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Specifics of cultivation, productivity, and energy efficiency of *miscanthus giganteus* for solid biofuel production

Abstract: Miscanthus is one of the most promising energy crops for growing on the infertile soils of Ukraine. Miscanthus cultivation will significantly increase Ukraine's energy independence and reduce the use of solid fuels. The research studies the specifics of using *Miscanthus giganteus* Terravesta AthenaTM. Guidelines have been developed regarding the peculiarities of pre-sowing storage of rhizomes, application of mineral fertilizers, and planting rhizomes in the ridge using GIS technologies. It allows us to obtain high germination capacity (more than 94%), effectively use soil moisture reserves at the beginning of the vegetation period, control weeds, and form the

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yield of vegetative mass at the level of 14.53 t/ha in the first year of vegetation, and in the second year of vegetation, it will achieve a stable yield due to the optimal planting density. Cultivation of *Miscanthus giganteus* of hybrid Terra vesta AthenaTM, especially on marginal lands, will provide valuable raw materials for the production of solid biofuel (pellets) that meets European standards by its essential environmental and energy characteristics.
The energy and calorific value of Miscanthus biomass are high, and less carbon dioxide enters the atmosphere during its burning, which becomes its main advantage over other types of energy crops. The highest economic and energy effect can be obtained if the energy-saving elements of *Miscanthus giganteus* cultivation technology are followed (in particular, reducing the costs for weed control products) when cultivating biomass for biofuel, having created an energy conveyor to supply raw materials to the consumer.

Keywords: cultivation technology, *Miscanthus giganteus*, energy efficiency, yield, solid biofuel

Introduction

A high potential for crop production characterizes Ukraine's agricultural sector (Hadzalo et al. 2018).

In Ukraine, the supply of domestic energy resources comprises only 53%, so it is an energy-deficit country with an annual consumption of about 200 million tons of equivalent fuel (according to the Classifier of the System of Designations for Measurement and Accounting Units https://zkg.ua/aktualnyj-klasyfikator-systemy-poznachen-odynyts-vymiryuvannya-ta-obliku--u-potochnomu-rotsi/; code 0887) (Palamarchuk et al. 2023). That is why the search for alternative energy sources with a constant decrease in the share of fossil fuels, primarily due to the products of the agricultural sector, is relevant and promising for Ukraine (Roik et al. 2013; Diachuk et al. 2017).

In 2021, the annual consumption of liquid fuels in Ukraine was as follows: gasoline – 2.0 million tons, diesel fuel – 5.7 million tons, liquefied propane and butane – 1.3 million tons (OECD 2021; Pryshliak et al. 2022). The total share of energy produced from renewable sources in Ukraine in final gross energy consumption in 2020 was 9.2%, in particular in the power industry – 13.9%; in heating systems – 9.3%; in the transport sector – 2.5% (Heletukha and Zheliezna 2023). Own production of raw materials – oil and gas condensates – provides only 20% of this amount; the rest of the gasoline is produced from imported oil or imported from neighboring countries (Holub et al. 2017).

There is a rapid increase in the production of traditional energy carriers, including oil, gas, and coal (Gontaruk et al. 2024). During just one century, people have used up the central part of the most valuable hydrocarbon resources, which have been created in the Earth's interior for hundreds of millions of years (Mills 2019; Litvinenko 2020). One of the reserves for replacing natural minerals is the biofuel production technology that uses renewable bio raw materials

(Kaletnik et al. 2020, 2021). Scientists have calculated that in the future, in a short period (5–
–15 years), current oil reserves will be used by 60–65%, the production will decrease by 30–40%, and the need for consumption will increase. However, the world reserves of natural gas will be enough for only 50–60 years, coal for 500–600 years (Biletsky et al. 2018).

1. Literature review

The possibility of growing the bioenergy crop *Miscanthus giganteus* on Ukraine's infertile soils (which, according to experts, range from 3 to 8 million hectares) will ensure obtaining raw materials for the production of solid fuel, wood-pulp products and biogas, which will reduce Ukraine's dependence on imported energy resources (Roik et al. 2019).

Among all types of energy crops, representatives of the leguminous (cereal) family are the most common in Ukraine: Miscanthus, sugar sorghum, switchgrass, etc. Willow clones and varieties of Paulownia are less common but highly productive in biomass formation and energy output per unit area (Kulyk et al. 2023).

Miscanthus is a perennial grass, and according to the botanical classification, it belongs to the family of grasses, genus Viialnyk or Miscanthus (Miscanthus Anderss), tribe sorghum (Roik et al. 2019). Like all breads of the second group, it is a typical representative of plants of C4 photosynthesis type (Kaletnik et al. 2020).

Miscanthus can be grown in the same area for over 20 years or more, with an annual productivity of 20-25 tons of dry mass per hectare. Miscanthus is reproduced by seeds, clonal micropropagation (through in vitro culture), division of the uterine rhizome (rhizomes), and cuttings (rooting of internodes) (Roik et al. 2019; Nedilska 2021).

When burning Miscanthus biomass, a small amount of carbon monoxide is released, compared to what plants accumulate in photosynthesis, which in turn will reduce the greenhouse effect (Horb et al. 2019). It was found that Miscanthus has a positive effect on soil fertility indicators; in particular, according to Roik et al. (2019), its four-year cultivation in one place accumulates 15–20 t/ha of rhizomes, which corresponds to 7.2–9.2 t/ha of carbon (Roik et al. 2019).

Miscanthus giganteus is a raw material used to produce alternative fuels and organic material from waste (Vo´ca et al. 2021).

The technologies of Miscanthus cultivation and techniques that are used in Ukraine do not always contribute to obtaining the potential yield and quality of bio raw material, which ultimately affects the cost of the obtained products (Honcharuk et al. 2023). In this regard, there arises the issue of optimizing the cultivation technology and substantiating the effectiveness of its main elements depending on the bioclimatic potential of the cultivation zone and hydrothermal conditions, taking into account the genetic characteristics of a specific variety or hybrid (Dekovets et al. 2021).

The soil and climatic conditions of most regions of Ukraine are favorable for the cultivation of perennial energy plants of the C4 group that can intensively transform sun energy into energy-intensive biomass, in particular in the conditions of global climate change (Lohosha et al. 2024). The use of Miscanthus for growing as a typical representative of the C4 type of photosynthesis in warming conditions will increase the assimilation of carbon dioxide due to the increase in the intensity of photosynthesis, will not require high soil fertility, intensive use of fertilizers and pesticides, will contribute to the reduction of erosion processes, preservation and improvement of agroecosystems (Palamarchuk et al. 2023).

Miscanthus products are widely used in various sectors of the national economy, but mostly in bioenergetics as solid fuel and even bioethanol and plastics (Yasnolob et al. 2019). Organic matter can be used as fertilizers, raw material for the production of cellulose and paper (fibers for lining packages, technical paper) (Kharitonov et al. 2020), building materials (lightweight concrete, construction, and insulating boards, plasters for exterior and interior works, sound insulation, window and door frames, roofs) (Kalenska et al. 2022), as bedding for animals and poultry that can hold three times more moisture than its mass and ensure more hygienic properties than cereal straw (Yastremska et al. 2017), as a raw material for injection molding of products from organic polymers that are decomposed by microorganisms, agricultural materials (pots for planting vegetables and flowers, threads and high-strength fibers for car body parts), for decorative purposes for landscaping decorative ponds, flower beds, gardens (Roik et al. 2019).

The study of adaptive technologies for the cultivation of *Miscanthus giganteus*, taking into account its biological features in the conditions of global warming and the shortage of traditional types of fertilizers on low-fertile soils of Ukraine, is an important scientific task regarding energy security and has high relevance, practical significance, and scientific novelty.

The research aimed to study the peculiarities of forming *Miscanthus giganteus* productivity and energy efficiency due to optimizing its cultivation technology.

2. Materials and methods

The research was conducted in 2023 to study the formation of *Miscanthus* productivity in the conditions of Miscanthus Technology LLC, the village of Kamianyi Brid, Zviahilivskyi district, Zhytomyr region.

The soil of the experimental site was sod poorly podzolic clay-sandy in terms of its mechanical composition. The humus-eluvial horizon had s a light gray color with an 18–22 cm thickness. The depth of groundwater was more than 1.8 meters. Humus content (according to Tiurin) in the upper layer of the soil was 2.55–2.64%; its amount decreased sharply with depth, and it was practically absent at a depth of 50–60 cm. The soil had an acidic reaction with the soil solution pH 5.27–5.36, high hydrolytic acidity, a low amount of absorbed bases, and saturation with bases. The content of easily hydrolyzed nitrogen was 67.2–70 mg/kg, mobile phosphorus – 86–95 mg/kg, exchangeable potassium – 62–66 mg/kg, calcium – 2.44–2.81 mmol/100g, and magnesium – 0.38–op 0.44 mmol/100 g.

The technology was generally accepted except for the factors that were studied. Soybean was a preceding crop. Tillage included under-winter plowing to a depth of 20–22 cm. In the process of the primary tillage, liming was carried out on the area set aside for *Miscanthus* planting at the rate of 600 kg/ha of limestone material. After applying lime, the soil was cultivated by disking. Cultivation was carried out in the spring with harrowing to retain soil moisture. Before planting *Miscanthus* rhizomes, the field was milled, rolled, and leveled.

The fertilization system included applying superphosphate at 100 kg/ha and KaliyMag-AGRO – 300 kg/ha in physical weight under the main tillage. In spring, urea was applied as an active ingredient at 46 kg/ha.

Planting material (rhizome) was planted in the soil at a density of 17,000 pieces/ha, with an 8-row Monosem 6 m seedling plant, with a variable productivity of 3.5 ha. Rhizomes were planted to a depth of 10 cm. Interrow width was 75 cm, and inter-plant spacing was 78 cm.

During the Miscanthus planting period in 2023, a significant amount of precipitation was observed, which delayed planting dates.

The hybrid Terravesta Athena plus (Terravesta AthenaTM) of foreign selection was used in the research.

Crop care included soil herbicides for weed control and post-emergent herbicides in 50 days. The soil was also treated with an organophosphorus insecticide to control the larvae of the beetles.

Field research was conducted using generally accepted scientific and special farming methods (Moiseichenko and Yeshchenko 1994). Records and observations were carried out during the growing season of the *Miscanthus giganteus* Terravesta AthenaTM hybrid. Biometric indicators were determined by measuring 10 plants at the end of the growing season in three repetitions: the height of the main shoot of plants was measured with a ruler from the soil surface to the top of the longest (extended upward) leaf (Volkodav 2001; Ushkarenko et al. 2016).

The biomass yield was calculated at the end of the growing season by weighing the sheaf samples. The statistical calculation of the obtained experiment results was carried out with the help of dispersion analysis using Excel and Statistica programs.

3. Results and discussion

In the research process, an important effect of preparing rhizomes for planting on the formation of *Miscanthus giganteus* plantations was established since they tend to dry out very quickly, lose germination capacity, and significantly reduce the programmed density per unit area. Before planting, miscanthus seeds were stored in a cold store with a controlled temperature of +1 degree Celsius and humidity of 85–90%. Due to this measure, the emergence of planted miscanthus rhizomes exceeded 94%.

It was established that the implementation of the above-mentioned technology elements influenced the indicators of the agrochemical composition of soil on the sites where miscanthus was grown (Table 1).

Table 1. Agrochemical composition of the soil on the experimental site according to the data of the "Institute of Soil Conservation of Ukraine (Public Institution "State Soil Conservation" ("Derzhgruntokhorona") of Zhytomyr branch of PI "State Soil Conservation" (as of 2023)

Tabela 1. Skład agrochemiczny gleby na stanowisku doświadczalnym

Data of soil sampling	Exchangeable acidity [pH]	Content of nutrients				
		easily hydrolyzed nitrogen (N) [mg/kg]	mobile phosphorus (P) [mg/kg]	exchangeable potassium (K) [mg/kg]	exchangeable calcium (Ca) [mmol/100 g of soil]	exchangeable magnesium (Mg) [mg/kg mmol/100 g of soil]
December 20, 2022	5.27	70.0	86.0	62.0	2.44	0.38
June 6, 2023	5.36	71.4	145.0	89.0	2.75	0.50

According to the data in Table 1, it can be found that the implementation of chemical reclamation practices and fertilizer application had a positive effect on reducing soil acidity and providing essential nutrients. The increase in the content of easily hydrolyzed nitrogen at the time of the second estimation amounted to 1.4 mg/kg of soil, phosphorus – 59.0 mg/kg, potassium – 27.0 mg/kg, calcium – 0.31 mmol/100 g of soil, and magnesium – 0.12 mmol/100 g of soil, which further ensured the optimization of mobile forms of nutrients necessary for the growth and development of *Miscanthus giganteus* plants.

When performing the main technological techniques aimed at growing Miscanthus, it is mandatory to use GIS technologies, which involve using machine-tractor units equipped with devices for parallel driving and speed control. This element is very effective in the precise planting of rhizomes in the ridge.

Research has confirmed the high efficiency of cutting ridges before planting, which ensures effective and even planting miscanthus rhizomes at a given depth, increasing the amount of a moisture-rich layer, using a soil herbicide for a long-term protective screen. Under this scheme of weed control, weeds emerged on the 40th day after planting (Fig. 1).

After 40–50 days of vegetation, there could be observed growth of weeds (Fig. 2), which included representatives of cruciferous, grass, and other weeds. On the established site, three plots with different indicators of weed plants and fertilization were selected. Application of post-emergent herbicides to a greater extent did not have a phytotoxic effect on cultivated plants; however, on one of the plots, Miscanthus plants slowed down their growth and development.

Therefore, it is recommended to apply post-emergent herbicides on the areas under Miscanthus together with foliar nutrition with trace elements and anti-stressors.

Fig. 1. The status of sites during crop emergence

Rys. 1. Stan stanowisk w czasie wschodów roślin uprawnych

Characteristics of plant parameters of *Miscanthus giganteus* hybrid Terravesta Atena plus as of October 14, 2023, are given in Table 2.

According to Table 2, during the observation period, the total plant density amounted to 34.67 thousand bushes per hectare, or 2.6 pcs per running meter. The average number of shoots per bush was 21.56 pcs. Plant height was 89.6 cm, stem diameter was 0.56 cm, the number of leaves was 10.2, and the average weight of one plant was 24.3 g. It provided a biological yield of vegetative mass at 14.53 t/ha in the first year of vegetation.

A field trial conducted in Eastern Poland to research grasses of the genus *Miscanthus giganteus* and Miscanthus sacchariferous showed that of the non-energy crops whose biomass can be used for agricultural biogas plants, Giant Miscanthus is characterized by the highest yield (15.5 Mg DM/ha) (Dubis et al. 2019).

Fig. 2. The status of the crop before applying post-emergent herbicide

Rys. 2. Stan uprawy przed zastosowaniem herbicydu powschodowego

Table 2. Productivity specifications of Miscanthus hybrid Terravesta Atena plus in the first year of vegetation (2023, as of October 14)

Tabela 2. Specyfikacje produktywności mieszańca Miscanthus Terravesta Atena plus w pierwszym roku wegetacji (2023, stan na 14 października)

Hybrid	Indicators						
Terravesta Athena plus	Plant density [pcs per running meter]	Number of shoots per rhizome [pcs]	Plant height [cm]	Stem diameter [cm]	Number of leaves [pcs]	Average weight of one plant [g]	Biological yield [t/ha]
	2.6	21.56	89.06	0.56	10.20	24.3	14.53

Nowadays, more than 20 types of fast-growing energy crops are being studied in Ukraine. They are considered suitable for growing to obtain plant biomass that can be used as raw materials for the production of alternative types of energy, in particular, fast-growing trees of various types of willow and poplar and annual and perennial herbaceous plants, e.g., sorghum, sugarcane, Miscanthus, amaranth, etc.

Compared to other energy plants, Miscanthus is very effective for the production of solid biofuel (pellets), which meets the primary European standards for the main environmental and energy characteristics, namely the yield of dry mass, heat of combustion, energy production, ash content, density, etc. (Table 3).

Table 3. Comparative characteristics of energy plants for the production of solid biofuel

Tabela 3. Charakterystyka porównawcza roślin energetycznych do produkcji biopaliw stałych

Crop	Dry matter output [(t/ha)/year]	Lower heat of combustion [MJ/kg of dry mass]	Energy production [GJ/ha]	Water content when harvesting [%]	Ash [%]
Giant Miscanthus	8.0–32.0	17.5	311.9–419	15.0	3.7
Switchgrass (*Panicum Virgatum L*)	9.0–18.0	17.0	266.8–312.2	15.0	6.0
Willow	8–20	18.5	280–315	53.0	2.0
Poplar	9–16	18.7	170–300	49.0	1.5
Wheat straw	8–10	12.0	120–150	20.0	4.2
Coal	–	20.0	–	12.0	22.5

Source: developed by the authors based on references (Yastremska et al. 2017; Khivrych et al. 2011).

The energy value of burning Miscanthus biomass equals wood and is up to 17.5 MJ/kg of dry mass (Nebeská et al. 2019). In addition, the ash that remains after burning can be used as a fertilizer in the system of crop fertilization. The main advantage of Miscanthus over switchgrass, wood, wheat straw, and coal is the annual output of up to 20–30 tons of dry raw materials per 1 ha for twenty years, which in terms of energy equivalent is about 10 tons of fuel oil or 15–20 tons of coal per1 ha. An important feature is the annual renewal capacity of this raw material base, i.e., the stability of the energy system created on its basis, which is its most important economic feature.

Miscanthus has heat power of 3.6–4 kWh per kg and weight of 70–90 kg per m^3. Being less dense than grain, Miscanthus will need more space to store enough fuel to generate the same heat. One ton of Miscanthus can produce 1.8 MW of electricity, equivalent to 0.7 tons of coal. The density of Miscanthus pellets is about 600 kg/m^3, and the density of Miscanthus briquettes is about 450–500 kg/m^3.

The advantage of Miscanthus is a large thermal energy output of 5 kW/h/kg or 18 MJ/kg and low leaf mass humidity of up to 15% during the harvesting period. When biofuel from Miscanthus is burned, much less carbon dioxide enters the atmosphere than is absorbed by plants during photosynthesis, 20–30 times less sulfur oxide is formed, and 3–4 times less ash is produced compared to coal (Roik et al. 2019).

According to Roik et al. (2019), one ton of Miscanthus biomass equals 419 kg of crude oil, 1.7 tons of wood, 515 m^3 of natural gas, or 900 kg of hard coal. Miscanthus stems reach a height of 4 meters and accumulate up to 64–71% of cellulose.

The highest economic and energy effect can be obtained if the energy-saving elements of Miscanthus cultivation technology are followed when cultivating biomass for biofuel, having created an energy conveyor to supply raw materials to the consumer (Huisman 1998; Jones 1992). Cultivation of *Miscanthus giganteus* applying the developed technology of maximum productivity on marginal lands is proposed for the production of biogas as well as pulp and paper products with the possibility of using its biomass to obtain biogas and the substrate (digestate) that remains after fermentation in the crop fertilization system.

Daraban (Oros) et al. (2015) found that a set of indicators (percentage of variable biomass mixed with Miscanthus and humidity fluctuations) affect the quality of the final product.

Kowalczyk-Juśko et al. (2022) studied the parameters of Miscanthus biomass from the point of view of its suitability for burning and anaerobic fermentation. In the conditions of the experiment, Miscanthus achieved a stable yield in the second year of vegetation, mainly due to the high planting density. In the second year of vegetation, it will achieve a stable yield due to the optimal planting density. The study of burning Miscanthus pellets in boilers with automatic fuel supply of the 5^{th} class of ecological design showed an effective result (high economic energy efficiency) from the technological solutions that meet modern energy efficiency standards and emissions.

Several studies have confirmed that the cost competitiveness of biofuel production and use is usually a significant bottleneck. Thus, for example, the production of biodiesel from microalgae is characterized by significant costs (84–93% of all costs), which indicates a low level of cost competitiveness compared to fossil biofuels.

Conclusions

The developed technology for growing *Miscanthus giganteus* hybrid Terra vesta AthenaTM involves pre-sowing storage of rhizomes (t +1 °C and humidity 85–90%), application of mineral fertilizers at the rate of N46P22K84 and 600 kg/ha of limestone material on sod poorly podzolic soils, planting rhizomes with using GIS technologies in the ridge at the depth of 10 cm, which makes it possible to obtain high germination capacity (over 94%) of rhizomes, effectively use soil moisture reserves at the beginning of the growing season, to control weedy vegetation and to form the yield of vegetative mass at the level of 14.53 t/ha in the first year of growing season, and in the second year of vegetation it will provide a stable yield due to optimal planting density. Planting Miscanthus rhizomes is suggested by cutting ridges to ensure effective weed control and regulate soil moisture. These elements of technology make it possible to obtain high productivity of *Miscanthus giganteus* plantations in the first year of vegetation. In the future, it is planned to research the impact of these elements of the technology on the productivity of *Miscanthus giganteus* plantations in the second and subsequent years of vegetation as well as the specifics of the chemical composition of *Miscanthus giganteu* plants for processed into biogas and obtaining paper, with the possibility of effective replacing the use of biomass of food and fodder crops, in particular corn silage, to obtain biogas.

Cultivation of *Miscanthus giganteus* of hybrid Terra vesta AthenaTM, especially on marginal lands, will allow valuable raw materials to be obtained for producing solid biofuel (pellets) that meet European standards by the leading environmental and energy characteristics. This concept has a high industrial potential and has been confirmed by production and field studies.

The highest economic and energy effect can be obtained if the energy-saving elements of *Miscanthus giganteus* cultivation technology are followed (in particular, reducing the costs for weed control products) when cultivating biomass for biofuel, having created an energy conveyor to supply raw materials to the consumer.

The Authors have no conflicts of interest to declare.

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Specyfika uprawy, produktywności i efektywności energetycznej *miscanthus giganteus* do produkcji stałych biopaliw

Streszczenie

Miskant jest jedną z najbardziej obiecujących roślin energetycznych do uprawy na nieurodzajnych glebach Ukrainy. Uprawa miskanta znacznie zwiększy niezależność energetyczną Ukrainy i zmniejszy zużycie paliw stałych. Badania dotyczą specyfiki wykorzystania *Miscanthus giganteus Terravesta AthenaTM*. Opracowano wytyczne dotyczące specyfiki przedsiewnego przechowywania kłączy, stosowania nawozów mineralnych i sadzenia kłączy w redlinie przy użyciu technologii GIS. Pozwala to uzyskać wysoką zdolność kiełkowania (ponad 94%), efektywnie wykorzystać rezerwy wilgoci glebowej na początku okresu wegetacji, kontrolować chwasty i kształtować plon masy wegetatywnej na poziomie 14,53 t/ha w pierwszym roku wegetacji, a w drugim roku wegetacji osiągnie stabilny plon dzięki optymalnej gęstości nasadzeń. Uprawa *Miscanthus giganteus hybrydy Terra vesta AthenaTM*, zwłaszcza na gruntach marginalnych, dostarczy cennych surowców do produkcji stałego biopaliwa (pelletu), które spełnia europejskie normy dzięki swoim podstawowym cechom środowiskowym i energetycznym.

Wartość energetyczna i kaloryczna biomasy Miscanthus jest wysoka, a podczas jej spalania do atmosfery dostaje się mniej dwutlenku węgla, co staje się jej główną zaletą w porównaniu z innymi rodzajami upraw energetycznych. Największy efekt ekonomiczny i energetyczny można uzyskać, jeśli elementy energooszczędne technologii uprawy *Miscanthus giganteus* zostaną zastosowane (w szczególności obniżenie kosztów środków chwastobójczych) podczas uprawy biomasy na biopaliwo, po stworzeniu przenośnika energii do dostarczania surowców do konsumenta.

Słowa kluczowe: technologia uprawy, *Miscanthus giganteus*, efektywność energetyczna, plon, biopaliwo stałe