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Sustainable energy and biofuel potential of energy willow (*Salix* L.) biomass in the first year after harvesting in a long growing cycle

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ABSTRACT

In the context of the objective threat of depletion of fossil fuels used to meet human needs, the issue of finding alternative sources to meet energy demands is becoming increasingly relevant. Currently, the primary task of national energy strategies is the search for and utilization of alternative types of fuel, characterized by their environmental friendliness and renewability. The production and use of biomass are still less efficient compared to traditional types of fuel. This is due to several factors, such as insufficient government support, underdeveloped material and technical infrastructure, and the dependence of its efficiency on market prices relative to conventional fuels. In recent years, there has been active development of bioenergy crops. However, a number of issues require resolution. The yield of bioenergy crops directly depends on climatic, soil, and other conditions. The results of the conducted studies indicate that the highest shoot height of energy willow in the first year after harvest, reaching 422 cm, was obtained with a planting density of 12 thousand plants ha^{-1}. In this variant, the diameter of the central shoot was 18 mm, and the average number of shoots per plant was 36. The latest biometric measurements showed a tendency for a sharp increase in the vegetative mass of energy willow. During this period, plant height ranged from 409 to 435 cm, and the diameter of the central shoot ranged from 26 to 35 mm. The highest shoot height, 435 cm, was recorded in the variant with a planting density of 5.6 thousand plants ha^{-1}. It was found that the highest biomass yield of energy willow in the first year after harvest was achieved with a planting density of 15 thousand plants ha^{-1} and the application of mineral fertilizers. This yielded 56.2 t ha^{-1} of green mass and 31.8 t ha^{-1} of dry mass. Under the conditions of the reporting year, the highest biomass yield of energy willow in the first year after harvest was obtained with a planting density of 6.7 thousand plants ha^{-1}, amounting to 57.0 t ha^{-1} of green mass and 31.7 t ha^{-1} of dry mass.

Keywords: energy sources, biomass, energy output, solid biofuel, mineral nutrition, yield, bioenergy, energy crops.

INTRODUCTION

Ukraine is an energy-dependent country, with imports of primary energy sources (excluding nuclear power plants) accounting for up to 72%. An important energy strategy for Ukraine involves ensuring the technical and economic feasibility of diversifying energy resource supplies. The priorities of energy policy should include energy efficiency and the use of renewable energy sources (RES), taking into account their environmental impact [Boyko, 2017; Fuchylo et al., 2019; Datsko et al., 2025].

Biomass is the fourth most important fuel in the world, providing approximately 2 billion tons of oil equivalent annually, or 14% of primary energy consumption. Biomass accounts for 70% of renewable energy sources. This creates an urgent need for a swift transition to and rational use of bioenergy resources. These indicators are increasing worldwide, making it crucial for Ukraine to stay aligned with global trends in this area, especially given the country's insufficient self-sufficiency in fuel resources [Sinchenko & Hnap, 2018; Szparaga et al., 2019; Radchenko et al., 2023]. In recent years, there has been active development of bioenergy crops. However, a number of challenges require resolution. The yield of bioenergy crops directly depends on climatic, soil, and other conditions. These crops have varying water requirements and may differ in frost resistance and drought tolerance [Tkachuk, 2019; Voitovyk et al., 2023; Karbivska et al., 2023].

It is also important to highlight the environmental aspect of cultivating and utilizing bioenergy plants. Scientists have calculated that one hectare of energy willow plantations absorbs approximately 200 tons of carbon dioxide from the air annually. This is equivalent to the amount of CO_2 emitted into the atmosphere over the same period by 100 cars. Thus, the cultivation of energy crops contributes to the purification of the atmosphere by reducing harmful chemical compounds and greenhouse gases [Hnap, 2019; Lü et al., 2019; Kolisnyk et al., 2024]. Among the promising crops for green energy, key bioenergy plants include energy willow, poplar, miscanthus, switchgrass, and perennial sida. These crops are low-maintenance in terms of soil and climatic conditions. Due to their long-term continuous cultivation, they improve soil structure, while fallen leaves and root residues left in the soil contribute to enhancing its fertility to some extent [Fuchylo, 2018; Liu et al., 2023; Datsko et al., 2024].

A relevant direction for the development of bioenergy in Ukraine is the establishment of perennial plantations of bioenergy crops, particularly energy willow. Energy willow is the primary energy crop for solid fuel production worldwide. This plant exhibits an exceptionally high biomass growth rate, 14 times greater than naturally growing forests. The average annual yield per hectare ranges from 15 to 30 tons of wood [Roik, 2015; Lys et al., 2018; Sikora et al., 2020; Zakharchenko et al., 2024].

MATERIAL AND METHODS

The research was conducted in the fields of the Prykarpattia State Agricultural Research Station of the Institute of Agriculture of the Carpathian Region. The Precarpathian region is characterized by a moderately warm and humid climate. Meteorological analysis of the conditions formed during the growing season of bioenergy crops is based on data from the Ivano-Frankivsk Regional Meteorological Station Analysis of meteorological conditions for all months included in the study period shows that the year under study (2024) is favorable for growing energy crops. It was found that the year under study was characterized by high temperatures and humidity. All analyzed months were characterized by above-normal temperatures and humidity. The temperatures were particularly high in July, August, and September. Such atmospheric conditions contributed to the rapid ripening of the crop.

Study the growth and development characteristics of energy willow depending on cultivation techniques in the conditions of the Western region for biofuel production during its long-term cultivation was carried out according to the scheme of field research (Table 1). The experimental design involves the influence of several factors on the growth, development, and productivity of the crop: Factor A – planting arrangement scheme: Planting density: 18 thousand ha^{-1}, 15 thousand ha^{-1}, 12 thousand plants ha^{-1}. Factor B – mineral nutrition. The experiment was set up with four replications. The area of the planting plot is 150 m², and the accounting plot is 125 m². The total area of the experimental plots is 0.36 ha.

According to the planting scheme, the crops were planted in paired rows with a spacing of 0.70 m and inter-row distances of 2 m. Traditional research methods were used during the studies. Mathematical analysis of the data was performed with Microsoft Excel 2010 and Statgraphics 18.1 [Ushkarenko, 2013].

RESULTS AND DISCUSSION

In our experiments, it was important to assess the dynamics of biometric indicators of energy willow plants over the years of research, depending on the density of planting and nutritional background. As of June 20, it was determined that the highest plant height of energy willow after cutting during the first half of the year (the ninth year of vegetation), reaching 155 cm, was achieved with a planting step of 50 cm and the application of mineral fertilizers $N_{80}P_{300}K_{300}$. In the first year after cutting during long-term cultivation, a sharp increase in shoot growth was

Table 1. Scheme of experiment

Crop	Planting density Factor A		Mineral nutrition Factor B
Energy willow (*Salix* L.)	1	18 thousand plants ha-1 (planting step 40 cm)	without fertilizers
	2		$N_{40}P_{300}K_{300} + N_{40}$
	3	15 thousand plants ha^{-1} (planting step 50 cm)	without fertilizers
	4		$N_{40}P_{300}K_{300} + N_{40}$
	5	12 thousand plants ha^{-1} (planting step 60 cm)	without fertilizers
	6		$N_{40}P_{300}K_{300} + N_{40}$

observed. The number of shoots across all experimental variants ranged from 24 to 36 per plant. The average shoot diameter in this period ranged from 4 to 9 mm.

The latest biometric measurements, conducted on October 16, revealed that the height of willow shoots ranged from 398 cm to 422 cm. The diameter of the central shoot during this period was between 14 and 18 mm, with the number of shoots ranging from 27 to 38 (Table 2).

The highest shoot height was recorded in the variant with a planting density of 12 thousand plants ha^{-1}, reaching 422 cm. The diameter of the central shoot in this variant was 18 mm, with an average of 36 shoots per plant. In the year of the study, the application of mineral fertilizers ($N_{80}P_{300}K_{300}$) before planting did not significantly affect plant growth.

For cultivating energy crops for biomass, the yield of vegetative mass is one of the decisive criteria, as higher yields result in greater product output and, accordingly, higher profits per unit area [Roik, 2013; Kravchuk, 2013; Zając et al., 2020; Voitovyk et al., 2024]. It was found that the highest biomass yield of energy willow in the first year after harvest was achieved with a planting density of 15 thousand plants ha^{-1} and the application of mineral fertilizers. This produced 56.2 t ha^{-1} of green mass and 31.8 t ha^{-1} of dry mass, which is 6.6 t ha^{-1} and 3.6 t ha^{-1} more, respectively, compared to the variant with a planting density of 18 thousand plants ha^{-1} with fertilizer application (Table 3).

It should be noted that mineral fertilizers provided energy willow plants with sufficient nutrients, which, in turn, contributed to increased yields across all experimental variants. The application of mineral fertilizers resulted in an average yield increase of 1.2 t ha^{-1} of green mass and 0.6 t ha^{-1} of dry mass across the variants.

The research results demonstrated that the highest biofuel output from energy willow was obtained with a planting density of 15 thousand plants ha^{-1} and the application of mineral fertilizers, reaching 35.0 t ha^{-1} (Table 4). The energy yield in this variant was 559.7 GJ ha^{-1}. The energy yield was 526.2 GJ ha^{-1} in the variant with a planting density of 18 thousand plants ha^{-1} and mineral fertilizers, and 471.7 GJ ha^{-1} in the variant with a planting density of 12 thousand plants ha^{-1} and mineral fertilizers. The application of mineral fertilizers ensures an increase in solid biofuel output ranging from 0.5 to 1.9 t ha^{-1} across all experimental variants.

Table 2. Biometric indicators of energy willow plants depending on planting density and nutrition background in the first year after harvest

No. variant	Recording date					
	20.06.2024			16.10.2024		
	Plant height, cm	Number of shoots, pcs.	Diameter of central shoot, mm	Plant height, cm	Number of shoots, pcs.	Diameter of central shoot, mm
1	140	24	4	398	28	14
2	170	25	7	402	27	17
3	135	32	5	408	33	15
4	155	36	7	410	38	17
5	120	31	5	418	34	17
6	140	35	9	422	36	18

Table 3. Biomass yield of energy willow depending on planting density and nutrition background in the first year after harvest

№	Planting density (Factor A)	Mineral nutrition (Factor B)	Green mass yield, t ha^{-1}	Dry mass yield, t ha^{-1}	Content of absolutely dry matter in biomass, %
1	18 thousand plants ha^{-1} (planting step 40 cm)	without fertilizers	49.6	28.2	56.8
2		$N_{40}P_{300}K_{300} + N_{40}$	52.8	29.9	56.6
3	15 thousand plants ha^{-1} (planting step 50 cm)	without fertilizers	55.6	31.4	56.5
4		$N_{40}P_{300}K_{300} + N_{40}$	56.2	31.8	56.6
5	12 thousand plants ha^{-1} (planting step 60 cm)	without fertilizers	46.4	26.0	56.9
6		$N_{40}P_{300}K_{300} + N_{40}$	47.6	26.8	56.4
$LSD_{0,5}$ t ha^{-1}: Factor A Factor B Interaction AB				 2.21 1.89 2.48	

Table 4. Energy and solid biofuel output from the obtained biomass of energy willow in the first year after harvest

No.	Planting density	Mineral nutrition	Dry mass yield, t ha^{-1}	Solid biofuel output, t ha^{-1}	Energy output, gj ha^{-1}
1	18 thousand plants ha^{-1} (planting step 40 cm)	without fertilizers	28.2	31.0	496.3
2		$N_{40}P_{300}K_{300} + N_{40}$	29.9	32.9	526.2
3	15 thousand plants ha^{-1} (planting step 50 cm)	without fertilizers	31.4	34.5	552.6
4		$N_{40}P_{300}K_{300} + N_{40}$	31.8	35.0	559.7
5	12 thousand plants ha^{-1} (planting step 60 cm)	without fertilizers	26.0	28.6	457.6
6		$N_{40}P_{300}K_{300} + N_{40}$	26.8	29.5	471.7

CONCLUSIONS

The research results established that: The highest shoot height of energy willow in the first year after harvest, 422 cm, was achieved in the variant with a planting density of 12 thousand plants ha^{-1}. The diameter of the central shoot in this variant was 18 mm, and the number of shoots per plant was 36.

It was found that the highest biomass yield of energy willow in the first year after harvest was obtained with a planting density of 15 thousand plants ha^{-1} and the application of mineral fertilizers, resulting in 56.2 t ha^{-1} of green mass and 31.8 t ha^{-1} of dry mass. This is 6.6 t ha^{-1} and 3.6 t ha^{-1}, respectively, more compared to the variant with a planting density of 18 thousand plants ha^{-1} and fertilizer application.

According to the research results, the highest biofuel output from energy willow was achieved in the variant with a planting density of 15 thousand plants ha^{-1} and the application of mineral fertilizers, amounting to 35.0 t ha^{-1}. The energy yield in this case was 559.7 GJ ha^{-1}.

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