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Impact of mineral fertilisers on the productivity of sorghum (*Sorghum bicolor* L.) cultivated as a feedstock for biofuel production in the context of climate change

Liudmyla Pravdyva[1*], Serhii Vakhnii[1], Olena Mostypan[1], Kostiantyn Pavlichenko[1], Taras Panchenko[1], Yurii Fedoruk[1], Mykhailo Ostrenko[1], Ihor Pokotylo[1], Mykola Stepanenko[1], Natalia Shushkivska[1]

[1] Department of Crop Production and Digital Technologies in Agronomy, Faculty of Agrobiotechnology, Bila Tserkva National Agrarian University, 8/1 Soborna Square, 09117, Bila Tserkva, Ukraine

* Correspondent author's e-mail: bioplant@ukr.net

ABSTRACT

The search for non-traditional biofuels, such as next-generation bioenergy crops, is one of the challenges in the world today. In the context of climate change, the cultivation of sorghum (*Sorghum bicolor* L.) as a feedstock for biofuel production is promising and relevant. The study was conducted in the Western Forest Steppe of Ukraine at the Yaltushkiv Experimental Breeding Station of the Institute of Bioenergy Crops and Sugar Beet NAAS in 2020–2024 using the 'Dniprovskyi 39' and 'Samaran 6' sorghum varieties and two application rates of fertilisers ($N_{60}P_{60}K_{60}$ and $N_{120}P_{120}K_{120}$). In both varieties, the highest yield of grain (3.30 t ha^{-1} and 3.45 t ha^{-1}, respectively), biomass (44.6 t ha^{-1} and 45.6 t ha^{-1}, respectively), bioethanol (1.09 t ha^{-1} and 1.14 t ha^{-1}, respectively), solid biofuel (12.22 t ha^{-1} and 12.59 t ha^{-1}, respectively) and estimated energy content (226.32 GJ ha^{-1} and 233.6 GJ ha^{-1}, respectively) were obtained at the application of $N_{120}P_{120}K_{120}$ fertiliser rate. A dispersion analysis of data on significant factors affecting net photosynthetic productivity and yield was conducted. A correlation between yield and energy indicators has been established.

Keywords: sorghum, fertiliser rate, biometric indicators, yield, bioethanol, solid biofuel, energy, correlation.

INTRODUCTION

Cereal crops, being the most consumed food on the planet, face significant challenges, caused by climate change. The detrimental impacts of climate change have threatened food security globally by hampering the production and quality of major cereal crops like rice, wheat, and maize (Ahmad et al., 2024).

Researchers agree that global climate change can have an impact on the crop yields and therefore must be addressed for attaining food security. Studies have shown that the earth surface temperature will increase at a pace of about 0.2 °C per decade over the next 30 years. Furthermore, estimates show that global temperatures will increase by 2.5 to 4.5 °C by the end of the 21st century as a result of the rising concentrations of greenhouse gases in the atmosphere (Wang et al., 2018; Rezaei et al., 2023). Such extreme climatic conditions negatively affect the main stages of plant growth and development, such as flowering and grain formation, which leads to a significant decrease in yield (Al-Faraoun *et al.* 2025).

Sorghum (*Sorghum bicolor* L.) occupies the 5th place after wheat, barley, rice, and corn. It is an insurance crop due to drought resistance, salt tolerance, and the formation of high productivity under unfavourable soil and climatic conditions (DeFries *et al.,* 2023; Khalifa *et al.,* 2023; Getahun *et al.,* 2025). It is also used in many industries: food, feed, technical, and in the energy industry as feedstock for the production of bioethanol and solid biofuels (pellets and briquettes) (Mlewa *et* *al.,* 2026; Andronoiu *et al.,* 2025; Bakari *et al.,* 2023). Therefore, the development of elements of cultivation technology, the study of the influence of fertiliser rates on the productivity formation, and intensity of plant growth and development are relevant today.

According to researchers (Ismaeil *et al.,* 2024), today many farmers use chemical fertilisers to grow sorghum, i.e., NPK complex fertiliser, urea and ammonium nitrate. These fertilisers contribute to the intensity of growth and development of sorghum plants, especially in fields with irrigation, where a greater effect is observed. Nitrogen fertilisers such as urea, ammonium nitrate, and ammonium sulphate can increase sorghum panicle weight, biomass, and grain yield. NPK complex fertiliser can not only increase crop yield but also improve the content of nutrients such as protein, fat, and starch.

Nitrogen fertilisers play an important role in the cultivation of sorghum, both for its good growth and for improving its quality. If nitrogen fertilisers are sufficient, sorghum plants will be taller, with larger leaves and thicker stems. Also, there will be more chlorophyll in the leaves, stronger photosynthesis and more vigorous growth of the entire plant (Bartzialis *et al.,* 2023; Wang *et al.,* 2024). It has been studied that insufficient supply of sorghum plants with water and nitrogen limits its growth, reduces yield (Obour *et al.,* 2022), and decreases the quality of grain (Modisapudi *et al.,* 2022).

Phosphorus is an important nutrient after nitrogen, as it represents about 0.2% of the dry weight of the plant and plays a significant role in plant growth, supporting metabolic and physiological processes (Alori *et al.,* 2017). Phosphorus is necessary in the early stages of crop growth, but its availability in the soil is limited; the amount of total phosphorus in the soil ranges from 100 to 2000 mg kg^{-1} of soil, which is approximately 350 to 7000 kg ha^{-1} at a depth of 25 cm (Khan *et al.,* 2023). Phosphorus is a very valuable element for sorghum, especially during the stages of intensive growth, flowering and seed formation. If phosphorus fertilisers are sufficient, sorghum can grow more vigorously, accumulate more nutrients and accumulate higher yields (Guo *et al.,* 2025). Some long-term field experiments have shown that phosphorus fertilisers can not only increase grain yields but also help the absorption of nitrogen fertilisers, saving fertilisers and money. In addition, phosphorus is mostly concentrated in grains, so it has a great impact on the final yield and quality (Schlegel *et al.,* 2021).

Potassium is also crucial for sorghum, especially for disease resistance, drought tolerance, and grain filling. Potassium is mainly stored in sorghum stems, which can increase the plant's resistance and help maintain water balance (Schlegel *et al.,* 2021). If potassium is applied correctly, it can make sorghum photosynthesis more efficient and improve its nutritional value. The effects of potassium are especially evident in difficult conditions, such as drought or saline alkaline soils. With more potassium, the grains are fuller, and yields and quality are naturally better (Schlegel *et al.,* 2021; Gulzhaina *et al.,* 2025).

Therefore, fertilisation can help increase and adjust the yield of sorghum to certain biofuel processing pathways. Based on this, the aim of the study was to study the effect of mineral fertilisers on the growth, development and productivity of sorghum and the yield of biofuels and energy content of biofuels in the Western Forest Steppe of Ukraine.

MATERIALS AND METHODS

The research was carried out in the zone of unstable moisture at the Yaltushkiv Experimental Breeding Station (48°59' N, 27°27' W) of the Institute of Bioenergy Crops and Sugar Beet of the National Academy of Agrarian Sciences of Ukraine in 2020–2024. The experiments were established on grey podzolic, slightly leached, coarse medium-loamy soils. The humus content of the soil was 1.87%. The content of alkaline hydrolysed nitrogen was 63 mg kg^{-1}, mobile phosphorus was 109 mg kg^{-1}, and exchangeable potassium was 119 mg kg^{-1}. Hydrolytic acidity was 2.9 mg.-eq. per 100 g of soil, soil pH was 5.3, and the amount of absorbent bases was 22.4 mg-eq. per 100 g of soil. Soil density was 1.25 g cm^{-3}, the content of productive moisture in the 1-metre soil layer was 110 mm. It was a two-factor experiment: sorghum variety (factor A) and fertiliser rate (factor B) (Table 1).

The area of a single plot was 50 m^2, and the harvest area was 25 m^2. Sorghum seeds were sown to a depth of 4–6 cm with a row spacing of 45 cm and a seeding rate of 200,000 plants per hectare. Observation and accounting of sorghum plants, as well as calculations of biofuel yield (bioethanol and solid), as well as estimated energy content, were carried out according to

Table 1. Experimental design

Factor A: Variety	Factor B: Fertiliser rate
'Dniprovskyi 39' 'Samaran 6'	No fertiliser (control)
	$N_{60}P_{60}K_{60}$
	$N_{120}P_{120}K_{120}$

the methodology developed by the Institute of Bioenergy Crops and Sugar Beet. The bioethanol yield was calculated taking into account the yield of sorghum grain, which at the time of harvest contains about 86% dry matter and starch. Solid biofuel yield was calculated taking into account biomass yield, biomass dry matter content, and solid biofuel moisture content (10%) (Roik et al., 2020; Pravdyva et al., 2021).

The climatic conditions of the growing season had some deviations from long-term data; drought was observed, but the conditions were typical for the research area and favourable for the growth and development of sorghum.

Statistical analysis

To determine the statistical significance of the effect of experimental treatment ($< p = 0.05$), after the first analysis of variance (ANOVA), all data were analysed with the use of the software SAS (SAS Institute Inc., USA). Significant differences between individual means were determined using the least significant difference (LSD) test.

RESULTS AND DISCUSSION

Fertilisation affected both growth and development indicators, as well as the quality and productivity of sorghum. Regarding the duration of the growing season and biometric indicators, it was found that the vegetation period in the control averaged 112–118 days and increased by 3–4 days with the application of $N_{60}P_{60}K_{60}$ and $N_{120}P_{120}K_{120}$ fertiliser rates (Table 2). Fertilisation significantly increased the height of plants in the 'Dniprovskyi 39' (from 116.5 cm to 119.6 cm) and 'Samaran 6' (from 114.8 cm to 117.9 cm) varieties. The average diameter of the stem in the experiment was 1.4–1.6 cm, and the number of tillers per plant was 1.2–1.4.

High net photosynthetic productivity (NPP) is observed with optimal growth of the assimilation surface as a result of providing sorghum plants with a significant amount of nutrients. Importantly, the assimilation area and the photosynthetic potential (PP) have a close relationship: the more plant leaves are in a functional state, the faster the productive processes in plants are. The leaf area index (LAI) increased with $N_{60}P_{60}K_{60}$ and $N_{120}P_{120}K_{120}$ fertilisation by 8.5 (18.1%) compared to control in 'Dniprovskyi 39' and by 7.1 (13.3%) in 'Samaran 6'. The highest PP was observed in treatments with high rates of fertilisers (Table 3). $N_{60}P_{60}K_{60}$ and $N_{120}P_{120}K_{120}$ fertilisation rates provided an increase in PP in varieties by 28.7–42.5% and by 29.8–43.3%, respectively. In the plots where mineral fertilisers were not applied, PP in 'Dniprovskyi 39' was 1.01, 1.08, and 1.07 million m^2 $ha^{-1} \times$ day ha^{-1} and in 'Samaran 6', 0.97, 1.02, and 1.03 million m^2 $ha^{-1} \times$ day ha^{-1}.

The NPP is the main indicator that reveals not only the period of dry matter formation per unit of assimilation area, but also its loss as a result of the process of respiration, death and partial loss of leaves during the growing season. The results of the experiment showed that the NPP increases along with an increase in fertiliser rates in all treatments of the experiment. It was the highest for the fertilisation rate $N_{120}P_{120}K_{120}$ and reached a minimum in the control.

Table 2. Duration of the growing season and biometric indicators of sorghum plants at different fertiliser rates (average for 2020–2024)

Variety	Fertiliser rate	Growing season, days	Plant height, cm	Stem diameter, cm	Number of tillers per plant
'Dniprovskyi 39'	Control	115	116.5	1.4	1.3
	$N_{60}P_{60}K_{60}$	116	118.4	1.5	1.4
	$N_{120}P_{120}K_{120}$	118	119.6	1.5	1.3
'Samaran 6'	Control	112	114.8	1.5	1.2
	$N_{60}P_{60}K_{60}$	114	116.7	1.6	1.3
	$N_{120}P_{120}K_{120}$	116	117.9	1.4	1.2
$LSD_{0.05}$		2	1.8	0.2	0.2

Table 3. Photosynthesis productivity of sorghum at different fertiliser rates (average for 2020–2024)

Indicator	Variety						$LSD_{0.05}$
	'Dniprovskyi 39'			'Samaran 6'			
	Fertiliser rate						
	Control	$N_{60}P_{60}K_{60}$	$N_{120}P_{120}K_{120}$	Control	$N_{60}P_{60}K_{60}$	$N_{120}P_{120}K_{120}$	
LAI (flowering period), thousand m^2 ha^{-1}	24.8	26.9	29.3	24.1	25.8	27.3	1.29
PP, (million m^2 ha^{-1}) × day	1.01	1.30	1.44	0.97	1.26	1.39	0.15
NPP, g m^{-2} ×day	2.84	3.38	3.56	2.75	3.22	3.35	0.56

Among the significant factors influencing the formation of NPP were fertiliser rates (29%), weather conditions of the study years (19%), variety (17 %) and the interaction between fertiliser rate and weather conditions of the year (13%) (Figure 1).

Sorghum reacts positively to the application of mineral fertilisers due to its biological characteristics. With a sufficient supply of plants with nutrients during the growing season, sorghum is able to form a high yield of grain.

A significant increase in the yield of both grain and biomass was noted for the application of fertilisers (Table 4). Thus, the increase in application rates from $N_{60}P_{60}K_{60}$ to $N_{120}P_{120}K_{120}$ provided an increase in grain yield in the 'Dniprovskyi 39' variety from 2.85 t ha^{-1} to 3.45 t ha^{-1}. In the 'Samaran 6' variety, the increase was from 2.74 t ha^{-1} to 3.30 t ha^{-1}, respectively.

In the control treatments, without fertilisers, the grain yield in 'Dniprovskyi 39' was 2.58 t ha^{-1}, 4.80 t ha^{-1}, and 5.42 t ha^{-1} and in 'Samaran 6', 2.51 t ha^{-1}, 4.32 t ha^{-1}, and 4.10 t ha^{-1}. The increase in the application rates from $N_{60}P_{60}K_{60}$ to $N_{120}P_{120}K_{120}$ ensured an increase in the dry matter content of grain in 'Dniprovskyi 39' by 0.8%, 0.6%, and 1.1%, depending on soil and weather conditions, and by 1.0%, 0.9%, and 0.6% in 'Samaran 6'. Dry matter content of biomass insignificantly increases with an increase in the rates of mineral fertilisers.

The application rate of fertilisers had a 32% share of influence on the crop yield. Other factors of the experiment include the influence of varietal characteristics (19%) and the weather conditions of the year (14%). At the same time, the interaction between the varietal characteristics and fertiliser rates amounted to 12% of the yield (Figure 2).

Parameters of the yield structure were the lowest in the control and increased with an increase in fertiliser rates (Table 5). Thus, in the conditions of unstable moisture of the Western Forest Steppe of Ukraine, on grey podzolic, slightly leached coarse medium-loamy soils,

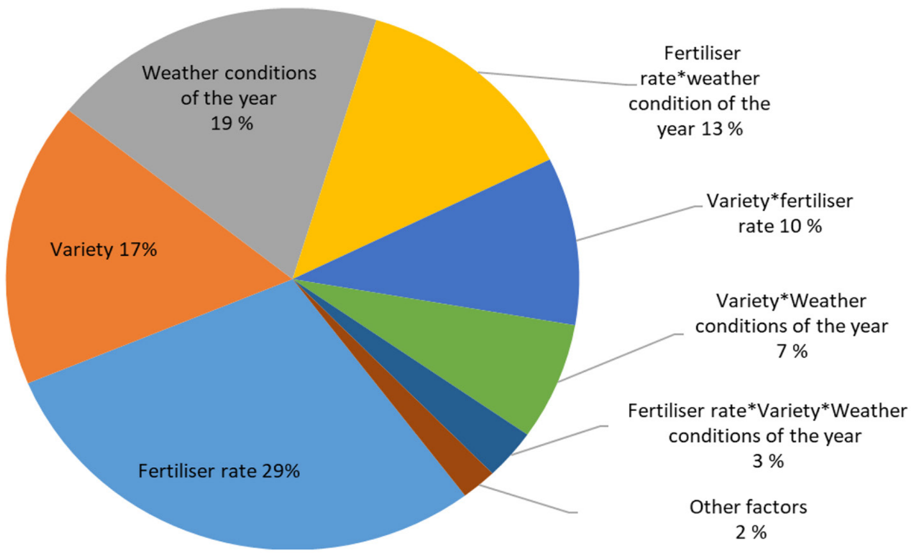


Figure 1. Share of the influence of the studied factors on the NPP (average for 2020–2024)

Table 4. Yield and dry matter content of sorghum at different fertiliser rates (average for 2020–2024)

Variety	Treatment	Yield, t ha^{-1}		Dry matter content, %	
		Grain	Biomass	Grain	Biomass
'Dniprovskyi 39'	Control	2.58	30.4	84.2	22.8
	$N_{60}P_{60}K_{60}$	3.20	40.8	85.0	24.4
	$N_{120}P_{120}K_{120}$	3.45	45.6	85.4	25.1
'Samaran 6'	Control	2.51	28.4	84.3	21.3
	$N_{60}P_{60}K_{60}$	2.99	38.9	85.6	24.6
	$N_{120}P_{120}K_{120}$	3.30	44.6	85.0	24.9
$LSD_{0.05}$		0.48	2.7	0.6	0.4

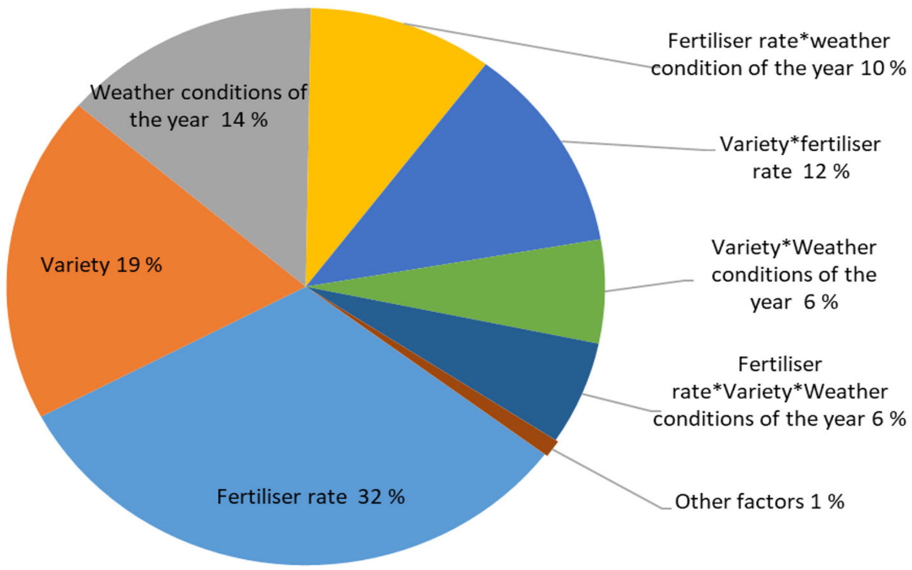


Figure 2. Share of the influence of the studied factors on sorghum yield (2020–2024)

$N_{60}P_{60}K_{60}$ fertiliser rates improved the elements of yield structure on average by 1.83–13.9% while $N_{120}P_{120}K_{120}$ improved them by 2.3–24.5% compared to the control.

The highest yields of bioethanol and solid biofuel were obtained for the application of $N_{60}P_{60}K_{60}$ and $N_{120}P_{120}K_{120}$: 1.05–1.14 t ha^{-1} and 10.95–12.59 t ha^{-1}, respectively, in 'Dniprovskyi 39' and 0.99–1.09 t ha^{-1} and 10.53–12.22 t ha^{-1}, respectively, in 'Samaran 6' (Table 6). The energy content of bioethanol was 26.37–28.43 GJ ha^{-1} in 'Dniprovskyi 39' and 24.64–27.20 GJ ha^{-1} in 'Samaran 6'. The energy content of solid biofuel was 178.50–205.22 GJ ha^{-1} in 'Dniprovskyi 39' and 171.58–199.12 t ha^{-1} in 'Samaran 6'. The total energy content was also the highest for the application of $N_{60}P_{60}K_{60}$ and $N_{120}P_{120}K_{120}$ fertiliser rates: 204.87 GJ ha^{-1} and 233.65 GJ ha^{-1}, respectively, in 'Dniprovskyi 39', 196.22 GJ ha^{-1} and 226.32 GJ ha^{-1}, respectively, in 'Samaran 6'.

Correlation-regression analysis of the data showed a strong dependence of bioethanol yield on grain yield (Figure 3a). The correlation coefficient was R = 0.9991, and the coefficient of determination was $R^2 = 0.9982$. The dependence of solid biofuel yield on biomass yield can be described by a second-order polynomial equation: $y = 0.0027x^2 + 0.539x - 6.3567$ (R = 0.9986; $R^2 = 0.9869$).

A strong correlation between biomass yield and solid biofuel yield was noted (Figure 3b). The coefficient of correlation was R = 0.9986, and the coefficient of determination was $R^2 = 0.9984$.

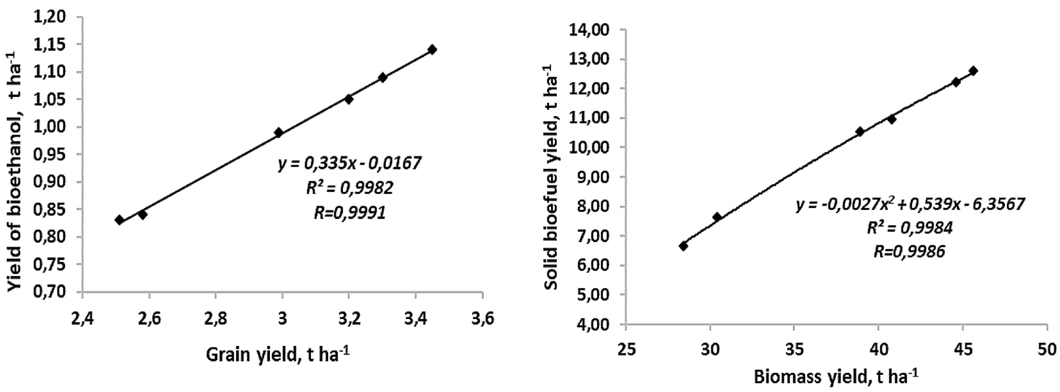
A strong linear correlation was also found between the energy content of bioethanol and grain yield (R = 0.9998; $R^2 = 0.9996$) (Figure 4a). The relationship between the energy content of solid biofuel and the biomass yield can also be described by a second-order polynomial $y = 0.044x^2 + 8.738x - 102.64$ (R = 0.9986; $R^2 = 0.9984$) (Figure 4b).

Table 5. Yield structure of sorghum at different fertiliser rates (average for 2020–2024)

Variety	Fertiliser rate	Panicle length, cm	Panicle weight, g	Number of grains per panicle	Grain weight per panicle, g	1000-kernel weight, g
‘Dniprovskyi 39’	Control	21.8	44.2	1209	33.7	22.1
	$N_{60}P_{60}K_{60}$	22.2	47.6	1316	38.4	24.9
	$N_{120}P_{120}K_{120}$	22.3	49.5	1410	42.1	25.8
‘Samaran 6’	Control	22.1	42.4	1159	34.3	21.9
	$N_{60}P_{60}K_{60}$	23.8	44.1	1218	35.3	23.5
	$N_{120}P_{120}K_{120}$	24.6	47.3	1304	37.9	24.6
$LSD_{0.05}$		1.3	2.0	11	0.9	0.7

Table 6. Estimated yield of biofuels and energy content of biofuels at different fertiliser rates (average for 2020–2024)

Variety	Fertiliser dose	Bioethanol yield t ha^{-1}	Solid fuel yield, t ha^{-1}	Energy content, GJ ha^{-1}		
				Bioethanol	Solid fuel	Total
‘Dniprovskyi 39’	Control	0.84	7.62	21.09	124.28	145.37
	$N_{60}P_{60}K_{60}$	1.05	10.95	26.37	178.50	204.87
	$N_{120}P_{120}K_{120}$	1.14	12.59	28.43	205.22	233.65
‘Samaran 6’	Control	0.83	6.65	20.69	108.46	129.15
	$N_{60}P_{60}K_{60}$	0.99	10.53	24.64	171.58	196.22
	$N_{120}P_{120}K_{120}$	1.09	12.22	27.20	199.12	226.32
$LSD_{0.05}$		0.12	1.33	2.35	7.59	8.22



a b

Figure 3. Correlation-regression relationship (a) between bioethanol yield and grain yield, and (b) between solid biofuel yield and biomass yield

The growth of the world’s population and the excessive consumption of energy at the national and international levels have led to serious global crises. Today, two major challenges facing by humanity are energy production and climate change (Gajdzik *et al.,* 2025). Bioenergy crops offer solutions to these challenges. Such crops are used to produce bioenergy and contribute to reducing global warming by replacing energy that causes global warming and greenhouse gas emissions. Moreover, these plants provide feedstock for biofuel production (Ali et al., 2025). The application of biomass for bioenergy production is consistent with European strategies aimed at reducing greenhouse gas emissions, thus promoting sustainable development and the development of renewable energy (Singh et al., 2024).

Thus, the results of research on the formation of sorghum productivity in the Western Forest Steppe of Ukraine allow us to recommend the best options for the application of fertilisers in agricultural production. Obtaining the planned yield

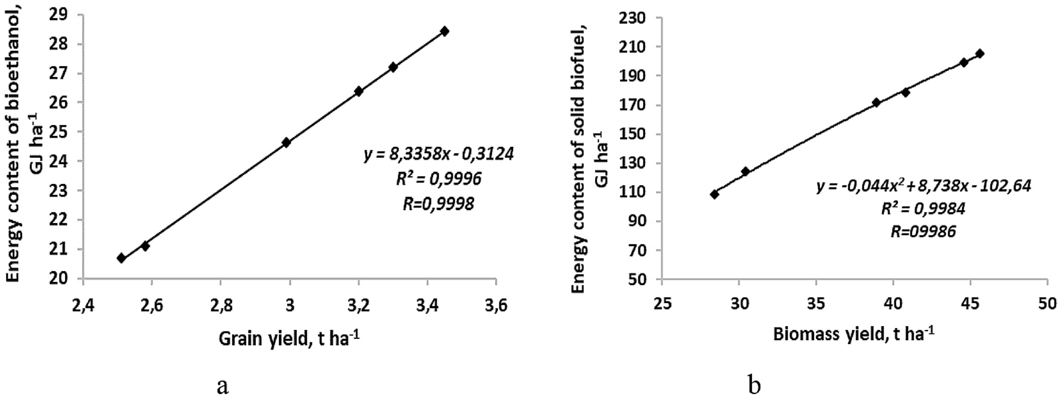


Figure 4. Correlation-regression relationship (a) between estimated energy content of bioethanol and grain yield, and (b) between estimated energy content of solid biofuel and biomass yield

and growth processes is relevant for the planning of crop cultivation for production of biofuels.

CONCLUSIONS

The studied elements of the cultivation technology had a positive effect on the growth processes of sorghum plants, the activity of photosynthesis, productivity, and, accordingly, the yield of biofuel and energy content. It was found that the highest crop yield is ensured by applying double rates of fertilisers ($N_{120}P_{120}K_{120}$). Slightly lower yields were obtained with the application of single rates of fertilisers ($N_{60}P_{60}K_{60}$). The lowest yield was obtained in the treatment without fertilisers (control). The use of fertilisers improves the development of physiological processes in plants and promotes intensive growth, which affects the elements of the yield structure and the quality of seeds.

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