

ECONOMIC AND ENERGY EFFICIENCY OF RESOURCE-SAVING TECHNOLOGY FOR SWITCHGRASS CULTIVATION

Purpose. *The study aimed to compare the efficiency of the resource-saving technology with the conventional technology for switchgrass cultivation using the developed methodology for assessing the economic and energy efficiency.*

Methodology / approach. *The study used general and special methods, including the methodology of scientific research in agronomy, laboratory determination of dry matter content in biomass, quantitative-weight analysis to establish crop yield, and the authors' improved methodology for assessing economic and energy efficiency. The research results were statistically processed using variance and comparative analysis.*

Results. *The results of the research on the use of resource-saving cultivation technology in comparison with conventional technology show an increase in switchgrass biomass yield from 14.6 to 15.7 t/ha, an increase in economic efficiency with profitability growth from 73.8 to 79.0 %, and an increase in energy efficiency with a growth of the energy efficiency coefficient by 0.7 – from 4 to 4.7 (average level of energy efficiency) when applying a specific complex of agrotechnical measures. When using resource-saving technology, the average full cost of cultivating switchgrass for six years is 8305.6 UAH/ha, compared to 7952.8 UAH/ha with conventional technology. However, resource-saving technology generates an average sales revenue of 14867.5 UAH/t, which is 1045 UAH/t more than conventional technology (13822.5 UAH/t).*

Originality / scientific novelty. *For the first time, a field experiment was conducted to compare switchgrass cultivation using resource-saving and conventional technologies. The authors have developed a methodology to assess the economic and energy efficiency of cultivating switchgrass. The results indicate that the efficiency of switchgrass biomass production is influenced by improved cultivation technology. The authors have developed a three-dimensional econometric model that demonstrates how the profitability level depends on the chosen switchgrass cultivation technology.*

Practical value / implications. *The research results have practical significance as they have led to the development of a methodology and evaluate the economic and energy efficiency of switchgrass cultivation. These results will be useful for agrarian enterprises to save resources.*

Key words: *economic efficiency, energy efficiency, yield, switchgrass, biomass.*

1. INTRODUCTION

Switchgrass is a perennial grass that is widely considered a promising feedstock for bioenergy production due to its high productivity and adaptability to different environmental conditions. Its cultivation is becoming increasingly important in the global transition to renewable energy sources due to its economic and energy efficiency. Compared to traditional crops, switchgrass is a cost-effective crop to cultivate, which can help reduce carbon emissions and improve the environment.

Switchgrass can be cultivated on marginal lands, making better use of available land resources (Sesmero et al., 2021). One of the peculiarities of switchgrass is its

potentially higher yield (Zhang et al., 2017). Typical switchgrass cultivation leads to increased yields over multiple growing seasons (Happs et al., 2024).

Switchgrass has a deep root system that enables it to grow effectively even in less fertile land where traditional crops may not perform well. This makes it an attractive option for growing in areas with limited access to fertile soil. Furthermore, switchgrass requires minimal care after planting, requiring far less water, fertiliser and pesticides than many traditional crops. Reducing the use of resources not only lowers production costs but also promotes the economic and energy efficiency of cultivating switchgrass as a source of biomass.

Switchgrass is an important resource in reducing dependence on fossil fuels due to its ability to convert switchgrass biomass into various forms of energy. Processing switchgrass biomass enables the production of biofuels with a lower environmental impact than traditional fuels. State interest in this area could expedite the development of new technologies for cultivating switchgrass. With the increasing demand for renewable energy, switchgrass could become an important element in the transition to a green energy future.

Renewable bioenergy is gaining popularity as it can meet the increasing demand for energy resulting from the decreasing availability of fossil fuels (Jiang et al., 2017). Currently, all necessary preconditions are in place for the implementation of the bioenergy development programme in Ukraine. The soil and climatic conditions contribute to obtaining a high yield of energy-intensive phytomass from energy crops. The use of adaptive technologies to cultivate energy crops on marginal lands, improvement existing technologies, proper processing phyto-raw materials, and use of biofuels in the fuel and energy complex could increase the proportion of bioenergy in Ukraine's overall energy mix. This could lead to a decrease in the use of non-renewable energy resources and an increase in demand for alternative energy sources, thereby contributing to the future development of the national economy (Gorb et al., 2018).

It has been established that Ukraine has a significant potential of biomass available for energy use. This includes plant residues that can be used for biofuel production, such as solid, liquid, and gaseous fuels. However, although switchgrass biomass has numerous benefits, there are certain challenges that must be addressed to ensure its economic and energy efficiency. These challenges include the need to develop infrastructure for collecting, transporting, and processing biomass (Rodias et al., 2017).

The cultivation of switchgrass depends on several key factors, including the location of crop cultivation, soil tillage, seed preparation for sowing, moisture content in the soil at the time of sowing, and soil temperature. It is important to consider all of these environmental factors to ensure optimal growth. Furthermore, in order to enhance switchgrass growth and development, it is very important to protect the crops against weeds. This can be achieved through the use of herbicides, which should be selected based on the soil-climatic zone of cultivation and the chosen ecotype for cultivation (Bransby et al., 1997; Peters et al., 1989).

Currently, the cultivation of switchgrass faces challenges in identifying the

optimal cultivation technology. It is urgent to determine the best technology to ensure maximum yield, economic efficiency, and energy efficiency of switchgrass. This will help reduce dependence on fossil fuels and support the global transition to renewable energy sources.

The purpose of the article is to compare the efficiency of the resource-saving technology with the conventional technology for switchgrass cultivation using the developed methodology for assessing the economic and energy efficiency.

2. LITERATURE REVIEW

Switchgrass is geographically widespread and can grow on soils of varying quality. It has low requirements for soil moisture and nutrient content, making it environmentally beneficial. These factors have led to extensive research on switchgrass worldwide (Dolan et al., 2020; Schmidt et al., 2020; Stephenson et al., 2021; Liu et al., 2022; Eudes et al., 2023).

Sanderson et al. (1996) and Christian et al. (2002) analysed the use of switchgrass and miscanthus biomass for energy and fibre production. These crops have high net energy production per hectare, low production costs, low nutritional requirements, low ash content in raw materials, high coefficient of moisture use, wide area of plant distribution, simplified cultivation technology, and high adaptability. Energy crops should be cultivated on unproductive or degraded land without changing land use.

The initial weakness of the European and American switchgrass studies was the lack of research conducted under production conditions. Production data, economic and ecological analyses were often extrapolated from small plots of land, resulting in unreasonably high crop yields. To address this issue, the “Bioenergy chains from perennial crops in Southern Europe” project conducted research in farm conditions and field experiments from 2001 to 2005 (CORDIS, 2005). This project conducted an interdisciplinary study comparing switchgrass, miscanthus, giant reed, and cardoon (*Cynara cardunculus* L.) grown in the Mediterranean region. The University of Bologna led the project, covering approximately 9 hectares, and including geostatistical (Di Virgilio et al., 2007), economic (Monti et al., 2007), agronomic (Monti et al., 2009), and agroecological (Monti et al., 2009) research on switchgrass.

Comprehensive studies on switchgrass are being conducted by Ukrainian scientists due to its adaptive characteristics, which enable effective use in various climatic conditions. The research involves studying various varieties of switchgrass to identify the most productive and best adapted to local conditions. Additionally, the analysis of technologies for switchgrass cultivation is an important aspect of the research, which includes learning about optimal planting conditions, crop care, and harvesting techniques.

Research conducted in the Forest-Steppe conditions of Ukraine suggests that switchgrass is a promising crop for cultivating on eroded and unproductive lands throughout most regions of Ukraine. This is due to its long-term use, unpretentiousness to moisture regimes and nutrition. However, it is important to note that switchgrass is sensitive to environmental conditions, particularly during the early stages of growth

and development. Optimal conditions can be achieved through various agrotechnical measures before and after sowing. This includes selecting appropriate varieties, agricultural techniques, and optimal seeding terms while considering the agrobiological peculiarities of the region and weather conditions of the year (Gumentyk & Kharytonov, 2018).

To ensure the long-term effective use of switchgrass energy plantations (up to 20 years), it is necessary to assess crops during the first few years. The highest yield is achieved in 3–4 years from the period of crop seeding (Elbersen et al., 2013).

The cultivation of energy crops in Ukraine presents a promising opportunity for the production of solid biofuels, particularly for heat and electricity generation. The Bioenergy Association of Ukraine reports that there are 4 million hectares of available agricultural land in the country, half of which can be used for sustainable energy crop cultivation (UABIO, 2020).

Conducting scientific research on switchgrass has the potential to enhance its energy value and increase the level of renewable energy production. This can be achieved by improving the energy value of switchgrass through breeding and biotechnology. Cooperation between the state, research institutions, and businesses can facilitate the establishment of bioenergy infrastructure in Ukraine. This involves cultivating switchgrass, producing biofuel, and making it accessible to end consumers. The state can provide funding for research and create the necessary infrastructure. Research institutions can focus on improving switchgrass cultivation technologies. Businesses can produce bioenergy and make it available to end consumers.

The cultivation of switchgrass biomass has positive effects on ecology, biofuel production, and the economic viability of agricultural areas (Wang et al., 2020). The analysis of literature sources has enabled the development of practical and effective mechanisms for optimising switchgrass cultivation technology.

The following research hypotheses were formulated for this study:

1. The economic indicators for cultivating switchgrass using resource-saving technology surpass those using conventional technology.
2. Improvements in the cultivation technology of switchgrass have a significant impact on biomass yield and energy output per hectare.
3. Producers of biomass should select switchgrass varieties that are adapted to their cultivation conditions.

Additionally, the study presented the following research questions:

1. Will there be the increase in switchgrass biomass yield annually during the research years for resource-saving and conventional cultivation technologies?
2. Will resource-saving cultivation technology be more profitable than conventional one?
3. What is the difference in the energy efficiency coefficient between cultivating switchgrass using resource-saving technology and conventional technology?

3. METHODOLOGY

Field studies were conducted on switchgrass using a two-factor long-term

experimental scheme. The plot recording area was 50 m² with four repetitions, meeting the necessary requirements for field crop experiments. Site placement was systematically alternated in repetitions. The experiment was planned and conducted according to the requirements of agronomy. Scientific research in this field is conducted at the intersection of several related branches of science, including agriculture, biology, economics, energy, and technology.

The experiment aimed to determine the yield, economic efficiency, and energy efficiency of switchgrass biomass production using various cultivation technologies in the Forest-Steppe conditions of Ukraine. Field trials were conducted between 2015 and 2020 using the Cave-In-Rock switchgrass variety. Crop sowing began in 2013.

The list of factors: factor A – years of research (2015–2020); factor B – variant 1 – conventional cultivation technology, variant 2 – optimised cultivation technology.

The results of the field research can be summarised as follows:

- the switchgrass biomass yield was calculated by weighing sheave samples from each plot of land aboveground vegetative mass and then recalculating it based on the moisture content of raw material to determine the dry mass;

- the dry matter content in plant materials was determined by drying the sample to a completely dry mass in a drying box at a temperature of 100–105°C for 4–6 hours. The samples were then cooled, weighed, and the results recalculated;

Table 1

Methodology for assessing (express analysis) the economic efficiency of switchgrass cultivation

Indicator	Formula	Definitions
Production cost (CP), UAH/ha	$CP = W + S + F + P + FL + D + FA + L + OM + I + G$	where <i>W</i> is the salary costs (basic, additional), UAH/ha; <i>S</i> is the seeds and planting material costs, UAH/ha; <i>F</i> is the fertiliser costs (mineral, organic), UAH/ha; <i>P</i> is the plant protection products costs, UAH/ha; <i>FL</i> is the fuel and lubricants costs, UAH/ha; <i>D</i> is the depreciation deductions, UAH/ha; <i>FA</i> is the fixed asset repair, UAH/ha; <i>L</i> is the land lease fee, UAH/ha; <i>OM</i> is the other material costs, UAH/ha; <i>I</i> is the insurance premiums, UAH/ha; <i>G</i> is the general production costs, UAH/ha
Full cost (FC), UAH/ha	$FC = CP + CS$	where <i>CP</i> is the production cost, UAH/ha; <i>CS</i> is the selling cost, UAH/ha
Sales revenue (R), UAH/t	$R = \sum_{i=1}^n VS_i \cdot PSP_i$	where <i>VS_i</i> is the sales volume, t; <i>PSP_i</i> is the selling price, UAH/t
Profit (PRO), UAH/ha	$PRO = R - FC$	where <i>R</i> is the sales revenue, UAH/ha; <i>FC</i> is the full cost, UAH/ha
Profitability level (PR), %	$PR = \frac{NP}{FC} \cdot 100$	where <i>NP</i> is the net profit, UAH/ha; <i>FC</i> is the full cost, UAH/ha

Source: compiled by the authors from materials (Kalinichenko & Plotnyk, 2012).

- the statistical processing of the research results was carried out using the

dispersion method with the licensed software Statistica-6.0;

– the economic efficiency of switchgrass cultivation was assessed according to the methodological instructions in Table 1;

– the energy efficiency of switchgrass cultivation was assessed according to the methodological instructions in Table 2.

Table 2

Methodology for assessing (express analysis) the energy efficiency of switchgrass cultivation

Indicator	Formula	Definitions
Total energy stored in biomass (<i>TES</i>), GJ/ha	$TES = \sum_{i=1}^n O_i \cdot DC_i \cdot DT_i \cdot 100$	where O_i is the output of biomass (yield), t/ha; DC_i is the biomass to dry matter conversion coefficient; DT_i is the energy content in 1 tonne of dry matter, GJ
Direct energy costs for biomass cultivation (<i>ED</i>), GJ/ha	$ED = \sum_{i=1}^n FLE_i + SMO_i + LL_i + FA_i$	where FLE_i is the energy costs embodied in fuel, lubricants, and electricity, GJ/ha; SMO_i is the energy costs embodied in seeds, mineral and organic fertilisers, plant protection products, GJ/ha; LL_i is the energy costs of living labour, GJ/ha; FA_i is the energy costs embodied in fixed assets of production, GJ/ha
Indirect energy costs for biomass cultivation (<i>EI</i>), GJ/ha	$EI = \sum_{i=1}^n MS_i + M_i + PS_i$	where MS_i is the energy costs of management and service personnel, GJ/ha; M_i is the energy costs for maintaining management and service personnel, GJ/ha; PS_i is the energy costs for maintaining production and social infrastructure, GJ/ha
Total energy costs for biomass cultivation (<i>TEC</i>), GJ/ha	$TEC = ED + EI$	where ED is the direct energy costs for biomass cultivation, GJ/ha; EI is the indirect energy costs for biomass cultivation, GJ/ha
Energy capacity of biomass cultivation (<i>EC</i>), GJ/UAH	$EC = \frac{TEC}{GB}$	where TEC is the total energy costs for biomass cultivation, GJ/ha; GB is the gross biomass, UAH/ha
Energy profit of biomass cultivation (<i>EPRO</i>), GJ/ha	$EPRO = TES - TEC$	where TES is the total energy stored in biomass, GJ/ha; TEC is the total energy costs for biomass cultivation, GJ/ha
Energy profitability level of biomass cultivation (<i>EPR</i>), %	$EPR = \frac{EPRO}{TEC} \cdot 100$	where $EPRO$ is the energy profit of biomass cultivation, GJ/ha; TEC is the total energy costs for biomass cultivation, GJ/ha
Energy efficiency coefficient (<i>EEC</i>)	$EEC = \frac{TES}{TEC}$	where TES is the total energy stored in biomass, GJ/ha; TEC is the total energy costs for biomass cultivation, GJ/ha; If $EEC < 1$ – switchgrass biomass cultivation is inefficient; 1–3,0 – low level of efficiency; 3,1–5,0 – average level of efficiency; $EEC > 5,0$ – high level of efficiency

Source: compiled by the authors from materials (Kalinichenko & Plotnyk, 2012).

To assess the economic efficiency of cultivating switchgrass, it is recommended to use the following indicators: production cost, full cost, sales revenue, profit, and profitability level (Table 1). The economic efficiency of cultivating switchgrass was calculated using an average biomass price of 950 UAH/t.

The use of a methodology for assessing energy efficiency allows for the measurement of the energy intensity of technological processes and the identification of opportunities to reduce it with minimal impact on the environment (Table 2).

4. RESULTS

4.1. Biomass yield depending on cultivation technology. Switchgrass is a versatile crop that can thrive in various climatic zones and soil types, making it an ideal choice for agricultural producers in different regions. It is valued for its adaptability and resilience, as it can produce stable yields even in poor weather conditions, which is a significant advantage over traditional crops.

The yield of switchgrass depends on cultivation technologies and the choice of a variety suitable for the environment. Additionally, the correct choice of planting site, soil preparation, sowing density, fertilisation, pest and disease control, and water supply are crucial for achieving maximum switchgrass biomass yield. Adherence to these agronomic practices is crucial for increasing switchgrass biomass yield from year to year.

Switchgrass is a perennial crop that has a positive impact on the environment. It helps to reduce soil erosion, improve water quality, and increase biodiversity. Furthermore, switchgrass has the potential to reduce carbon dioxide emissions through the production of biofuels from its biomass.

The technology for optimising switchgrass growth on marginal lands involves using semi-fallow primary tillage systems, two spring cultivations, rolling before and after sowing the crop, and sowing in the second decade of April with a seeding rate of 300 germinated seeds per 1 m² or 3 million pieces per 1 ha (5.7 kg/ha) using the wide-row method of sowing (45 cm) along with a legume component. Furthermore, it is necessary to fertilise plants with spring nitrogen at a dose of 15–30 kg/ha of active substance. Implementing these agrotechnological measures, taking into account the weather conditions, had a significant impact on the increase of switchgrass biomass yield. The yield ranged from 13.8 to 16.6 t/ha throughout the research years (Table 3).

Table 3

Switchgrass biomass yield depending on cultivation technology, 2015–2020, t/ha

Technology (factor A)	Years (factor B)						Average
	2015	2016	2017	2018	2019	2020	
Conventional	13.80	14.00	14.40	14.60	15.10	15.40	14.60
Resource-saving	14.50	15.10	15.50	15.90	16.30	16.60	15.70
LSD ₀₅ (factor A)	0.06	0.09	1.00	0.07	0.07	0.08	0.13
LSD ₀₅ (factor B)	–	–	–	–	–	–	0.38
LSD ₀₅ (factor AB)	–	–	–	–	–	–	0.68

Source: authors' research.

The biomass yield of switchgrass is significantly higher when using resource-saving technology compared to conventional technology. The yield gain was 0.7 t/ha in 2015, 1.1 t/ha in 2016 and 2017, 1.3 t/ha in 2018, and 1.2 t/ha in 2019 and 2020.

The implementation of resource-saving switchgrass cultivation technology in the Forest-Steppe conditions of Ukraine has resulted in a significant increase in biomass yield. Over six years, the yield has increased to 16.6 t/ha, which is 1.2 t/ha higher than the yield obtained through conventional technology.

Both technologies for cultivating switchgrass demonstrate a gradual increase in yield over several years, indicating their relevance. The introduction of new technologies in agricultural production can significantly improve land use efficiency, particularly for resource-efficient technology that enhances productivity without harming the environment (Figure 1).

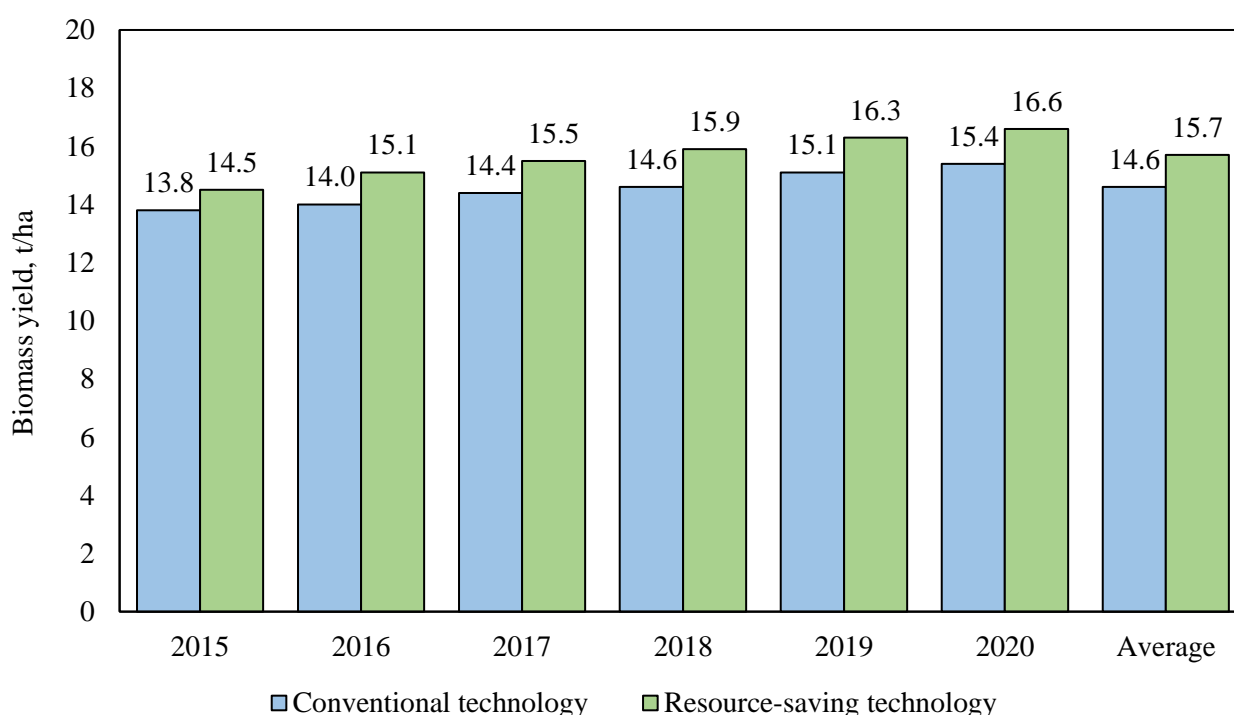


Figure 1. Dynamics of switchgrass biomass yield depending on cultivation technology, 2015–2020, t/ha

Source: authors' research.

Over a period of six years, the average yield of switchgrass biomass using resource-saving technology was 15.7 t/ha. This is 1.1 t/ha higher than the yield obtained using conventional technology, which was 14.6 t/ha (Figure 2, Figure 3).

Figure 3 shows the range of variation in biomass yield for different switchgrass cultivation technologies during the third to eighth growing seasons. The range of variation of the resource-saving technology indicators across years does not overlap, indicating that switchgrass consistently produced a significantly higher yield each year.

The dependencies between conventional and resource-saving technologies showed significant differences at the 5 % level of significance in dry biomass yield during the period of 2015–2020 (Table 4).

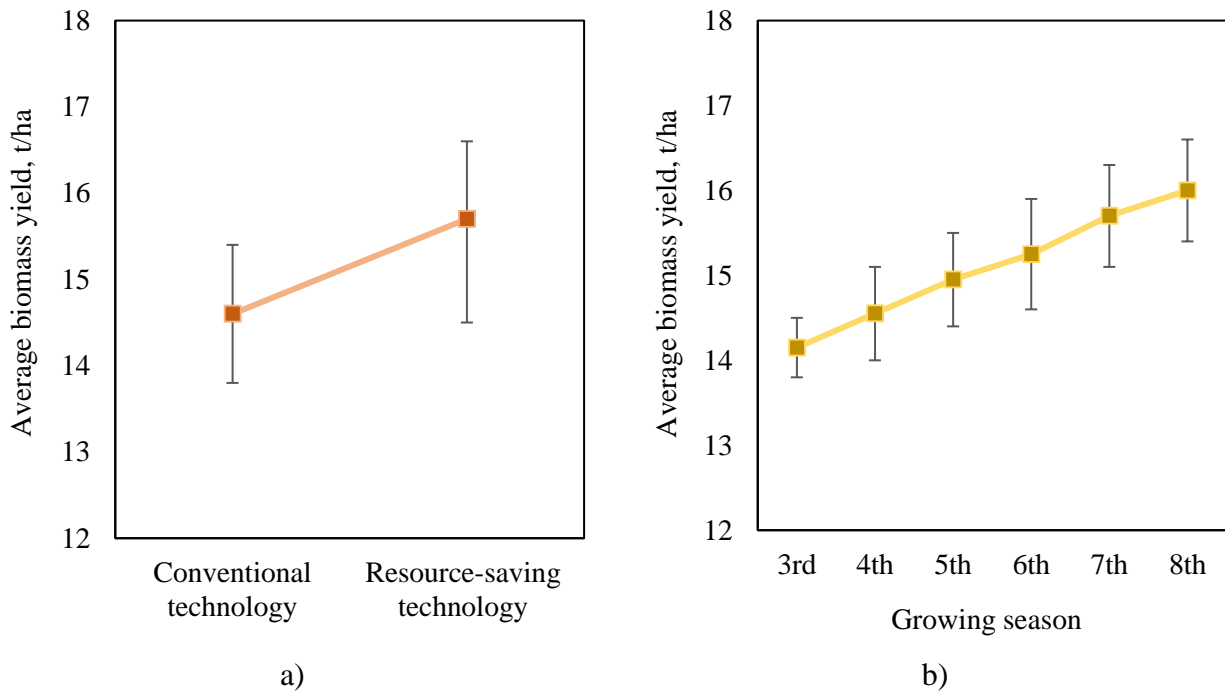


Figure 2. Dependence of switchgrass biomass yield on cultivation technology: a) separate value for each over six years; b) overall value for both annually, 2015–2020, t/ha

Source: calculated by the authors.

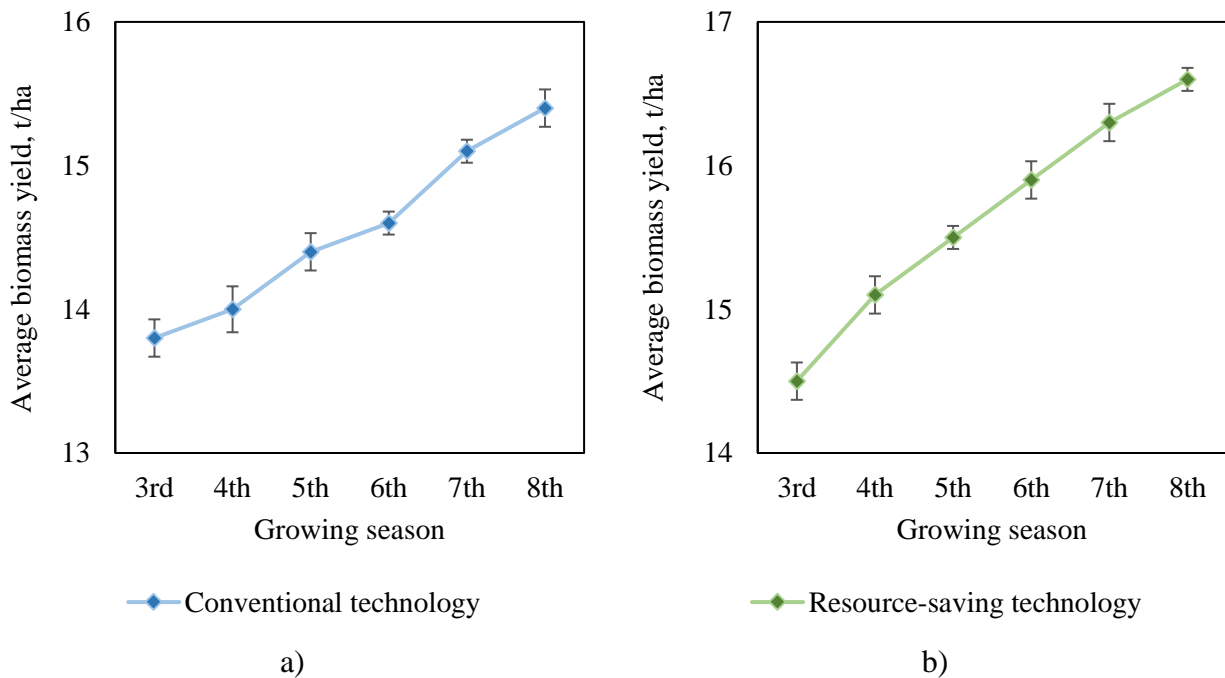


Figure 3. Dependence of switchgrass biomass yield on cultivation technology: a) conventional; b) resource-saving, 2015–2020, t/ha

Source: calculated by the authors.

Table 4

Results of the dispersion analysis of variance (MANOVA)

Indicator	SS	Degr. of	MS	F	p
Intercept	10941.46	1	10941.46	1994393	< 0.05
Factor A	14.19	1	14.19	2587	< 0.05
Factor B	19.48	5	3.90	710	< 0.05
Factor AB	0.40	5	0.08	15	< 0.05
Error	0.20	36	0.01	–	< 0.05

Source: calculated by the authors.

4.2. Economic efficiency depending on cultivation technology. Measuring economic efficiency is necessary for any economic activity (Aparicio et al., 2023; Ahmed, 2019; Barbero & Zofio, 2023; Prieto, 2021; Tuan, 2023). Assessing economic efficiency is essential in determining the viability of cultivating an agricultural crop under conditions of limited resources and market competition. It enables producers to make informed decisions regarding resource allocation, crop planning, and production optimisation. Economic efficiency aims to increase profit and optimise resource use while considering market requirements. Effective resource use helps to reduce costs, which, in turn, increases competitiveness in the market.

This study compares the economic efficiency of cultivating switchgrass using conventional and resource-saving technologies based on key economic indicators such as production cost, full cost, sales revenue, profit, and profitability level (Table 5).

Table 5

Economic efficiency of switchgrass biomass production depending on cultivation technology, 2015–2020

Technology	Growing season	Yield, t/ha	Economic efficiency indicator				
			Production cost, UAH/ha	Full cost, UAH/ha	Sales revenue, UAH/t	Profit, UAH/ha	Profitability level, %
Conventional	3rd	13.8	7016.0	7856.0	13110.0	5254.0	66.9
	4th	14.0	7260.0	7986.1	13300.0	5313.9	66.5
	5th	14.4	7280.0	7953.6	13680.0	5726.4	72.0
	6th	14.6	7290.0	7960.0	13870.0	5910.0	74.2
	7th	15.1	7310.0	7976.1	14345.0	6368.9	79.8
	8th	15.4	7320.0	7985.0	14630.0	6645.0	83.2
Average		14.6	7246.0	7952.8	13822.5	5869.7	73.8
Resource-saving	3rd	14.5	7520.0	8347.2	13775.0	5427.8	65.0
	4th	15.1	7610.0	8363.6	14345.0	5981.4	71.5
	5th	15.5	7410.0	8213.0	14725.0	6512.0	79.3
	6th	15.9	7496.0	8290.0	15105.0	6815.0	82.2
	7th	16.3	7500.0	8300.0	15485.0	7185.0	86.6
	8th	16.6	7530.0	8320.0	15770.0	7450.0	89.5
Average		15.7	7511.0	8305.6	14867.5	6561.9	79.0

Source: calculated by the authors.

Resource-saving technology, despite its higher production cost, is more economically effective over time than conventional technology. The use of resource-saving technology can result in higher revenue due to increased yields and better selling

prices for biomass produced by this technology. Using conventional technology, the average sales revenue is 13822.5 UAH/t with a profitability level of 73.8 % over six years. However, resource-saving technology yields a higher average sales revenue of 14867.5 UAH/t with a profitability level of 79.0 % over the same period (Figure 4).

The profitability level, which measures net profit as a percentage of the full cost, consistently shows higher results for resource-saving technology across all years. This demonstrates that resource-saving technology is more effective at converting used resources into profit and highlights the economic benefits of adopting more resource-efficient cultivation practices for switchgrass biomass production.

It has been established that using the proposed complex of agrotechnological measures, according to resource-saving technology, in comparison to conventional technology in the Forest-Steppe conditions of Ukraine, can increase the economic efficiency of biomass production.

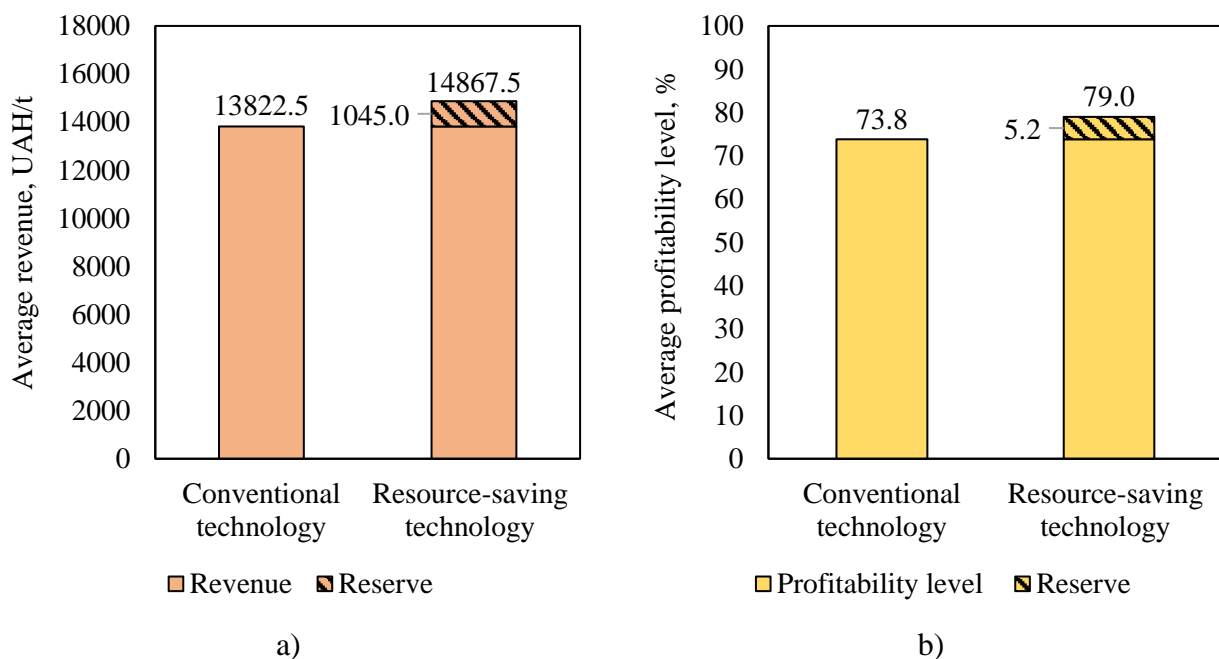


Figure 4. Economic efficiency indicators: a) revenue; b) profitability level for switchgrass production using conventional and resource-saving cultivation technologies, 2015–2020

Source: calculated by the authors.

A three-dimensional econometric model established the dependence of the profitability level on the technology used for switchgrass cultivation. The model is described by the regression equation:

$$z = -1014.2527 + 7.1875x + 3.4982y, \quad (1)$$

where z is the profitability level (%), x is the growing season, y is the technology.

The statistical reliability of the model has been confirmed by the Fisher test ($F_{fact} > F_{theor}$) with a significance level < 0.05 . Resource-saving technology is recommended for cultivating switchgrass, rather than conventional technology. Furthermore, profitability has increased annually from the third to the eighth growing season of switchgrass (Figure 5).

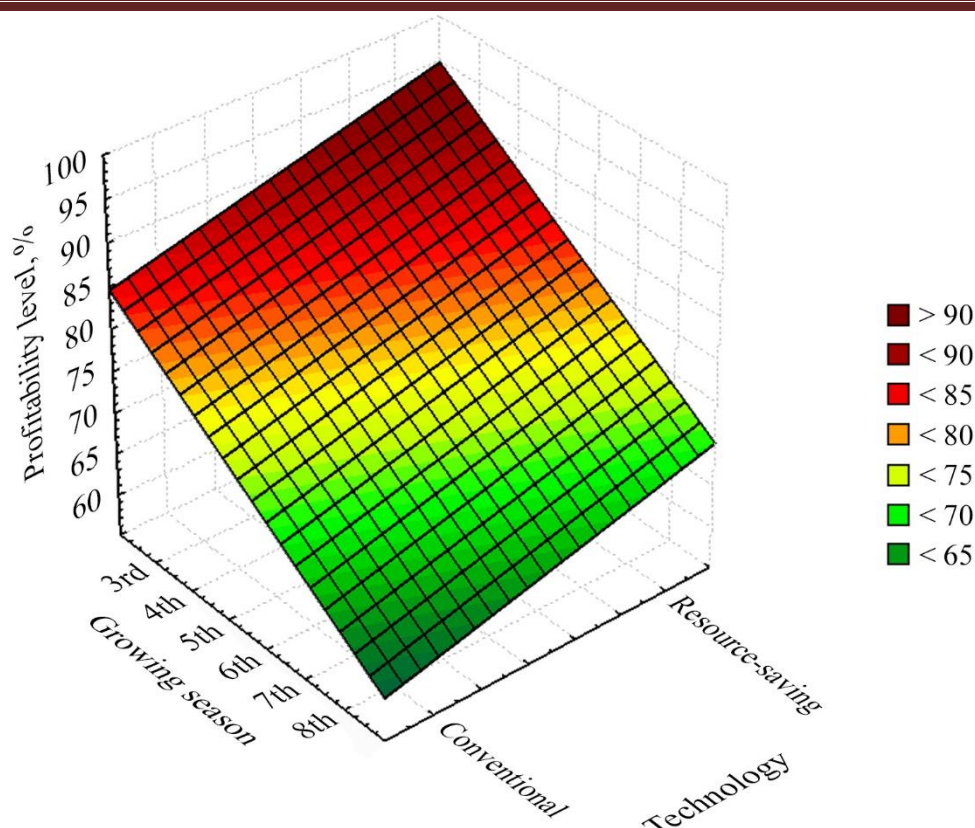


Figure 5. Three-dimensional econometric model of the dependence of the profitability level from application of resource-saving technology in comparison with conventional technology of switchgrass cultivation, 2015–2020

Source: calculated by the authors.

Switchgrass has the potential to be a significant biomass source for economically effective renewable energy production. An integrated approach that takes into account the economic, ecological and social aspects of cultivation, processing and use is necessary for the effective use of switchgrass. With appropriate investments in research, infrastructure development, and producer incentives, switchgrass biomass could become an important component of the future energy landscape.

4.3. Energy efficiency depending on cultivation technology. In the era of global climate change and the need to reduce carbon emissions, energy efficiency is a crucial issue. Resource-saving technology, particularly in the agricultural sector and the production of biomass, plays a significant role in achieving this goal. Switchgrass is an attractive crop for biomass production due to its high energy efficiency and adaptability to various growing conditions, including dry and moist soils. Its biomass has a high energy density, making it an effective source for electricity and heat production. The energy derived from switchgrass biomass can fulfil the requirements of agrarian enterprises and even entire communities.

The energy efficiency of switchgrass growth relies on the use of resource-saving production technology. It is defined as a combination of interconnected operations that reduce energy costs per unit of product. In this case, the product is biomass with an energy intensity of 16.1–16.5 MJ/kg.

The use of the proposed resource-saving technology, as compared to conventional

switchgrass cultivation technology, in the Forest-Steppe conditions of Ukraine, allows for an increase in the energy efficiency of switchgrass biomass production (Table 6).

Table 6

Energy efficiency of switchgrass biomass production depending on cultivation technology, 2015–2020

Technology	Growing season	Yield, t/ha	Energy efficiency indicator					
			Solid biofuel output, t/ha	Total energy stored in biomass, GJ/ha	Total energy costs for biomass cultivation, GJ/ha	Energy capacity of biomass cultivation, GJ/UAH	Energy profit of biomass cultivation, GJ/ha	Energy efficiency coefficient
Conventional	3rd	13.8	15.2	242.9	82.4	5.4	160.5	2.9
	4th	14.0	15.4	254.1	70.5	4.6	183.6	3.6
	5th	14.4	15.7	251.7	66.1	4.2	185.6	3.8
	6th	14.6	16.1	257.6	61.4	3.8	196.2	4.2
	7th	15.1	16.6	263.9	58.2	3.5	205.7	4.5
	8th	15.4	16.9	270.4	55.4	3.3	215.0	4.9
Average		14.6	16.0	256.8	65.7	4.1	191.1	4.0
Resource-saving	3rd	14.5	16.2	258.7	54.8	3.4	203.9	4.7
	4th	15.1	16.6	290.7	73.5	4.4	217.2	4.0
	5th	15.5	17.4	278.1	67.7	3.9	210.4	4.1
	6th	15.9	17.5	280.0	62.4	3.6	217.6	4.5
	7th	16.3	17.9	286.4	55.2	3.1	231.2	5.2
	8th	16.6	18.3	292.8	50.1	2.7	242.7	5.8
Average		15.7	17.3	281.1	60.6	3.5	220.5	4.7

Source: calculated by the authors.

As the growing seasons progress, the performance differences between the two technologies become more pronounced. The resource-saving technology consistently demonstrates a higher energy profit of biomass cultivation and a higher energy efficiency coefficient, indicating its greater efficiency in producing energy from biomass at lower costs. Therefore, the introduction of resource-saving technology for biomass production has advantages over conventional technology. The use of resource-saving technology in biomass production offers benefits such as increased efficiency, yield, and sustainability.

Compared to conventional technology, the use of resource-saving technology increased the total energy stored in biomass by 24.3 GJ/ha and improved the energy efficiency coefficient from 4 to 4.7 (an average level of energy efficiency) during the third to eighth growing seasons. Resource-saving technology has a higher energy capacity of biomass cultivation compared to conventional technology, averaging 3.5 GJ/UAH compared to 4.1 GJ/UAH. The use of resource-saving technology resulted in an increase of 29.4 GJ/ha in energy profit compared to conventional technology.

It has been established that the energy efficiency coefficient increases as energy costs for technological operations decrease during the multi-year growing cycle of switchgrass (Figure 6).

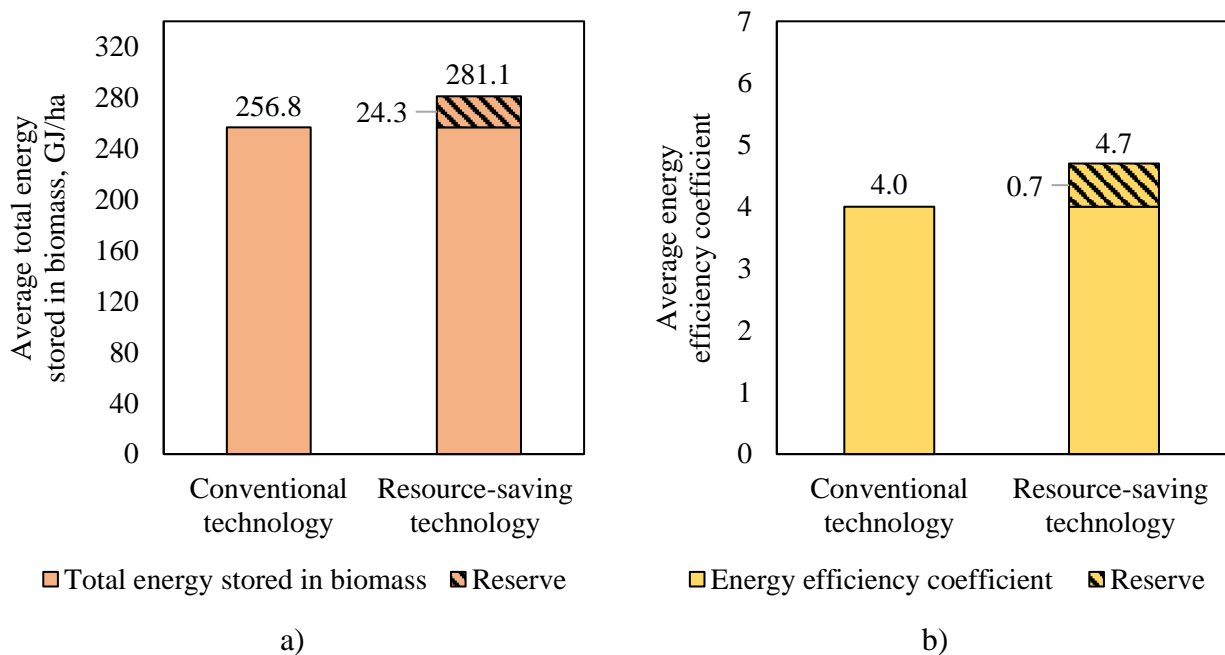


Figure 6. Energy efficiency indicators: a) total energy stored in biomass; b) energy efficiency coefficient) for switchgrass production using conventional and resource-saving cultivation technologies, 2015–2020

Source: calculated by the authors.

A three-dimensional energetometric model established the dependence of the energy efficiency coefficient on the technology used for switchgrass cultivation. The model is described by the regression equation:

$$z = -98.8982 + 0.6417x + 0.3679y, \quad (2)$$

where z is the energy efficiency coefficient, x is the growing season, y is the technology.

The statistical reliability of the model has been confirmed by the Fisher test ($F_{fact} > F_{theor}$) with a significance level < 0.05 . The energy efficiency coefficient is higher when using resource-saving technology compared to conventional technology for cultivating switchgrass. An upward trend was observed in this indicator annually, from the third to the eighth growing season of switchgrass, using both technologies (Figure 7).

Switchgrass biomass is a promising modern energy source due to its high energy efficiency. It has the potential to become a significant source of electricity and heat in the future, thanks to its high productivity and environmental benefits. This could aid in reducing carbon emissions and combating global climate change.

Cultivating energy crops on marginal lands, which are low-productive and polluted, can create alternative sources of fuel. This approach avoids using land that is suitable for cultivating food crops. Agrarian enterprises can achieve a synergistic effect by obtaining both main agricultural products and energy products, such as switchgrass biomass. This allows for the possibility of profiting from the sale or processing of the main agricultural products while also saving money when cultivating energy crops for biofuels.

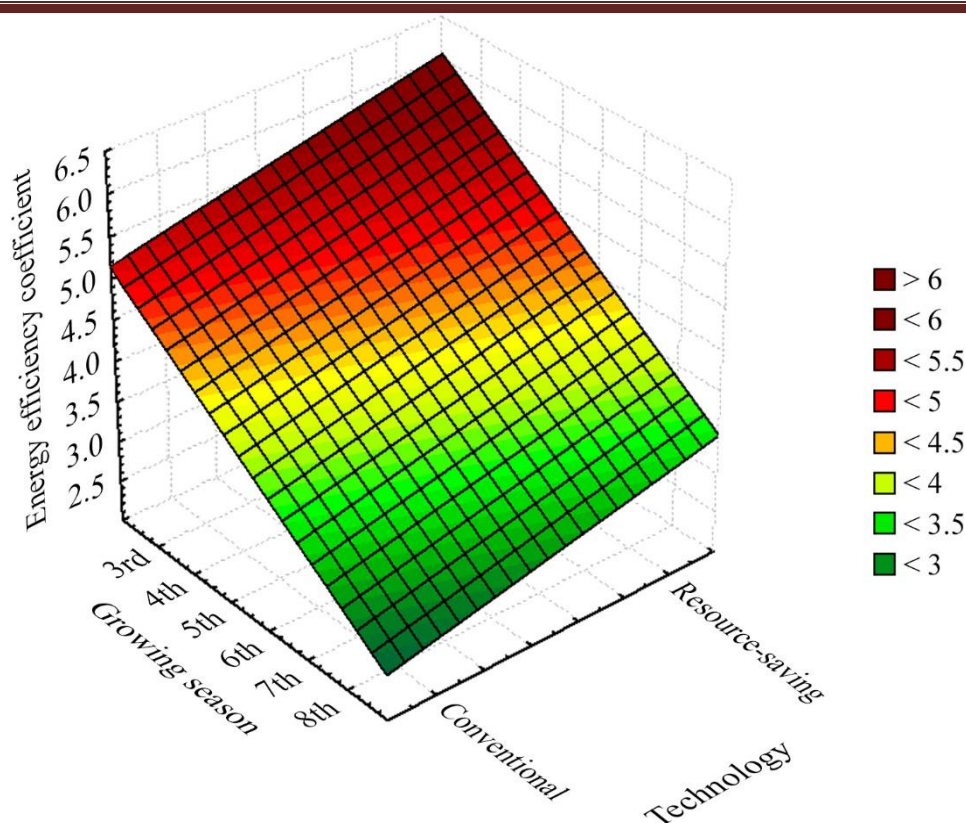


Figure 7. Three-dimensional energometric model of the dependence of the energy efficiency coefficient from application of resource-saving technology in comparison with conventional technology of switchgrass cultivation, 2015–2020

Source: calculated by the authors.

When cultivating energy crops, the cost of seed material is a significant cost item. To encourage their cultivation, it is recommended to provide state support to agrarian enterprises by introducing subsidies for energy crop seed material. The annual cost of producing biomass is decreasing due to simplified technology for cultivating perennial energy crops. This presents an opportunity to study ways to reduce costs during long-term cultivation of not only switchgrass but also other perennial energy crops, while considering their environmental impact.

5. DISCUSSION

The study confirms that the technology used to grow energy crops affects biomass yield, which is consistent with the findings of other authors. When cultivating switchgrass, it is important to consider external environmental factors of the growing region. The authors recommend using different models for cultivating switchgrass based on agroclimatic indicators, with the option to adjust them using agricultural technology (Volvach et al., 2022).

Previous studies in Ukraine have demonstrated that the yield of switchgrass biomass can range from 20.6 to 25.0 t/ha, depending on the agricultural cultivation technology used. This can result in energy output ranging from 304.3 to 371.5 GJ/ha. Additionally, the profitability level of switchgrass biomass production in the second growing season is 84.0 %. These findings support our initial conclusions: an increase

in switchgrass biomass yield leads to a higher energy output per hectare (Gumentyk & Kharytonov, 2018).

According to a study by Mazur et al. (2020), the biomass yield of switchgrass ranges from 9.0 to 12.0 t/ha, and the energy output ranges from 135.0 to 180.0 GJ/ha depending on the agricultural technology used. The energy efficiency coefficient is within 2.3–2.9. These indicators are influenced by both the switchgrass variety and the sowing time of the crop. The use of nitrogen resulted in an increase in biomass yield (up to 10.8–13.5 t/ha) and energy output (from 162.3 to 210.0 GJ/ha), leading to an energy efficiency coefficient of 2.7 to 3.4. In contrast to our results, the authors obtained lower energy indicators. This difference may be due to their use of averaged data from 2015–2017 (Mazur et al., 2020), which does not account for changes in energy indicators over the years of the study.

The economic efficiency of switchgrass biomass production was analysed by investigating the impact of different cultivation methods. The most profitable variants were found to be joint and mixed sowing of switchgrass with legumes, as well as spring nitrogen fertilisation of plants. Improving the cultivation technology of switchgrass can enhance the crop's economic efficiency (Kalinichenko & Kulyk, 2018).

Humentyk & Bondar (2018) obtained additional results by comparing woody and herbaceous energy crops. The highest energy efficiency indicators were found in miscanthus and energy willow, in comparison with switchgrass. However, switchgrass still showed a high coefficient of energy efficiency, making it a viable option for energy production in southern regions of Ukraine.

The data obtained by foreign authors support the authors' opinion that switchgrass can be used not only as an energy crop but also as a forage crop in regions with high rainfall or in areas with moderately shallow groundwater levels (Giannoulis et al., 2013).

6. CONCLUSIONS

The following conclusions can be drawn based on the conducted research:

1. The resource-saving technology of switchgrass cultivation on marginal lands involves semi-fallow primary tillage systems, two spring cultivations, and rolling before and after sowing. The seeding is done in the second decade of April with a seeding rate of 300 germinated seeds per 1 m² or 3 million pieces per 1 ha (5.7 kg/ha). Using the wide-row method of sowing (45 cm) in conjunction with a legume component and spring fertilisation of plants with a dose of 15–30 kg/ha of active substance, starting from the third growing season, can increase biomass yield up to 15.7 t/ha. This is 1.1 t/ha higher than the yield achieved using conventional technology (14.6 t/ha).

2. The economic indicators for cultivating switchgrass using resource-saving technology were significantly higher than those using conventional technology. Specifically, the profitability level was 79.0 % with resource-saving technology compared to 73.8 % with conventional technology. The use of resource-saving technology resulted in an increase in revenue of 1045 UAH/ha and profitability of 5.2 % compared to conventional technology. At the same time, the full cost of

cultivating switchgrass using resource-saving technology is 352.8 UAH/ha higher than with conventional technology.

3. The implementation of resource-saving technology led to a 1.3 t/ha increase in solid biofuel output and a 24.3 GJ/ha increase in total energy stored in biomass. Additionally, the energy efficiency coefficient improved from 4 to 4.7, which is an average level of energy efficiency. This was achieved while reducing the total energy costs for biomass cultivation from 65.7 to 60.6 GJ/ha.

The study by the authors provides a noteworthy contribution to current bioenergy research by demonstrating the potential of annual plant biomass production as an alternative energy source for biofuels. This is the first study to compare the efficiency of resource-saving cultivation technology with conventional cultivation technology of switchgrass in the forest-steppe conditions of Ukraine. The authors' methodology for assessing the economic and energy efficiency of cultivating switchgrass was used. The findings can be used to provide the processing industry with plant-based raw materials that are high in energy for the production of biofuels. This can meet the demand of consumers for cost-effective energy and decrease the energy reliance of local communities in Ukraine.

7. LIMITATIONS AND FUTURE RESEARCH

The authors acknowledge that the analysis is limited to data on the use of agricultural technologies. It does not include broader economic and energy impacts at the regional or national level. Additionally, there is no available data on the impact of using energy crops on national GDP and employment trends when creating new jobs for cultivating and processing biomass of energy crops. The study provides practical recommendations for agricultural producers. However, it does not analyse the existing policies and institutional frameworks that could facilitate or impede the progress of alternative fuels and environmentally friendly biomass production. The study could be improved by including a comparative analysis with the experience of other countries. This would provide a broader perspective and allowed for a more comprehensive comparison of the results of cultivating switchgrass using different technologies in different countries.

The limitations mentioned above indicate potential areas for future research that could improve our understanding of the needs of agricultural producers. Such research could promote sustainable development in local communities, develop logistical solutions for biomass production, and strengthen environmental protection.

In future scientific work, the authors aim to expand research areas and develop methods to make the cultivation of switchgrass more environmentally friendly under different soil cultivation techniques. This is important in addressing the issue of soil fertility restoration.

The perspectives for further research are to assess the economic and energy efficiency of biofuel production from various types of plant-based bio-raw materials and to develop a logistics chain from production to the consumer.

Conflicts of interest: the authors declare no conflict of interest.

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