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Photosynthetic activity of sugar sorghum under weed infestation of sowings as affected by the components of cultivation technology in Ukraine

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Abstract

Purpose. To reveal the peculiarities of the photosynthetic activity and formation of sugar sorghum agrophytocenosis productivity with different row spacing and plant density, application of plant growth stimulator Vympel 2 and the intensity of weed infestation of sowings in the Forest-Steppe of Ukraine. **Methods.** The study investigated hybrids ‘Dovista’ and ‘Huliver’ with a row spacing of 45 and 70 cm and plant density of 150,000, 200,000 and 250,000 plants/ha. Growth stimulator Vympel 2 (0.5 L/t) was used in pre-sowing seed treatment. The same growth stimulator was used as a foliar application in the tillering stage at the application rate of 0.5 L/ha. **Results.** The summative content of chlorophylls *a* and *b* in the leaves of ‘Dovista’ at the stage of tasseling with using growth stimulator was 9.3 mg/kg of dry matter and in ‘Hulliver’ 9.5 mg/kg of dry matter. The increase in the content of chlorophylls compared to the control treatments was 0.30 and 0.60 %, respectively. A plant density of 250,000 plants/ha and a row spacing of 45 cm contributed to the optimal photo responsibility of sugar sorghum agrophytocenosis and the minimum intensity of weed infestation. The latter made up 13.3 plants/m^2, with a formation of vegetative mass of 112.0 g/m^2 and dry mass of 37.4 g/m^2 in ‘Dovista’ and 13.4 plants/m^2 119.0 g/m^2 and 39.5 g/m^2 in ‘Huliver’, respectively. Seed treatment with Vympel 2 and its use for foliar dressing was effective for the phytocenotic restriction of weed growth and development. The study has shown that ‘Dovista’ hybrid has significant productivity potential due to a longer vegetation period. With varying row spacing and plant density, ‘Dovista’ yield exceeded ‘Huliver’ by 3.6 t/ha on the average of the experiment. Seed treatment with Vympel 2 (0.5 L/t) + foliar dressing in the tillering stage (0.5 L/ha) at a row spacing of 45 cm and increased plant density from 150,000 to 250,000 plants/ha ensured a yield increase from 7.3 to 13.0 t/ha. Similar treatments at a row spacing of 70 cm ensured yield values higher by 6.7–12.6 t/ha than in control treatments. **Conclusions.** Hybrid ‘Dovista’ ensured the highest yield of green biomass at a plant density of 250,000 plants per hectare and seed treatment with growth stimulator Vympel 2 (0.5 L/t) + foliar dressing in the tillering stage (0.5 L/ha) amounting to 98.8 t/ha, which was 5.3 t/ha higher than ‘Huliver’ with row spacing of 45 cm. The maximum FAR efficiency was obtained by growing sorghum sugar plants with a plant density of 250,000 plants per hectare, row spacing of 45 cm, and application of growth stimulator Vympel 2. It made up 5.2 % in ‘Dovista’ and 4.7 % in ‘Huliver’. It was found that using growth stimulator Vympel 2 together with a row spacing of 45 cm and plant density of 250,000 plants per hectare appeared the most effective limiting factor of the reoccurring weed infestation of the sowings. The highest energy yield, 457.35 GJ/ha in ‘Dovista’ and 467.82 GJ/ha in ‘Huliver’ was obtained at the row spacing of 45 cm with the increased plant density of 250,000 plants per hectare and seed treatment with growth stimulator Vympel 2 (0.5 L/t) + foliar dressing in the tillering stage (0.5 L/ha).

Keywords: row spacing, plant growth regulators, weed infestation of crops, energy efficiency, FAR efficiency

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INTRODUCTION

Currently, there has been an increase in drought intensity, duration and frequency, both on a global scale and within individual agricultural regions (Sheffield and Wood 2008, Dai 2013, Kuroda et al. 2020). Thus, in Ukraine, global warming has significantly limited the climatic potential of crop production in the most fertile Forest-Steppe zone. Therefore, exploring the possibilities of such drought-tolerant crops as sugar sorghum in the region which is considered unsuitable for

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sugar sorghum cultivation is of interest not only in terms of expanding the country's food security but also in increasing biofuels production (Storozhy`k 2018).

Sugar sorghum, due to its optimal adaptation to dry climate and saline soils, produces high yields not only in subtropical but also in temperate climates (Zegada-Lizarazu and Monti 2012, Almodares et al. 2011). For the time being, in addition to drought-tolerant, there are cold-resistant sugar sorghum hybrids capable of growing effectively in temperate regions (Bennett et al. 1990).

Sorghum is a plant that captures CO_2 through C4-type photosynthesis (Ghannoum, 2009). Therefore, the technology of its cultivation should be built taking into account the features of its photosynthesis type. In particular, for sugar sorghum plants, optimal lightning at the beginning of vegetative growth is crucial. The combined impact of other stresses causes growth retardation and, consequently, low plant productivity (Tari et al. 2013, Beck et al. 2007, Muller et al., 2011). Therefore, the formation of crop yield is significantly affected by the structure of sugar sorghum sowings, with the optimal spatial location of plants ensuring the realization of plants' maximum biological and economic productivity. The structure of sugar sorghum agrophytocenosis is formed not only due to certain morphological features of the specific hybrids, but also due to spatial location of the plants and features of their adaptation to the conditions of cultivation and, accordingly, adaptation of structural components (Shepel, 1994, Storozhy`k, 2018).

At the same time, a high level of photosynthetic activity of sorghum plants can be ensured by not only optimization of the agrophytocenoses through adjustment of row spacing and optimal plant density. The correct selection of sugar sorghum hybrids suitable to a specific climatic zone of cultivation capable of overcoming the deficiency of nutrients in the periods critical in terms of moisture provision, accumulated temperatures, and nutrients availability has significant influence (Fedorchuk et al., 2017).

Sugar sorghum plants also need reliable weed control early in the vegetation period in the first 40–50 days after emergence. At this time, not only is the first, most powerful, wave of weeds emerges, but also the sugar sorghum plants grow slowly and are therefore unable to control and fill all the free ecological niches in agrophytocenosis. In addition, weed control measures cannot be applied at later stages of crop growth and development, which in turn leads to the growth of survived weeds and reoccurring weed infestation of sowings (Smith, Scott, 2010).

The best measures of weed control in sugar sorghum sowings are considered pre-emergence herbicides. Unlike other crops, sugar sorghum is more sensitive to herbicides; therefore, in the case of incorrect application rate or timing (which is three to five-leaf stages), the plants begin to retard in growth and yield becomes significantly reduced (Grichar et al., 2005).

In addition, the application of vegetation herbicides in the three to five-leaf stages leads to a decrease in the herbicide efficiency, as well as the inhibition of sorghum plant growth. However, pre-emergence herbicide formulations also do not fully work, because some weeds start to sprout already in sorghum sowings when the protective film of the formulation on the soil surface is destroyed by rainfall, or as a result of the negative effects of drought (Rosales-Robles et al., 2005, Kaczmarek 2017). Therefore, for sugar sorghum, along with the correct selection and application of herbicides for weed control, the formation of optically light-resistant agrophytocenoses is important in preventing the emergence of a reoccurring weed wave (Gricharci et al., 2004, Pannacci et al., 2004, Pannac, Bartolini, 2018).

From the agrotechnical point of view, correct phytocenotic weed control can be ensured by the correction of the duration of the growing season in general and the duration of individual phonological stages of plant growth and development with the aid of plant growth stimulators. The correct selection of the stimulators and their timely application contribute to the acceleration or prolongation of the individual stages of growth and development. In addition, such agrotechnical measures can help plants avoid to avoid the stress from the lack of life factors at critical stages of growth and development (Almodares et al., 2007, Storozhy`k, Muzy`ka, 2017).

The reasonable choice of sugar sorghum hybrids and the components of the cultivation technology allows optimizing the level of absorption of photosynthetically active radiation by plants and, as a consequence, to ensure the formation of high productivity, efficiency and adaptability of cultivation technologies to the current conditions of agriculture.

MATERIALS AND METHODS

The experiments were carried out in the years 2016–2018 at the Bila Tserkva Experimental and Breeding Station of the Institute of Bioenergy Crops and Sugar Beets NAAS of Ukraine, in the zone of unstable soil moisture of the Right-Bank Forest Steppe of Ukraine.

The soil of the experimental site was typical deep medium-loamy chernozem with low humus content and coarse soil grading composition. The arable soil layer (0–30 cm) contents: humus 3.5 %, total nitrogen 0.31 %, hydrolytic acidity 2.41 mg/equivalent, easily hydrolysed nitrogen (N) 13.4 mg, P_2O_5 27.6 mg, K_2O 9.8 mg per 100 g of soil. The degree of the alkali saturation of the soil was 90 %.

The weather conditions of the years of the study were quite contrasting. Thus, in 2016, in April, May, June, July, August, and September, rainfall amounted to 59.4, 95.2, 37.7, 24.5, 22.3 and 4.6 mm, respectively, that was

126, 207, 52, 29, 37 and 13 %, respectively, of the annual average. However, 2017 proved to be the driest year and in the same months, rainfall made up 25.8, 32.7, 28.8, 62.2, 3.9 and 7.0 mm, respectively, 55, 71, 39, 73, 7 and 20 % of the annual average. In addition, the air temperature during this period exceeded the average long-term values by 0.1–3.4 °C. Rainfall during the 2018 vegetation year amounted to 286.4 mm, during the agricultural year 546.6 mm, that was 83 and 97 %, respectively, and the temperature in the month of vegetation exceeded the long-term averages by 1.5–4.5 °C.

In general, the soil and climatic conditions were typical for the zone of unstable soil moisture of the Central Forest-Steppe of Ukraine and allowed to obtain sufficient sugar sorghum yield in the represented region. For research, we used a mid-early ripening sugar sorghum hybrid 'Huliver' and a mid-late hybrid 'Dovista' belonging to the Synelnykiv Breeding and Research Station of the Institute of Agriculture of the Steppe Zone NAAS of Ukraine.

The layout of the four-factor field experiment was as following: *Factor A, hybrid:* 'Dovista' and 'Huliver'; *Factor B, row spacing*: 45 and 70 cm; *Factor B, plant density*: 150,000, 200,000, and 250,000 plants/m^2; *Factor D, seed treatment with growth stimulator*: control treatment (seeds treated with water), seed treatment with growth stimulator Vympel 2 (0.5 L/t) + foliar dressing in the tillering stage (0.5 L/ha).

The experiment was carried out in a randomized block design in four replications. The total experimental plot area was 50 m^2 and the accounting area was 25 m^2.

Vympel 2 is a growth stimulator consisting of humates and their derivatives, manufactured in Ukraine. Sugar sorghum seeds were treated before sowing. In the treatments where the growth stimulator was not used, seeds were treated with water.

To determine the content of chlorophyll in the leaves of the sugar sorghum samples were collected in the tasseling stage. Analyses of chlorophyll content were carried out according to the Pochynok's method (1976) (Hrytsaienko et al. 2003).

To determine the FAR utilization rate we used reference materials for the north climatic region to which the Kyiv region belongs. Total FAR input was calculated for the interphase periods of sugar sorghum growth. For Kyiv region, the average monthly FAR intake (kJ/cm^2) was 30.2 in May, 32.3 in June, 32.3 in July, 27.2 in August, and 19.3 in September (Barabash et al., 2005).

Solar energy accumulated in the harvest was calculated by multiplying its caloric value by the amount of dry biomass. The caloric content of the dry matter of sugar sorghum averages 4.5 kcal per gram. FAR was calculated from the ratio of incoming solar energy to the FAR energy stored in the crop.

The energy costs required to carry out the basic agrotechnical operations and the studied components of cultivation technology were determined in accordance with the technological maps of cultivation of the crop and the calculation of the energy inputs of machinery, fuel and lubricants, seeds, fertilizers, pesticides, and labour.

The total energy yield in harvest was calculated as the energy component of the solid biofuel obtained with a standard moisture content of 11 % and bioethanol.

Statistical analysis of the results was performed using the method of analysis of variance using computer software Excel and Statistica 6.0 (Ermantraut et al. 2007).

RESULTS

The photosynthetic activity of the sugar sorghum, above all, ensures normal growth and development of the plants and is the basis for the formation of high crop yields. In the process of photosynthesis, plants absorb carbon dioxide from the air and transform it into the chemical energy of organic matter using solar energy, (Zhu et al. 2010, Wang et al. 2008). The main compound of the plant photosynthetic apparatus is chlorophyll. Therefore, the content of chlorophyll in leaves is an important physiological parameter that characterizes the potential ability of the photosynthetic apparatus to synthesize organic compounds. In different stages of plant growth, the plant response to the action of different factors, the content of chlorophyll in the leaves is different, and therefore it differently shapes the biological productivity of plants (Taiz et al. 2018).

Sugar sorghum belongs to C4-type CO_2-fixing plants and therefore has high photosynthesis rates and high productivity. Besides, crops of this type of photosynthesis are capable of easier overcoming moisture deficiency, high air temperatures, and excessive sunlight. However, to form a dry matter unit, they have to spend twice as much synthesized energy as C3-type crops (Ghannoum 2009).

Indicators of chlorophyll content in sugar sorghum leaves as affected by row spacing, plant density and growth stimulator are shown in **Table 1**.

Besides chlorophyll *a,* chlorophyll *b* is present in the leaves of plants. The content of chlorophyll *b* in higher plants amounts to about 1/3 of the content of chlorophyll *a*. It usually increases with the adaptation of plants to the lack of solar radiation due to the increase in the size of the light antenna of the photosystem II. At the same time, dark adaptation broadens the range of wavelengths absorbed by chloroplasts adapted to low lightening (Ghannoum 2009).

For sugar sorghum, the average summative chlorophyll content in the tasseling stage in 'Dovista' was 9.0 mg/kg of dry matter without growth stimulator and 9.3 mg/kg in the treatment with growth stimulator, in 'Huliver' it was 8.9 and 9.5 mg/kg, respectively. This is since improving plant nutrition promotes the vital activity of protoplasts, and hence the growth and size of plastid-

Table 1. Chlorophyll content in sugar sorghum leaves as affected by row spacing, plant density and growth stimulator treatment (average of 2016/2018)

Hybrid (Factor A)	Row spacing (cm) (Factor B)	Plant density (thousand plants/ha) (Factor C)	Treatment with growth stimulator (Factor D)	Content of chlorophyll (mg/kg of dry matter)		
				a + b	a	b
'Dovista'	45	150	Control	8.6	6.2	2.4
			Vympel 2	9.1	6.6	2.5
		200	Control	8.9	6.3	2.6
			Vympel 2	9.3	6.7	2.6
		250	Control	9.0	6.3	2.7
			Vympel 2	9.4	6.7	2.7
	70	150	Control	8.8	6.3	2.5
			Vympel 2	9.2	6.6	2.6
		200	Control	9.1	6.4	2.7
			Vympel 2	9.3	6.6	2.7
		250	Control	9.3	6.5	2.8
			Vympel 2	9.6	6.7	2.9
'Huliver'	45	150	Control	8.3	6.1	2.2
			Vympel 2	9.2	6.7	2.5
		200	Control	8.7	6.2	2.5
			Vympel 2	9.3	6.7	2.6
		250	Control	9.1	6.4	2.7
			Vympel 2	9.5	6.8	2.7
	70	150	Control	8.7	6.2	2.5
			Vympel 2	9.4	6.8	2.6
		200	Control	9.1	6.4	2.7
			Vympel 2	9.7	6.9	2.8
		250	Control	9.3	6.4	2.9
			Vympel 2	9.8	6.9	2.9
		$LSD_{0.05}$		0.4	0.2	0.1

bearing cells increases, as well as new cells grow, which causes an increase in chloroplasts in the cell.

With increasing plant density, an increase in chlorophyll *b* content was observed. In general, this type of chlorophyll content increased in the treatments with Vympel 2 in proportion to the increase in the content of chlorophyll *a*. However, in the control treatments of 'Dovista' at a row spacing of 45 cm and plant density increase from 150,000 to 250,000 plants/m^2, the content of chlorophyll *b* in sorghum leaves increased from 2.4 to 2.7 mg/kg of dry matter, and at a row spacing of 70 cm, respectively, from 2.5 to 2.8 mg/kg of dry matter. Similarly, in 'Huliver', with a row spacing of 45 cm and a plant density increase from 150,000 to 250,000 plants/m^2, the content of chlorophyll *b* increased from 2.2 to 2.7 mg/kg of dry matter and at a row spacing of 70 cm increased from 2.5 to 2.9 mg/kg, respectively.

For a broader understanding of the growth and development patterns of sugar sorghum and its survival during vegetation, it is necessary to look in more detail on the processes of the weed infestation peculiarities, which is especially relevant given the long period of low growth activity of the crop.

The reoccurring weed infestation of sugar sorghum sowings is caused not only by the misuse of the cultivation technology components, such as weed control through herbicides or mechanical weed control but also by the biological characteristics of the crop (Rosales-Robles et al. 2005, Kaczmarek 2017).

The most common weed species in sugar sorghum agrophytocenosis are spring weeds that start their germination before the emergence of the crop (*Polygonum convolvulus* L., *Chenopodium album* L., *Ambrosia artemisifolia* L., and *Galinsoga parviflora* Cav.) and late-spring weeds that germinate along with sugar sorghum (*Amaranthus retroflexus* L., *Echinochloa crus-galli* L., *Setaria glauca* L., *Solanum nigrum* L., and others).

Table 2 shows the numbers and weights of weeds in reoccurring weed infestation of sorghum sowings under different row spacing, sowing rates, and growth stimulator treatments.

On average, 33.6 plants/m^2 of weed plants regrew in the sugar sorghum crops. They formed an average aboveground mass of 262.9 g/m^2, which in the dry mass equivalent was 89.8 g/m^2.

Growing sugar sorghum with a row spacing of 70 cm promoted significantly more weeds in agrophytocenoses, compared to a row spacing of 45 cm. Thus, in the control treatment, 51.2−13.3 weed plants per 1 m^2 was found in the sowings of 'Dovista' at a row spacing of 45 cm and 64.7−15.7 plants/m^2 at a row spacing of 70 cm. Similarly, in the sowings of 'Huliver', 51.0−13.4 plants/m^2 was found in the control treatment at the row widths of 45 cm, and 64.9−16.2 plants/m^2 at the row widths of 70 cm.

In addition to the effects of row spacing on the peculiarities of weeds reoccurring, plant density and the use of a growth stimulator, which accelerated the growth and development of plants during the early stages of the sorghum vegetation, had a significant effect. Thus, at the sorghum plant density of 150 000 plants/m^2, maximum weed number and aboveground mass were formed. In the sowings of 'Dovista', 51.2 plants/m^2 were found at the row spacing of 45 cm with an aboveground mass of 399.0 g/m^2 and dry mass of 137.8 g/m^2. However, in

Table 2. Number and weight of weeds in the reoccurring weed infestation of sugar sorghum sowings as affected by row spacing, plant density and growth stimulator treatment (average of 2016/2018)

Hybrid (Factor A)	Row spacing (cm) (Factor B)	Plant density (thousand plants / ha) (Factor C)	Treatment with growth stimulator (Factor D)	Weed number (per 1 m²)	Green mass of weeds (g/m²)	The dry mass of weeds (g/m²)
'Dovista'	45	150	Control	51.2	399.0	137.8
			Vympel 2	47.2	243.0	86.5
		200	Control	30.4	214.0	74.1
			Vympel 2	25.6	168.0	57.2
		250	Control	13.3	112.0	37.4
			Vympel 2	10.2	73.0	25.0
	70	150	Control	64.7	532.0	18.4
			Vympel 2	60.1	456.0	155.9
		200	Control	37.2	344.0	109.3
			Vympel 2	32.3	297.0	103.9
		250	Control	15.7	147.0	52.9
			Vympel 2	13.0	114.0	41.1
'Huliver'	45	150	Control	51.0	407.0	137.6
			Vympel 2	47.3	244.0	80.0
		200	Control	30.6	218.0	72.9
			Vympel 2	25.8	175.0	60.5
		250	Control	13.4	119.0	39.5
			Vympel 2	10.5	101.0	32.8
	70	150	Control	64.9	541.0	188.9
			Vympel 2	60.5	472.0	168.2
		200	Control	37.6	356.0	123.7
			Vympel 2	32.8	310.0	100.0
		250	Control	16.2	151.0	50.8
			Vympel 2	13.8	116.0	39.6
$LSD_{0.05}$				0.3	6.0	2.3

general, the maximum values for weeds was found in the treatments with the row spacing of 70 cm and the minimum plant density (150,000 plants/ha). For example, 64.7 plants/m^2 was found in the sowings of 'Dovista' forming an aboveground mass of 532.0 g/m^2 and dry mass of 180.4 g/m^2. In the sowings of 'Huliver', 64.9 weed plants per 1 m^2 was found. They formed an aboveground mass of 541.0 g/m^2 and a dry mass of 188.9 g/m^2.

Plant density of 250,000 plants/ha and row spacing of 45 cm contributed to the optimum parameters of the light impermeability of sorghum sugar sowings and the minimum number and weight of weeds. Thus, in 'Dovista' sowings, 13.3 plants/m^2 of weed plants were established with an aboveground mass of 112.0 g/m^2 and dry mass of 37.4 g/m^2, while in 'Huliver', these values were 13.4 plants/m^2, 119.0 g/m^2, and 39.5 g/m^2, respectively.

The most efficient application of growth stimulator was observed in the treatments with a row spacing of 45 cm and a plant density of 250 000 plants/ha. Thus, in the sowings of 'Dovista', 10.2 plants/m^2 of weed plants were found with an aboveground mass of 73.0 g/m^2 and dry mass of 25.0 g/m^2, while in the sowings of 'Huliver' the values were 10.5 plants/m^2, 101.0 g/m^2, and 32.8 g/m^2, respectively.

Thus, reoccurring of weed infestation in sugar sorghum sowings at a row spacing of 70 cm and plant density of 150,000 plants/ha is a constraining factor to the effective growth and development of plants and further obtaining of a high level of productivity.

In the solar spectrum, there are two main energy components, the visible and the infrared light spectrum. Visible range is important for the process of photosynthesis, i.e. the converting light energy into the energy of chemical bonds of organic substances by phototrophic organisms with the participation of photosynthetic pigments. However, only about half of the visible light spectrum is photosynthetically active. In addition, cultivated plants practically do not absorb blue, green and yellow waves (Nychyporovych 1980).

Increasing the leaf area of crops leads to an increase in the efficiency of photosynthetically active radiation (FAR). Optimal consistency of growth processes with successful adaptation of the photosynthetic apparatus of crops to the peculiarities of the radiation regime leads to high FAR efficiency, 5–6 % on average for vegetation (Willey 2016).

The efficiency of photosynthetically active radiation (FAR) of sugar sorghum plants as affected by row spacing, plant density and growth stimulator treatment presented in **Table 3**.

In the field, plants often use 1−3 % of the total FAR, but at certain stages of plant growth and development, FAR efficiency can reach 4−6 %. According to Nychyporovych (Nychyporovych, 1980), these values can be raised to 7−8 and even 10 % (that corresponds to 10−15 t/ha of grain crops) through optimization of growing conditions. However, the theoretically possible limit of the FAR efficiency equals 22 %.

In the three-leaf stage of sugar sorghum plants, FAR efficiency averaged 2.04 % over the experiment. FAR of 'Dovista' averaged 1.85 % and 'Huliver' 2.24 %.

Minimal FAR efficiency was in the treatments with a plant density of 150,000 plants/ha: 0.8−0.9 % in 'Dovista', and 0.9−1.0 % in 'Huliver'.

For the cultivation of sugar sorghum of both hybrids under study with plant density, 200 000 to 250 000

Table 3. FAR efficiency (%) of sugar sorghum as affected by row spacing, plant density and growth stimulator treatment (average of 2016/2018)

Row spacing (cm) (Factor B)	Plant density (thousand plants/ha) (Factor C)	Treatment with growth stimulator (Factor D)	Growth stage					
			Three leaves	Tillering	Leaf-tube formation	Tasseling	Milky ripeness	Full ripeness
45	150	Control	0.9	0.4	1.6	1.1	1.0	2.8
		Vympel 2	1.4	0.5	2.0	1.3	1.2	3.1
	200	Control	1.4	0.6	2.8	1.8	1.6	4.9
		Vympel 2	2.3	0.8	3.4	2.3	2.1	5.4
	250	Control	2.3	0.9	4.2	2.8	2.7	7.1
		Vympel 2	3.5	1.3	5.2	3.7	3.1	8.3
70	150	Control	0.8	0.3	1.4	0.9	0.9	2.4
		Vympel 2	1.1	0.4	1.7	1.1	1.0	2.8
	200	Control	1.4	0.6	2.5	1.7	1.5	4.3
		Vympel 2	2.1	0.7	3.1	2.1	1.9	4.8
	250	Control	2.0	0.8	3.6	2.4	2.2	6.0
		Vympel 2	3.0	1.0	4.4	3.0	2.6	7.2
45	150	Control	1.0	0.4	1.5	1.0	0.8	4.1
		Vympel 2	1.7	0.6	2.0	1.4	1.1	4.4
	200	Control	1.8	0.7	2.8	1.9	1.6	7.5
		Vympel 2	3.1	1.0	3.4	2.4	1.8	8.1
	250	Control	2.5	1.0	3.6	2.4	2.2	9.7
		Vympel 2	4.2	1.4	4.7	3.3	2.7	10.5
70	150	Control	0.9	0.4	1.3	0.9	0.8	3.6
		Vympel 2	1.5	0.5	1.7	1.2	0.9	3.9
	200	Control	1.6	0.7	2.4	1.6	1.4	6.5
		Vympel 2	2.7	1.0	3.0	2.2	1.7	7.0
	250	Control	2.2	1.0	3.3	2.3	2.1	8.9
		Vympel 2	3.7	1.3	4.2	3.3	2.2	9.6

plants/ha and seed treatment with growth stimulator Vympel 2, maximum values of FAR efficiency were obtained. Thus, at a row spacing of 45 cm in 'Dovista' this value was 3.5 %, and in 'Huliver' 4.2 %.

During the stage of tillering, the growth processes of the plants became even after the adaptation to different crop density, which is why, according to the whole experiment data, FAR efficiency was 0.76 %, 0.69 % in 'Dovista' and 0.84 % in 'Huliver'. The use of the growth stimulator Vympel 2 was positively reflected in the absorption of solar energy by plants, and therefore significant differences remained between the control and the treatments with the stimulator. At the same time, the treatments with different plant densities were roughly aligned in terms of FAR efficiency, except for minimal plant densities.

During the leaf-tube formation stage, the processes of growth and development of sugar sorghum plants significantly increased, and therefore the absorption of solar energy by plants increased too. On average over the experiment, FAR efficiency was 2.91 %, in 'Dovista' 2.99 % and 'Huliver' 2.84 %. The maximum FAR efficiency values were obtained in the treatments with a plant density of 250,000 plants/ha and the use of a growth stimulator Vympel 2 with a row spacing of 45 cm: 5.2 % in 'Dovista' and 4.7 % in 'Huliver'.

In the tasseling stage, the FAR efficiency of sugar sorghum plants averaged 2.00 % over the experiment, 2.01 % in 'Dovista' and 1.99 % in 'Huliver'.

In the stage of full ripeness of the sorghum grain, FAR efficiency, on average over the experiment, increased to 5.95 %, in 'Dovista' to 4.92 % and in 'Huliver' to 6.97 %. Contrary to the fact that FAR efficiency in September sharply decreases the spectral composition of light changes, in the spectrum of photosynthetically active radiation, the infrared range of waves begins to prevail.

The infrared range of the solar spectrum is an extremely important source of energy in the biosphere, as it determines the temperature conditions of the lower layers of the atmosphere, the Earth's surface, and the water warming. It is believed that at the end of vegetation, in September, infrared rays dominate in the atmosphere and in this way increase the level of photosynthesis efficiency (Willey 2016).

The yield of sugar sorghum biomass is determined by the optimal ratio of individual plant productivity and their number per unit area. In determining the optimal growing space of sugar sorghum plants, besides plant density, biological features of the hybrid are of great importance. The hybrids under study belong to different groups of ripeness, therefore it is not advisable to compare them with each other; however, their interaction with the soil and climatic conditions of the region and the studied components of cultivation technology reveal differently.

According to the classification, 'Huliver' is a mid-early ripening hybrid that reaches waxy ripeness on the 96–110 day and full-grain ripeness on the 106–116 day. 'Dovista' is mid-late ripening hybrid, with a vegetation period of 120–130 days to wax ripeness and 130–140 days to full grain ripeness. Given in **Table 4** is biomass yield of sugar sorghum hybrids as affected by such agrotechnical factors as row spacing, plant density, and treatment with the growth stimulator.

Table 4. Yield and energy efficiency of sugar sorghum hybrids with different row spacing, plant density and growth stimulator treatment (average of 201/2018)

Hybrid (Factor A)	Row spacing (cm) (Factor B)	Plant density (thousand plants/ha) (Factor C)	Treatment with growth stimulator (Factor D)	Yield (t/ha)	Energy yield (GJ/ha)	Energy efficiency
'Dovista'	45	150	Control	54.5	198.7	5.3
			Vympel 2	61.9	228.0	6.0
		200	Control	64.3	307.0	8.1
			Vympel 2	74.6	362.3	9.1
		250	Control	82.9	457.4	12.1
			Vympel 2	98.8	548.2	14.5
	70	150	Control	49.6	172.2	4.6
			Vympel 2	56.9	199.9	5.3
		200	Control	59.4	279.9	7.4
			Vympel 2	68.3	330.7	8.8
		250	Control	76.3	392.4	10.4
			Vympel 2	89.8	466.7	12.3
'Huliver'	45	150	Control	49.5	174.9	4.6
			Vympel 2	56.8	211.3	5.6
		200	Control	61.1	293.9	7.8
			Vympel 2	70.9	343.6	9.1
		250	Control	80.5	386.9	10.2
			Vympel 2	93.5	467.8	12.3
	70	150	Control	47.0	159.8	4.2
			Vympel 2	53.7	189.1	5.0
		200	Control	56.4	260.4	6.9
			Vympel 2	65.2	308.2	8.2
		250	Control	73.3	358.7	9.5
			Vympel 2	85.9	423.0	11.2
$LSD_{0.05}$				1.0	-	-

Given the varying row spacing and plant density of the sowings, 'Huliver' is slightly inferior to 'Dovista'. The yield of 'Dovista' exceeded 'Huliver' by 3.6 g/ha on average. The yield of individual hybrid is a quantitative expression of its genetic characteristics under certain soil and climatic conditions.

For the cultivation of sugar sorghum at a row spacing of 45 and 70 cm and a plant density of 150,000 plants/ha, the minimum biomass yield values were obtained ranging from 47.0 to 54.5 t/ha.

In the experiment, the bushiness of the studied sugar sorghum hybrids ranged between 1.2 and 1.8 stems per plant, while in general, hybrids of grain sorghum form an average of 3–4 stems per plant. Therefore, at a lower crop density, sugar sorghum plants are unable to compensate for the loss of optical density with other elements of the structure similar to grain sorghum or other grain crops.

In the treatments where the seeds were treated with a growth stimulator Vympel 2 (0.5 L/t) + foliar feeding in the tillering stage (0.5 L/ha), an increase in the productivity of sorghum plants was obtained. Thus, with pre-sowing seed treatment, the difference between the control treatment without treatment for row width of 45 cm and different plant density ranged from 7.4 to 15.9 t/ha, and for row width of 70 cm from 7.3 to 13.5 t/ha, respectively.

By analogy with the hybrid described above, the response of 'Huliver' to the use of Vympel 2 was the same. Thus, seed treatment with growth stimulator Vympel 2 (0.5 L/t) + foliar dressing in the tillering stage (0.5 L/ha) for row spacing of 45 cm and increased plant density from 150,000 to 250,000 plants/ha ensured a yield increase of 7.3–13.0 t/ha. In similar treatments with a row spacing of 70 cm, the yield of sugar sorghum biomass was 6.7–12.6 t/ha above the control treatment.

DISCUSSION

Chlorophyll *a* is a special form of chlorophyll used for photosynthesis and most intensively absorbs light in the violet-blue and orange-red parts of the spectrum. This pigment is vital for photosynthesis because of its ability to deliver excited electrons to the electron transport chain (Willey 2016).

In total over the experiment, the increase in chlorophyll content for the sugar sorghum hybrids under study ranged between 0.30 and 0.60 %, respectively, which indicates a positive effect of the growth stimulator on the state of the plant photosynthetic system. Growing sugar sorghum plants at different row spacing did not significantly affect the change in the total content of chlorophylls in the leaves. All deviations were trending and within the error of the experiment. Here it should be noted that the additional shading of the lower tiers of leaves is caused by an increase in plant density and thickening resulted from rectangular growing space layout (70 cm) as compared with the square growing space layout (45 cm). This circumstance leads to an increase in the total content of so-called shadow chlorophylls *b*. On the one hand, this indicates that the lighting of the photosynthetic apparatus of sugar sorghum is not optimal, and on the other, it shows how effectively plants are able to rebuild their photosynthetic system to reach the maximum efficiency of photosynthesis using the energy of the sun that falls on their leaves under such circumstances.

Regarding the number and weight of weeds in reoccurring weed infestation of sugar sorghum agrophytocenosis at different row spacing, plant density and growth stimulator treatment it was found that the differences between the mean values of the treatments for the studied hybrids were within the insignificant deviations, and therefore the plots selected for studies were characterized by the same type of weed infestation and the number of major weed species.

The use of Vympel 2 plant growth stimulator in seed treatment and during sugar sorghum vegetation has been proven effective for phytocenotic restriction of weed growth and development. The first use of the formulation for seed treatment promoted the growth of crops after germination. The second application was done in the stage of budding and, accordingly, enhanced plant growth and development, although continuous application methods could promote activation of growth and development of weed plants as well.

An analysis of the data in **Table 2** indicates that the use of growth stimulator Vympel 2 (0.5 L/t) in pre-sowing treatment of sorghum sugar seeds, and its second foliar application in the tillering stage (0.5 L/ha) contributed to increased competition for nutrients and reducing the biometric parameters of weeds. Compared to the treatments of the experiment with untreated seeds, in 'Dovista' sowings, the number of weeds decreased by 2.7–4.8 plants/m^2, their green mass decreased by 33.0-156.0 g/m^2 and dry mass decreased by 5.3–51.3 g/m^2. Similarly, in 'Huliver' sowings, the number of weed plants decreased by 2.4–4.8 plants/m^2, the green mass by 35.0–163.0 g/m^2, and the dry mass by 6.7–57.6 g/m^2.

Concerning the re-contamination of sugar sorghum agrophytocenoses with weeds, it should be noted that this is the limiting factor to the effective growth and development of plants and the formation of high crop productivity.

In the early stages of growth and development of sugar sorghum plants, the significant part of photosynthetically active radiation and the prevalence of high seeding rates over the minimum were achieved due to increasing plant density per unit area of the field. It is the increase in the number of plants that results in a significant increase in the FAR efficiency, although the use of Vympel 2 formulation even against this background has proved to be quite effective.

In the tasselling stage as well as in the stage of grain milk ripeness at a plant density of 250,000 plants/ha, the use of a growth stimulator Vympel 2 and a row spacing of 45 cm ensured maximum values of FAR efficiency. In fact, the physiological maturation of late-ripening varieties and hybrids of sugar sorghum in the last months of the growing season is due to the activation of infrared energy, although the total intensity of sunlight in August is 27.2 kJ/cm^2, and in September only kJ/cm^2.

With regard to the crop yield, the minimum values were obtained for row spacing of 45 and 70 cm and plant density of 150,000 plants/ha. This is due to the peculiarity of the formation of the optical structure of

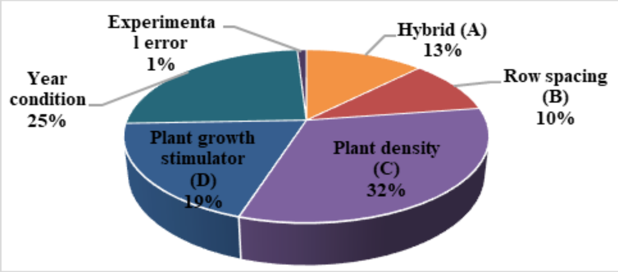

Fig. 1. The influence of factors on the formation of sugar sorghum biomass yield

agrophytocenosis and a high level of reoccurring weed infestation at the above-mentioned plant density. Thus, in the early stages of growth and development (the tillering stage), when sugar sorghum plants grow slowly and are unable to form a large leaf area, the microclimate of agrophytocenosis is impaired and significant amount of available moisture evaporates from the field surface. At this time, weeds can still be controlled, both mechanically through hoeing and using herbicides. In the leaf-tube formation stage, sorghum plants reach heights of 90–105 cm, which is why hoeing and herbicide application in the absence of special sprayers for tall crops is impossible without damaging plants. In addition, the problem of dramatic changes in the structural parameters of sorghum crops, as a result, changed plant density is also associated with the fact that, unlike grain sorghum, plants of sugar sorghum are less bushy. Accordingly, not optically dense sowings of sugar sorghum show a regrowth of weeds and an intensification of the growth of their tall species, which avoided destruction from the weed control measures. Even a few plants of tall weed species per square meter can significantly reduce solar energy input to the photosynthetic apparatus of sugar sorghum plants, which results in a decrease in crop yield.

The presented analysis of variance allows us to fully evaluate not only the reliability of the obtained data but also to determine the influence of factors on the formation of the sugar sorghum biomass yield (**Fig. 1**).

It was found that plant density is the most effective factor in sorghum biomass productivity (32 %), which corresponds to the data obtained on the tillering and second wave of weed infestation.

The growth regulator stimulates the plants quite well and allows them to avoid nutritional deficiencies during the critical periods of vegetation. Thus, seed treatment with the growth stimulator Vympel 2 (0.5 L/t) + foliar feeding in the tillering stage (0.5 L/ha) allows influencing the harvest formation at the level of 19 %.

Despite the fact that hybrids 'Dovista' and 'Huliver' were created by the same breeding institution, their differences in the duration of the vegetation (mid-early and mid-late ripening) affected the formation of productivity of agrophytocenosis within 13 %.

The cultivation of the studied hybrids at different row spacing slightly influenced the formation of their productivity level only within 10%, which needs to be emphasized.

As the years of the field experiment were sufficiently contrasting, in 2016, there was a partial suppression of plants due to a significant excess of average daily temperatures and lack of rainfall, whilst in 2017, rainfall was significant, and 2018, it was close to optimal values; therefore, the share of influence of the weather conditions during vegetation on biomass yield was 25 %.

The efficiency of the investigated technology of growing sugar sorghum and its components can be determined as the difference between the amount of energy obtained with the harvest and the energy costs of cultivation technology. Due to the peculiarities of the individual components of the cultivation technology for sugar sorghum hybrids, the main differences in different row spacing and plant density were only in the spatial optimization of plant location on the field surface. Therefore, the treatments with different row widths, plant densities, and growth stimulator use varied by no more than 0.1–0.3 GJ/ha, with an average of 37.8 GJ/ha. Accordingly, the minimum experimental values were observed for the cultivation of plants with a density of 150,000 plants/ha for row widths of 45 and 70 cm. Thus, in crops of the ‘Dovista’ hybrid energy was obtained 172.18–227.98 GJ/ha, and in the crops of the ‘Huliver’ hybrid respectively 159.79–211.32 GJ/ha. The use of even additional measures of stimulation of plants did not allow to obtain indicators similar to the higher density of standing plants.

The maximum energy yield in the experiment was obtained for row spacing of 45 cm, plant density of 250,000 plants/ha and pre-sowing treatment with growth regulator Vympel 2 (0.5 L/t) + foliar application in the tillering stage (0.5 L/ha). Thus, in ‘Dovista’, the energy yield was 457.35 GJ/ha, and in ‘Huliver’ 467.82 GJ/ha. Similarly, with virtually unchanged production costs, maximum energy efficiency was obtained by sowing sugar sorghum at a row spacing of 45 cm and seed treatment with a growth stimulator Vympel 2 (0.5 L/t) + foliar application in the tillering stage (0.5 L/ha). Such sowings formed the maximum yield of solid biofuels. Thus, at a plant density of 250,000 plants per hectare in ‘Dovista’, energy efficiency was 14.46, and in ‘Huliver’, 12.34.

The potential yield of sugar sorghum for biofuel production depends significantly on the growing technology. In agronomic terms, specific components of the harvest structure, which are of interest for second-generation biofuels, can be maximally altered by the use of appropriate components of cultivation technology (Guiying et al. 2000, Barbanti et al. 2012, Zegada-Lizarazu and Monti 2012).

However, according to other authors, row spacing and crop density do not affect the yield and sugar content in the sorghum stems (Ferraris and Charles-Edwards 1986a, b, Lueschen et al. 1991, Wortmann et al. 2010). To illustrate, a higher crop density with narrower than usual spacing can provide higher yields of stems and sugar content. In addition, it can further improve weed control (Broadhead and Freeman 1980, Lueschen et al. 1991).

Even though sugar sorghum can be grown under minimal tillage systems (Saballos 2008), timely weed control provides a high level of productivity (Tsuchihashi and Goto 2004). Therefore, the analysis of the works of other scientists shows that the results of our research on establishing the peculiarities of growth and development of sugar sorghum plants under the effect of various components of cultivation technology conform with earlier works.

CONCLUSION

It has been investigated that the summative content of chlorophylls *a* and *b* in the tasselling stage on the average was 9.0 mg/kg of dry matter for ‘Dovista’ without the use of a growth stimulator and 9.3 mg/kg of dry matter using growth stimulator Vympel 2; in ‘Huliver’ these values were 8.9 and 9.5 mg/kg, respectively. In general, the increase in chlorophyll content was 0.30 and 0.60 %, respectively, which indicates a positive effect of the growth stimulator on the state of the plant photosynthetic system.

It was found that the most effective limiting factor in reoccurring weed infestation in the sowings of sugar sorghum is the use of the plant growth stimulator Vympel 2 under the summative action of the two factors: row spacing (45 cm) and the plant density (250,000 plants/ha). Thus, in the sowings of ‘Dovista’, 10.2 plants/m^2 of weeds was found, which formed a vegetative mass of 73.0 g/m^2 and a dry mass of 25.0 g/m^2. In the ‘Huliver’ sowings, these values were 10.5 plants/m^2, 101.0 g/m^2, and 32.8 g/m^2.

It was calculated, that in the stage of leaf-tube formation, the process of growth and development of sugar sorghum significantly accelerated, and therefore the absorption of solar energy by plants increased significantly too. Thus, on average in the experiment, FAR efficiency amounted to 2.91 %; in ‘Dovista’ it made up 2.99 % and in ‘Huliver’ 2.84 %. The maximum values of the FAR efficiency were obtained for the cultivation of sugar sorghum with a plant density of 250,000 plants/ha using a growth stimulator Vympel 2 at a row spacing of 45 cm. In ‘Dovista’ it reached 5.2 % and in ‘Huliver’ 4.7 %.

The maximum energy yield in the experiment was obtained for row spacing of 45 cm, high plant density (250,000 plants/m^2) and pre-sowing seed treatment with a growth stimulator Vympel 2 (0.5 L/t) + foliar application in the tillering stage (0.5 L/ha). In the sowings of ‘Dovista’, the energy yield amounted to 457.35 GJ/ha, and in the sowings of ‘Huliver’, it was 467.82 GJ/ha, respectively. In the treatments with different row spacing, plant density, and growth stimulator, energy yield ranged from 0.1 to 0.3 GJ/ha, with an average of 37.8 GJ/ha.

Application of growth stimulator Vympel 2 for pre-sowing seed treatment (0.5 L/t) + foliar application in the tillering stage (0.5 L/ha) at a row spacing of 45 cm and increased plant density from 150,000 to 250,000 plant/ha ensured a yield increase of 7.3–13.0 t/ha. Similar treatments of the experiment at a row spacing of 70 cm ensured yield of vegetative mass of sugar sorghum by 6.7–12.6 t/ha higher than in the control treatment.

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