoe 20"		
Without treatment with biologically active substances		
Without fertilizers (control)	4.29	0.38
$N_{60}P_{60}$	4.30	0.42
$N_{90}P_{90}$	4.34	0.49
Treatment Celeste Top		
Without fertilizers (control)	4.32	0.40
$N_{60}P_{60}$	5.34	0.45
$N_{90}P_{90}$	6.10	0.57
Treatment Gumi 20		
Without fertilizers (control)	4.33	0.41
$N_{60}P_{60}$	5.36	0.46
$N_{90}P_{90}$	6.24	0.62
Treatment with Potassium Humate		
Without fertilizers (control)	4.35	0.43
$N_{60}P_{60}$	5.40	0.47
$N_{90}P_{90}$	6.41	0.73
Variety "Sazhen"		
Without treatment with biologically active substances		
Without fertilizers (control)	4.30	0.39
$N_{60}P_{60}$	4.32	0.40
$N_{90}P_{90}$	4.38	0.43
Treatment Celeste Top		
Without fertilizers (control)	4.34	0.42
$N_{60}P_{60}$	5.36	0.38
$N_{90}P_{90}$	5.46	0.57
Treatment Gumi 20		
Without fertilizers (control)	4.36	0.41
$N_{60}P_{60}$	5.38	0.41
$N_{90}P_{90}$	5.79	0.58
Treatment with Potassium Humate		
Without fertilizers (control)	4.38	0.44
$N_{60}P_{60}$	5.42	0.42
$N_{90}P_{90}$	6.19	0.62

The highest yield of feed units in the Kazakhstanskoe 20 variety (6.41 t/ha) was obtained when treating seeds with Potassium Humate against the background of $N_{90}P_{90}$ application, which was 1.5 times higher than the control variant. In the Sazhen variety, the maximum yield of feed units (6.19 t/ha) was also noted when treating seeds with Potassium Humate against the background of $N_{90}P_{90}$ application, which was 1.4 times higher than the control variant. The yield of digestible protein in the Kazakhstanskoe 20 variety varied from 0.38 to 0.73 t/ha, and in the Sazhen variety, from 0.39 to 0.62 t/ha, depending on the experimental variant. The highest values (0.73 and 0.62 t/ha, respectively) were obtained when treating seeds with Potassium Humate against the background of $N_{90}P_{90}$ application, which was 1.9-1.6 times higher than the control variant.

The obtained results indicate a significantly positive effect of the complex use of biologically active substances and mineral fertilizers on the photosynthetic productivity and quality of sweet sorghum.

In the experiment, pre-sowing treatment of seeds with biostimulants (especially potassium humate) against the background of compliance with control doses of fertilizers ($N_{90}P_{90}$) ensured maximum development of the foliar regime and an increase in photosynthesis rates.

Thus, the leaf area increased to 49.4 thousand m²/ha (76% higher than the control), the photosynthetic potential of crops - to 2,431 million m²•day/ha (2.1 times higher than the control), and the net productivity of photosynthesis reached 3.65 g/m² per day.

The same coefficient of PAR use increased to 2.6%, which is more than 2 times higher than the control. These improvements in photosynthetic activity directly affected plant productivity: dry matter accumulation increased to 8.6 t/ha (approximately 39% more), which was accompanied by a significant level of sorghum green mass yield compared to the control. High coefficients are correlated (r=0.88–0.97) between green foliage, photosynthetic potential, and productivity, confirming that the increase in the assimilation surface and the duration of its growth directly support the growth of biomass.

Thus, optimizing nutritional conditions in combination with the specified biostimulants allows for more fully realizing the potential of the C_4-culture of sugar sorghum, which has high photosynthetic productivity.

The obtained data are consistent with the results of other studies. In particular, the increase in sorghum growth and productivity under the influence of humic preparations and fertilizers that we have identified is supported by the works of foreign authors. Thus, Asif et al. [20] report that the combined use of phosphorus fertilizer (60 kg P_2O_5/ha) and the biostimulant "Aktibion" (analog of the humic complex) in Pakistan increases the yield of green mass of sorghum to 47.8 t/ha and the dry matter yield to 13.8 t/ha, the crude protein content in the feed increased from ~9.5% to 13.0% [20].

Our results (maximum crude protein content of about 12.4%) are in good agreement with the data of other studies, despite the difference in climatic conditions and types of fertilizer application. positive effects of biologically active substances, previously discovered also during cultivation. Similar effects of biologically active substances were noted on other crops. For example, in the experiments of Baiseit and Konkarova [21] with bright rapeseed, the use of humic preparations contributed to an increase in yield and preservation of seed quality [21]. Thus, biostimulants of humus origin, arising sequentially, allow stimulating plant processes, increasing the content of nutritional elements and ensuring the productive capacity of the crop.

It is known that humic acids perform regulatory functions, stimulating photosynthesis and growth, as well as increasing plant resistance to stress factors.

Probably, it is the complex action of potassium humate, as a source of available elements (Potassium, humic substances) and as a stimulator of metabolism that determines its greatest effectiveness among the tested biopreparations.

An important result of our study is the improvement of the qualitative composition of the forage mass of sweet sorghum with the combined use of fertilizers and bioadditives. The content of crude protein in dry mass increased by 1.4–1.5 percentage points compared to the control and reached 12.3–12.4% in the studied varieties. This is significantly higher than the typical results of protein content in sorghum without fertilizers (usually about 8–10%). Abdrakov and Kunypiyaeva [22] and correspond to the principles of good corn silage. The increased accumulation of nitrogenous substances in sorghum plants against the background of a decrease in nitrogen-phosphorus nutrition and humates is consistent with the known data on the stimulating effect of humic substances on protein synthesis and nitrogen content in plants. However, it should be noted that the obtained maximum content of digestible protein in one feed unit (~96–97 g) still does not reach the zootechnical standard (105–110 g/feed unit).

Nevertheless, complex treatment allowed to significant increase in this indicator compared to the control (where it was ~84–86 g/feed unit), thereby improving the nutritional value of the feed.

From a practical point of view, an increase in content by almost 1.5% means a significant increase in the feed value of sorghum mass, which is important for observing the principle of animal husbandry in protein nutrition in arid regions.

The practical originality of the obtained results is especially great for the conditions of southern Kazakhstan and other arid regions [23].

Sweet sorghum has potential as a forage crop for arid regions due to its unique resistance to moisture deficiency and the ability to provide high biomass yields.

With the traditional use of silage crops, such as corn, productivity drops sharply under moisture deficiency conditions, while sorghum is more resistant to drought and heat.

Our studies show that the competent use of agricultural practices (moderate approval in cooperation with biostimulants) allows for an even greater increase in sorghum yields under such stressful conditions. The increase in green mass yield against the background of the use of $N_{90}P_{90}$ + potassium humate was up to 1.5–1.6 times compared to the control, and the yield of digestible protein per hectare was up to 1.9 times higher. In conditions of forage deficit on irrigated Kazakh and dry lands of the south, such an increase in productivity and quality of forage is of great importance for the stable provision of cattle with nutritious forage. In addition, the use of biostimulants can reduce the need for high doses of mineral fertilizers. It is known that an increase in fertilizer application does not always lead to a change in crop growth and can negatively affect soils and the environment.

Thus, the complex use of moderate doses of mineral fertilizers in combination with biological substances is a more environmentally friendly and cost-effective approach to increasing the yield of sweet sorghum compared to extensive increase.

Despite the complete results obtained, this study has a number of limitations.

Firstly, the conducted experiments covered only one agro-ecological region (Southern Kazakhstan, sierozems) and were limited by vegetation seasons. The obtained results can be applied depending on the climatic conditions and soil types in other arid regions, which requires additional testing.

Secondly, only the effect of fixed doses of nitrogen and phosphorus fertilizers was studied, while the effect of potassium fertilizers and microelements, which can also be limiting factors for the growth and productivity of sorghum on low-type soils, was not considered.

In addition, the objects of the study were varieties of two sugar (fodder) sorghum, so the response of other genotypes (for example, grain forms of sorghum) to similar agricultural practices may be worse. Also, humic biopreparations were used as part of the treatment, while the effectiveness of other classes of biostimulants (for example, bacterial inoculants, amino acid complexes, or phytohormones) was not studied. Finally, the green mass quality parameters were measured mainly by protein content and forage quality. Other important nutritional value parameters, such as micronutrient content, feed content, and digestibility, were not taken into account in this work and require further study.

In the future, further development of research, including the study of new classes of biologically active substances and fertilizers. A promising direction is the use of biopreparations based on nitrogen-fixing and phosphorus-mobilizing substances, sea extracts, humic and fulvic acids, as well as other biostimulants.

Of particular interest is also the use of nanofertilizers, which, according to literature data, can significantly increase the efficiency of introducing plant nutrients and reduce the consumption of mineral fertilizers.

Of interest is the study of the combined use of biostimulants with small or reduced doses of potassium fertilizers to further improve the quality of the crop (for example, protein content to the standard level).

It is also important to study different varieties of sorghum - both forage and grain - to identify the genotypes that are most sensitive to biostimulants and fertilizers. A separate issue is the economic assessment of the proposed technology: it is necessary to take into account the costs of biopreparations and fertilizers and correlate them with the increase in yield and quality in order to exclude the optimal application schemes from the standpoint of profitability. In addition, it is important to study such agricultural practices on fertile soil and the agroecosystem as a whole with long-term use.

For example, humic substances, in addition to the direct effect on plants, can improve the structure of the soil and microbiome, which is worth checking in ongoing experiments.

Thus, continuing research in this direction will help to obtain high-quality and sustainable agricultural technologies for increasing the productivity of sorghum and other crops in conditions of moisture and nutrient deficiency.

4. Conclusion

The results of the conducted studies showed that the use of biologically active substances in combination with mineral fertilizers has a significant positive effect on the photosynthetic productivity and qualitative composition of the green mass of sugar sorghum in the conditions of Southern Kazakhstan.

It was found that the combined use of growth stimulants (Celest Top, Gumi 20, Potassium Humate) and nitrogen-phosphorus fertilizers in doses of N60-90P60-90 helps to increase the field germination of seeds by 10-18%, increase the leaf surface area by 15-25%, and increase the chlorophyll content by 10-15% compared to the control.

The greatest positive effect was noted when treating seeds with Potassium Humate against the background of N90P90, which ensured an increase in the yield of green mass of sugar sorghum to 19.3 t / ha, which is 5.4 t / ha higher than the control. The use of Gumi 20 in combination with the N90P90 fertilizer dose contributed to obtaining a green mass yield of 18.2 t/ha. Seed treatment with Celeste Top against the background of N90P90 provided a yield of 18.0 t/ha, which is 4.1 t/ha higher than the control.

The effect of using biologically active substances without fertilizers amounted to 5-8% increase in the green mass yield. With the combined use of mineral fertilizers and biologically active substances, the yield of green mass of sugar sorghum increased by an average of 10-12%.

It was found that Celeste Top, Gumi 20, and Potassium Humate contribute to an increase in the nutrient absorption coefficient, which allows for a reduction in the dose of mineral fertilizers.

The research results indicate the high efficiency of the complex use of biologically active substances and mineral fertilizers in the cultivation of sugar sorghum in the arid zone of Southern Kazakhstan, which can be recommended for implementation in the agricultural production of the region in order to increase the productivity of the livestock feed base.

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