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Effect of fertilisers on yield, water consumption and energy capacity of grain sorghum (*Sorghum bicolor* L.)

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Abstract: This study aimed to determine how fertiliser rates affect biological yield, water use, and energy capacity of grain sorghum. Field experiment was conducted at the Uladovo-Lyulynetsk Research and Selection Station (49° 35' N, 28° 24' E) in 2017–2021. Trial was arranged using a randomized experimental design in four replications with a seeding plot area of 62 m^2, a harvesting area of 50 m^2. The investigated factors were: control, without fertiliser, winter wheat straw at the rate of 4 t ha^{-1} as a background, mineral fertilisers at rates of $N_{60}P_{60}K_{60}$, $N_{90}P_{90}K_{90}$, $N_{120}P_{120}K_{120}$ and the estimated rate of $N_{105}P_{35}K_{60}$. Grain sorghum produced high yields of biomass on black soils against the background of natural fertility with a yield of grain 5.96 t ha^{-1}, stems 30.3 t ha^{-1}. Application straw and mineral fertilisers ensured efficient moisture consumptions by plants. Estimated fertilisers rate $N_{105}P_{35}K_{60}$ against the background of 4 t ha^{-1} of straw provided similar productivity of sorghum with the maximal rate of $N_{120}P_{120}K_{120}$ and can be recommended for fertilising as more cost-effective. This fertilisation increased grain yield by 35 %, bio-ethanol output by 41 %, solid biofuel by 17 %, total energy output by 23 %.

Key words: grain sorghum, fertiliser rates, productivity, biofuel

Učinek gnojil na pridelek, porabo vode in vsebnost energije pri navadnem sirku za zrnje (*Sorghum bicolor* L.)

Izvleček: Namen raziskave je bil določiti učinek odmerkov gnojil na biološki pridelek, porabo vode in energetsko vsebnost navadnega sirka za zrnje. Poljski poskus je potekal na Uladovo-Lyulynetsk Research and Selection Station (49° 35' N, 28° 24' E) v rastnih sezonah 2017–2021. Poskus je potekal kot naključni poskus s štirimi ponovitvami s površino setve 62 m^2 in površino žetve 50 m^2. Obravnavanja so obsegala: kontrola brez gnojil, slama ozimne pšenice v odmerku 4 t ha^{-1} kot ozadje, mineralna gnojila v odmerkih $N_{60}P_{60}K_{60}$, $N_{90}P_{90}K_{90}$, $N_{120}P_{120}K_{120}$ in ocenjen odmerek $N_{105}P_{35}K_{60}$. Sirek za zrnje je imel velik pridelek biomase na črnih tleh kot ozadju naravne rodovitnosti s pridelkom zrnja 5.96 t ha^{-1} in stebel 30.3 t ha^{-1}. Uporaba slame in mineralnih gnojil je zagotovila zadostno vlago za potrebe rastlin. Ocenjen odmerek gnojila $N_{105}P_{35}K_{60}$ in uporaba slame v odmerku 4 t ha^{-1} sta dala podobno produktivnost sirka z največjo vrednostjo z odmerkom mineralnih gnojil $N_{120}P_{120}K_{120}$, kar bi lahko priporočili za cenovno učinkovito gnojenje. Takšno gnojenje je povečalo pridelek zrnja za 35 %, bioetanola za 41 %, goriva iz slame za 17 % in celokupni energetki izkopiček za 23 %.

Ključne besede: sirek za zrnje, odmerki gnojil, produktivnost, biogorivo

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1 INTRODUCTION

The problem of food and energy resources are the main challenges of the modern economy. Rapid population growth and the reduction of fossil fuels require alternative solutions capable of ensuring a delicate balance between rising living standards and the ability to satisfy the population with food and energy. A series of recent EU legislative decisions, summarized in the "European Climate Law", outlines a new map of Europe's climate neutrality, which envisages a phase-out of fossil fuels and a full transition to renewable energy sources by 2050 (Chiaramonti et al., 2021).

Ukraine lags far behind in the use of renewable energy, but large areas of land, high soil fertility, favorable climatic conditions and geographical location make it a promising player in the market of cheap energy carriers. The energy strategy of Ukraine until 2035, approved by the resolution of the Cabinet of Ministers of Ukraine dated August 18, 2017 No. 605-r, provides for increasing the share of energy obtained from renewable sources by 25 % by 2030 (Energy…, 2017).

According to Sinchenko et al. (2020), in recent years, special interest in Ukraine has focused on the production of bio-ethanol, which is planned to increase to 12 million tons by 2030.

The production of bio-ethanol requires the cultivation of highly productive and undemanding crops, among which grain sorghum deserves special attention. Grain sorghum, originating from the African continent, has genetically inherited high drought resistance, unpretentiousness to soil and climatic conditions, has high productivity, which guarantees stable biomass yields in conditions of global warming (Stamenkovic et al., 2020).

At the same time, grain sorghum, like other crops, needs sufficient supply of moisture and nutrients, particular nitrogen (Abunyewa et al., 2017). Insufficient supply of sorghum plants with water and nitrogen limits its growth, decreases yield (Obour et al., 2022), deteriorates grain quality (Modisapudi & Sebetha, 2022); the acute moisture deficit stagnates plant growth and increases nutrition requirement (Schlegel & Bond 2020). To obtain a high biological yield, grain sorghum requires the application of 70-90 kg ha^{-1} (Masebo & Menamo, 2016; Munagilwar et al., 2020; Kovalenko, 2023) to 160 kg ha^{-1} of nitrogen (Bartzialis et al., 2023; Said et al., 2023).

Organic-mineral fertilisations are much more effective in increasing the yield of grain sorghum (Kedir, 2023). The combined application of organic and mineral fertilisers has a complex effect on the soil, improves its structure and moisture supply, forms a balanced nutrition of plants in terms of macro- and micronutrients, increases the resistance of plants to drought, which is the key to obtaining stable crops in the era of global warming (Hu et al., 2018; Lu 2020, Mujdeci et al., 2020). According to Teshome et al. (2023), the application of mineral fertilisers in combination with manure in Western Ethiopia provided the highest grain sorghum yield of 5.09 t ha^{-1} with an increase compared to the control by 84.2 %.

Winter wheat straw is often used to fertilise agricultural crops. This practice is widespread in Ukraine, where there is an acute shortage of manure, while the area sown with winter wheat exceeds 6.5 million hectares with an annual straw production of over 33 million tons. For most crops, winter wheat is a good predecessor, and grain sorghum is mainly grown after it (Malyarchuk, 2019).

According to Liu et al. (2017) use of straw as a fertiliser has economic advantages over manure, it is cheaper to produce, its application does not require costs associated with transporting fertiliser to the field as is the case with manure and therefore it is more cost-effective. Application of straw in the semi-arid regions of China at the rate of 4.5-13.5 t ha^{-1} had a versatile positive effect on the soil and sorghum yield increased microbial activity in the 0-60 cm soil layer by 19.6-44.3 %, water use efficiency - by 15.7-34.6 %, grain yield by 10.6-22.8 % (Zhang et al., 2016).

According to Poliovyi et al. (2021), straw is inferior to manure in terms of filling the soil with nutrients. At a dose of straw of 5 t ha^{-1}, nitrogen enters the soil - 27 kg ha^{-1}, phosphorus - 15, potassium - 62 kg ha^{-1}. Compared to manure (30 t ha^{-1}), it is 5,6 times less for nitrogen, 5.0 times less for phosphorus and 2.9 times less for potassium, and therefore the application of mineral fertilisers is effective when applying straw into the soil.

The use of mineral fertilisers for grain sorghum against a background of straw is a little-studied issue that requires research and is relevant for obtaining high biomass yields.

This study aims to answer: (1) How fertiliser rates applied against background of straw affect biological yield, water use, and energy capacity of grain sorghum? To determine the optimal rate of fertilisers that ensure the maximum biological and energy productivity of grain sorghum.

2 MATERIALS AND METHODS

Field experiment during research years of 2017-2021 was conducted at the Uladovo-Lyulynetsk Research and Selection Station (49° 35' N, 28° 24' E). Trial was organized using a randomized experimental design in four replications with a seeding plot area of 62 m^2, a harvesting area of 50 m^2. The investigated factors were:

control, without fertiliser, winter wheat straw at the rate of 4 t ha^{-1} as a background, mineral fertilisers at rates of $N_{60}P_{60}K_{60}$, $N_{90}P_{90}K_{90}$, $N_{120}P_{120}K_{120}$ and the estimated rate of $N_{105}P_{35}K_{60}$.

Soil of the experimental site was leached chernozem, loamy composition, with agrophysical and agrochemical properties of the 0–30 cm soil layer: pH_{KCl} – 5.8-6.1, organic matter – 3.9-4.0 % (DSTU 4289:2004), easily hydrolyzed nitrogen – 140-145 mg (DSTU 7863:2015), mobile P_2O_5 – 133-137 and K_2O – 82-88 mg kg^{-1} of the soil (DSTU 4115-2002) (Soils, 2002, 2004, 2015).

Hybrid 'Dniprovskyi 39' was sown at first decade of May. An early-ripening hybrid matures in 100-110 days with a potential yield of over 8 t ha^{-1}. Predecessor of grain sorghum was winter wheat 'Bogdana'.

Sorghum was harvested at the beginning of September under grain moisture of 14 %. The content of starch was determined by a polarimeter, protein by the content of total nitrogen, determined by the Kjeldahl method (DSTU 7169-2010) with subsequent conversion to protein.

The Kalynivka meteorological station provided weather data.

To determine soil water reserves (SWR), soil samples were taken twice (sowing and harvesting) from the 0-150 cm layer.

The formula for determining the water use efficiency (WUE index) (m^3 t^{-1}):

$$WUE = (SWR_s - SWR_h + P) \times 10 / Y,$$

where SWR_s – soil water reserves at sawing, SWR_h – at harvest, mm; P – precipitation, mm; 10 – conversion coefficient, mm into m^3; Y – total yield (grain and stems), t ha^{-1} dry biomass.

The IBCSB methodology was used to determine the output of bio-ethanol, solid fuel and energy from sorghum grain (Roik et al., 2020).

The formula that defines bio-ethanol output:

$$Me = Y \times d \times S \times r \times f / 10000,$$

where Me – bio-ethanol, t ha^{-1}; Y – grain yield, t ha^{-1}; d – grain dry matter, %; S – starch content, %; r – the ratio of the molecular weight of ethanol to starch (0.5679); f – coefficient of bio-ethanol output at the factory (0.9).

The formula that defines solid biofuel output:

$$Ms = Ys \times d \times (100 + h) / 10000,$$

where Ms – solid biofuel, t ha^{-1}; Ys – stems yield, t ha^{-1}; d – dry matter, %; h – humidity coefficient of 10 %.

The heat of combustion for solid biofuel – 16 GJ t^{-1}, bioethanol – 25 GJ t^{-1} was used to calculate the energy output.

2.1 STATISTICAL ANALYSIS

All obtained data were analyzed with the technique of analysis of variance (ANOVA). Significant differences between individual means were assessed using the least significant difference test (*LSD,* $p < 0.05$). Microsoft Excel, version 2013, (USA) was used to determine correlation-regression dependencies between research data.

2.2 METEOROLOGICAL CONDITIONS

During 2017-2021, weather conditions were favorable for growing grain sorghum. 2017 was warm and uneven in precipitation distribution. The average daily temperature during the growing season exceeded the long-term average by 1.4 °C, the amount of precipitation was 37 mm less. In May, June and July, precipitation fell by 27, 36 and 52 mm more than the average multi-year norm, in August and September – by 47 and 25 mm less (Figure 1 and 2). The year 2018 was the warmest during the research period, the growing season was marked by an excess of the average long-term temperature by 2.9 °C with the amount of precipitation within the normal range (397 mm). 2019 was a warm year, with the average daily temperature exceeding the long-term norm by 1.9 °C. Precipitation corresponded to the norm with an uneven distribution during the growing season. May and June were excessively wet – the amount of precipitation exceeded the long-term norm by 52 and 61 mm, July-August were dry – 108 mm less precipitation fell in three months. 2020 was slightly dry. The average daytime temperature exceeded the norm by 1.4 °C, the amount of precipitation during the growing season was 45 mm less. A decrease in precipitation was marked in August by 20 mm and in September by 14 mm. Weather conditions the year 2021 best corresponded to the multi-year average. The amount of precipitation during the growing season was within the long-term norm – 389 mm, the temperature was higher by 0.6 °C.

3 RESULTS AND DISCUSSION

The research results showed that grain sorghum responded positively to the application of fertilisers. In the control without fertilisers and with application of 4 t ha^{-1} of straw, the yield of grain in average for research years was the lowest of 5.96 and 6.13 t ha^{-1}, respectively (Table 1). With rate of fertilisers $N_{60}P_{60}K_{60}$ over the background of 4 t ha^{-1} of straw, the yield increased compared to control without fertilisers by 0.85 t ha^{-1} or by 14.3 %, $N_{90}P_{90}K_{90}$ – by 1.78 t ha^{-1} or by 29.9 %, $N_{120}P_{120}K_{120}$ – by

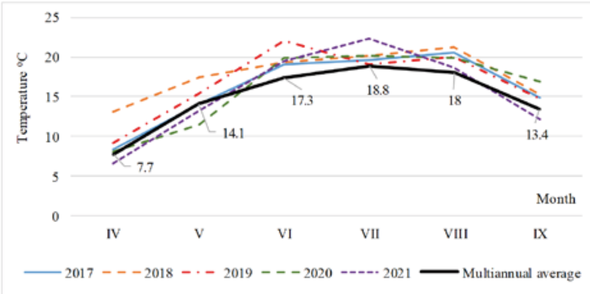

Figure 1: Average daily temperature during the growing season

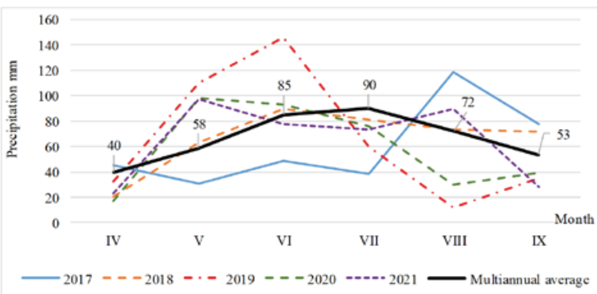

Figure 2: Amount of precipitation during the growing season

2.14 t ha^{-1} or 35.9 %, estimated rate of $N_{105}P_{35}K_{60}$ – by 2.06 t ha^{-1} or 34.6 %. All rates of mineral fertilisers statistically significantly (*$p < 0.05$*) increased grain yield of sorghum. The highest yield value ensured fertilisers rate of $N_{120}P_{120}K_{120}$ and estimated rate of $N_{105}P_{35}K_{60}$ applied over the background of 4 t ha^{-1}, it was amounted to 8.10 and 8.02 t ha^{-1}, respectively. Application of high rates of nitrogen fertilizers of 105 to 120 kg ha^{-1}, which is observed in these options, was decisive in obtaining a high yield of grain sorghum. In years with regular moistening during the growing season (2017-2018), mineral fertilisers showed maximum efficiency, the increase in grain yield compared to the control without fertilisers was 2.80-3.26 t ha^{-1}, in dry years (2019-2020) the effectiveness of fertilisers decreased significantly, the increase in grain yield was 0.91-1.87 t ha^{-1}, which was half as much. These results are consistent with the findings of Munagilwar et al. (2020), Bartzialis et al. (2023), Kovalenko (2023) on the effectiveness of high nitrogen doses of 70 to160 kg ha^{-1} for this crop.

The application of fertilisers substantially affected the yield of sorghum stems. An increase in the rate of fertilisers from $N_{60}P_{60}K_{60}$ to $N_{120}P_{120}K_{120}$ on the background of 4 t ha^{-1} of straw was accompanied by an increase in the yield of stems compared to the control without fertilisers by 2.8-4.7 t ha^{-1}. The maximum yield of 35.2 and 35.0 t ha^{-1} was provided by the fertilizer rate $N_{120}P_{120}K_{120}$ and the estimated rate $N_{105}P_{35}K_{60}$ against the background of 4 t ha^{-1} of straw. Fertilisers reliably increased stem yield compared to the control without fertilisers by 15.5-16.2%, which is consistent with the studies of Said et al. (2023), where the highest stem yield of 16.8 t ha^{-1} was achieved at nitrogen fertiliser rate of 150 kg ha^{-1}. Weather conditions in the years of research had a less pronounced influence on the yield of stems compared to their influence on the yield of grain. The maximum effectiveness of fertiliser application was achieved in the year 2017, which was favorable in terms of moisture, the application of high rates of fertilisers $N_{120}P_{120}K_{120}$ and $N_{105}P_{35}K_{60}$ this year increased the yield of stems compared to the control without fertilisers by 4.7-4.9 t ha^{-1}, while in the dry year of 2020 only by 2.5-2.8 t ha^{-1}.

The quality of the grain of sorghum plants depends on the accumulation of protein in it. The application of fertilisers significantly increased the protein content in sorghum grain: at rate of $N_{60}P_{60}K_{60}$ by 0.6 %, $N_{90}P_{90}K_{90}$ by 1.5 %, $N_{120}P_{120}K_{120}$ by 1.8 %, calculated rate of $N_{105}P_{35}K_{60}$ by 1.5 %, if compared to the control without fertilisers. The years of research had little effect on the quality of sorghum grain.

The starch content in sorghum grain is an indicator of its quality and a source of bio-ethanol production. The lowest starch content was recorded in the control without fertilisers – 63.2 % and against the background of straw application – 63.5 %. Fertilisers applied against the background of 4 t ha^{-1} of straw have reliably increased the accumulation of starch in sorghum grains by 2.9-4.4 %. At fertilisers rate $N_{60}P_{60}K_{60}$ starch content was 66.1 %, $N_{90}P_{90}K_{90}$ 67.0 %, $N_{120}P_{120}K_{120}$ – 67.6 %, estimated rate $N_{105}P_{35}K_{60}$ – 67.3 %. Fertilisers in the dose of $N_{120}P_{120}K_{120}$ and the estimated dose of $N_{105}P_{35}K_{60}$ maximally contributed to the increase in starch content. Weather conditions had an insignificant effect on the accumulation of starch in sorghum grains; application of fertilizers proportionally increased its content through the years of research.

The productivity of grain sorghum and the stability of obtaining crops largely depends on the accumulation of moisture in the soil and the efficiency of its use by plants during the growing season. According to Souza et al. (2021), water stress caused by water deficit in the pre-flowering stage of grain sorghum can reduce its yield by 45 %, and after the post-flowering stage by more than 48 %.

On average, for 2017-2021, the SWR in the spring during the sowing of grain sorghum was 229-244 mm in a 1.5 m soil layer (Figure 3). In the control without fertilisers, the moisture content in the soil was the lowest, and with the application of straw and mineral fertilisers, the SWR increased by 10-15 mm. The accumulation of moisture in the soil was facilitated by the application of winter wheat straw, while the application of mineral fertilisers

Table 1: Effect of fertilisers on biomass yield and grain quality of grain sorghum

Treatment	Years					Mean	SD	CV
	2017	2018	2019	2020	2021			
Grain yield, t ha^{-1}								
Without fertilisers (control)	6.80	6.22	5.25	5.47	6.06	5.96	0.62	10.4
4 t ha^{-1} of straw (fond)	6.96	6.50	5.44	5.68	6.08	6.13	0.61	10.0
$N_{60}P_{60}K_{60}$	8.05	7.50	5.53	6.23	6.76	6.81	1.00	14.7
$N_{90}P_{90}K_{90}$	9.39	8.69	6.04	7.02	7.55	7.74	1.33	17.2
$N_{120}P_{120}K_{120}$	10.06	9.06	6.20	7.38	7.79	8.10	1.50	18.5
estimated fertiliser rate	9.78	9.02	6.16	7.34	7.80	8.02	1.42	17.7
LSD ($p < 0.05$)	0.74	0.66	0.52	0.60	0.47	0.64		
Stems yield, t ha^{-1}								
Without fertilisers (control)	33.7	32.0	27.3	28.8	29.7	30.3	2.55	8.42
4 t ha^{-1} of straw (fond)	32.3	32.1	26.7	28.4	29.0	29.7	2.43	8.20
$N_{60}P_{60}K_{60}$	36.2	35.8	29.5	30.6	33.4	33.1	3.01	9.09
$N_{90}P_{90}K_{90}$	37.7	36.4	31.2	31.3	35.4	34.4	2.99	8.69
$N_{120}P_{120}K_{120}$	38.4	37.2	32.6	31.6	36.2	35.2	2.96	8.40
estimated fertiliser rate	38.6	36.2	32.0	31.3	36.9	35.0	3.19	9.11
LSD ($p < 0.05$)	2.44	2.52	2.06	2.12	2.33	2.14		
Content of protein, %								
Without fertilisers (control)	9.5	9.6	11.0	10.7	9.7	10.1	0.70	6.90
4 t ha^{-1} of straw (fond)	9.4	9.6	10.6	9.5	9.9	9.8	0.48	4.95
$N_{60}P_{60}K_{60}$	9.9	10.2	11.4	11.1	10.9	10.7	0.63	5.87
$N_{90}P_{90}K_{90}$	10.4	11.3	12.3	11.8	12.2	11.6	0.78	6.71
$N_{120}P_{120}K_{120}$	10.7	11.7	12.5	12.1	12.0	11.8	0.68	5.75
estimated fertiliser rate	10.4	11.5	12.5	11.9	11.7	11.6	0.77	6.62
LSD ($p < 0.05$)	0.17	0.20	0.27	0.23	0.28	0.24		
Content of starch, %								
Without fertilisers (control)	64.6	64.0	62.4	62.7	62.3	63.2	1.04	1.64
4 t ha^{-1} of straw (fond)	64.8	64.7	62.4	63.0	62.6	63.5	1.16	1.83
$N_{60}P_{60}K_{60}$	67.0	66.9	65.8	65.1	65.7	66.1	0.82	1.24
$N_{90}P_{90}K_{90}$	67.6	67.8	66.2	66.0	67.4	67.0	0.84	1.25
$N_{120}P_{120}K_{120}$	67.9	68.0	67.2	67.1	67.8	67.6	0.42	0.62
estimated fertiliser rate	67.9	67.8	66.4	67.0	67.4	67.3	0.62	0.92
LSD ($p < 0.05$)	0.43	0.37	0.40	0.34	0.42	0.40		

SD–standard deviation; CV–coefficient of variation

had an insignificant effect on its reserves. Our data are consistent with the studies of Wang et al. (2016), where the application of 15-23 t ha^{-1} of manure under corn crops formed high moisture reserves in the soil at the stage of tassel formation, which may be a consequence of improving the soil structure and increasing its ability to retain moisture.

At harvest, SWR in the 1.5 m soil layer decreased by 1.93-2.46 times. The smallest SWR was recorded for the fertiliser rate $N_{120}P_{120}K_{120}$ and the estimated rate $N_{105}P_{35}K_{60}$, it amounted to 99 and 101 mm, respectively. In these options, grain sorghum yield was the highest, which required additional moisture inputs.

During the growing season, grain sorghum used

118-145 mm of moisture from the soil, which was 24-28 % of the plant's moisture needs, the remaining 72-76 % of the needs was covered by precipitation, which averaged 378 mm over the years of research.

The yield of dry biomass (grain and stems) of grain sorghum was the lowest in the control without fertilisers and for the application of 4 t ha^{-1} of straw –12.6 and 12.7 t ha^{-1}, respectively, and the highest was for the fertilisers rate of $N_{120}P_{120}K_{120}$ and the estimated rate of $N_{105}P_{35}K_{60}$ – 15.7 and 15.4 t ha^{-1}. The use of fertilisers increased the yield of dry biomass compared to the control without fertilizers by 1.22-1.25 times (Figure 4). These results are consistent with the findings of Abunyewa et al. (2017) on a reliable increase in sorghum yield under sufficient supply of water and nutrients.

The calculation of moisture consumption for the formation of 1 ton of dry biomass (WUE index) reflects the efficiency of moisture use by plants. In the control without fertilisers, WUE was the highest – 394 m^3, and the lowest at fertilisers rate of $N_{120}P_{120}K_{120}$ and the estimated dose of $N_{105}P_{35}K_{60}$ – 333 and 337 m^3, respectively. Application of mineral fertilisers reduced moisture consumption for the formation of one ton of biomass compared to the control without fertilizers by 61 and 57 m^3. High rates of mineral fertilisers $N_{120}P_{120}K_{120}$ and $N_{105}P_{35}K_{60}$, which provided increased nitrogen nutrition, resulted in the lowest WUE. These results are consistent with the research of Bastaubayeva et al. (2022) on the effectiveness of high fertiliser rates in reducing water consumption by sugar beet.

Grain sorghum is a valuable bioenergy crop for the production of bio-ethanol. Bio-ethanol is obtained from sorghum grain, its output depends on the yield of the grain and its starch content. On average, over the years of research, the lowest output of bioethanol was recorded in the control without fertilisers – 1.66 t ha^{-1}, which was

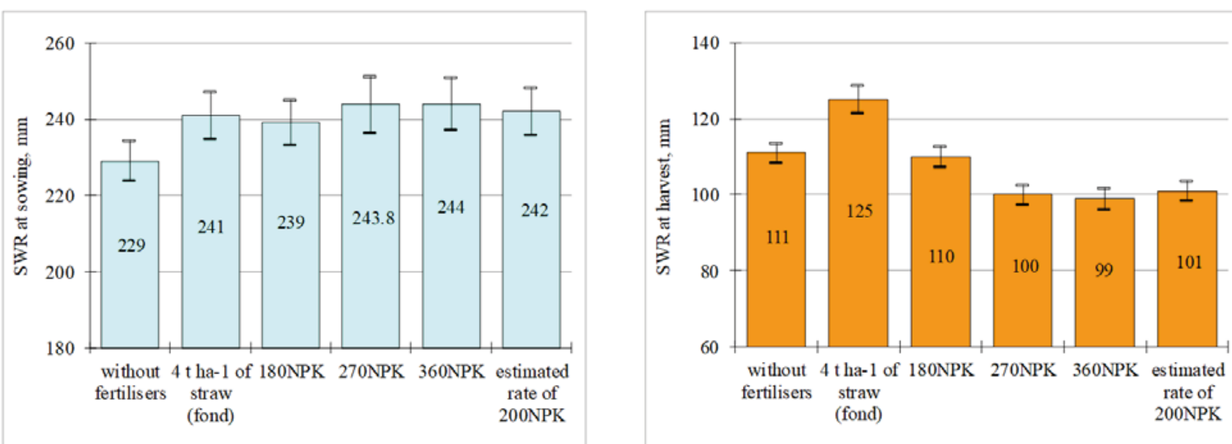

Figure 3: Effect of fertilisers on SWR in 1.5 m soil layer, mm, 2017–2021 years

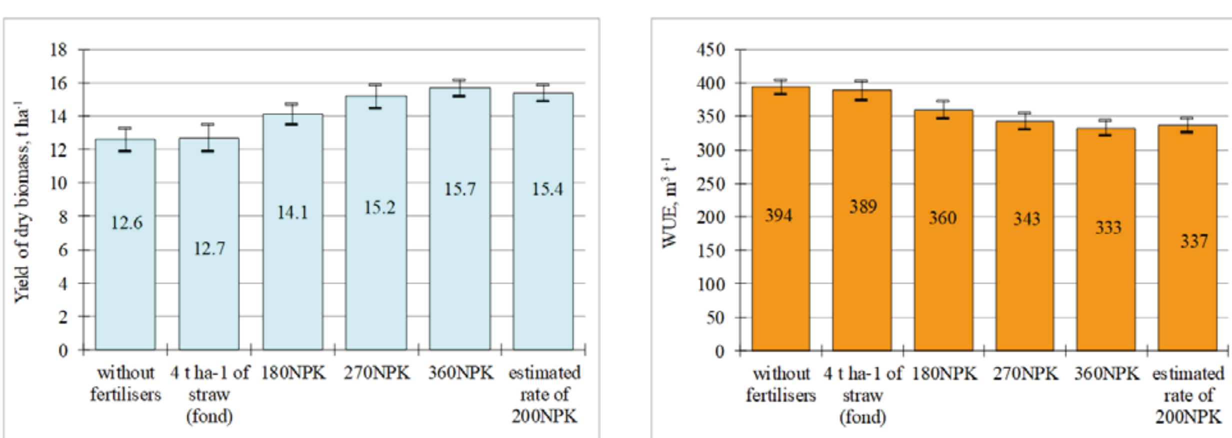

Figure 4: Effect of fertilisers on sorghum dry biomass yield and WUE index, 2017–2021 years

Table 2: Effect of fertilisers on the biofuel output and energy capacity of grain sorghum, 2017-2021 years

Treatment	Biofuel t ha-1		Energy GJ ha^{-1}		Total energy GJ ha^{-1}
	bio-ethanol	solid biofuel	bio-ethanol	solid biofuel	
Without fertilisers (control)	1.66	8.20	41.5	131	172.5
4 t ha^{-1} of straw (fond)	1.71	8.16	42.8	131	173.8
$N_{60}P_{60}K_{60}$	1.98	9.08	49.5	145	194.5
$N_{90}P_{90}K_{90}$	2.28	9.44	57.0	151	208.0
$N_{120}P_{120}K_{120}$	2.41	9.60	60.3	154	214.3
estimated fertiliser rate	2.34	9.56	58.5	153	211.5
LSD ($p < 0.05$)	0.19	0.26	4.7	5.1	6.4
Mean	2.06	9.01	51.6	144	195.8
SD	0.33	0.67	8.20	10.67	18.79
CV	15.9	7.4	15.9	7.4	9.6

SD–standard deviation; CV–coefficient of variation

28 % of the grain yield. The highest output of bio-ethanol was obtained by applying fertilisers rate of $N_{120}P_{120}K_{120}$ and the estimated rate of $N_{105}P_{35}K_{60}$ against the background of 4 t ha^{-1} of straw – 2.41 and 2.34 t ha^{-1}, respectively. The application of fertilisers increased the output of bio-ethanol compared to the control without fertilisers by 0.68-0.75 t ha^{-1} or 41-45 % (Table 2). These results are consistent with the findings of Gamayunova et al. (2022), Pravdyva et al. (2022), where application fertilisers under grain sorghum increased bio-ethanol output by 33-74 %.

When producing bio-ethanol, grain sorghum stems can be reliable source for production of solid biofuel. Research results showed that the output of solid biofuel from sorghum stems was 4.0-6.4 times higher than the output of bio-ethanol from grain. The rate of fertilisers $N_{120}P_{120}K_{120}$ and the estimated rate $N_{105}P_{35}K_{60}$ against the background of 4 t ha^{-1} of straw provided the maximum yield of solid biofuel of 9.60 and 9.56 t ha^{-1} with an increase compared to the control without fertilisers by 17 %.

Energy capacity of grain sorghum is the energy that is concentrated in bioethanol and solid biofuel and is the result of their combustion. In the current experiment, 72-76 % of the total energy was concentrated in solid biofuel, 24-28 % in bio-ethanol. Fertiliser application increased energy storage in sorghum plants compared to the unfertilised control by 22.0–41.8 GJ ha^{-1}, to the fond of 4 t ha^{-1} of straw – by 20.7-40.5 GJ ha^{-1}. The highest energy capacity of sorghum was recorded when applying fertilisers at the rate of $N_{120}P_{120}K_{120}$ and the estimated rate of $N_{105}P_{35}K_{60}$ against the background of 4 t ha^{-1} of straw, it was 214.3 and 211.5 GJ ha^{-1}, respectively.

It was established that the highest accumulation of energy per one kilogram of nutrients (NPK) of mineral fertilisers was achieved with the application of an estimated rate of $N_{105}P_{35}K_{60}$ against the background of 4 t ha^{-1}

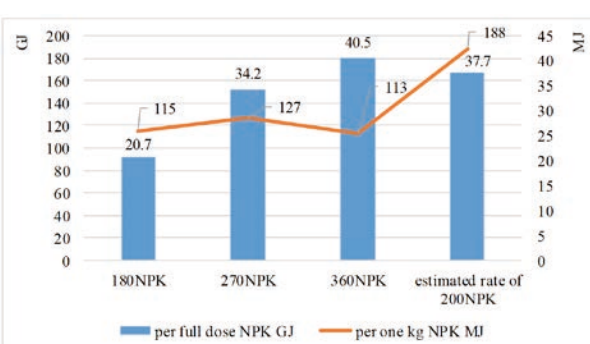

Figure 5: Total energy increase from mineral fertilisers application, 2017–2021 years

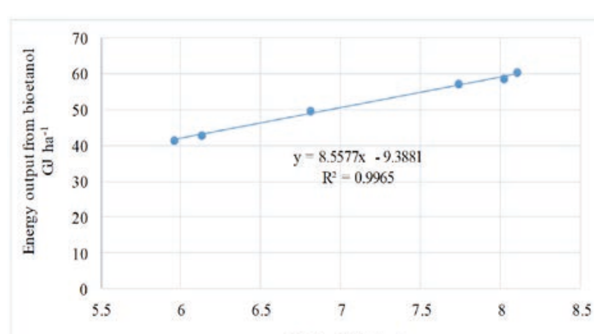

Figure 6: Correlation between grain yield and energy output from bio-ethanol, 2017–2021 years

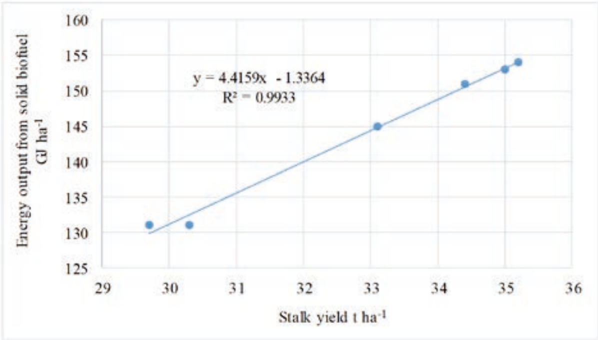

Figure 7: Correlation between stem yield and energy output from solid biofuel, 2017–2021 years

of straw, it amounted to 188 MJ (Figure 5). This rate of fertilisers was the most effective in the formation of high-energy capacity of grain sorghum.

A strong linear correlation was established between grain yield and output of energy from bioethanol, stalk yield and energy output from solid biofuel with a coefficient of determination of 0.9965 and 0.9933, respectively (Figure 6 and 7).

4 CONCLUSION

1. Grain sorghum produces high yields of biomass on black soils, which is a raw material for the production of bioethanol and solid biofuel. Against the background of natural fertility, the yield of sorghum grain was 5.96 t ha^{-1}, stems 30.3 t ha^{-1}, from which 1.66 t ha^{-1} of bio-ethanol and 8.2 t ha^{-1} of dry biofuel can be obtained, with a total energy capacity of 172 GJ ha^{-1}.

2. It is advisable to grow grain sorghum after winter wheat. The use of wheat straw for fertiliser increases the accumulation of moisture in the soil, and its application with mineral fertilisers ensures economical and efficient use of moisture by plants.

3. Estimated fertilisers rate $N_{105}P_{35}K_{60}$ against the background of 4 t ha^{-1} of straw provided almost the same productivity of sorghum with the maximal rate of $N_{120}P_{120}K_{120}$ and can be recommended for fertilising as more cost-effective. This organic-mineral fertilisation led to an increase in grain yield by 35 %, bio-ethanol output by 41 %, solid biofuel by 17 %, total energy output by 23 %.

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