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Yield capacity and energy value of sorghum grain depending on the application of mineral fertilisers

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Abstract

The paper covers the research into the productivity of sorghum (*Sorghum bicolor* (L.) Moench) grain for its widest use: nutrition, fodder for animals, and as a bioenergy crop, depending on the rates of mineral fertilisation. The purpose of the experiment was to analyse the effect of the fertiliser rates on the productivity of sorghum grain, its biofuel output, and energy received from it. The following methods were used: the field method, to investigate biological and ecological features of growth and development of the crop productivity and quality; the laboratory method, to determine the correlation between the crop and the environment (plant and soil analysis); the generalised method, to identify common properties and features. The application of fertilisers improved the quality of sorghum grain considerably: protein and fat content increased from 9.7% to 12.4% and from 3.37% to 3.62%, respectively; with higher fertiliser rates, starch content increased from 67.1% to 70.1% for cultivar 'Dniprovskyi 39' and from 65.8% to 68.8% for cultivar 'Vinets'. Compared with the control treatment (without fertilisers) and under the effect fertiliser rates, grain yield capacity and above-ground mass increased. In the case of 'Dniprovskyi 39', at fertiliser rates $N_{90}P_{90}K_{90}$, $N_{120}P_{120}K_{120}$ and estimated rate of $N_{50}P_{40}K_{70}$, grain yield capacity increased reliably, compared with the control treatment, and it amounted to 7.1, 7.9, and 7.3 t ha^{-1}; grain yield capacity of 'Vinets' was 7.2, 7.8 and 7.0 t ha^{-1}, respectively. Biomass yield capacity of 'Dniprovskyi 39' and 'Vinets' increased reliably only at the highest and estimated fertiliser rates. When 'Dniprovskyi 39' was grown, the highest total energy output was equal to 181.0 and 187.8 GJ ha^{-1}; this indicator was 169.8 and 178.3 GJ ha^{-1} for 'Vinets'. This was due to the estimated and maximal fertiliser rates. More than 80% of this energy is concentrated in solid biofuel and only 20% in bio-ethanol. The decrease in fertiliser rates led to a lower energy output of 1 ha.

Keywords: rates, grain quality, productivity, biofuel, energy, *Sorghum bicolor*.

Introduction

With considerable potential for bioenergy development, Ukraine still lags far behind the rest of the world, especially Europe. Some countries have already achieved the substitution of 40% of fossil fuels for biological fuels, while Ukraine produces only 3.5% of total energy consumed. The renewed interest in the use of biofuels in the last 2–3 years, the availability of bulk raw material base, and an increase in demand and prices for biological fuels make it possible for Ukraine to double the achieved level of biofuel production and bring it up to 6.2 million tonnes of oil equivalent in 2025, and up to 12 million tons in the longer term (Sinchenko et al., 2020).

Energy demand is increasing due to population growth and improved living standards. This has resulted in an increase in global pollution and a reduction in fossil energy resources. To mitigate these negative effects, natural energy resources should be used effectively. Moreover, the share of renewable energy should be of a high proportion (Nitsenko et al., 2018; Bórawski et al., 2019; Koval et al., 2020). Overall, the use of renewable energy may be a viable option. This decision could meet energy requirements and, simultaneously, reduce harmful emissions, including CO_2 emissions (Rocha et al., 2018).

As feedstock for biofuel production, organic raw materials can be used. The use of energy crops such as maize, sorghum, etc. as biofuel production feedstock competes with other food crops for arable land. It is possible to cultivate lignocellulosic plants on marginal

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lands to avoid competition for land. Some grasses (e.g., miscanthus, switchgrass, foxtail millet, etc.) are suitable to be grown on marginal lands (Bazaluk et al., 2021).

Sorghum (*Sorghum bicolor* (L.) Moench) grain is one of the most productive, drought-resistant cereal crops, which is very adaptable to soil-climatic conditions (Mahama et al., 2014). The crop has a diversified use as it is grown for food, fodder, and technical purposes (Begna, 2021 a; b). Sorghum is in the top five grain crops, and it is a very attractive raw material in bioenergy in the future (Dahlberg, 2019).

Sorghum grain uses moisture economically for the formation of a dry substance unit. It is ensured by biological features of the plant. Sorghum has a well-developed root system, which penetrates the soil at a depth of 2.0–2.5 m, and, also, the ability to reflect excessive solar radiation due to a wax layer on the plant surface (Parra-Londono et al., 2018). It is characterised by short and not-numerous internodes and a relatively low height.

Sorghum belongs to the short-day crops (Dziubetskyi et al., 2014). Sorghum is among the top ten crops, which feed the whole world. They are C_4 species with a high efficiency of photosynthesis and a typically high potential of biomass yield capacity. A high level of tolerance to drought and high temperatures as well as adaptation to problem soils makes it more relevant for the guarantee of food security in view of climate change (Miri et al., 2012; Kumar et al., 2015).

From ancient times, sorghum has been grown to be used in food industry and in fodder production. In recent years, sorghum has been considered a bioenergy crop, as it can be used to produce bio-ethanol (ethyl alcohol) and solid fuel: the above-ground mass is used for the manufacturing of briquettes and pellets (Stamenkovic et al., 2020).

According to the prediction, by 2050, the world's population will have grown to over nine billion people, and production of food for people and fodder for animals will have to be doubled to satisfy the expected demand. In addition, many countries have certain ambitions to increase the manufacture of biofuel for economic and ecological reasons and those of national security. Biofuel derived from sorghum has a strong effect on displacing greenhouse gases, which can help hinder the increase of CO_2 level in the atmosphere, partly caused by burning fossil fuel (Olson et al., 2012). Updated achievements in the development of the production system of energy crops and biofuel will assist in the preparation for possible depletion of fossil fuel, which can be mined using a more economically efficient method (Mullet et al., 2014). Thus, it becomes relevant and urgent to investigate the issue of the cultivation technology of sorghum grain as a raw material for the manufacture of biofuel.

An important step in the technology of crop cultivation is application of mineral fertilisers. This is one of the most effective factors influencing the dynamics of sorghum growth and development, and the ability to form high yield and good grain quality under changeable climatic conditions. This crop responds well to the application of fertilisers, because from the total uptake it uses only 38.7% of nutrition elements from soil resources (Kuh, Sereda, 2014; Melaku et al., 2018).

Many authors (Sujathamma et al., 2015; Munagilwar et al., 2020) have reported that fertilisers facilitate not only the increase in the crop productivity but also the change in the plant height, photosynthetic apparatus, etc. The correct determination of fertiliser rates is of great importance considering the soil composition and the moisture level.

Sorghum grain has a high ability to use natural resources. Nevertheless, grain cultivation and productivity depend on the correlation of the plant and the environment as well as on some technological factors, one of them being the application of fertilisers, which promote the increase of its yield capacity (Oprea et al., 2016).

Since sorghum is not very popular in Ukraine, the issue of fertilisation of sorghum grain has not been studied enough, but it requires detailed research.

The purpose of the experiment was to investigate the effect of fertiliser rates on the productivity of sorghum grain and on the biofuel output and energy from it.

Materials and methods

The experiment was carried out between 2016 and 2020 in the conditions of Bila Tserkva Research and Breeding Station of the Institute of Bioenergy Crops and Sugar Beet of the National Academy of Agricultural Sciences of Ukraine (NAAS) – the Right-Bank Forest-Steppe zone of Ukraine. According to the trial scheme, the following factors were studied: sorghum (*Sorghum bicolor* (L.) Moench) two cultivars (factor A) 'Dniprovskyi 39' and 'Vinets', and fertilisation (factor B): 1) without fertilisers (control), 2) $N_{30}P_{30}K_{30}$, 3) $N_{60}P_{60}K_{60}$, (4) $N_{90}P_{90}K_{90}$ and 5) $N_{120}P_{120}K_{120}$; on the average of the experimental years, the estimated fertiliser rate was $N_{50}P_{40}K_{70}$. The estimated rate of fertilisers was calculated on the basis of the estimated balance method.

The area of the sown plot was 50 m^2, the area of the accounting plot 25 m^2. The method of regular replications was used in the trial: in each replication, trial treatments were placed in succession on the plot. A four-fold replication was applied in the experiment.

The leaf surface area was measured in different growing seasons by the formula:

$$S = a \times b \times 0.67,$$

where S is the leaf surface area, thousand m^2 ha^{-1}; a – leaf length cm; b – leaf width cm; 0.67 – the configuration factor.

The starch content in the grain was determined by the polarimetric method.

Sorghum was harvested when the grain reached the moisture content of 14% during the stage of full maturation.

The output of bio-ethanol, solid fuel, and energy was determined by the technique developed at the Institute of Bioenergy Crops and Sugar Beet considering the fact that grain dry mass was 86% and the average starch content was 75% (Roik et al., 2020).

The output of bio-ethanol from starch was calculated by the formula:

$$M = U \times n \times S \times b \times k / 10000,$$

where M is output of bio-ethanol per hectare of grain sorghum, t ha^{-1}; U – grain yield, t ha^{-1}; n – dry matter content in grain, %; S – total starch content in dry matter of grain, %; b – the ratio of the molecular weight of ethanol to the molecular weight of starch, b = 0.5679; k – the coefficient of the factory output of bio-ethanol, k = 0.9.

Energy output from bio-ethanol was determined by the formula:

$$E_m = M \times e_m,$$

where E_m is the energy output, GJ ha^{-1}; M – the output of bio-ethanol per hectare of sorghum grain, t ha^{-1}; e_m – specific heat of combustion, GJ t^{-1} (25 GJ t^{-1}).

The output of solid biofuels was calculated by the formula:

$$T = U \times c \times (100 + w) / 10000,$$

where T is the output of solid biofuels, t ha^{-1}; U – biomass yield of sorghum stalks, t ha^{-1}; c – dry matter of stem biomass, %; w – humidity of solid biofuel, %, (10 %).

The energy output from solid biofuels was determined by the formula:

$$E_T = T \times e_T,$$

where E_T is the energy output from solid biofuels, GJ ha^{-1}; T – the output of solid biofuels, t ha^{-1}; e_T – specific heat of combustion of solid biofuels, MJ ha^{-1} (16 MJ ha^{-1}).

The soils of the experimental plot are chernozems of typically deep low-humus coarse dust average loamy granule-metric composition (according to WRB, 2014). Magnesium and calcium carbonates lie at the depth of 55–65 cm. About 17% of silt particles and 46–54% of coarse dust are in the ploughing layer (0–30 cm). The relief is flat; the depth of ground water is 8 m. Agrophysical and agrochemical properties of a ploughing layer (0–30 cm) are characterised by such indicators: humus 3.5%, total nitrogen (N) 0.31%, hydrolytic acidity 2.41 mg^{-1}; easily-hydrolysed N 134 mg, P_2O_5 276 mg and K_2O 98 mg per 1000 g of the soil. The saturation degree of bases is 90%.

Meteorological conditions. In the experimental years, weather conditions were typical for this zone and favourable for the cultivation of sorghum grain.

In 2016, during the growing season, the air temperature was 2.4°C higher than the long-term average (Figure 1). In terms of rainfall, 2016 was marked by a certain unevenness of precipitation; in April and May, the precipitation was 12.4 and 49.2 mm higher than the long-term average, respectively. But in June, July, August, and September, precipitation was 35.3, 60.5, 38.0, and 30.4 mm lower than the long-term average (Figure 2).

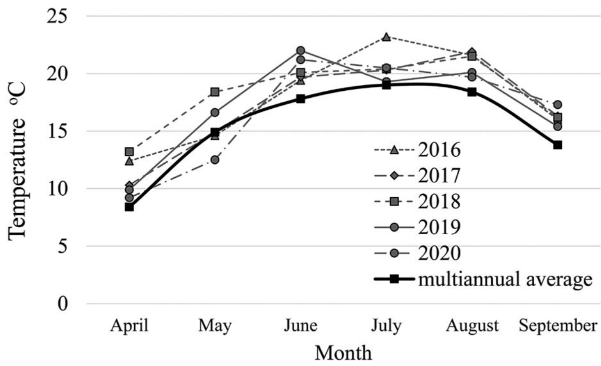


Figure 1. Average daily temperature during the sorghum grain growing (data of Bila Tserkva Meteorological Station)

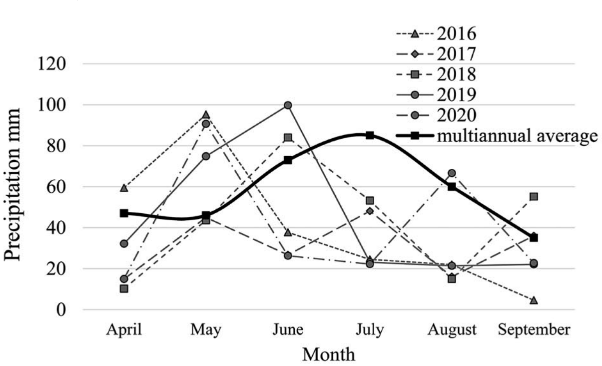


Figure 2. Amount of precipitation the sorghum grain growing season (data of Bila Tserkva Meteorological Station)

In 2017, the monthly air temperature was 1.9°C higher than the long-term average. In general, during the growing season, the amount of precipitation in 2017 was 159.2 mm lower than the average long-term values. During the growing season of 2018, the air temperature was 2.9°C higher than the long-term values. The amount of precipitation during the growing season was 84.8 mm lower than the long-term average. In 2019, the average air temperature during the growing season exceeded the long-term data by 1.8°C. In terms of rainfall, the year 2019 was marked by certain unevenness in precipitation. In May and June, its level exceeded the long-term precipitation by 28.8 and 26.7 mm, respectively. In April, July, August, and September, the level of precipitation was 14.8, 61.9, 38.6, and 12.9 mm lower than the long-term average, respectively. In 2020, the air temperature by months was 1.4°C higher than the long-term average. It should be noted that 2020 was a dry year, as precipitation was much lower than the average long-term data. In April, June, July, and September, the precipitation was 32.0, 46.7, 62.8, and 12.3 mm lower than the long-term average, respectively; in May and August its level slightly exceeded the average long-term data by 44.7 and 6.6 mm.

The characteristics of the studied cultivars are presented below (Cherenkov et al., 2017). Cultivar 'Dniprovskyi 39': the originator is Synelnykivska Breeding and Research Station of the Institute of Grain Crops NAAS of Ukraine. It is an early-ripening type; it matures within 100–105 days after germination. The cultivation purpose is to receiving grain; potential grain yield capacity is 6–7 t ha^{-1}. Cultivar 'Vinets': the originator is Henychesk Research Station of the Institute of Grain Crops NAAS of Ukraine. It is an early-ripening type, a grain-fodder cultivar; it matures within 90–95 days after germination. The cultivation purpose is to receiving grain; potential grain yield capacity is 4–6 t ha^{-1} (on the non-irrigated soils). The studied cultivars are infested with cereal aphids to an average degree; they respond well to irrigation and to fertilisers.

Statistical analysis. To determine statistical significance for 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. The assessment of the interaction between different years was not significant, thus only average data were analysed.

Results

Sorghum grain actively assimilates nutrition elements and moisture from the soil through its root system forming high yield capacity; it responds positively to the application of mineral fertilisers. Mineral fertilisers have the effect on both the enhancement of crop productivity and soil fertility (Dremliuk et al., 2013). The application of fertilisers resulted in the increase in area of the leaf apparatus of the plant and, in turn, the intensity of photosynthesis and productivity (Table 1).

The increase in the leaf apparatus of the sorghum grain plant was observed from the emergence to the panicle initiation flowering stage; there the highest indicators of the leaf surface area were received. For instance, without the application of fertilisers, the leaf surface area was 34,620 m^{-2} ha^{-1} for 'Dniprovskyi 39'. When fertilisers were applied at the rate $N_{30}P_{30}K_{30}$, it increased by 2,260 m^{-2} ha^{-1}; at the highest rate $N_{120}P_{120}K_{120}$,

Table 1. Effect of fertilisation on the change in the leaf surface area of sorghum grain, thousand m^2 ha^{-1} (average of 2016–2020)

Cultivar	Treatment	Area of leaf surface at a stage:			
		tillering	shooting	panicle initiation	full maturation
Dniprovskyi 39	without fertilisers (control)	6.92	21.50	34.62	5.14
	$N_{30}P_{30}K_{30}$	7.40	24.64	36.88	6.74
	$N_{60}P_{60}K_{60}$	7.96	27.18	38.45	7.21
	$N_{90}P_{90}K_{90}$	8.24	29.96	39.67	7.89
	$N_{120}P_{120}K_{120}$	8.43	30.80	40.24	8.17
	estimated fertiliser rate	8.29	28.92	38.74	7.76
Vinets	without fertilisers (control)	6.74	20.61	31.37	4.88
	$N_{30}P_{30}K_{30}$	6.92	23.86	35.40	5.34
	$N_{60}P_{60}K_{60}$	7.22	26.78	36.72	6.73
	$N_{90}P_{90}K_{90}$	7.53	28.46	37.96	7.12
	$N_{120}P_{120}K_{120}$	7.96	30.24	38.69	7.98
	estimated fertiliser rate	7.76	27.89	37.54	7.64

For the tillering stage: LSD_{05} (factor A – cultivar) 0.12, LSD_{05} (factor B – fertilisation) 0.13, LSD_{05} (A × B) 0.18; for the shooting stage: LSD_{05} (factor A) 0.58, LSD_{05} (factor B) 0.59, LSD_{05} (A × B) 0.83; for the panicle initiation stage: LSD_{05} (factor A) 0.11, LSD_{05} (factor B) 0.12, LSD_{05} (A × B) 0.16; for the full maturation stage: LSD_{05} (factor A) 0.09, LSD_{05} (factor B) 0.10, LSD_{05} (A × B) 0.12

the leaf surface area increased by 5,620 m^{-2} ha^{-1}, or by 16.2%. The estimated rate of fertilisers ensured the increase of the leaf surface area by 4,120 m^{-2} ha^{-1}, or by 11.9%.

When fertilisers were applied, the leaf surface area for ‘Vinets’ was smaller, which was due to varietal features, but the principles of its increase depending on fertiliser rates were similar. The formation of generative organs and the death of lower leaves resulted in the decrease in the leaf surface area by 14.0–15.0%, but the leaf apparatus responded positively to the increase in the mineral fertiliser rates till full grain maturity. In the stage of full maturation, the leaf surface area ranged from 5.140 to 8.170 m^{-2} ha^{-1} for ‘Dniprovskyi 39’ and from 4.880 to 7.980 m^{-2} ha^{-1} for ‘Vinets’.

Based on the results of analysis of variance, it was found that weather conditions and fertilisation had the strongest influence on the formation of the leaf surface area, 26.8% and 24.4%, respectively; the influence of varietal characteristics was slightly lower (9.8%). The interaction of factors totalled 38.2%; other unexplored factors accounted for 0.8% (Figure 3).

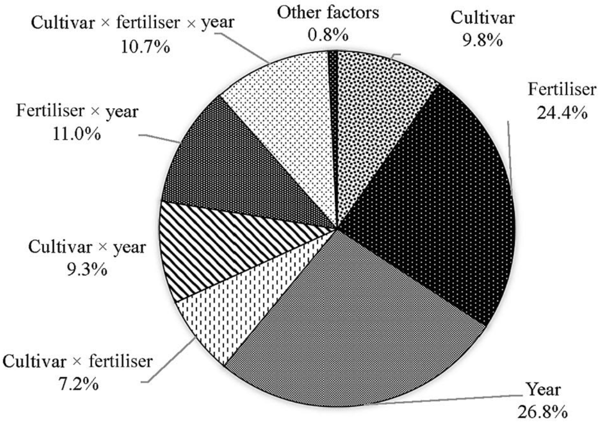


Figure 3. Influence of the studied factors on the formation of the leaf surface area of sorghum grain (average of 2016–2020)

The application of fertilisers improved the grain quality of sorghum grain considerably: the grain protein content increased from 9.7% to 12.4% for ‘Dniprovskyi 39’ and from 9.1% to 12.2% for ‘Vinets’ (Table 2).

The increase in mineral fertiliser rates led to a considerable increase in the fat content for ‘Dniprovskyi 39’ and ‘Vinets’: at a lower rate $N_{30}P_{30}K_{30}$, the fat content was 3.37% and 3.34%, respectively; at the highest rate, the indicators were 3.62% and 3.52%, respectively. At the estimated fertiliser rate, the fat content was the same as at the highest rate. A similar correlation concerning the ash content was recorded for both cultivars when fertiliser rates increased.

Sorghum has a great energy value due to high starch content in its grain. It was found out that fertilisers had a positive effect on the starch accumulation in sorghum grain. Thus, at a higher fertiliser rate from $N_{30}P_{30}K_{30}$ to $N_{120}P_{120}K_{120}$, the starch content increased in ‘Dniprovskyi 39’ from 67.1% to 70.1% and in ‘Vinets’ from 65.8% to 68.8%. Its lowest content was recorded in the treatment without the application of fertilisers.

When fertilisers were applied, the yield capacity of grain and above-ground mass increased both, compared with the treatment without fertilisers (control) and depending on the rates. In ‘Dniprovskyi 39’, at rates $N_{90}P_{90}K_{90}$, $N_{120}P_{120}K_{120}$ and the estimated fertiliser rate $N_{50}P_{40}K_{70}$, the grain yield capacity reliably increased, compared with the treatment without fertilisers, and it amounted to 7.1, 7.9, and 7.3 t ha^{-1}, respectively. The same correlation of the grain yield capacity increase was received for ‘Vinets’. The biomass yield capacity of ‘Dniprovskyi 39’ and ‘Vinets’ increased reliably only at the highest and estimated fertiliser rates.

The correlation and regression analysis of data showed a strong linear correlation between grain yield and the starch content index with the determination coefficient of 0.9297 for ‘Dniprovskyi 39’ and 0.9268 for ‘Vinets’ (Figure 4).

In recent years, sorghum grain has been considered a raw material for the production of biofuel. It has been found out that the output of bio-ethanol depends on both varietal features and fertiliser application rates. The largest output of bio-ethanol was received when fertilisers were applied at the rate $N_{120}P_{120}K_{120}$ and the estimated rate: for ‘Dniprovskyi 39’, 1.98 and 1.82 t ha^{-1}; these indicators were much smaller for ‘Vinets’: 1.88 and 1.70 t ha^{-1}, respectively. For both cultivars, the smallest output of bio-ethanol was recorded in the treatment without fertilisers (control) and at the rate $N_{30}P_{30}K_{30}$. Dry mass of sorghum grain is a valuable raw material for the production of solid biofuel, fuel granules, and briquettes. For instance, it is possible to obtain from 7.81 to 8.48 t ha^{-1} of solid fuel per one hectare of ‘Dniprovskyi 39’ sorghum grain at the increased fertiliser rate from $N_{30}P_{30}K_{30}$ to $N_{120}P_{120}K_{120}$; as to ‘Vinets’, the maximal output of solid

Table 2. Quality and yield capacity of grain and biomass of sorghum at different fertilisation (average of 2016–2020)

Cultivar	Treatment	Grain quality %				Yield capacity t ha^{-1}	
		protein	fat	ash	starch	grain	biomass
Dniprovskyi 39	without fertilisers (control)	9.7	3.12	1.68	65.4	5.2	31.2
	$N_{30}P_{30}K_{30}$	10.1	3.37	1.79	67.1	5.6	33.8
	$N_{60}P_{60}K_{60}$	11.2	3.41	1.82	68.2	6.4	34.5
	$N_{90}P_{90}K_{90}$	11.8	3.57	1.86	68.6	7.1	36.1
	$N_{120}P_{120}K_{120}$	12.4	3.62	1.91	70.1	7.9	36.7
	estimated fertiliser rate	12.1	3.56	1.84	69.8	7.3	36.0
Vinets	without fertilisers (control)	9.1	3.10	1.71	63.7	4.3	29.4
	$N_{30}P_{30}K_{30}$	9.6	3.34	1.78	65.8	5.2	31.5
	$N_{60}P_{60}K_{60}$	10.8	3.38	1.83	66.7	6.5	32.9
	$N_{90}P_{90}K_{90}$	11.8	3.45	1.87	67.4	7.2	33.7
	$N_{120}P_{120}K_{120}$	12.2	3.51	1.90	68.6	7.8	34.9
	estimated fertiliser rate	11.9	3.52	1.89	68.3	7.0	33.8

For protein: LSD_{05} (factor A – cultivar) 0.47, LSD_{05} (factor B – fertilisation) 0.48, LSD_{05} (A × B) 0.66; for fat: LSD_{05} (factor A) 0.04, LSD_{05} (factor B) 0.05, LSD_{05} (A × B) 0.16; for ash: LSD_{05} (factor A) 0.06, LSD_{05} (factor B) 0.07, LSD_{05} (A × B) 0.09; for starch: LSD_{05} (factor A) 2.59, LSD_{05} (factor B) 2.60, LSD_{05} (A × B) 3.67; for grain yield: LSD_{05} (factor A) 0.63, LSD_{05} (factor B) 0.64, LSD_{05} (A × B) 1.40; for biomass yield: LSD_{05} (factor A) 2.47, LSD_{05} (factor B) 2.49, LSD_{05} (A × B) 3.51

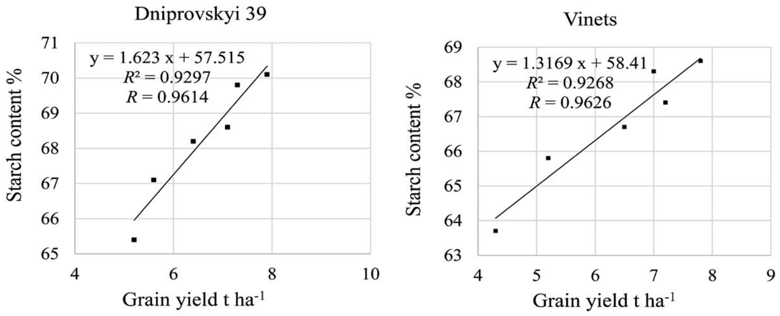
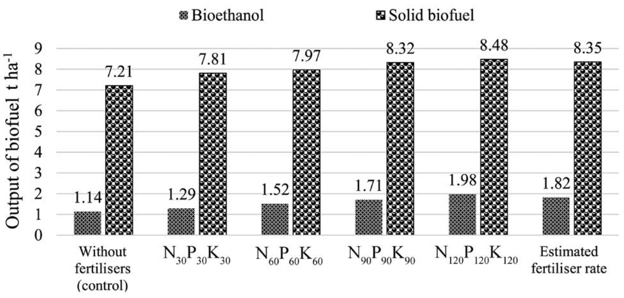
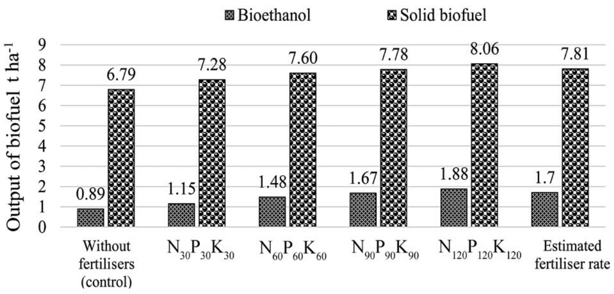


Figure 4. Correlation and regression relationship between sorghum grain yield and the starch content (average of 2016–2020)



For bio-ethanol: LSD_{05} (factor A – cultivar) 0.09, LSD_{05} (factor B – fertilisation) 0.10, LSD_{05} (A × B) 0.14; for solid biofuel: LSD_{05} (factor A) 0.21, LSD_{05} (factor B) 0.22, LSD_{05} (A × B) 0.31

Figure 5. Biofuel output from sorghum cultivar 'Dniprovskyi 39' grains depending on fertilisation (average of 2016–2020)



For bio-ethanol: LSD_{05} (factor A – cultivar) 0.09, LSD_{05} (factor B – fertilisation) 0.10, LSD_{05} (A × B) 0.14; for solid biofuel: LSD_{05} (factor A) 0.21, LSD_{05} (factor B) 0.22, LSD_{05} (A × B) 0.31

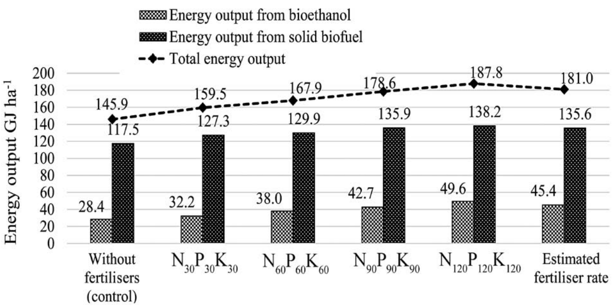
Figure 6. Biofuel output from sorghum cultivar 'Vinets' grains depending on fertilisation (average of 2016–2020)

biofuel was from 7.28 to 8.06 t ha^{-1} (Figures 5 and 6).

The energy output was calculated from bio-ethanol and solid biofuel received from 1 ha of sorghum grain fields (Figures 7 and 8).

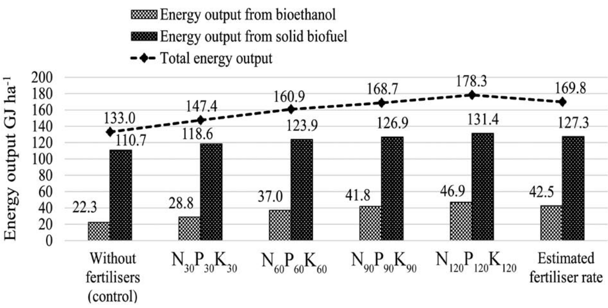
When 'Dniprovskyi 39' was grown, the largest total energy output amounted to 181.0 and 187.8 GJ ha^{-1}, and it was recorded at the estimated fertiliser rate and the rate $N_{120}P_{120}K_{120}$. Over 80% of this energy was concentrated in solid biofuel, and only 20% of it was in bio-ethanol. The total energy output resulted from burning bio-ethanol and solid biofuel, which were obtained from one hectare of sorghum grain fields: the total energy output of 'Vinets' was much lower compared with that of 'Dniprovskyi 39'. When fertilisers were applied at the estimated rate and the rate $N_{120}P_{120}K_{120}$, the total energy output per area unit for 'Vinets' was 169.8 and 178.3 GJ ha^{-1}, or lower by 11.2 and 9.5 GJ ha^{-1}. The lower was the fertiliser rate, the lower was the energy output of 1 ha.

The results of our experiment showed a considerable increase in the energy output from bio-ethanol depending on the increase in grain productivity. This fact was confirmed by the correlation analysis, which proved significant dependence between grain yield and energy output from bio-ethanol: the correlation coefficient was $R = 0.9985$ for 'Dniprovskyi 39' and $R = 0.9966$ for 'Vinets' (Figure 9). It was also determined that the energy yield from solid biofuels was closely related to the yield of sorghum biomass. The correlation coefficient was $R = 0.999$, and the coefficient of determination $R^2 = 1$ (Figure 10).



For bio-ethanol: LSD_{05} (factor A – cultivar) 2.82, LSD_{05} (factor B – fertilisation) 2.83, LSD_{05} (A × B) 3.99; for solid biofuel: LSD_{05} (factor A) 3.71, LSD_{05} (factor B) 3.72, LSD_{05} (A × B) 5.25; for total energy output: LSD_{05} (factor A) 3.08, LSD_{05} (factor B) 3.10, LSD_{05} (A × B) 4.36

Figure 7. Energy output from sorghum cultivar 'Dniprovskyi 39' grains depending on fertilisation (average of 2016–2020)



For bio-ethanol: LSD_{05} (factor A – cultivar) 2.82, LSD_{05} (factor B – fertilisation) 2.83, LSD_{05} (A × B) 3.99; for solid biofuel: LSD_{05} (factor A) 3.71, LSD_{05} (factor B) 3.72, LSD_{05} (A × B) 5.25; for total energy output: LSD_{05} (factor A) 3.08, LSD_{05} (factor B) 3.10, LSD_{05} (A × B) 4.36

Figure 8. Energy output from sorghum cultivar 'Vinets' grains depending on fertilisation (average of 2016–2020)

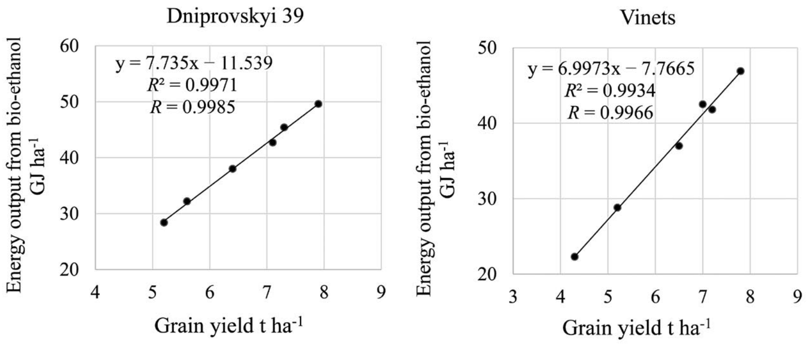


Figure 9. Relationship between grain yield and energy output from bio-ethanol

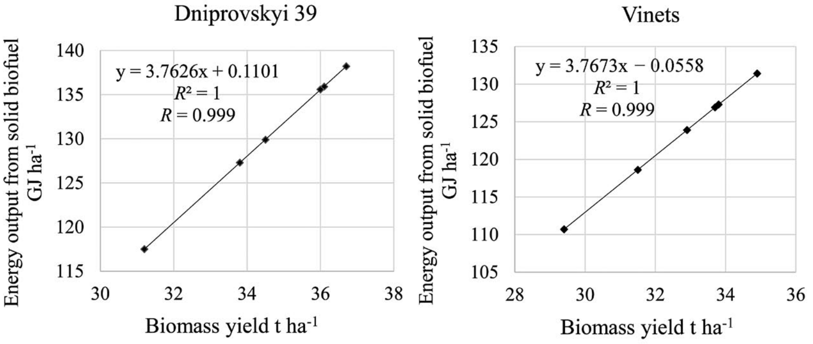


Figure 10. Relationship between sorghum biomass yield and energy output from solid biofuel

Discussion

Since climate change requires a revision of crop rotations in favour of drought-resistant crops, sorghum is one of the most promising crops for growing for grain, green fodder, and especially for the production of an alternative fuel such as biofuel. The relevance of in-depth research into this crop, the assessment of the state and potential of sorghum grain plants in Ukraine, the most important components of their rational and versatile use are obvious and appropriate. Among numerous crops suitable for ethanol production, sorghum is considered one of the most promising. It has high photosynthetic efficiency, and it can form a powerful biomass rich in energy in a short growing season. In addition, sorghum contains most of its energy in substances that are easily converted to ethanol. In sorghum grain, such a substance is starch in the grain. Sorghum grain has a much higher starch yield (70–74%) than, for example, the starch yield of maize (67–72%). That is why this culture is the future of bio-ethanol production. In the USA, sorghum is a major crop in the production of bio-ethanol: it provides an alcohol yield that is 25–30% higher than maize and wheat (Gamayunova et al., 2021).

The use of fertilisers enhanced the growth and development of the leaf surface area of sorghum plants. When applying fertilisers, the leaf surface area in the panicle ejection stage was 0.23–0.27 m^{-2} plant, which is 0.01–0.05 m^{-2} plant higher than the control; during the stage of full maturation, the leaf surface area was 0.15–0.17 m^{-2} plant, which is 0.01–0.03 m^{-2} plant higher than the control. The maximum leaf surface area was observed at the ejection stage with the application of mineral fertilisers $N_{120}P_{120}K_{120}$ or their combination with 4 t ha^{-1} of straw: the leaf surface area was 0.26 and 0.27 m^{-2} per plant, respectively. In the conditions of sufficient moisture on leached light loam chernozem, the application of fertilisers for sorghum grain increased grain yield by 12–39%, compared to the treatment without fertilisers. The highest food productivity of sorghum grain was achieved with an alternative organo-mineral fertilisation system (straw 4 t ha^{-1} + $N_{120}P_{120}K_{120}$): grain yield was 8.5 t ha^{-1} higher than the dose of fertiliser $N_{120}P_{120}K_{120}$ – 0.6 t ha^{-1}, and without fertilisers – 2.4 t ha^{-1} (Ivanina et al., 2019). According to the authors, the optimal fertiliser for sorghum cultivation was the application of $N_{60}P_{60}K_{60}$. Based on this technology, productivity of culture was 8.0–8.49 t ha^{-1} (Ovsiienko, 2015; Hryshchenko et al., 2021).

To implement the bioenergy development programme in Ukraine, all the necessary prerequisites are available. Firstly, the soil-climatic conditions that contribute to the high yield of energy-intensive phytomass of energy crops. Secondly, the use of adaptive cultivating technologies on marginal lands of bioenergy crops, improvement of existing, appropriate processing of phytosterol and biofuel use in fuel and energy complex will provide an increase in the share of bioenergy in the overall energy structure of Ukraine and significantly reduce energy dependence of our country. As a result, the use of non-renewable energy sources will be reduced against the backdrop of growing demand for alternative energy sources, which in the long run will contribute to the development of the national economy and the growth of the welfare of the population (Kurilo et al., 2018).

Conclusions

1. The obtained experimental data are statistically reliable, relevant, and probable for growing other cultivars in different conditions. High productivity and the largest total energy output from liquid and solid biofuel received per one hectare of sorghum grain cultivars ‘Dniprovskyi 39’ and ‘Vinets’ were recorded at the estimated ($N_{50}P_{40}K_{70}$) and maximal ($N_{120}P_{120}K_{120}$) fertiliser rates.

2. There is a tendency, that with increasing fertiliser rates, grain yield and biomass of sorghum cultivars increase; accordingly, the output of biofuels and energy from it increases.

3. The application of the maximal and estimated fertiliser rates led to almost identical indicators of the productivity of both cultivars and the output of biofuel; therefore, it is appropriate to apply the estimated fertiliser rate for the planned yield capacity, which will reduce the production cost of the output.

4. The results of the experiment showed great increase in sorghum grain productivity depending on the conditions of the year and the application of mineral fertilisers. There is also a close correlation between sorghum yield and the energy output, which is relevant for the cultivation of sorghum grain as an energy crop in different soil and climatic conditions.

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Sorgų grūdų derlingumas ir energinė vertė, priklausomai nuo tręšimo mineralinėmis trąšomis

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Santrauka

Straipsnyje pateikti dvispalvio sorgo (*Sorghum bicolor* (L.) Moench) grūdų produktyvumo panaudojimo mitybai, pašarui ir kaip bioenergetinio augalo, priklausomai nuo tręšimo mineralinėmis trąšomis, tyrimo rezultatai. Eksperimento tikslas – išanalizuoti trąšų normų įtaką sorgų grūdų produktyvumui, biokuro išeigai ir iš jų gaunamai energijai. Siekiant ištirti biologines ir ekologines augalų augimo bei vystymosi savybes, produktyvumą ir kokybę, vykdytas lauko eksperimentas; siekiant nustatyti augalų bei aplinkos ryšį, atliktos augalų ir dirvožemio laboratorinės analizės. Tręšimas labai pagerino sorgų grūdų kokybę: baltymų ir riebalų kiekis padidėjo atitinkamai 9,7–12,4 ir 3,37–3,62 %. Tręšiant didesnėmis normomis trąšų, krakmolo kiekis veislės ‘Dniprovskyi 39’ grūduose padidėjo 67,1–70,1 %, veislės ‘Vinets’ – 65,8–68,8 %, palyginus su kontroliniu (be trąšų) variantu. Skirtingos trąšų normos nevienodai didino grūdų derlingumą ir augalų antžeminę masę. Lyginant su kontroliniu variantu, patręšus $N_{90}P_{90}K_{90}$, $N_{120}P_{120}K_{120}$ ir apskaičiuota $N_{50}P_{40}K_{70}$ norma trąšų, veislės ‘Dniprovskyi 39’ grūdų derlingumas esmingai padidėjo ir siekė 7,1, 7,9 bei 7,3 t ha^{-1}, o veislės ‘Vinets’ grūdų derlingumas buvo atitinkamai 7,2, 7,8 ir 7,0 t ha^{-1}. Veislių ‘Dniprovskyi 39’ ir ‘Vinets’ sorgų biomasės derlingumas esmingai padidėjo tik tręšiant didžiausiomis ir apskaičiuotomis normomis trąšų. Auginant veislės ‘Dniprovskyi 39’ sorgus, didžiausias bendrosios energijos išeigos rodiklis buvo 181,0 ir 187,8 GJ ha^{-1}; veislės ‘Vinets’ sorgų šis rodiklis buvo 169,8 ir 178,3 GJ ha^{-1}; tai sąlygojo apskaičiuotos ir maksimalios trąšų normos. Daugiau kaip 80 % šios energijos sutelkta kietajame biokure ir tik 20 % – bioetanolyje. Tręšiant mažesnėmis normomis trąšų, iš 1 ha buvo gauta mažiau energijos.

Reikšminiai žodžiai: normos, grūdų kokybė, produktyvumas, biokuras, energija, *Sorghum bicolor*.