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Revista Facultad Nacional de Agronomía

UNIVERSIDAD NACIONAL DE COLOMBIA

Effect of mineral fertilizer doses on sweet sorghum productivity and nutrient balance for bioethanol

Efecto de dosis de fertilizante mineral en productividad y balance de nutrientes de sorgo dulce

https://doi.org/10.15446/rfnam.v79.119327

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ABSTRACT

Keywords:
Biomass yield
Fertilizer efficiency
Nutrient uptake
Sugar accumulation
Sustainable agriculture

CITATION: Ivanina V, Zaryshniak A, Chernuskiy V, Hanzhenko O, Strilets O, Zatserkovna N and Kopchuk K (2026) Effect of mineral fertilizer doses on sweet sorghum productivity and nutrient balance for bioethanol. Revista Facultad Nacional de Agronomía Medellín 79(1): e119327. doi: https://doi.org/10.15446/rfnam.v79.119327

The purpose of the study was to determine the mineral fertilizer dose that ensures maximum sweet sorghum biomass yield and bioethanol production in the eastern Forest-Steppe of Ukraine, as well as to establish the nutrient balance and the consistency of fertilizer doses with sustainable development principles. The research was conducted at the Ivanivka Research and Breeding Station (50°11ˈN, 35°03ˈE) from 2021 to 2023. The experimental design included five treatments: an unfertilized control and mineral fertilizer applications at rates of $N_{60}P_{30}K_{30}$, $N_{90}P_{60}K_{60}$, $N_{120}P_{90}K_{90}$, and the estimated rate $N_{110}P_{45}K_{55}$. The study was carried out in four replications; each plot had a usable area of 100 m² and a harvested area of 73.1 m². It was established that the $N_{120}P_{90}K_{90}$ and $N_{110}P_{45}K_{55}$ fertilizer doses provided the highest biological productivity, with stem yields of 77.1 and 74.2 t ha^{-1}, stem sugar content of 15.6%, and bioethanol outputs of 3.88 and 3.73 t ha^{-1}, respectively. These fertilizer doses formed a positive soil phosphorus balance (9–49 kg ha^{-1}), a slight nitrogen deficit (17–20 kg ha^{-1}), and a pronounced potassium deficit (108–139 kg ha^{-1}). In the long term, a potassium dose of 55–90 kg ha^{-1} may cause instability in potassium nutrition and require higher potassium fertilizer applications. Nitrogen doses of 110–120 kg ha^{-1} and phosphorus doses of 45 kg ha^{-1} were sufficient to achieve biomass yields above 70 t ha^{-1} and to meet sustainable development principles.

RESUMEN

Palabras clave:
Rendimiento de biomasa
Eficiencia del fertilizante
Absorción de nutrientes
Acumulación de azúcares
Agricultura sostenible

El propósito del estudio fue determinar la dosis de fertilizantes minerales que asegura el máximo rendimiento de biomasa de sorgo dulce y la producción de bioetanol en el este de la Estepa Forestal de Ucrania, así como establecer el balance de nutrientes y la correspondencia de las dosis de fertilización con los principios del desarrollo sostenible. La investigación se llevó a cabo en la estación de investigación y mejoramiento de Ivanivka (50°11′N, 35°03′E) entre 2021 y 2023. El diseño experimental incluyó cinco tratamientos: control sin fertilización y aplicaciones de fertilizantes minerales en las dosis $N_{60}P_{30}K_{30}$, $N_{90}P_{60}K_{60}$, $N_{120}P_{90}K_{90}$ y la dosis estimada $N_{110}P_{45}K_{55}$. El estudio se desarrolló con cuatro repeticiones; el área útil de cada parcela fue de 100 m² y el área de cosecha de 73,1 m². Se determinó que las dosis $N_{120}P_{90}K_{90}$ y $N_{110}P_{45}K_{55}$ proporcionaron la mayor productividad biológica, con rendimientos de tallos de 77,1 y 74,2 t ha^{-1}, contenido de azúcares en el tallo del 15,6% y producción de bioetanol de 3,88 y 3,73 t ha^{-1}, respectivamente. Estas dosis generaron un balance positivo de fósforo en el suelo (9–49 kg ha^{-1}), una ligera deficiencia de nitrógeno (17–20 kg ha^{-1}) y una marcada deficiencia de potasio (108–139 kg ha^{-1}). A largo plazo, una dosis de potasio de 55–90 kg ha^{-1} podría generar inestabilidad en la nutrición de potasio y requerir un incremento en las aplicaciones de fertilizantes potásicos. Las dosis de nitrógeno de 110–120 kg ha^{-1} y de fósforo de 45 kg ha^{-1} resultaron suficientes para obtener rendimientos de biomasa superiores a 70 t ha^{-1} y cumplir con los principios del desarrollo sostenible.

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Received: June 5, 2025; Accepted: October 18, 2025

Rev. Fac. Nac. Agron. Medellín 79: e119327. 2026.

ISSN 0304-2847 / e-ISSN 2248-7026

The growing need for energy resources requires searching for new energy sources. The European Union's policy today is aimed at the comprehensive development and widespread use of renewable energy sources, among which bioenergy occupies an important place. Bioethanol is one of the types of alternative fuel, which is increasingly used as fuel for cars instead of fossil hydrocarbons, in particular oil and its products. According to the RED II European Directive, the share of energy use from renewable sources in European transport should increase to 14% by 2030 (Directive - European Union 2018).

According to Chiaramonti et al. (2021), the widespread use of bioethanol is extremely important today. It allows reducing carbon emissions into the atmosphere, forms the basis of a climate-neutral economy, and develops the energy space within the framework of the European Green Deal.

Ukraine does not have its own oil deposits, so the production and use of bioethanol is extremely important for the energy and economic independence of the state. According to Sinchenko et al. (2020), in the coming years, bioethanol production in Ukraine should increase to 12 million tons per year.

The growing demand for bioethanol requires well-balanced and scientifically grounded approaches to its production. Bioethanol is generated from sugar-rich biological raw materials, which are obtained by cultivating crops that naturally accumulate sugars. The main requirements for these crops are their high biological productivity, good adaptability to drought conditions, and low demand for soil (Zhang et al. 2016). In the context of global warming, sweet sorghum best meets these requirements. Originating from the African continent, it has inherited high drought resistance and unpretentiousness to growing conditions. Sweet sorghum produces a high yield of stems, accumulates a large volume of stem juice and fermented sugar, which is the basis for bioethanol production (Pannacci and Bartolini 2018).

Mineral fertilizers are the main factor in preventing stress and obtaining high biomass yields (Gamayunova et al. 2022). Nitrogen plays a main role in fertilizing and increasing the yield of sweet sorghum (Kering et al. 2017). Nitrogen affects the course of redox reactions in the plant body, intensifies photosynthesis processes, enhances plant growth and development, and ensures the formation of powerful biomass. Nitrogen application at a dose of 100 kg ha^{-1} under sweet sorghum increased leaf length by 7.5%, leaf width by 12.8%, plant height by 2.5%, and stem mass by 27.4% (Ahmad et al. 2022). In the semi-arid tropics of India, the most effective for sweet sorghum was nitrogen dose of N_{90} (Kurai et al. 2015; Uchino et al. 2013); in Iran, N_{100} dose (Almodares et al. 2009); in Nigeria and the USA, the N_{120} dose (Olugbemi and Ababyomi 2016; Kering et al. 2017).

On soils with low potassium content, sweet sorghum responded well to nitrogen and potassium fertilizers. In Iran, on soils with low potassium content, the effective dose for sweet sorghum was $N_{90}K_{10}$ (Almodares et al. 2008); in Turkey, the dose of $N_{150}K_{100}$ (Sadighfard and Geren 2022). Balanced for nitrogen and potassium nutrition of sweet sorghum plants provided the highest biomass yield, increasing stem height by 12.65%, fresh stem weight by 24.57%, total sugar content by 39.25%, and juice extract by 34.96% compared to the control without fertilizers (Almodares et al. 2008).

The most effective for sweet sorghum is complete mineral fertilizer (Xuan et al. 2017). Optimizing the doses and ratios of nutrients applied with fertilizers allows increasing the yield of sweet sorghum biomass by 30–48% (Zaituniguli et al. 2021). Maximum productivity of sweet sorghum was achieved when the complete mineral fertilizer included an increased dose of nitrogen against a background of significantly lower doses of phosphorus and potassium (Muhammad et al. 2023). In Nigeria, the rate of $N_{90}P_{45}K_{45}$ with an NPK ratio of 2:1:1 (Muhammad et al. 2023), in India, the rate of $N_{100}P_{50}K_{50}$ (Bhutada et al. 2020) has provided maximum sweet sorghum biomass yield.

When growing sweet sorghum for bioethanol, it is important to achieve sustainable development conditions by balancing the supply of nutrients to the soil as part of fertilizers with their removal by the crop. According to Singh et al. (2012), nutrient removal by sweet sorghum was dependent on the variety and its yield. At a dry biomass yield of 19.4 t ha^{-1}, sorghum plants removed 136 kg ha^{-1} of nitrogen, 28 kg ha^{-1} of phosphorus, and 81 kg ha^{-1} of potassium from the soil. Increasing biomass yield to 40 t ha^{-1} dry matter increased nitrogen removal to 339 kg ha^{-1}, phosphorus to 75 kg ha^{-1}, and potassium to 300 kg ha^{-1} (Han et al. 2011).

Thus, sweet sorghum is drought-resistant and capable of producing high biomass yields, making it a promising crop for bioethanol production in Ukraine. The issues of fertilization and the formation of the foundations of sustainable development require research and in-depth study.

The aim of this research was twofold: (1) to determine the mineral fertilizer dose that ensures maximum sweet sorghum biomass yield and bioethanol output in the eastern Forest-Steppe of Ukraine, and (2) to establish the nutrient balance and assess whether the applied fertilizer doses align with the principles of sustainable development.

MATERIALS AND METHODS

Research design and methods

The research was conducted at the Ivanivka Research and Breeding Station (50°11ʹN, 35°03ʹE) from 2021 to 2023. The scheme of the experiment included five options: control, without fertilizer, mineral fertilizers at rates of $N_{60}P_{30}K_{30}$, $N_{90}P_{60}K_{60}$, $N_{120}P_{90}K_{90}$, and the estimated rate of $N_{110}P_{45}K_{55}$. The study was conducted in four-fold replications; the area of the sowing plot was 100 m², and the harvesting area was 73.1 m².

The soil of the experimental site was a typical heavy loamy chernozem. The upper layer of 0–30 cm had the following agrochemical parameters: pH (6.8-7.1), absorption capacity of exchangeable cations (46–51 mg-eq) per 100 g of soil, humus content by Tyurin (4.5–4.7%), alkaline hydrolyzed nitrogen (168–174 mg kg^{-1}), mobile phosphorus and potassium by Chirykov (92–98 and 105–111 mg kg^{-1} of soil).

The experiment sowed a hybrid of the Ukrainian selection “Dovista”. This is a mid-season hybrid with a growing season of 130 days. The hybrid was created at the Institute of Agriculture of the Steppe Zone of the National Academy of Agrarian Sciences of Ukraine. The hybrid was sown in the first decade of May and harvested in the first decade of September in the waxy grain ripeness phase.

Harvest accounting was carried out by the method of trial plots with conversion to an area of 1 ha. Juice from the stems of sweet sorghum was obtained using a manual press, and the sugar content was determined with a refractometer. In the selected plant samples, dry matter was determined by the thermal-weight method, the content of total nitrogen by the Kjeldahl method (DSTU 7169-2010), phosphorus by photocolorimetry, and potassium by flame photometer.

The balance of nutrients for the harvesting period was calculated by different methods, from the input of nutrients to the soil with mineral fertilizers, and their removal by the harvest was subtracted.

Weather data was provided by the Ivanivka meteorological station.

The aridity of weather conditions in the research years was determined by the Hydro-thermal coefficient (HTC) (Selyaninov 1928). Equation 1 for determining HTC was:

$$HTC = R/0.1 \sum T \quad (1)$$

Where HTC – hydro-thermal coefficient, R is the amount of precipitation during the period with a temperature above 10 °C, and $\sum T > 10°$ is the sum of active temperatures above 10 °C.

The output of bioethanol from sweet sorghum was determined by the IBCSB methodology (Hanzhenko et al. 2020). The Equation 2 to determine the bio-ethanol output was:

$$Bi = Ys \times 0.64 \times S \times 0.51/100 \quad (2)$$

Where Bi is the bio-ethanol output (t ha^{-1}), Ys is the stems yield (t ha^{-1}), 0.64 is the coefficient of juice output from the stems, S is the sugar content in juice (%), and 0.51 is the yield rate of ethyl alcohol (bioethanol) from sugar.

Weather conditions

The weather during the research years was excessively warm and humid. According to the Selyaninov hydrothermal coefficient (HTC), sweet sorghum was adequately supplied with moisture in all years (HTC>1.0).

In 2021, the amount of precipitation during the growing season corresponded to the long-term average (339 mm), the average daily temperature was 2.3 °C higher, and the HTC was 1.03. This year was slightly drier compared to the other research years. April and May were excessively wet, with precipitation exceeding the long-term average by 23 and 18 mm, and the HTC in these months was 2.40 and 1.48, respectively. July was very dry: precipitation was 41 mm below the long-term average, while temperature exceeded it by 5.9 °C, and the HTC was 0.43 (Tables 1 and 2).

Table 1. Weather conditions in the year of research.

Indexes	Year	Month						For vegetation
		IV	V	VI	VII	VIII	IX	
Temperature (°C)	2021	8.2	16.2	21.2	26.3	23.9	13.6	18.2
	2022	10.6	14.1	21.9	21.4	24.4	12.2	17.4
	2023	10.7	15.9	19.7	21.7	23.5	18.4	18.3
Multi-year average (°C)		8.0	15.1	18.7	20.4	19.4	13.7	15.9
Precipitation (mm)	2021	59	72	68	34	52	54	339
	2022	101	46	70	67	36	82	402
	2023	72	29	37	101	103	70	412
Multi-year average (mm)		36	54	69	75	53	44	331

Table 2. Hydro-thermal coefficient (HTC) during the years of research.

Year	Month						For vegetation
	IV	V	VI	VII	VIII	IX	
2021	2.40	1.48	1.07	0.43	0.73	1.32	1.03
2022	3.18	1.09	1.07	1.04	0.49	2.24	1.28
2023	2.24	0.61	0.63	1.55	1.46	1.27	1.25
Multi-year average	1.50	1.19	1.23	1.23	0.91	1.07	1.16

The year 2022 was warm and excessively wet. The average daily temperature during the growing season was 17.4 °C, and total precipitation reached 402 mm, exceeding the long-term average by 1.5 °C and 71 mm, respectively. Precipitation was evenly distributed throughout the growing season, creating favorable moisture conditions for plant growth (HTC=1.28). Excessively high temperatures (24.4 °C) and a slight precipitation deficit (17 mm) were observed only in August, when weather conditions were dry (HTC=0.49).

The year 2023 was the warmest and wettest during the years of research; the average daily temperature during the growing season exceeded the average long-term indicator by 2.4 °C, the amount of precipitation by 81 mm, and the HTC was 1.25. Dry conditions prevailed in May and June. In these months, the average daily temperature was higher than the long-term norm by 0.8 and 1.0 °C, the amount of precipitation was less by 25 and 32 mm, and the HTC was 0.61 and 0.62. The rest of the months were favorable for sweet sorghum plants.

Statistical analysis

Research data were analyzed with the technique of analysis of variance (ANOVA). The least significant difference (LSD, $P<0.05$) test was used to assess significant differences between individual means. Correlation-regression dependencies between research data were determined with the use of Microsoft Excel, version 2010 (USA).

RESULTS AND DISCUSSION

The results of the research showed that, on average for 2021 to 2023, the biomass yield of sweet sorghum stems in the control without fertilizers was 56.1 t ha^{-1}, leaves of 18.0 t ha^{-1}, and total biomass of 74.1 t ha^{-1} (Table 3). Sweet sorghum showed high adaptability to cultivation in conditions of unstable moisture on typical chernozems. The accumulation of biomass by sweet sorghum plants occurred more intensively in stems, the mass of which exceeded the mass of leaves by 3.1 times. These results are consistent with the findings of Singh et al. (2012), where 73% of the total biomass of sweet sorghum was accumulated in stems, 13% in leaves.

Table 3. Effect of fertilizers on the yield of biomass and sugar accumulation in sorghum stems.

Treatment	Year			Mean	Increase (%)
	2021	2022	2023		
Stems yield (t ha^{-1})					
Without fertilizers (control)	44.1±3.4	61.0±5.0	63.2±5.0	56.1±4.1	-
$N_{60}P_{30}K_{30}$	49.0±4.2	75.8±6.7	70.2±5.8	65.0±5.1	15.9
$N_{90}P_{60}K_{60}$	57.3±5.0	87.2±7.5	72.1±5.8	72.2±5.6	28.7
$N_{120}P_{90}K_{90}$	62.2±5.0	84.0±6.7	85.1±7.5	77.1±5.9	37.4
estimated rate $N_{110}P_{45}K_{55}$	60.1±5.0	85.4±7.1	77.1±6.7	74.2±5.7	32.3
LSD (*P*<0.05)	3.2	4.8	4.6	3.8	-
Leaves yield (t ha^{-1})					
Without fertilizers (control)	16.0±1.6	20.9±1.6	17.1±1.6	18.0±1.5	-
$N_{60}P_{30}K_{30}$	17.8±1.6	25.3±2.1	23.5±1.6	22.2±1.7	23.3
$N_{90}P_{60}K_{60}$	22.1±1.6	29.3±2.6	23.9±1.6	25.1±1.8	39.4
$N_{120}P_{90}K_{90}$	23.2±1.6	30.8±2.6	24.0±1.6	26.0±1.8	44.4
estimated rate $N_{110}P_{45}K_{55}$	23.3±1.6	30.2±2.6	22.4±1.6	25.3±1.8	40.6
LSD (*P*<0.05)	1.4	1.5	1.3	1.3	-
Sugar content in sorghum stems (%)					
Without fertilizers (control)	17.0±1.4	13.6±1.2	14.1±1.2	14.9±1.1	-
$N_{60}P_{30}K_{30}$	17.1±1.4	14.0±1.2	14.5±1.2	15.2±1.1	2.0
$N_{90}P_{60}K_{60}$	17.4±1.4	14.5±1.2	14.9±1.2	15.6±1.2	4.7
$N_{120}P_{90}K_{90}$	17.4±1.4	14.7±1.2	14.7±1.2	15.6±1.2	4.7
estimated rate $N_{110}P_{45}K_{55}$	17.3±1.4	14.7±1.2	14.8±1.2	15.6±1.2	4.7
LSD (*P*<0.05)	0.6	0.5	0.5	0.5	-

The application of mineral fertilizers significantly (*P*<0.05) increased the biomass yield of sweet sorghum stems. Specifically, the $N_{60}P_{30}$K30, $N_{90}P_{60}K_{60}$, and $N_{120}P_{90}K_{90}$ doses resulted in yields of 65.0, 72.2, and 77.1 t ha^{-1}, respectively, while the estimated optimal dose ($N_{110}P_{45}K_{55}$) produced 74.2 t ha^{-1}. Compared with the unfertilized control, the $N_{60}P_{30}K_{30}$ dose increased stem biomass yield by 8.9 t ha^{-1} (15.9%), $N_{90}P_{60}K_{60}$ by 16.1 t ha^{-1} (28.7%), $N_{120}P_{90}K_{90}$ by 21.0 t ha^{-1} (37.4%), and the estimated $N_{110}P_{45}K_{55}$ dose by 18.1 t ha^{-1} (32.3%). The highest stem biomass yields were obtained with the $N_{120}P_{90}K_{90}$ treatment and the estimated $N_{110}P_{45}K_{55}$dose. These fertilization systems have enhanced nitrogen nutrition, indicating the leading role of nitrogen in increasing the biomass yield of sweet sorghum stems. These results are consistent with the findings of Olugbemi and Ababyomi (2016), where a nitrogen dose of 120 kg ha^{-1} provided the highest growth parameters of sorghum plants – height, leaf area index, crop growth rate, fresh and dry stalk yield. They are also consistent with the findings of Zaituniguli et al. (2021) on the importance of optimizing the composition of fertilizers, a factor that allows for increasing the biomass yield of sweet sorghum by 30–48%.

Favorable conditions for growing sweet sorghum were observed in 2022 and 2023. In these years, sweet sorghum was better supplied with moisture during the growing season (HTC=1.25–1.28) than in 2021 (HTC=1.03). The fertilizer doses of $N_{120}P_{90}K_{90}$ and the estimated doses of $N_{110}P_{45}K_{55}$ showed the highest efficiency: the yield of stems (85.4 and 77.1 t ha^{-1}), the increase compared to the control without fertilizers, 49 and 22%, respectively.

The application of mineral fertilizers significantly increased the development of leaf biomass of sweet sorghum. The dose of $N_{120}P_{90}K_{90}$ fertilizers provided the greatest increase in leaf yield compared to the control without fertilizers, by 44.4%; the smallest increase was for doses of $N_{60}P_{30}K_{30}$, by 23.3%. The estimated dose of $N_{110}P_{45}K_{55}$ was determined to be effective: the yield of leaves was 26.0 t ha^{-1}, with growth compared to the control without fertilizers by 40.6%. Fertilization systems with enhanced nitrogen nutrition had a more pronounced effect on the yield of leaf biomass. These results are consistent with the findings of Holou and Stevens (2012), who noted that significant increases in sweet sorghum biomass could be achieved when nitrogen was applied at a rate of more than 67 kg ha^{-1}.

In 2022, sweet sorghum plants had the highest yield of leaves: 20.9 t ha^{-1} in the control without fertilizers, 25.3–30.8 t ha^{-1} with the application of mineral fertilizers. It was a year when an excessive amount of precipitation fell during the growing season, and the temperature regime slightly exceeded the average long-term norm.

The accumulation of sugars in the stems of sweet sorghum is a significant factor affecting the production of bioethanol. The higher sugar content of the stem juice causes a greater output of bioethanol, which is formed in the process of fermentation of sugar by alcoholic yeast. On average, during the years 2021 to 2023, the sugar content of the stem juice was 14.9%. In the drier year 2021 (HTC=1.03), it was the highest (17.0%), and in the years with more precipitation (2022 to 2023), the sugar content of the juice decreased to 13.6–14.1%. Dry weather conditions contributed to an increase in the accumulation of sugars in the stems of sweet sorghum by 2.9–3.4%, while the yield of the stems decreased by 38–43%.

The application of mineral fertilizers increased the sugar content of stem juice compared to the control without fertilizers by 0.3–0.7 absolute (%). Similar results were obtained by Holou and Stevens (2012), where the application of nitrogen fertilizers increased the sugar content in sweet sorghum juice. For the $N_{60}P_{30}K_{30}$ dose, sugar content reached 15.2%, and for the $N_{90}P_{60}K_{60}$ dose, it was 15.6%, compared with 14.9% in the unfertilized control. The high $N_{120}P_{90}K_{90}$ dose and the estimated $N_{110}P_{45}K_{55}$ dose significantly increased ($P<0.05$) the sugar content of stem juice relative to the control, reaching an absolute value of 15.6%. This regularity was manifested in all years of research and did not depend on weather conditions. This gives reason to believe that mineral fertilizers in a dose higher than $N_{90}P_{60}K_{60}$ increase the yield of sweet sorghum biomass and do not affect the sugar content of stem juice. These results are consistent with the study by Almodares et al. (2008), where application of $N_{90}P_{25}$ increased total sugar in sorghum stems by 39.3%, and sucrose content by 9%.

The variance analysis of the research results showed that fertilizers and weather conditions had a dominant influence on the yield of sweet sorghum biomass. The contribution of fertilizers to stem yield was 28% and to leaf yield 41%, while weather conditions accounted for 55 and 41%, respectively. Sugar accumulation in stems was primarily determined by yearly weather conditions, which explained 57% of the variation, whereas fertilizers contributed only 3% (Figure 1).

The yield of stems and the sugar content of the stem juice of sweet sorghum are the basic factors that determine the production of bioethanol. An increase in the yield of stems increases the yield of juice, and an increase in the content of sugars in the juice significantly increases the volume of sugar output. An increase in both parameters leads to an increase in bioethanol production. The average output of bioethanol in control without fertilizers was 2.68 t ha^{-1} over the years of research (Figure 2). The use of fertilizers increased bioethanol output by 18.3–44.8%. With the $N_{60}P_{30}K_{30}$ dose, bioethanol production reached 3.17 t ha^{-1}; with $N_{90}P_{60}K_{60}$, it reached 3.62 t ha^{-1}; with $N_{120}P_{90}K_{90}$, 3.88 t ha^{-1}; and with the estimated $N_{110}P_{45}K_{55}$ dose, 3.73 t ha^{-1}. The $N_{120}P_{90}K_{90}$ dose and the estimated $N_{110}P_{45}K_{55}$ dose resulted in the highest bioethanol yields, increasing production by 1.05–1.20 t ha^{-1} compared to

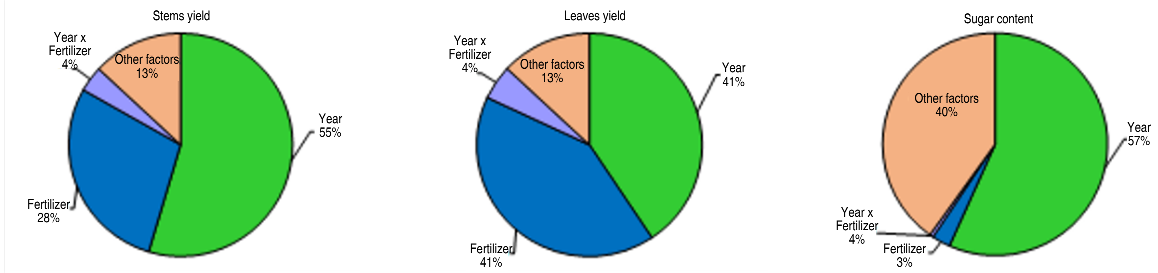

Figure 1. Influence of researched factors on the indicators of sweet sorghum productivity, 2021–2023 years.

the unfertilized control. These results are consistent with the findings of Xuan et al. (2017) regarding the maximum ethanol yield from sweet sorghum at the fertilizer rate of $N_{90}P_{90}K_{60}$ and with the findings of Olugbemi and Ababyomi (2016) regarding the high efficiency of the nitrogen dose of 120 kg ha^{-1}.

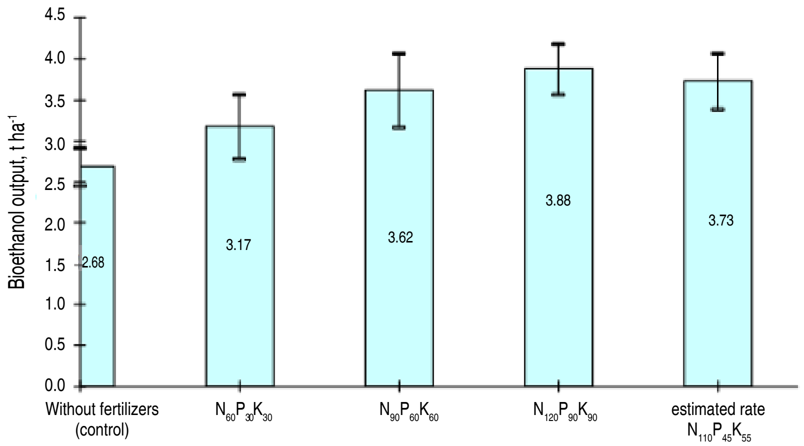

Figure 2. Effect of fertilizers on the output of biofuel from sweet sorghum, 2021 to 2023.

A strong linear correlation was established between the stem yield of sweet sorghum and bioethanol output with a coefficient of determination of 0.9992 (Figure 3).

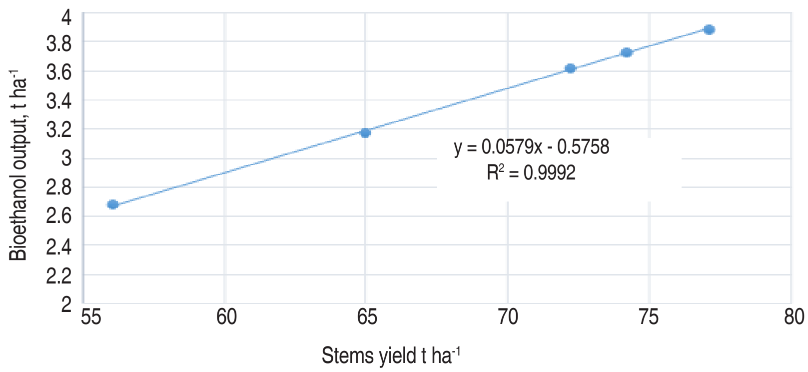

Figure 3. Correlation between stem yield of sweet sorghum and bioethanol output, 2021 to 2023.

An important aspect of growing sweet sorghum for bioethanol and other energy purposes is achieving sustainable conditions. Fertilizers should be applied in an amount that creates a balance between the application of nutrients into the soil and their removal by plants. Such a fertilization system preserves the fertility of the soil and forms a sustainable underground for cultivation. Applying too low doses of fertilizers leads to gradual depletion of soil, while too high doses of fertilizers increase the risks of environmental pollution and economic costs.

The research results showed that sweet sorghum accumulated a significant amount of nutrients in the biomass at the time of harvesting. On average, for the years 2021 to 2023, the stems of sweet sorghum in the control without fertilizers contained dry matter (23.1%), nitrogen (0.72%), phosphorus (0.21%), and potassium (1.04%); leaves (35.7, 1.03, 0.28, and 0.92%), respectively (Table 4). The leaves had a higher content of dry matter, nitrogen, and phosphorus, and the stems had a higher content of potassium. The use of fertilizers did not significantly affect the chemical composition of plant biomass.

Table 4. Content of dry matter and nutrients in sweet sorghum depending on fertilization (%), 2021 to 2023.

Treatment	Stems				Leaves			
	Dry matter	N	P	K	Dry matter	N	P	K
Without fertilizers (control)	23.1±1.7	0.72±0.05	0.21±0.02	1.04±0.07	35.7±2.4	1.03±0.07	0.28±0.02	0.92±0.06
$N_{60}P_{30}K_{30}$	24.2±1.8	0.73±0.06	0.21±0.02	1.04±0.06	37.0±2.5	1.04±0.08	0.29±0.03	0.95±0.07
$N_{90}P_{60}K_{60}$	23.8±1.8	0.72±0.05	0.20±0.01	1.08±0.08	36.8±2.5	1.07±0.08	0.28±0.02	0.93±0.07
$N_{120}P_{90}K_{90}$	24.0±1.7	0.74±0.06	0.22±0.03	1.07±0.07	37.1±2.6	1.06±0.08	0.30±0.03	0.97±0.08
Estimated rate $N_{110}P_{45}K_{55}$	24.0±1.7	0.73±0.05	0.21±0.02	1.09±0.08	37.1±2.6	1.07±0.09	0.29±0.03	0.96±0.08
LSD (P<0.05)	0.7	0.02	0.01	0.03	0.11	0.04	0.01	0.03

Nutrient removal by sweet sorghum plants depended on the yield of biomass and the nutrient content in it.

On average across the research years, the lowest nutrient removal occurred in the unfertilized control. In this treatment, stems removed 95 kg ha^{-1} of nitrogen, 28 kg ha^{-1} of phosphorus, and 139 kg ha^{-1} of potassium, while leaves removed 69, 18, and 61 kg ha^{-1}, respectively (Table 5). Stems absorbed substantially more nutrients than leaves, with uptake being 1.38 times higher for nitrogen, 1.56 times higher for phosphorus, and 2.28 times higher for potassium. The highest nutrient removal was recorded under the $N_{120}P_{90}K_{90}$ mineral fertilizer dose. In this treatment, total nutrient uptake by the biological harvest (stems + leaves) reached 239 kg ha^{-1} of nitrogen, 70 kg ha^{-1} of phosphorus, and 292 kg ha^{-1} of potassium. Compared with the unfertilized control, fertilizer application increased nutrient removal by the biological harvest by 1.46–1.52 times, and nutrient uptake by stems alone by 1.42–1.45 times.

These results are consistent with the findings of Singh et al. (2012), where with a yield of 19.4 t ha^{-1} dry biomass, sweet sorghum carried out nitrogen (136 kg ha^{-1}), phosphorus (28 kg ha^{-1}), and potassium (81 kg ha^{-1}); with the findings of Han et al. (2011), where an increase in the yield of dry biomass to 40 t ha^{-1} increased the removal of nitrogen, up to 339 kg ha^{-1}, phosphorus (75 kg ha^{-1}), and potassium, up to 300 kg ha^{-1}.

Table 5. Nutrient uptake by sweet sorghum plants depending on fertilization (kg ha^{-1}), 2021 to 2023.

Treatment	Stems			Leaves		
	N	P	K	N	P	K
Without fertilizers (control)	95±9	28±3	139±13	69±6	18±2	61±5
$N_{60}P_{30}K_{30}$	115±10	33±3	164±15	85±8	24±2	78±7
$N_{90}P_{60}K_{60}$	124±11	34±3	186±17	99±9	26±2	86±8
$N_{120}P_{90}K_{90}$	137±12	41±4	198±18	102±9	29±3	94±8
Estimated rate $N_{110}P_{45}K_{55}$	130±12	37±3	194±17	100±9	27±2	90±8

Calculation of the nutrient balance based on their removal by the stems showed that fertilizer application only partially covered the removal of nitrogen and potassium by the sweet sorghum plants and was mostly sufficient to provide the plants with phosphorus. Fertilizers – covered plants' removal for nitrogen by 52–88%, potassium by 18–46%, and the rest of the nitrogen and potassium plants used from the soil (Figure 4). At the dose of $N_{60}P_{30}K_{30}$, the greatest deficit of nutrients was formed in the soil: nitrogen (55 kg ha^{-1}), phosphorus (3 kg ha^{-1}), potassium (134 kg ha^{-1}); and the smallest was at the dose of $N_{120}P_{90}K_{90}$ and was associated only with nitrogen and potassium nutrition: nitrogen deficit (17 kg ha^{-1}), and potassium (108 kg ha^{-1}). At the same time, the balance of phosphorus in the soil was positive in the amount of 49 kg ha^{-1}.

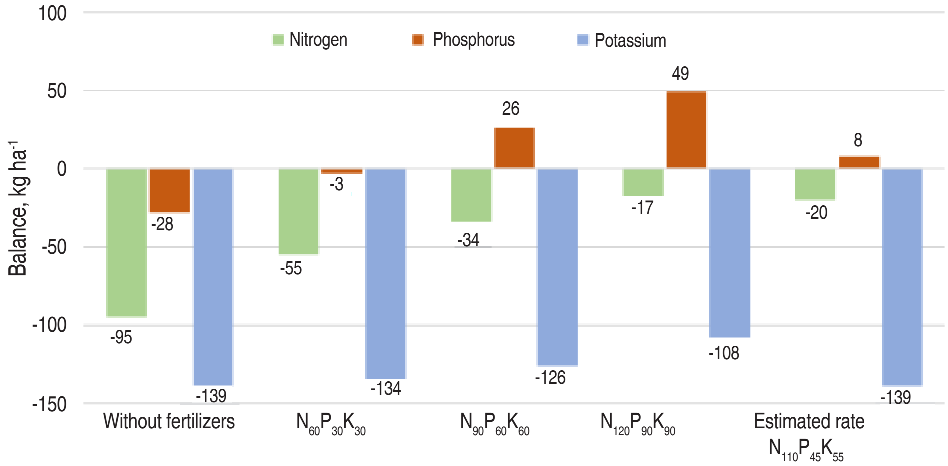

Figure 4. Effect of fertilizers on the nutrient balance in sweet sorghum crops, 2021 to 2023. Note: balance of nutrients was calculated based on their removal by sorghum stems only.

An assessment of fertilizer systems from a sustainable development perspective showed that the fertilizer dose $N_{120}P_{90}K_{90}$ and the calculated dose $N_{110}P_{45}K_{55}$ may be effective only in the short term. On fertile black soils, they are able to provide high yields of sweet sorghum biomass within a short period. In the long term, applying potassium at doses of 55-90 kg ha^{-1} will lead to depletion of the soil in terms of potassium content, worsen potassium nutrition, and cause a decrease in the yield of sweet sorghum. Long-term cultivation of sweet sorghum for bioethanol on chernozem soils in the east of the Forest-Steppe of Ukraine will require a significant increase in the doses of potash fertilizers. Regarding nitrogen nutrition, nitrogen doses of 110-120 kg ha^{-1} covered their removal by plants by 85-88%, which is acceptable for long-term fertilization of sweet sorghum based on sustainable development. A nitrogen deficiency within 15-12% is not critical; it can be compensated for by a legume predecessor, for example, by growing sweet sorghum after soybeans, the area of which in Ukraine exceeds 2 million hectares. Phosphorus fertilizer application at a dose of 45 kg ha^{-1} is sufficient to obtain sustainable yields of sweet sorghum biomass of over 70 t ha^{-1}. This dose is balanced for economic and environmental reasons.

CONCLUSION

Sweet sorghum is well adapted to growing for bioethanol production under unstable moisture conditions in the eastern Forest-Steppe of Ukraine on chernozem soils, and the dose of $N_{120}P_{90}K_{90}$ fertilizers together with the estimated dose of $N_{110}P_{45}K_{55}$ ensured maximum biological productivity, with stem yields of 77.1 and 74.2 t ha^{-1}, a stem sugar content of 15.6%, and a bioethanol output of 3.88 and 3.73 t ha^{-1}. Moreover, in the stem biomass, sorghum plants removed 137 and 130 kg ha^{-1} of nitrogen, 41 and 37 kg ha^{-1} of phosphorus, and 198 and 194 kg ha^{-1} of potassium from the soil, while the fertilizer dose $N_{120}P_{90}K_{90}$ and the estimated dose $N_{110}P_{45}K_{55}$ formed a positive phosphorus balance in the soil of 9–49 kg ha^{-1}, a slight nitrogen deficiency of 17–20 kg ha^{-1}, and an acute potassium deficiency of 108–139 kg ha^{-1}. In the long term, the application of potash fertilizers at a dose of 55–90 kg ha^{-1} will therefore lead to soil depletion in terms of potassium content, create conditions of instability, and require a significant increase in potash fertilizer doses; however, nitrogen doses of 110–120 kg ha^{-1} and phosphorus doses of 45 kg ha^{-1} are sufficient to obtain stable sweet sorghum biomass yields greater than 70 t ha^{-1} on the chernozem soils of the eastern Forest-Steppe of Ukraine and to comply with the principles of sustainable development.

CONFLICT OF INTERESTS

The authors declare no known financial or personal conflicts of interest that could have influenced the work reported in this manuscript.

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