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# Justification of the Optimal Harvesting Times for *Miscanthus giganteus* Biomass Based on Quality, Economic, and Energy Efficiency Indicators

**Volodymyr Kvak* · Volodymyr Kravchuk · Oleksandr Hanzhenko**

Institute of Bioenergy Crops and Sugar Beet, National Academy of Agricultural Sciences of Ukraine, Kyiv, Ukraine

* Corresponding author email: kvak-vm@ukr.net

**Summary:** The growing environmental challenges are prompting humanity to seek ways to reduce the use of fossil fuels by turning to renewable energy sources, including high-yield perennial bioenergy crops. The aim of this study was to improve the economic and energy efficiency of *Miscanthus giganteus* production by optimizing biomass harvest timing, taking into account yield dynamics, moisture loss, and quality criteria for processing into solid biofuel. The study employed field, laboratory, and statistical methods. The research was conducted in a temperate-continental climate zone with annual precipitation ranging from 500 to 800 mm and an average annual air temperature of +6–7 °C. It was established that harvesting *Miscanthus giganteus* for processing into solid biofuel is recommended before the onset of new shoot growth (March–April). This reduces the biomass moisture content from 56.3% to 18.3% and, accordingly, decreases the biomass yield at natural moisture content from 45.1 to 22.4 t/ha, and the dry matter yield from 19.7 to 18.3 t/ha. At the same time, the ash content of the biomass decreases from 2.8 to 0.7%, the specific heat value increases from 7.6 to 15 MJ/kg, and the profitability of pellet production rises from 54.5 to 72.6 percent. Based on five years of experimental data, empirical relationships were established between moisture content ($R^2 = 0.957$), wet biomass yield ($R^2 = 0.993$), and dry biomass yield ($R^2 = 0.962$) and the timing of harvest.

**Keywords:** bioenergy, biomass, *Miscanthus giganteus*, harvesting time, quality indicators, solid biofuels, production efficiency

## Introduction

The EU's ambitious policy, driven by a commitment to environmental protection and aimed at reducing $CO_2$ emissions from the combustion of fossil fuels, has spurred the use of biomass as a renewable energy source (Wnorowska et al., 2018; Soldatos, 2015; Sharew et al., 2022; Tetere & Zeverte-Rivza, 2023). One of the leading candidates for the supply of sustainable biomass is recognised as *Miscanthus giganteus* (*Miscanthus*×*giganteus*) (Awty-Carroll et al., 2023; Xi Liang et al., 2019). According to the literature of European researchers, the yield of dry biomass of *Miscanthus giganteus* can vary from 8 to 44.1 t/ha (Lewandowski et al., 2000; Heaton et al., 2008; Miguez et al.,

2008; Maughan et al., 2012). Such significant variation in the yield of *Miscanthus giganteus* across different regions of Europe is due to the complex interaction of soil types, climatic conditions, and interannual weather fluctuations (Kus & Matyka, 2009). Long-term field trials in Central and Eastern Europe show that, although high dry matter yields (averaging 15.5 metric tons per hectare per year) can be achieved with long-term cultivation, yield stability remains highly sensitive to seasonal weather patterns and agronomic management (Dubis et al., 2019; Larsen et al., 2014). Shoots of the plant can grow more than 2 metres in the first year of planting and up to 4 metres in subsequent years (El Bassam & Huisman, 2001) and forms tussocks (or clumps) of 18 - 81 shoots (Christian et al., 2001; Heaton et al., 2010; Borkowska & Molas, 2013; Bilandžija et al., 2020).

Different machines and methods are used to harvest *Miscanthus giganteus* biomass (Huisman & Kortleve, 1994). The harvested biomass can be in the form of chips or bales, depending on the end product and the equipment at the processing plant (Piaia et al., 2023). In the first case, harvesting is carried out with simultaneous shredding (direct harvesting), in the second case, mowing into swaths with subsequent selection and formation of bales (separate harvesting) (Roik et al., 2019; Kravchuk et al., 2022).

Planning the methods and timing of biomass harvesting should be carried out taking into account the biological characteristics of *Miscanthus giganteus*, weather conditions, plant maturity, moisture and ash content of biomass (Le Ngoc Huyen et al., 2010). An important criterion in choosing the optimal harvesting time should be the quality of biomass, namely moisture and ash content. A number of studies have been devoted to this issue (Lewandowski & Heinz, 2003; Bilandzija et al., 2017; Kadžiulienė et al., 2014; Parrish et al., 2021), which state that *Miscanthus giganteus* can be harvested from November until the onset of new shoot growth (mid-April). The quality of biomass depends on the soil and climatic conditions of cultivation and genotypes of *Miscanthus giganteus*, while it can be improved by selecting the optimal harvesting time (Purdy et al., 2015; Jorgensen, 1997; Smith & Slater, 2011; Hayes, 2013; Kludze et al., 2013; Bilandzija et al., 2017).

During the fall and winter, *Miscanthus giganteus* sheds a significant portion of its leaves, which reduces the yield while improving the quality of the biomass and ensuring that the nutrients contained in the leaves are returned to the soil. In addition, the cost of *Miscanthus giganteus* biomass depends on its moisture and ash content and varies considerably. Regional studies conducted in Central and Eastern Europe indicate that the yield of *Miscanthus giganteus* is highly sensitive to moisture availability in the spring during canopy formation and to fall and winter precipitation during the plant's senescence phase (Von Cossel et al., 2019). Although fall harvesting yields the highest amount of fresh biomass, it is accompanied by high moisture content and elevated levels of minerals in the biomass. Conversely, delayed harvesting from winter into spring promotes natural drying of the stems and the transfer of nutrients to the rhizomes, albeit at the cost of yield losses caused by leaf fall and stem lodging (Kalinina et al., 2017). A detailed regional assessment of these fluctuations in biomass yield and trade-offs in quality is crucial for establishing optimal agronomic practices and harvest logistics.

Therefore, determining the optimal harvest times for *Miscanthus giganteus* is crucial for its effective cultivation, as this ensures the proper quality of the raw material and high economic efficiency of its cultivation. However, for the conditions of the Central Forest-Steppe of Ukraine, which has a temperate continental climate, the impact of *Miscanthus giganteus* harvest timing on biomass quality indicators has not been sufficiently studied, which underscores the relevance of this research.

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The objective of this study was to improve the economic and energy efficiency of *Miscanthus giganteus* production by optimizing biomass harvest timing, taking into account yield dynamics, moisture loss, and quality criteria for processing into solid biofuel. To achieve this objective, the following tasks must be addressed:

- investigate changes in the moisture content of *Miscanthus giganteus* biomass during the fall and spring periods depending on weather conditions;
- determine the relationship between yield and the quality of *Miscanthus giganteus* biomass and harvest timing;
- determine the optimal harvest times for *Miscanthus giganteus* biomass based on quality, economic, and energy efficiency indicators.

**Materials and Methods**

The study was conducted on experimental plots at the Institute of Bioenergy Crops and Sugar Beets of the National Academy of Agrarian Sciences of Ukraine (Kyiv) from 2021 to 2026 using the 'Osinnyi Zoretvit' variety of *Miscanthus giganteus* (*Miscanthus giganteus* J.M. Greef & Deuter ex Hodkinson and Renvoize). According to agroclimatic zoning, the experimental plot is located in the zone of unstable moisture of the Central Forest-Steppe of Ukraine, or, according to B.P. Alisov's classification, in the zone of a temperate continental climate, characterized by a predominance of air masses originating from the Atlantic Ocean (Lipinskyi et al., 2003).

The climatic conditions of the study area are characterised by the following average long-term indicators: annual precipitation is 538 mm; the average long-term air temperature is +6.9°C. The average number of days with a thaw is 40-45 in December-February. Low air temperatures are observed mainly from December through February, and there are on average 10–15 such days per month (Lipinskyi et al., 2003). The dynamics of biomass yield in *Miscanthus giganteus* were determined during the dormant period from November through April (before the onset of new shoot growth) once a month (on the 15th). To do this, at least 10 plants were sampled consecutively (without gaps) from a row located at least 3 m from the edges of the survey plot Figure 1. The selected plants were cut and their total weight was determined. Biomass yield (t/ha) was calculated by the formula:

$$Y = M*G/N,$$

Where
Y – *Miscanthus giganteus* biomass yield, t/ha;
M – weight of *Miscanthus giganteus* biomass sample, kg;
G – density of *Miscanthus giganteus* plants, thousand units/ha;
N – number of plants in the sample, pcs.

The moisture content of *Miscanthus giganteus* leaf and stem biomass was determined by the thermo-gravimetric method (Hrytsaienko et al., 2003) Figure 2; raw ash content - by combustion with air access (CEN/TS 14775, 2012) Figure 3. The calorific value was determined by the calculation method (Roik et al., 2019) using the formula:

$$eT = \frac{(100-W-Z)}{100} \times eT_0$$

Where
$eT$ – energy content of solid biofuels, MJ/kg;
$W$ – moisture content of solid biofuels, %;
$Z$ – ash content of solid biofuels, %;
$eT_0$ – energy content of absolutely dry ashless solid biofuels, MJ/kg; $eT_0$=18.5 MJ/kg.

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a b

**Figure 1.** *Miscanthus giganteus* plants (a) in autumn, (b) in spring



a b c

**Figure 2.** Determination of moisture content of *Miscanthus giganteus* leaf and stem biomass by thermogravimetric method (a) chopped biomass before drying, (b) weighing biomass on an analytical balance with a measurement accuracy of 0.01 g, (c) drying biomass in a drying oven

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a b c

**Figure 3.** Determination of the crude ash content - air-access combustion method (a) chopped biomass before combustion, (b) weighing biomass on an analytical balance with a measurement accuracy of 0.0001 g, (c) combustion of biomass in a muffle furnace

To assess the technological and economic suitability of biomass as a raw material for the production of pelletized solid biofuel, mathematical modeling of the preparation and processing steps was employed. The obtained values of ash content (Z) and moisture content (W) of the biomass were compared with the requirements of ISO 17225-2 [31] to determine the potential quality category of the fuel pellets. Class A1 – ash content $Z \leq 0.7\%$; Class A2 – ash content $Z \leq 1.5\%$; Class B – ash content $Z \leq 3.0\%$. The specific energy consumption required to remove excess moisture from the biomass to the specified level prior to pelletization ($W_{spec} = 10\%$) was calculated based on the initial moisture content of the raw material for each month of harvest. The production cost of pellets included direct costs for growing, harvesting, and transporting biomass, as well as energy costs for artificial drying and mechanical pressing. Gross revenue was calculated based on market prices for pellets of the corresponding quality categories (A1, A2, B), converted to per 1 metric ton and per 1 hectare.

**Results with Discussion**

According to meteorological observations for the period 2021–2026, temperatures remained relatively stable, but were 2.1 °C above the long-term average (Figure 4). Precipitation patterns were variable, both by year and by month: in December, precipitation exceeded the long-term average by 33.5 mm, and in February, by 6.2 mm.

It was found that the moisture content of the biomass of *Miscanthus giganteus* in autumn and spring decreases from 56.3 (in November) to 18.3% (in April). The most intensive decrease in the moisture content of the biomass of *Miscanthus giganteus* was observed at positive air temperatures and lack of precipitation. Thus, in November-December, the biomass moisture content decreased by 14.0% (from 56.3% to 42.3%), and in March-April - by 9.6% (from 27.9% to 18.3%). During the winter months, biomass moisture decreased by an average of 4.8% per month (Figure 5).

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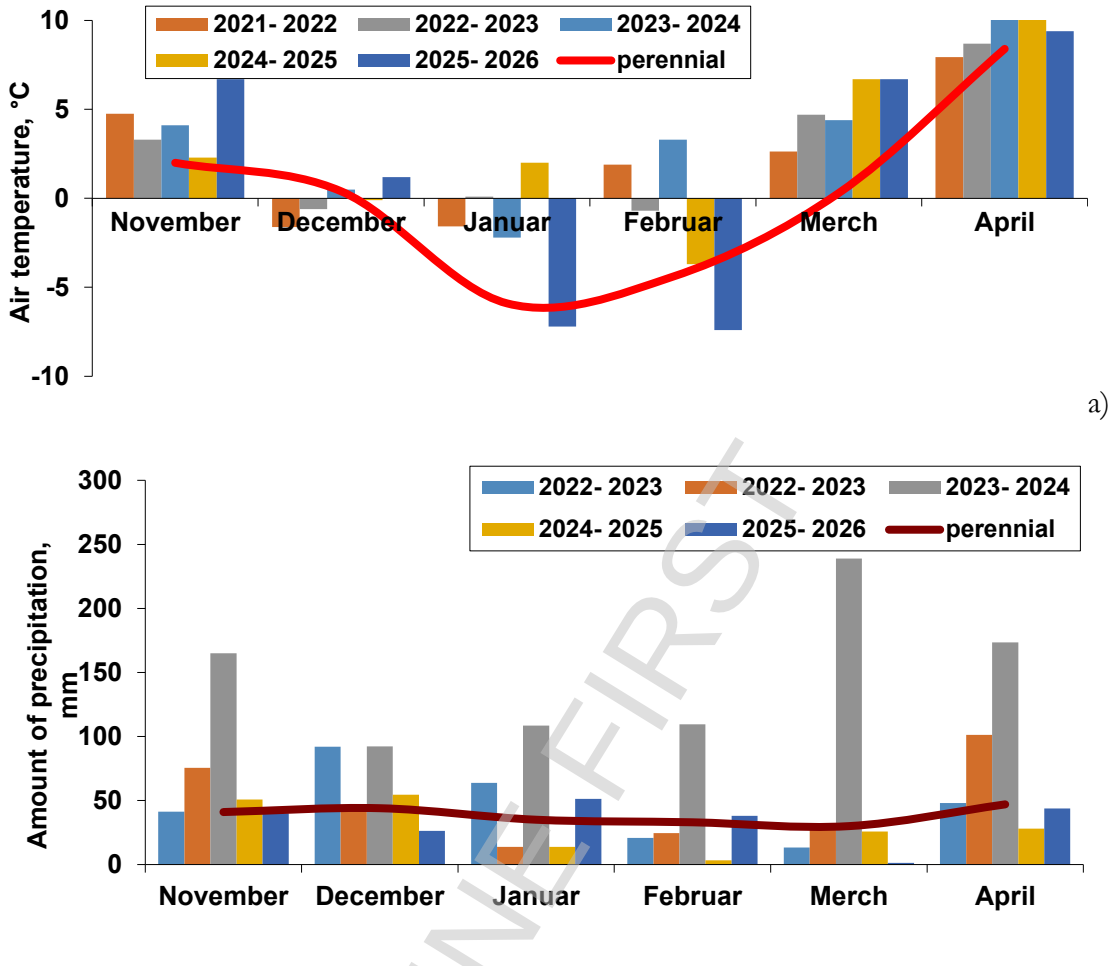



**Figure 4.** Air temperature (a) and precipitation (b) for the years of research (2022-2026)

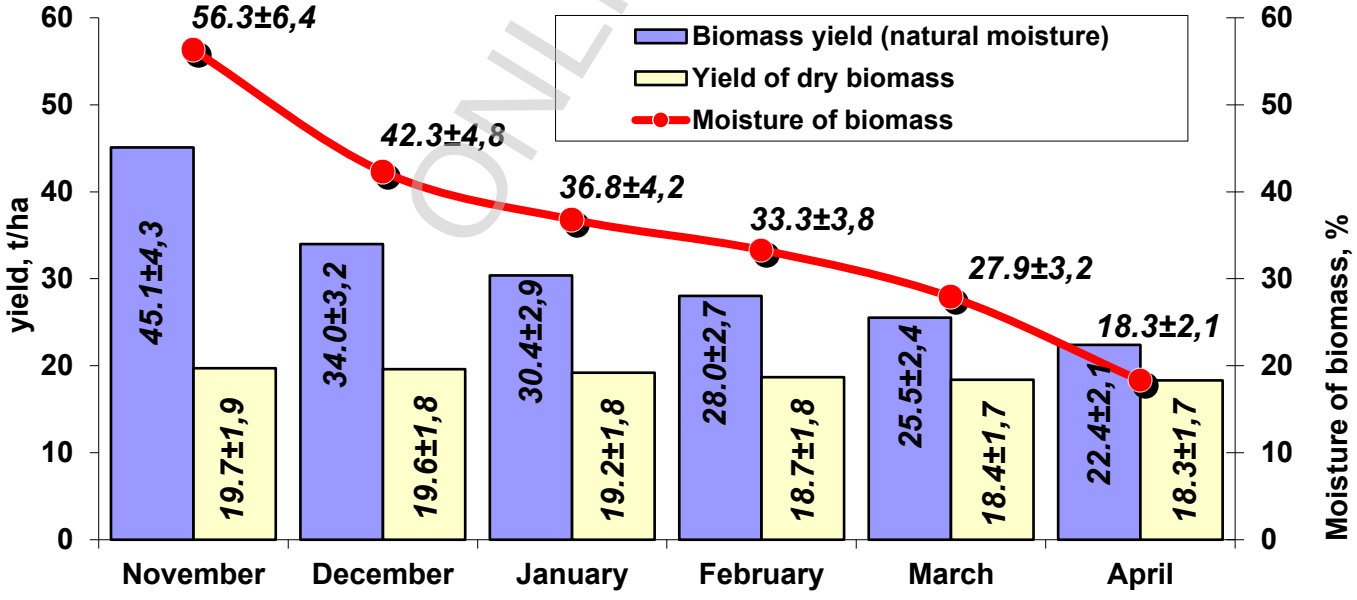



**Figure 5.** Dynamics of changes in the yield and moisture content of *Miscanthus giganteus* (X=±SD) biomass depending on the harvesting period

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Based on five years of experimental data, an empirical relationship has been established between the moisture content of *Miscanthus giganteus* biomass and the duration of the post-vegetation period—biomass harvesting, (Figure 6):

$W = -0.2251 \cdot t + 56.26$,

where $W$ – moisture content of *Miscanthus giganteus* biomass, %; $t$ – duration of the period from the end of the growing season to the harvesting of biomass, days.

The application of the above linear regression correlation allows to predict the moisture content in the biomass of *Miscanthus giganteus* depending on the time of its harvesting at a high level of accuracy ($R^2$=0.9571).

The yield of leaf and stem biomass at natural moisture in November-April decreases due to a decrease in biomass moisture and leaf fall. Thus, in November it was 45.1 t/ha, in April - 22.4 t/ha, i.e. it decreased by half. The most rapid decrease in air-moisture biomass yields (-11.1 t/ha) is observed in the period November-December and is a consequence of intensive moisture loss during this period.

The dynamics of *Miscanthus giganteus* biomass yield at natural moisture depending on the harvesting time is described by the logarithmic equation (Figure 7):

$Yw = -9.0136 \cdot ln(t) + 69.291$,

where $Yw$ – biomass yield of *Miscanthus giganteus* at natural humidity, t/ha; $t$ – duration of the period from the end of the growing season to the harvesting of biomass, days.

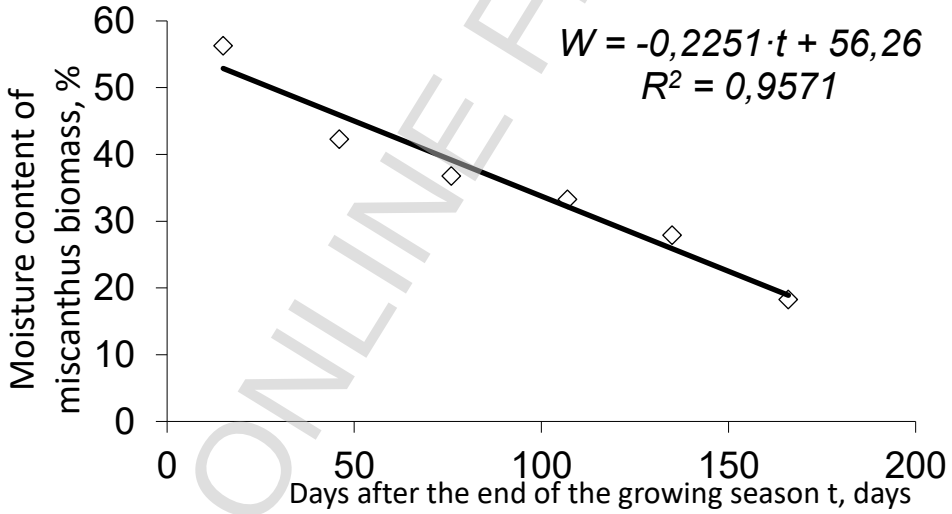



**Figure 6.** Regression dependence of *Miscanthus giganteus* biomass on days after the end of the growing season

According to the results of long-term studies, a decrease in the yield of absolutely dry biomass was found, which is due to the fall of leaves. Thus, at the end of the plant growing season (mid-November), the yield of absolutely dry biomass of *Miscanthus giganteus* averaged 19.7 t/ha, and at the beginning of regrowth (mid-April) - 18.3 t/ha. The yield of dry biomass decreases most intensively in winter (by 0.3-0.5 t/ha per month), which is due to leaf fall due to snowfall and the winds.

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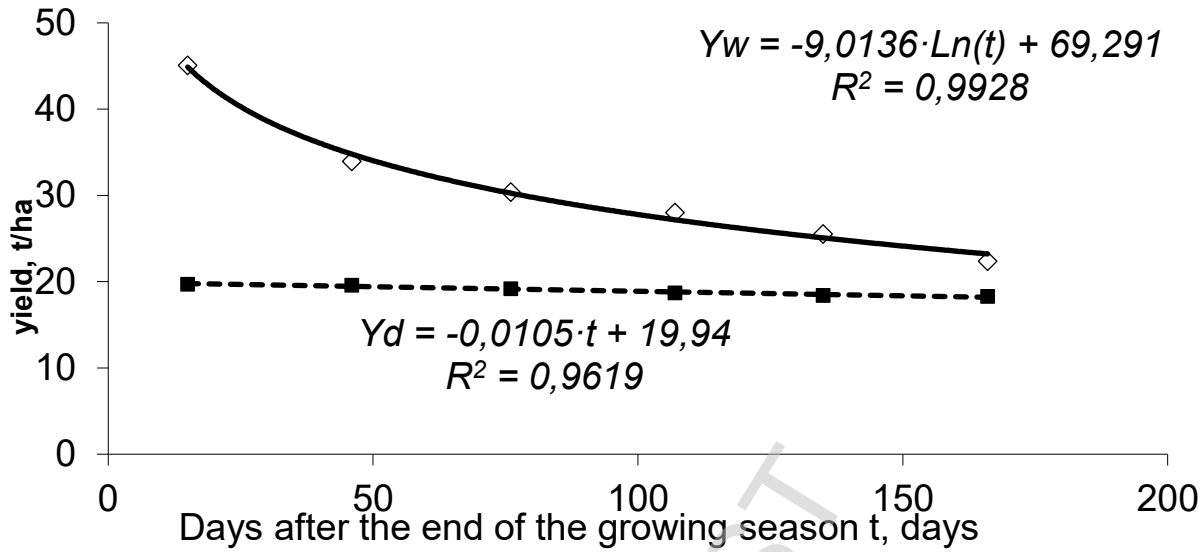



**Figure 7.** Regression dependence of *Miscanthus giganteus* biomass yield on days after the end of the growing season

The yield of absolutely dry biomass of *Miscanthus giganteus* depending on the harvesting time is described by the linear regression equation (Figure 7):

$Y_d = -0.0105 \cdot t + 19.94$,

where $Y_d$ – yield of absolutely dry biomass of *Miscanthus giganteus*, t/ha; $t$ – duration of the period from the end of the growing season to the harvesting of biomass, days.

*Miscanthus giganteus* is characterized by high mechanical resilience; however, extreme weather events such as ice storms, heavy wet snow, and strong winds during the winter pose a risk of stem breakage and lodging. Accordingly, the recommended spring harvest dates should not apply to regions with a high frequency of severe winter icing, snow breakage, and strong winds. However, during the 5-year experimental period at our research site, no cases of winter lodging were observed, confirming the safety and feasibility of spring harvesting under these regional conditions.

The research results showed that leaving the stalks in the ground over the winter significantly improves the quality of the raw material due to the natural transformation of the ash content. Raw biomass harvested in the fall has a higher ash content (up to 2.8%), which is explained by the high proportion of leaves (which contain larger amounts of silica, potassium, and chlorine) and contamination with surface soil dust. During the winter months, natural leaf fall and precipitation wash away water-soluble inorganic elements and remove external soil impurities. As a result, biomass harvested in the spring consists mainly of structural stems, with an ash content reduced to 0.7% (Table 1). Such a low ash concentration reduces the risk of slag and clinker formation on boiler grates, lowers particulate matter emissions, and enables the production of high-quality commercial pellets that meet the highest quality standards.

Thus, although the fall harvest yields the maximum total volume of raw biomass per hectare, the delayed spring harvest produces raw material with better structural characteristics, low ash and moisture content, and is optimized for direct mechanical compaction into high-quality fuel pellets.

Due to the decrease in moisture content and non-combustible ash elements, the amount of energy that can be obtained by burning a unit of *Miscanthus giganteus* biomass increases (Baxter et al., 2012; Christian et al., 2008). Thus, while at the end of the growing season (November) the

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specific calorific value of *Miscanthus giganteus* biomass was 7.6 MJ/kg, at the end of the dormant period (April) this figure doubled to 15.0 MJ/kg, which partially compensates for the decrease in dry biomass yield.

Improving the quality and calorific value of biomass by postponing the harvesting period from autumn to spring allows obtaining higher quality categories of biomass pellets from *Miscanthus giganteus*. Thus, in the case of harvesting biomass immediately after the end of the *Miscanthus giganteus* plants' vegetation, solid biofuels made from such biomass will correspond to category "B". Postponement of harvesting to the winter months (December-February) allows to improve the quality of solid biofuels to category 'A2', and harvesting *Miscanthus giganteus* in spring (March-April) provides the highest quality biomass, fuel pellets from which correspond to category 'A1' according to ISO 17225-2 (ISO 17225-2; Sampson & Mahdi, 1998) (Table 1).

An analysis of the computational model shows that with each additional month of harvest delay, the production costs for manufacturing pellets decrease from 3,491.5 €/ha (November) to 3,119.5 €/ha (April). The main factor behind these savings is the natural decrease in biomass moisture content in the field from 56.3% to 18.3%, which minimizes the thermal energy required for artificial drying to the technologically necessary 10–12% prior to pressing. Although the physical yield of dry biomass drops to 20.1 metric tons per hectare in the spring (due to fallen leaves), the maximum profitability (72.6%) is achieved in April precisely because of the higher price for higher-quality fuel. This is due to a significant price premium for high-quality raw materials: the market price for "B" category pellets is 248.5 €/t, for "A2" category—258.3 €/t, while high-quality "A1" category biofuel sells for 268.0 €/t.

Thus, the optimal time for harvesting *Miscanthus giganteus* biomass in a temperate continental climate—when the highest solid biofuel quality and maximum economic efficiency are achieved—is during the spring months of March and April.

The research is coordinated with the work of (Heaton et al., 2009; Christian et al., 2006; Parrish et al., 2021) where it is determined that when harvesting biomass of perennial crops, it is necessary to take into account that too late harvesting leads to a decrease in yield, and too early - to an increased content of minerals, in particular nitrogen (N). According to the results of research at three sites in Illinois, a decrease in the concentration of nitrogen in the biomass of *Miscanthus giganteus* plants from 379 kg d.m./ha in June to <17 kg d.m./ha in February was observed (Heaton et al., 2009).

According to the results of the European project OPTIMISC (Iqbal et al., 2017), the study was conducted on five *Miscanthus giganteus* genotypes at two sites with a similar climate (Stuttgart, Germany and Adana, Turkey). biomass samples were collected between August and March. It was found that harvesting in the spring led to significant differences in the quality of the biomass during combustion. In Stuttgart, for example, the nitrogen content decreased from 0.64 to 0.21%, the ash content from 5.15 to 2.60%, and the ash sintering index from 1.30 to 0.20. At the same time, the nitrogen content of Adana decreased from 0.62% to 0.23%, ash content from 10.63% to 3.84% and the sintering index from 0.54% to 0.07%.

Our research is also in line with the work of (Himken et al., 1997; Lewandowski & Heinz, 2003; Zub et al., 2011; Bilandzija et al., 2017; Bilandžija et al., 2018), where it was determined that early harvesting allows for maximum yields, while late harvesting leads to its loss. This is primarily due to a decrease in moisture content from 64.11% to 19.13% during the autumn-winter period. However, this is a positive factor for storing the harvested biomass without additional drying and contributes to the growth of economic efficiency in the production of solid biofuels.

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**Table 1.** Economic calculation of the effective harvest time for biomass

| Parameter | Month of harvesting XI | XII | I | II | III | IV |
|---|---|---|---|---|---|---|
| Solid biofuel yield (at 10% moisture content), t/ha | 21.7 | 21.6 | 21.1 | 20.6 | 20.2 | 20.1 |
| Ash content, % | 2.8 | 2.6 | 1.7 | 1.0 | 0.7 | 0.7 |
| Specific calorific value, MJ/kg | 7.6 | 10.2 | 11.4 | 12.2 | 13.2 | 15.0 |
| Quality standard for ISO 17225-2 (ISO 17225-2) | B | A2 | A2 | A2 | A1 | A1 |
| Market price of fuel pellets, €/t (Biofire-tech, 2026) | 248.5 | 258.3 | 258.3 | 258.3 | 268.0 | 268.0 |
| Revenue from biofuel sales, thousand €/ha | 5385.9 | 5567.9 | 5454.3 | 5312.3 | 5423.5 | 5394.1 |
| Cost of pellets from *Miscanthus giganteus* biomass*: | | | | | | |
| • per 1 tonne, €/t | 160.9 | 158.8 | 158.0 | 157.5 | 156.7 | 155.2 |
| • per 1 hectare, €/ha | 3491.5 | 3430.1 | 3333.8 | 3244.5 | 3165.3 | 3119.5 |
| Net profit, €/ha | 1900 | 2144 | 2118 | 2073 | 2253 | 2269 |
| Profitability level, % | 54.5 | 62.6 | 63.5 | 86.4 | 71.0 | 72.6 |

* Including the costs of growing, transporting, storing and processing.

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## Conclusions

It has been established that in a temperate continental climate zone with annual precipitation of 500–800 mm and an average annual temperature of +6–7 °C, it is recommended to harvest *Miscanthus giganteus* for processing into solid biofuel before the onset of new shoot growth (March–April). This reduces the biomass moisture content from 56.3% to 18.3% and, accordingly, the biomass yield at natural moisture content from 45.1 to 22.4 t/ha, and the dry matter yield from 19.7 to 18.3 t/ha. At the same time, the ash content of the biomass decreases from 2.8 to 0.7%, the specific heat value increases from 7.6 to 15 MJ/kg, and the profitability of pellet production rises from 54.5 to 72.6 percent.

**Author contributions**: Volodymyr Kvak: Conceptualization, Methodology, Formal analysis, Investigation, Data Curation, Writing – Original Draft, Writing – Review & Editing, Visualization.
Volodymyr Kravchuk: Conceptualization, Supervision, Project administration, Resources.
Oleksandr Hanzhenko: Methodology, Investigation, Validation, Writing – Review & Editing.

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**Ethical issues statement**: AI tools (OpenAI ChatGPT / Gemini) were used solely for English language editing, proofreading, and stylistic refining of the text. The generation, processing, and interpretation of scientific data were performed entirely by the authors.

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## Opravdanost optimalnog vremena žetve biomase *Miscanthus giganteus* na osnovu pokazatelja kvaliteta, ekonomske i energetske efikasnosti

**Volodymyr Kvak · Volodymyr Kravchuk · Oleksandr Hanzhenko**

**Sažetak**: Rastući izazovi u oblasti životne sredine navode čovečanstvo da traži načine za smanjenje upotrebe fosilnih goriva prelaskom na obnovljive izvore energije, uključujući višegodišnje bioenergetske useve visokog prinosa. Cilj ove studije bio je da poboljša ekonomsku i energetsku efikasnost proizvodnje *Miscanthus giganteus* optimizacijom vremena žetve biomase, uzimajući u obzir dinamiku prinosa, gubitke vlage i kriterijume kvaliteta za preradu u čvrsto bio gorivo. U studiji su primenjene terenske, laboratorijske i statističke metode. Istraživanje je sprovedeno u zoni umereno-kontinentalne klime sa godišnjom količinom padavina od 500 do 800 mm i prosečnom godišnjom temperaturom vazduha od +6–7 °C. Utvrđeno je da se žetva *Miscanthus giganteus* za preradu u čvrsto biogorivo preporučuje pre početka rasta novih izdanaka (mart–april). To smanjuje udeo vlage u biomasi sa 56,3% na 18,3% i, u skladu s tim, smanjuje prinos biomase pri prirodnom udelu vlage sa 45,1 na 22,4 t/ha, kao i prinos suve materije sa 19,7 na 18,3 t/ha. Istovremeno, sadržaj pepela u biomasi se smanjuje sa 2,8 na 0,7%, specifična vrednost toplote raste sa 7,6 na 15 MJ/kg, a profitabilnost proizvodnje peleta raste sa 54,5 na 72,6 procenata. Na osnovu petogodišnjih eksperimentalnih podataka, uspostavljeni su empirijski odnosi između sadržaja vlage ($R^2$ = 0,957), prinosa vlažne biomase ($R^2$ = 0,993) i prinosa suve biomase ($R^2$ = 0,962) i vremena žetve.

**Ključne reči**: bioenergija, biomasa, *Miscanthus giganteus*, vreme žetve, pokazatelji kvaliteta, čvrsta biogoriva, efikasnost proizvodnje

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