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# Efficiency of mineral fertilizers and biostimulant application in increasing the bioenergy potential of energy crops on low-productivity lands under the conditions of the western Forest-Steppe of Ukraine

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## ABSTRACT

The increase in the cost of traditional energy carriers and the need to diversify fuel resources encourage the search for alternative energy sources, which is critically important for Ukraine's energy security and economic competitiveness. The utilization of the pottential of bioenergy crops makes it possible to effectively involve low-productivity lands, improve the ecological condition of regions, and ensure a stable supply of renewable raw materials for the production of solid and gaseous biofuels. The article presents the results of research on the cultivation of perennial energy crops in the western Forest-Steppe zone. The influence of mineral fertilizers and the biostimulant BlackJak on the productivity of green and dry biomass of Virginia mallow (*Sida hermaphrodit*a), giant miscanthus (*Miscanthus giganteus*), and perennial sorghum (*Sorghum almum*) was analyzed. It was established that intensification of plant nutrition ensured an increase in dry matter yield at the level of 36.5–42.5%, which directly correlates with an increase in energy output. Special attention was paid to the calculated biogas yield, where Virginia mallow was identified as the leader with an indicator exceeding 10000 m³/ha under combined fertilization. The expediency of introducing modern growth stimulants to optimize the bioenergy potential of second-year plantations was substantiated.

**Keywords:** bioenergy crops, sod-podzolic soil, Virginia mallow, perennial sorghum, giant miscanthus, yield, biofuel, mineral nutrition.

## INTRODUCTION

Under modern conditions of global development, humanity faces acute energy and environmental challenges, which necessitates the expansion of production and use of renewable energy sources [Shaikh et al., 2021; Butenko et al., 2025]. Despite Ukraine's significant dependence on imported energy carriers, the share of renewable sources in the total primary energy supply remains low and amounts to only 6.6% [State Statistics Service of Ukraine, 2020; Hryhoriv et al., 2024b]. Given favorable soil and climatic conditions, bioenergy is the most promising direction for renewable energy development in Ukraine; however, the share of biomass energy in final energy consumption currently does not exceed 4.2% [Zheliezna et al., 2018; Vozhehova et al., 2021; Vozhehova et al., 2022]. One of the key reasons for the restrained development of the bioenergy sector is the lack of a systematic approach to forming a raw material base based on the cultivation of specialized bioenergy crops. In the context of global climate change, manifested by rising average annual air temperatures and decreasing precipitation, giant miscanthus, Virginia mallow, and perennial sorghum are becoming particularly relevant as some of the most promising crops for biofuel production [Dar et al., 2018; Stamenkovic et al., 2020; Hryhoriv et al., 2024a]. Belonging to plants with a C4 photosynthesis pathway, they are capable of consistently forming high biomass yields even under conditions of low soil fertility and moisture deficiency, as confirmed by numerous scientific studies [Mehmood et al., 2017; Appiah-Nkansah et al., 2019; Dahlberg, 2019; Ayodele et al., 2020].

Ukraine's Energy Strategy until 2035 defines the expansion of renewable energy use as one of the key tools for strengthening national energy security. According to forecast calculations, the share of alternative energy in the structure of total primary energy supply should increase to 12% in 2025 and reach at least 25% in 2030 [Vozhehova et al., 2022; Karbivska et al., 2022a]. A significant role in achieving these goals is assigned to the development of bioenergy, particularly sectors based on the use of solid biofuels and biogas, ensuring relative stability of bioenergy production and creating prerequisites for expanding generation capacities at the regional level.

Strategic priorities include the combined production of heat and electricity in cogeneration plants, as well as the gradual replacement of fossil fuels with renewable energy sources. It is expected that by 2035 the bioenergy sector will supply about 11 million tons of oil equivalent, corresponding to 11.5% of total primary energy supply [Energy Strategy of Ukraine, 2017].

An important aspect is the structure of Ukraine's energy consumption, which directly determines the nature and scale of demand for various types of fuels produced from plant biomass [Fuchylo et al., 2022; Karbivska et al., 2022b]. Biofuels, similar to fossil fuels, are classified into solid, liquid, and gaseous forms, with their use varying significantly depending on economic sectors.

According to calculations, Ukraine has significant potential for forming a raw material base for plant bioenergy. The theoretical biomass potential is estimated at nearly 50 million tons of oil equivalent, while the economically feasible volume of its use ranges from 2 to 27 million tons. For non-traditional perennial herbaceous energy crops, such as silphium, Jerusalem artichoke, miscanthus, and Virginia mallow, the production potential is estimated at 0.60 and 0.35 million tons, respectively [Kurhak et al., 2013; Kurhak et al., 2021; Voytovyk et al., 2024].

The introduction of new high-yielding herbaceous energy crops into production, which are still insufficiently widespread in Ukraine's agricultural sector, is characterized by several significant advantages. Heat energy output per unit area varies considerably depending on the crop species [Kurhak and Tkachenko, 2016; Radchenko et al., 2022]. In particular, Virginia mallow and miscanthus exhibit the highest energy potential, making them suitable for solid biofuel production [Heletukha et al., 2010].

Analysis of scientific sources [Heletukha et al., 2013; Roik et al., 2011; Dumych et al., 2013] indicates that studies on assessing the energy potential of perennial herbaceous phytocenoses in Ukraine and developing measures to increase their energy productivity remain fragmented and limited. The need for deeper research is driven, on the one hand, by the rising cost of non-renewable energy resources and, on the other hand, by reduced demand for forage grasses due to declining livestock numbers [Kurhak, 2010; Zheng et al., 2024].

Therefore, one of the priority tasks for researchers and agricultural practitioners is the development and improvement of technologies for growing energy crops, along with comprehensive economic and energy justification considering specific soil and climatic conditions of cultivation regions [Fedorchuk et al., 2017; Voitovyk et al., 2023].

The productivity of energy crop agrocenoses and the volumes of biofuel obtained from them remain limited due to the lack of scientifically substantiated cultivation technologies with an energy orientation, particularly on lands with reduced natural fertility. Increasing energy crop yields is thus a crucial prerequisite for activating the development of the national bioenergy sector, strengthening energy independence, and fulfilling Ukraine's strategic commitments toward a climate-neutral economic model.

## MATERIAL AND METHODS

The research was conducted during 2024–2025 at the experimental site of the Department of Forestry and Agricultural Management of Vasyl

Stefanyk Precarpathian National University. The soil of the experimental plot was sod-podzolic, surface-gleyed, heavy loam with a coarse-silty structure. Agrochemical characteristics of the arable layer were as follows: humus content (Tyurin method) – 1.76%; alkaline hydrolyzable nitrogen (Kornfield method) – 63.0 mg $kg^{-1}$; mobile phosphorus and potassium (Machigin method) – 49 and 119 mg $kg^{-1}$; hydrolytic acidity (Kappen method) – 2.9 mg-eq/100 g; salt pH – 5.0; sum of absorbed bases – 12.4 mg-eq/100 g.

Field experiments were established as a two-factor design. The sowing plot area was 50 m², accounting area 30 m², total experimental area 0.36 ha, with four replications. Three bioenergy crops were studied: Virginia mallow (*Sida hermaphrodita* Rusby), cultivar Virginia; perennial sorghum (*Sorghum almum* Parodi), cultivar Columbo; and giant miscanthus (*Miscanthus giganteus*), cultivar Autumn Star. Crops were grown under the following fertilization schemes: 1. No fertilizers (control); 2. $N_{65}P_{45}K_{65}$; 3. BlackJak; 4. $N_{65}P_{45}K_{65}$ + BlackJak.

Superphosphate (32% $P_2O_5$), KalPro40 (40% $K_2O$), ammonium nitrate (34.4% N), and the biostimulant BlackJak were applied according to the experimental scheme.

BlackJak is a highly effective concentrated preparation based on natural humic substances, widely used in agriculture as a biostimulant and soil anti-stress agent. It is produced from high-quality leonardite and contains humic and fulvic acids, as well as ulmic acids and humin.

Biofuel output (bioethanol, biogas, and solid biofuel) and energy productivity indicators were determined according to the methodological recommendations of the Institute of Bioenergy Crops and Sugar Beets of NAAS [Hanzhenko et al., 2020]. Statistical processing was performed using descriptive statistics and ANOVA in Statistica 12 [Ermantraut et al., 2007]. Meteorological conditions during 2024–2025 were characterized by deviations from long-term averages; however, the hydrothermal coefficient indicated sufficient moisture availability, and the accumulated active temperatures were favorable for crop development.

## RESULTS AND DISCUSSION

Within the structure of renewable energy sources in Ukraine, the segment of solid biofuels predominates, represented mainly by fuel pellets, briquettes, and wood chips. The traditional raw material base for their production consists of by-products of the wood-processing industry and crop residues from the agricultural sector. However, the use of such biomass is limited by the instability of supply due to seasonal fluctuations. In addition, a high concentration of mineral impurities (ash content up to 10%) negatively affects the calorific value and operational characteristics of the final energy product.

Among the most efficient bioenergy crops, giant miscanthus occupies a leading position due to its agrobiological characteristics, which allow obtaining up to 25 t $ha^{-1}$ of dry biomass with a specific calorific value of approximately 18 MJ $kg^{-1}$. Optimal moisture content at harvest simplifies further processing. An alternative renewable energy source is perennial sorghum, which, together with miscanthus, demonstrates the ability to maintain stable yields on low-productivity and eroded soils, contributing to rational land use.

According to the research results, the highest accumulation of vegetative mass was observed in giant miscanthus and Virginia mallow (Table 1). The green biomass yield of miscanthus amounted to 34.2 t $ha^{-1}$ under control conditions (without fertilizers) and increased to 47.8 t $ha^{-1}$ under fertilization. For Virginia mallow, the respective values were 33.5 and 47.1 t $ha^{-1}$. The lowest yield among the studied crops was recorded for perennial sorghum (29.4 and 39.2 t $ha^{-1}$, respectively).

**Table 1.** Green biomass yield of energy crops in the 2nd year of vegetation, t $ha^{-1}$

| Fertilization variant | Green mass yield, t $ha^{-1}$ | | |
|---|---|---|---|
| | Virginia mallow | Perennial sorghum | Giant miscanthus |
| No fertilizers (control) | 33.5 | 29.4 | 34.2 |
| $N_{65}P_{45}K_{65}$ | 43.7 | 33.8 | 44.4 |
| BlackJak | 39.9 | 33.1 | 41.0 |
| $N_{65}P_{45}K_{65}$+BlackJak | 47.1 | 39.2 | 47.8 |
| $LSD_{05}$ | 1.54 | 0.76 | 1.78 |

It was established that the highest increase in green biomass yield was achieved under the combined application of mineral fertilizers and the humic biostimulant BlackJak. Yield increments ranged from 36.5 to 42.5%, depending on crop species. Our research results are confirmed by the studies of Shelenko, Gusak and others [2025], who reported that the efficiency of energy crop cultivation is closely correlated with soil and climatic conditions, while balanced mineral nutrition serves as the key factor in intensifying growth processes. A rational fertilization strategy not only maximizes biomass output but also contributes to maintaining a positive nutrient balance in the soil profile [Dar et al., 2018; Shelenko et al., 2025]. Dry matter yield is of particular importance, as it represents the primary raw material for biofuel production (Table 2).

Among the studied crops, Virginia mallow demonstrated the highest dry matter productivity in the second year of vegetation. Under control conditions, its yield reached 10.8 t $ha^{-1}$, exceeding giant miscanthus by 3.8 t $ha^{-1}$ and perennial sorghum by 4.6 t $ha^{-1}$.

The analysis of fertilization systems showed that the most significant yield increase for all crops was ensured by the combined application of mineral fertilizers ($N_{65}P_{45}K_{65}$) and BlackJak. Under this variant, dry biomass yield increased to 20.1 t $ha^{-1}$ for Virginia mallow, 13.9 t $ha^{-1}$ for perennial sorghum, and 14.5 t $ha^{-1}$ for giant miscanthus.

It should be noted that the independent application of BlackJak proved to be an effective agronomic practice, increasing dry matter yield by 24–35% compared to the control. This indicates a strong stimulatory effect of the biostimulant on root system development in second-year crops.

Although perennial sorghum exhibited lower absolute yield values, it demonstrated the highest relative response to complete fertilization, doubling dry biomass yield compared to the unfertilized variant (from 6.2 to 13.9 t $ha^{-1}$). The $LSD_{05}$ values confirm the statistical significance of the differences between experimental variants.

The obtained results are consistent with studies conducted by Borkowska et al. [2009] and Kalembasa and Symanowicz [2012], which emphasize the high adaptive potential of perennial bioenergy crops. Polish researchers [Krzyżaniak et al., 2019; Radchenko et al., 2024] reported that Virginia mallow is capable of forming substantial biomass even at early growth stages under balanced nutrition. Similar conclusions regarding miscanthus productivity on marginal lands were drawn by Heaton et al. [2008], who noted yield increases of 40–60% under optimized nitrogen fertilization.

As a result of our research, we determined the estimated biogas yield with the yield of energy crops (Table 3). Based on the obtained dry biomass yields, the calculated biogas output varied from 3150 to 10050 $m^3$/ha, depending on crop species and fertilization system.

The highest biogas yield on sod-podzolic soils of the western Forest-Steppe was obtained from Virginia mallow under the combined application of mineral fertilizers and BlackJak (10050

**Table 2.** Dry biomass yield of energy crops in the 2nd year of vegetation, t $ha^{-1}$

| Fertilization variant | Dry mass yield, t $ha^{-1}$ | | |
|---|---|---|---|
| | Virginia mallow | Perennial sorghum | Giant miscanthus |
| No fertilizers (control) | 10.8 | 6.2 | 7.0 |
| $N_{65}P_{45}K_{65}$ | 16.4 | 9.3 | 11.5 |
| BlackJak | 14.6 | 8.4 | 10.7 |
| $N_{65}P_{45}K_{65}$+BlackJak | 20.1 | 13.9 | 14.5 |
| $LSD_{05}$ | 1.84 | 0.79 | 1.23 |

**Table 3.** Calculated biogas yield depending on crop species and fertilization system, $m^3$/ha

| Fertilization variant | Dry biomass collection, t $ha^{-1}$ | | |
|---|---|---|---|
| | Virginia mallow | Perennial sorghum | Giant miscanthus |
| No fertilizers (control) | 5400 | 3150 | 3720 |
| $N_{65}P_{45}K_{65}$ | 8200 | 5175 | 5580 |
| BlackJak | 7300 | 4815 | 5040 |
| $N_{65}P_{45}K_{65}$+BlackJak | 10050 | 6525 | 8340 |

m³/ha), which is directly related to its highest dry biomass productivity.

At the same time, the greatest relative increase in energy productivity was observed for giant miscanthus. The application of $N_{65}P_{45}K_{65}$ + BlackJak increased biogas output by 4620 m³/ha, or 2.24 times, compared to the control. The independent application of BlackJak also proved effective across all crops; for miscanthus, the increase amounted to 1320 m³/ha, confirming the feasibility of using biostimulants to enhance the energy potential of second-year plantations.

## CONCLUSIONS

The combined application of mineral fertilizers and the biostimulant BlackJak on sod-podzolic soils is a highly effective method for intensifying the growth of second-year energy crops. Virginia mallow achieved the highest dry biomass yield (20.1 t ha$^{-1}$) under the $N_{65}P_{45}K_{65}$ + BlackJak treatment, exceeding the control by 86%. Under the same fertilization scheme, giant miscanthus and perennial sorghum produced 14.5 and 13.9 t ha$^{-1}$, respectively. The use of BlackJak as an independent technological element increased dry matter yield by 24–35%, stimulating root system development. Perennial sorghum exhibited the highest response to complete fertilization, doubling biomass yield compared to the unfertilized background.

Calculated biogas yield showed a direct dependence on crop yield and species. The highest energy potential was recorded for Virginia mallow (10050 m³/ha), while giant miscanthus and perennial sorghum provided 8340 and 6525 m³/ha, respectively. These results confirm the feasibility of integrating biostimulants into fertilization systems to maximize biofuel output and ensure rational use of low-productivity lands.

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