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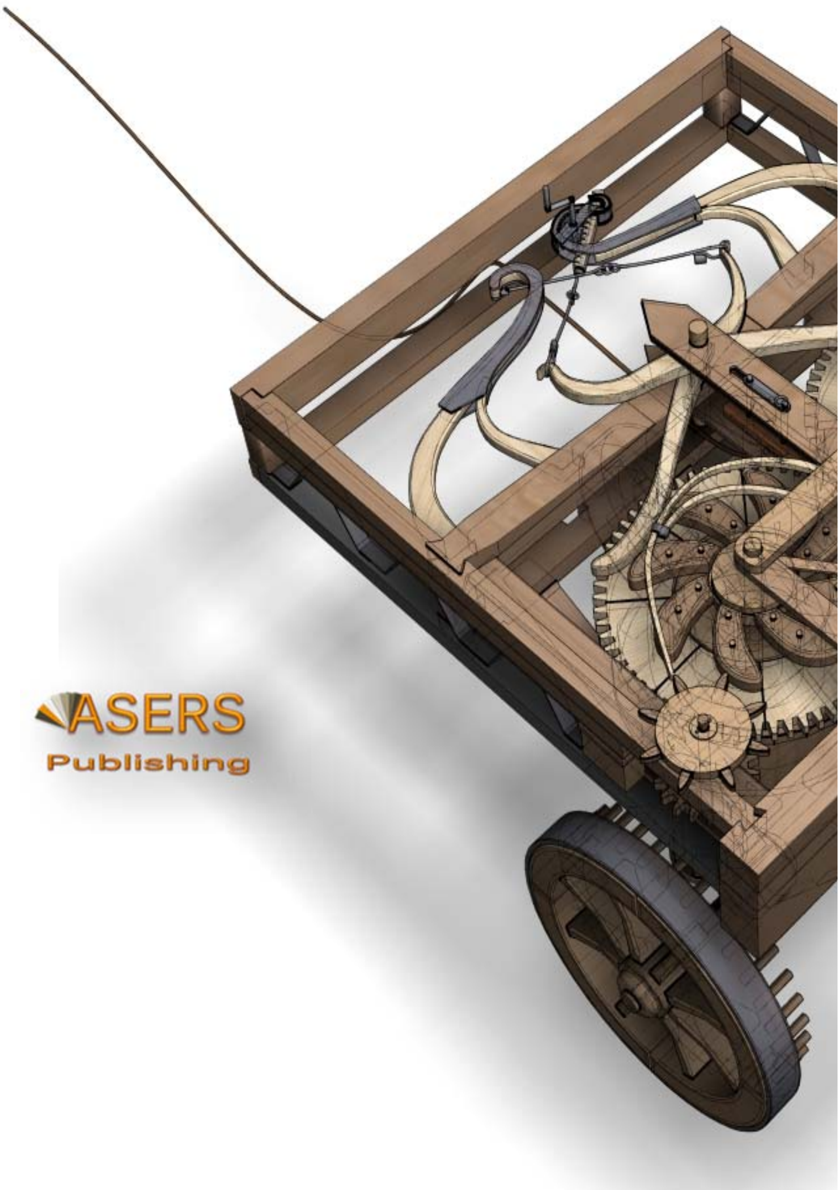


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# Call for Papers
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# Journal of Environmental Management and Tourism

**Journal of Environmental Management and Tourism** is an interdisciplinary research journal, aimed to publish articles and original research papers that should contribute to the development of both experimental and theoretical nature in the field of Environmental Management and Tourism Sciences.

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# Efficiency of Optimized Technology of Switchgrass Biomass Production for Biofuel Processing

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**Abstract**:

In order to reduce the dependence on fossil energy sources in Ukraine, the need to develop its own alternative energy fuels production has arisen. Switchgrass is used in many countries as an efficient energy non-food crop for biofuel production. The main methods to use switchgrass for energy purposes is the production of electricity through gasification, combined combustion and the production of second-generation biofuels. Due to the relevance of the energy security problem in Ukraine, the need to develop an optimized switchgrass growing technology is substantiated in the article. The energy efficiency of optimized cultivation technology based on calculated indicators has been established. The impact of conditions and cultivation techniques on yield of switchgrass has been investigated. The effects of optimized growing technology and growing conditions on the energy efficiency of switchgrass biomass production have been studied. The energy output and energy efficiency coefficient, depending on the technology of growing switchgrass has been established. The results of long-term studies show an increase in the yield of this crop (at a level or above 15.0 t / ha), depending on the elements of the cultivation technology and growing conditions.

**Keywords:** energy; ecology; environment; efficiency; emissions; biofuels; biomass; switchgrass; productivity; technology.

**JEL Classification**: N54; Q01; Q20.

## Introduction

The EU Energy Efficiency Directive from 2012 establishes a set of mandatory measures to help the EU achieve 20% energy efficiency by 2020. In accordance with the Directive, all EU countries must use more energy and more efficiently at all stages of the energy chain – from production to the final consumer.

On November 30, 2016, the European Commission proposed updating the energy efficiency directive in the published proposals “Clean energy for all Europeans”, including a new targeted program for energy efficiency and switching to alternative sources by 30% until 2030.

The cultivation of energy crops in Ukraine and countries with developing economies, with agronomic, scientific and energy justification is a promising area and an urgent issue. It allows getting high-quality solid biofuels for further energy use and production of heat and electricity, which is a good alternative for non-renewable resources.

Nowadays the efficiency of using agricultural feedstock for bioenergy production in discussed widely. Zulauf C. *et al* (2018) states that Ukraine’s agricultural sector is a potential resource for biofuels production. Authors conclude that the possibility exists for Ukraine to both develop a biofuels industry and satisfy its export and domestic markets for agricultural crops. However, Kaletnik H. *et al.* (2019) discusses the issues that arose along with the production of biofuels from food agricultural crops. Berezyuk S. *et al.* (2019) emphasize on the opportunity of producing biofuels from waste in order to provide environmental and energy safety.

A significant number of scientific publications are devoted to the study of the efficiency of growing agricultural and energy crops. Among them one of the outstanding works is “Assessment of the energy potential of biomass in Ukraine” by G. Geletukha *et al.* (2011). Scientists have assessed the economic efficiency of growing biomass and the energy potential of energy crops biomass in Ukraine. Along with this, Kalinichenko A. *et al.* (2017) found that Ukraine has a significant potential of plant biomass and phytomass of energy crops available for the bioenergy development. Başar, İ. A., *et al.* (2020) studies the opportunity to produce ethanol or/and methane from untreated energy crop switchgrass varieties.

According to the data of Geletukha G.G., Zheleznaya T.A., Triboy A.V. (2015) about 4 million hectares of free land are concentrated in Ukraine, some of which can be used for growing energy crops. Considering that the sustainability criteria that are developed according to the “Energy Strategy of Ukraine until 2035” are met, the ecological, economic and social efficiency of growing energy crops can be achieved. Along with this, Geletukha G., Zhelezna T. and E. Oliynik (2013) found that the use of unproductive soils in Ukraine will allow increasing energy production from biomass of energy crops to 18% of total energy consumption. Also, biomass can be used to meet the needs for thermal energy.

To provide practical opportunities for farmers and producers Sims R. *et al.* (2015) propose the rational use of farmland and the integrated use of land for the operation of wind generators, solar panels, biogas production, biomass cultivation and others. Food production plants will be able to purchase electricity that is generated locally. Also, the use of biomass can be used to meet the needs for thermal energy.

According to Elbersen W. and M. Kulyk (2013), switchgrass (Panicum virgatum L.) is the most adapted to growing conditions among energy crops. This crop is able to form a powerful stalk and provide a stable biomass yield from the third year of cultivation. Development of commercially relevant bioenergy switchgrass cultivars requires reducing recalcitrance for bioprocessing without compromising biomass yield (Alexander *et al.* 2020).

As stated by Kulyk M. and N. Shokalo (2018), switchgrass is a perennial herbaceous plant belonging to the Myatlikovye (Poacea) family. According to its morphological structure, the plant consists of a fibrous root system, hollow stems, long leaves and panicle inflorescence, on which fruits are formed in the ears (small grains) (Figure 1).

The productivity of the aboveground phytomass of switchgrass, depending on the variety and growing conditions, during the panicle appearance is 42-64 tons per hectare, during the flowering period – 42.7-70.2 tons per hectare; dry weight – 10.0-15.0 tons per hectare; seeds –500-600 (sometimes up to 1000) kilograms per hectare. Energy productivity of plants – 40-60 (up to 80) Giga calories per hectare (Rakhmetov, Verhun and Rakhmetova 2014).

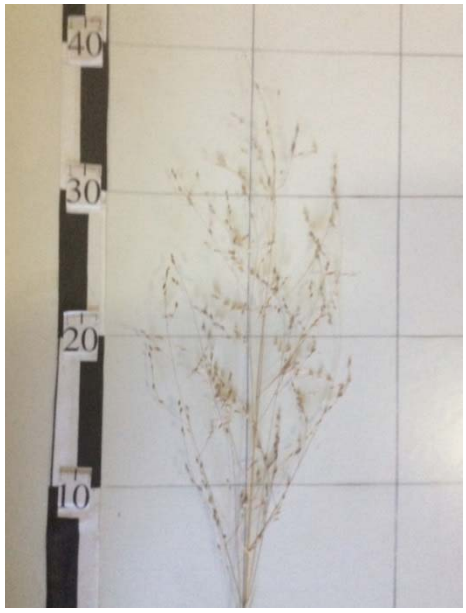
At the same time, studies have shown that the productivity of switchgrass in different growing conditions can vary from 9.2 to 14.7 tons per hectare (Elbersen *et al.* 2001).

It has been determined that in order to ensure long-term effective use of switchgrass energy plantations (up to 20 years), it is necessary to carry out precise management of crops during the first few years (Christian 1996). It was found that the highest yield is achieved after 3-4 years from the time of sowing crops. After 4–5 years, an increase in yield was recorded on heavy soils in the northern regions and on insufficiently moistened southern soils (Samson, Girouard and Chen 1997).

Switchgrass is one of the crops that have a low cost of growing and high productivity of phytomass, which depend on the elements of growing technology. This view is supported by Kumar Amit and Sokhansanj Shahab (2007), who developed a switchgrass feedstock delivery scheme to a biorefinery using integrated biomass supply analysis and logistics.

Figure 1. The structure of the switchgrass plant

a – general view of the plant



b – inflorescence (panicle)

c – root system (fibrous)

d – seeds (small grains)

*Source*: photos of authors.

Features of agricultural technologies in agriculture, and the prospects for their implementation in most world countries are presented in the works of leading foreign authors Robert P. (2000), Plant R. (2005), McBratney A. *et al*. (2005). The technological means of precision farming, the economic and environmental aspects of its application, as well as the long-term plan for supporting the European Union farmers for the period 2014-2020 are described in detail and are set out in a collective work prepared by the Committee of the European Parliament on the Development of Agriculture and Rural Areas.

A great scientific and organizational contribution to the popularization of the ideas of precision farming is made by the International Society of Precision Agriculture (ISPA), a scientific organization that began its activities in the 90s of the last century in the state of Minnesota (USA).

In the works of Petrenko I. (2017) and Tsyganenko M., Makarenko M. (2017), the experimentally obtained indicators of fuel saving due to the improvement of the management of agricultural units, as well as the savings of fertilizers with automatic accurate application are presented.

According to Schmer M.R., Vogel K.P., Mitchell R.B., Perrin R.K. (2008), the need for energy costs for growing switchgrass can reach up to 2 Gig Joules per hectare per year of plantation creation, and about 5 Gig Joules per hectare for each subsequent year.

Bullard and Metcalfe (2001) calculated the total energy coefficient (energy input ↔ energy output) of production processes for switchgrass and miscanthus in the UK. They found that the main difference between switchgrass and miscanthus is that miscanthus requires additional energy input to obtain the source material of the rhizomes and plant them. And for switchgrass this process is less energy-intensive, because for sowing its seeds use conventional seeders. The energy output from miscanthus is higher due to the higher biomass yield from 4 to 20 years of use of energy plantation.

Radiotis, T. *et al.* (1999) argue that the energy intensity of ethanol that is produced from switchgrass corresponds to the energy intensity of ethanol brought from energy willow. The authors established this on the basis of an analysis of the chemical composition of switchgrass.

Therefore, to determine the available potential of phytomass of energy crops in Ukraine, it is necessary to take into account the biological characteristics of various plant species (including switchgrass). An equally important issue is the improvement of switchgrass cultivation technology, taking into account the soil cultivation system, the characteristics of sowing and the use of spring fertilizing. Improvement of the existing switchgrass growing technology (its optimization) can also increase the biomass yield per unit area. This determines the relevance and priority of the studies covered in this scientific publication.

## 1. The Aim and Objectives of the Study

The aim of the research is to study the yield potential and energy efficiency of growing switchgrass in different conditions.

To reach the aim of the research, the following objectives have been set:

1. To establish the variability of the yield of switchgrass biomass depending on the conditions and technology of cultivation.

2. To determine the relationship between growing conditions, the year of vegetation and the productivity of switchgrass with different technologies for its cultivation.

3. Determine the energy efficiency of biomass growing technologies depending on the conditions of cultivation of switchgrass.

## 2. Methodology

In order to determine the response of switchgrass plants to a complex of agricultural activities, studies were conducted in Ukraine in 2015-2019.

The switchgrass variety – Cave-in-Rock (Cave-in-Rock) was selected as the material for research.

The locations of the research sites are Polissia and Forest-Steppe of the Ukrainian agro-climatic zone. They comply with the conditions of the EU countries: Poland, the Czech Republic, Germany and the Netherlands. In this connection, the research results can be partially interpreted to the conditions of these countries according to agro-climatic conditions.

Figure 2. The layout of options in the field experiment

| A.1 – Polissia | | | | |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | reiteration |
| B.2 | B.3 | B.1 | B.2 | variation |
| B.3 | B.2 | B.3 | B.3 | |
| B.1 | B.1 | B.2 | B.1 | |

a

| A.2 – Forest-Steppe | | | | |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | reiteration |
| B.2 | B.1 | B.1 | B.3 | variation |
| B.3 | B.2 | B.2 | B.1 | |
| B.1 | B.3 | B.3 | B.2 | |

b

a – soil and climatic conditions of Polissia (A.1),
b – soil and climatic conditions of the Forest-Steppe (A.2).

The experiment was carried out according to the methodology of the experimental case in agronomy. The experimental plots had a total area of 700 m$^2$, the protective strips with an area of 100 m$^2$, four repetitions in which the experimental plots were located, each with an area of 50 $m^2$ (10 m × 5 m). They were placed in a randomized manner in each repetition (Figure 2).

Research factors and their components:

Factor A (A) – places for growing switchgrass, included: A.1 – Polissia, A.2 – Forest-steppe.

**Factor B (B)**– the technology for growing switchgrass, included the following options: B.1 – technology for growing switchgrass without herbicides (control), B.2 – the existing technology for growing switchgrass, B.3 – advanced technology for growing switchgrass (the bean component is included in the row spacing – meadow clover (red clover)).

**B.1.**Technology for growing switchgrass without herbicides (control): growing a crop on a carefully prepared field using a semi-steam system for basic tillage, without applying a herbicide, three spring cultivations, including pre-sowing, rolling before and after sowing, sowing in the second decade of April at a sowing rate of 300 germinating seeds per 1 m2, or 3 million germinating seeds per 1 ha (5.7 kg / ha), wide-row sowing method (45 cm ) without a bean component (meadow clover), the use of spring dressing of plants from 3 years ($N_{30}$) after each collection of biomass.

**B.2.** Existing technology for growing switchgrass: growing a crop on a carefully prepared field using a semi-steam system for basic tillage, applying a herbicide, three spring cultivations, including pre-sowing, rolling before and after sowing, sowing in the second decade of April at a sowing rate of 300 germinating seeds per 1 $m^2$, or 3 million germinating seeds per 1 ha (5.7 kg / ha), wide-row sowing method (45 cm) without a bean component (meadow clover), the use of spring dressing of plants from 3 years ($N_{30}$) after each collection of biomass.

**B.3.** Improved switchgrass cultivation technology: cultivating a crop on a carefully prepared field using a semi-steam system for basic tillage, without herbicide, three spring cultivations, incl. pre-sowing, rolling before and after sowing; sowing in the second decade of April at a sowing rate of 300 germinating seeds per 1 $m^2$, or 3 million germinating seeds per 1 ha (5.7 kg / ha), a wide-row sowing method (45 cm) together with a legume component (meadow clover), application of spring dressing of plants from 3 years ($N_{30}$) after each collection of biomass.

The above described technologies for growing switchgrass were used both in Polissia and in the Forest-Steppe (Figure 3).

Figure 3. Justification of options for experience: growing technology

| | summer | autumn | winter | spring | summer | autumn |
|---|---|---|---|---|---|---|
| B.1 | + | + | | = × | | … |
| B.2 | + | + | | * = × | | … |
| B.3 | + | + | | = ± × | | … |

*Note*: (+) - systems of the main semi-steam tillage, (*) - application of the herbicide, (=) - spring measures (3 cultivations, sowing the switchgrass, rolling before and after sowing), (±) - sowing of clover in the aisles, (×) - top dressing from the third year of vegetation, (...) - harvesting from the third year of vegetation.

Biomass productivity (wet – WB and dry – DB) was determined annually, after the end of the growing season of the culture (Kulyk and Elbersen 2012). The emphasis was on dry biomass, since this indicator more objectively reflects the output of biofuel from 1 ha (with a coefficient of 1.1).

Switchgrass is a perrenial crop, therefore, the counts were carried out at a third year of plant vegetation (2015-2017), fourth year of plant vegetation (2016-2018) and fifth year of plant vegetation (2017-2019).

A swath of 1 meter wide and 10 meters long was carried out across the width of the plot to calculate the yield of switchgrass. This phytomass was weighed immediately on the field. Then from this phytomass, 5 kg of plants were taken in different parts. They were placed in an airtight bag, transported to a laboratory, and moisture was determined by drying. Samples were weighed before and after drying. Drying was carried out for 1 hour at a temperature of 120 °C. Then recalculation was carried out, the yield of dry biomass was determined, minus the percentage of moisture that it contained.

The energy efficiency of biomass production was determined according to the author's technique (Kalinichenko, Kalinichenko and Kulyk 2017). For calculations, the following indicators were used:

- Output of solid biofuel (B), t/ha;
- Aggregate energy accumulated in switchgrass biomass (Eaa), GJ/ha;
- Total energy expenditures on switchgrass biomass cultivation (Ec), GJ/ha;
- Energy profit of switchgrass biomass cultivation (EPc), GJ/ha;

• Coefficient of energy efficiency of switchgrass biomass cultivation (Kee).

Statistical processing of digital results of the research was performed using dispersion, correlation and regression analysis methods. For this, the software of the computer program Statistics was used.

When determining the significant difference between the experimental variants, the LSD indicators were used – the smallest significant difference, at a level of values $p < 0.05$.

## 3. Results of the Research

*The influence of growing conditions and technology on the productivity of switchgrass biomass.*

The complex of agrotechnical measures during the cultivation of switchgrass: conventional or optimized technology, compared with the control, significantly increased the biomass yield (DB) in two sections A.1 (up to 15.9 t / ha) and A.2 (up to 15.0 t / ha ) (Table 1).

It was established that the variation in yield in the conditions of plot A.1 beyond the experimental options was in the range from 12.9 to 16.9 t / ha, and in the experimental plots A.2 from 12.2 to 15.5 t / ha. This is confirmed by the results of mathematical calculations at a significance level of less than 5%, and is shown in the dispersion table (table 2).

Table 1. Yield of dry biomass of switchgrass depending on growing conditions and technologies, t / ha (2015-2019)

| Growing conditions (Factor B) | Growing technology (Factor C) | Year of vegetation (Factor A) | | | Options average |
|---|---|---|---|---|---|
| | | third | fourth | fifth | |
| A.1 | B.1 | 12,9 | 13,8 | 14,5 | 13,7 |
| | B.2 | 14,2 | 14,9 | 15,3 | 14,8 |
| | B.3 | 15,1 | 15,8 | 16,9 | 15,9 |
| A.2 | B.1 | 12,2 | 13,1 | 13,9 | 13,1 |
| | B.2 | 13,8 | 14,0 | 14,4 | 14,1 |
| | B.3 | 14,5 | 15,1 | 15,5 | 15,0 |
| Average over the years | | 13,8 | 14,5 | 15,1 | 14,4 |
| LSD05 (Factor A) | | - | - | - | 0,59 |
| LSD05 (Factor B) | | - | - | - | 0,48 |
| LSD05 (Factor C) | | - | - | - | 0,42 |
| LSD05 (Facto ABC) | | - | - | - | 0,19 |

*Source*: calculated by the authors

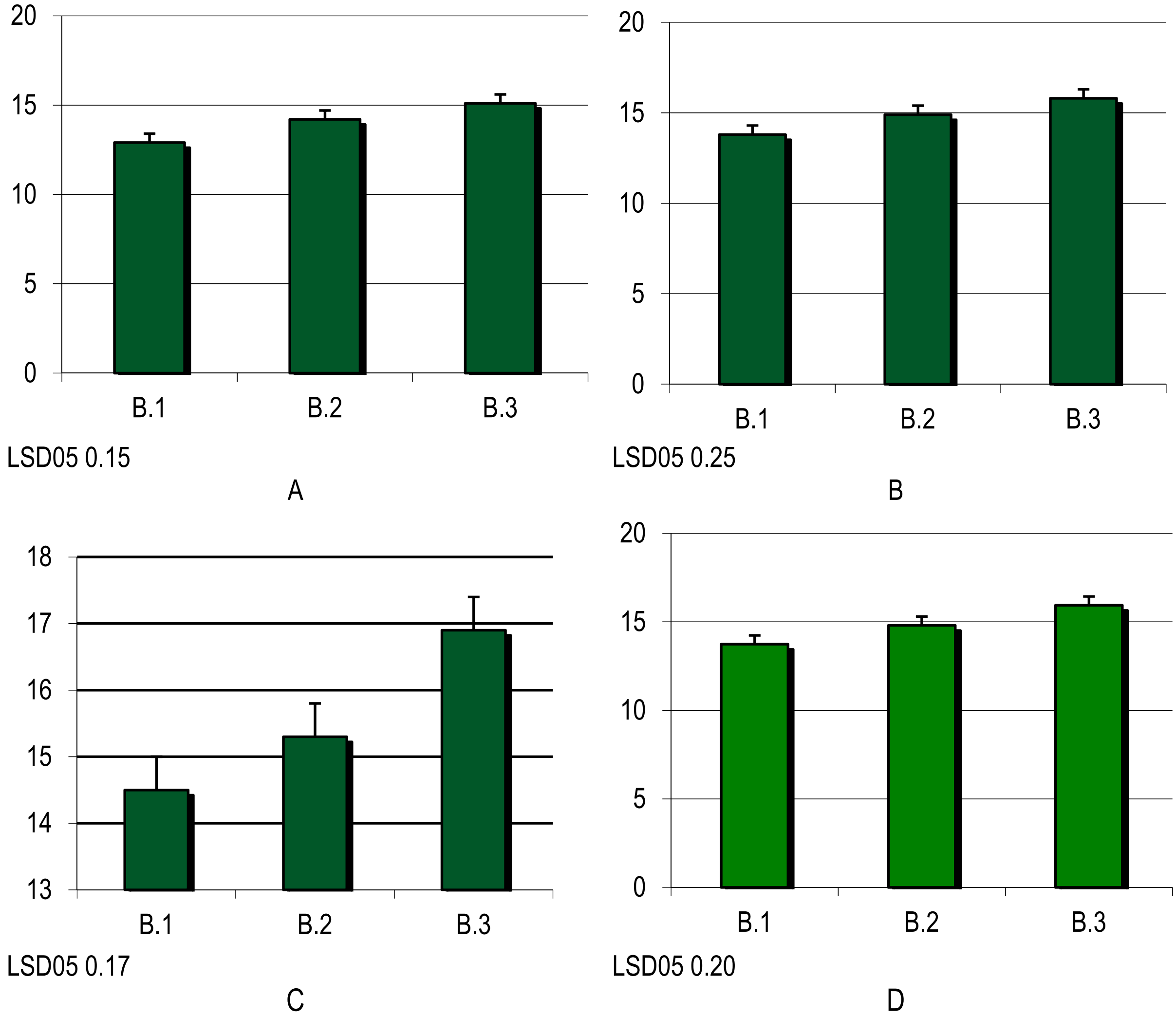
Table 2. Dispersion table of yield data of dry biomass of switchgrass depending on growing conditions and technologies

| | SS | Degr. of | MS | F | p |
|---|---|---|---|---|---|
| Intercept | 14958,73 | 1 | 14958,73 | 1196699 | 0,000000 |
| Factor A | 19,39 | 2 | 9,69 | 776 | 0,000000 |
| Factor B | 10,58 | 1 | 10,58 | 846 | 0,000000 |
| Factor C | 51,25 | 2 | 25,63 | 2050 | 0,000000 |
| Factors A and B | 0,59 | 2 | 0,30 | 24 | 0,000000 |
| Factors A and C | 1,50 | 4 | 0,37 | 30 | 0,000000 |
| Factors A and B | 0,19 | 2 | 0,09 | 8 | 0,001336 |
| A and B and C | 0,77 | 4 | 0,19 | 15 | 0,000000 |
| Error | 0,67 | 54 | 0,01 | | |

Under the conditions of Polissia (A.1), on options B.1, the yield of switchgrass biomass varied from 12.9 to 14.5 t / ha, on options B.2, the yield was significantly higher – from 14.2 to 15.3 t / ha. Options B.3. provided the highest yield of switchgrass compared to B.1 and B.2 (from 15.1 to 16.9 t / ha), which is confirmed by NDS – the smallest significant difference (LSD05) for each year of crop growing (Figure 4).

Under the conditions of the Forest-Steppe (A.2), on options B.1 the productivity of switchgrass biomass varied from 12.2 to 13.9 t / ha, on options B.2 it was significantly higher – from 13.8 to 14.4 t / ha. Options B.3 – an optimized switchgrass growing technology ensured the highest yield compared to B.1 and B.2 (Figure 5).

Figure 4. Dynamics of productivity of switchgrass 3 years of vegetation (a), 4 years (b), 5 (c) years of vegetation and the average of three years (d) depending on the cultivation technology in the conditions of Polissia (A.1), 2015-2019



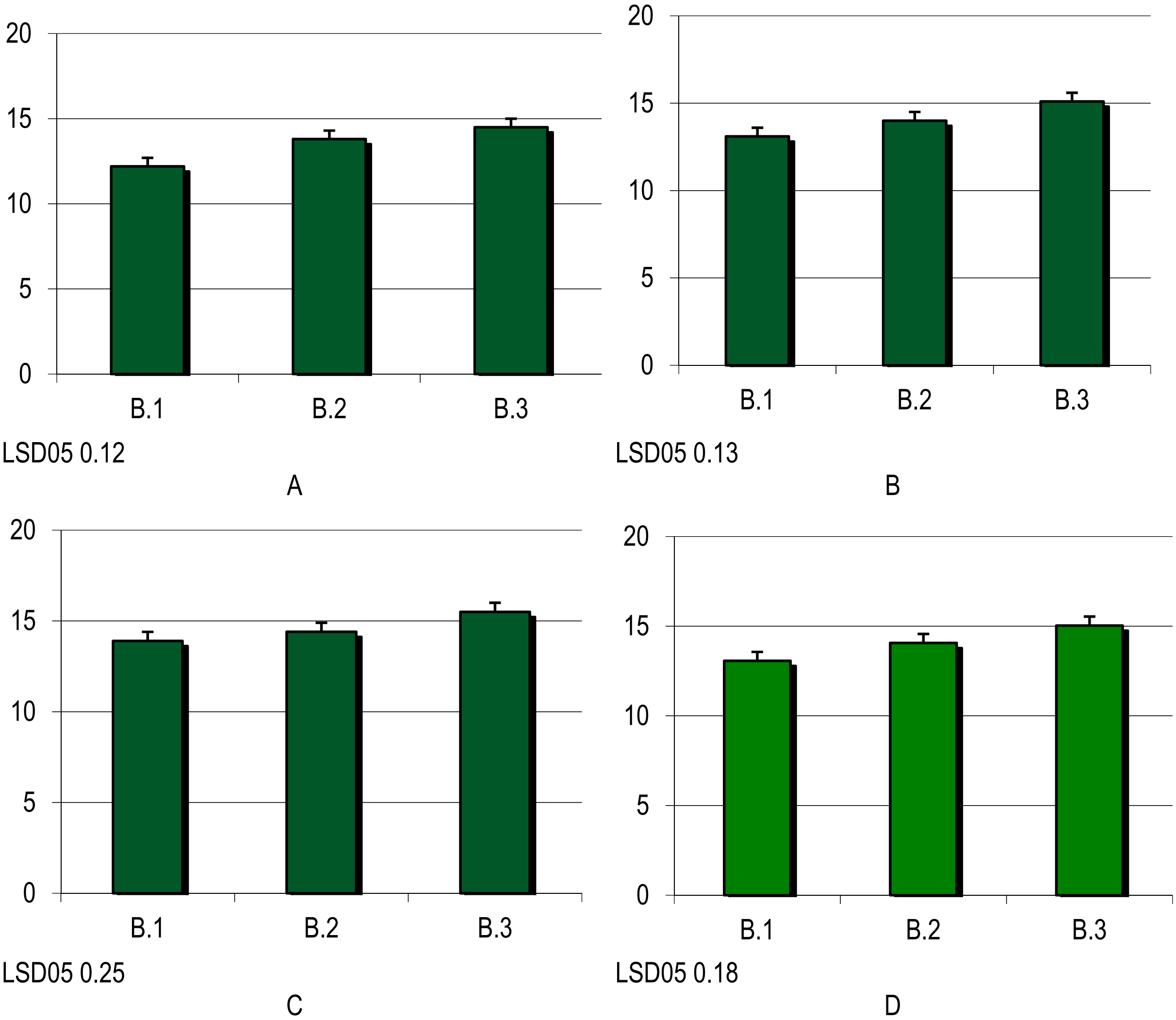

*Note*: B.1 is the technology for growing switchgrass without herbicides (control), B.1 is the existing technology for growing switchgrass, B.2 is an advanced technology for growing switchgrass (the bean component in the row spacing is meadow clover).

On average, for three years, the highest yield of switchgrass was provided in the conditions of Polissia (13.7-15.9 t / ha), lower – in the conditions of the Forest-Steppe (13.1-15.0 t / ha). At the same time, it was established that regardless of the growing conditions, the yield of switchgrass was significantly higher on the variants of optimized growing technology (more than 15.0 t / ha).

*The relationship between the year of vegetation, growing conditions, technology and productivity of biomass switchgrass.*

The established dependence between the years of vegetation of switchgrass, growing conditions, technologies and biomass productivity make it possible to determine the relationships between them (Figure 6).

Figure 5. Dynamics of productivity of switchgrass 3 years of vegetation (a), 4 years (b), 5 years (c) of vegetation and the average of three years (d) depending on the growing technology in the conditions of the Forest-Steppe (A.2), 2015-2019




*Note*: B.1 is the technology for growing switchgrass without herbicides (control), B.1 is the existing technology for growing switchgrass, B.2 is an advanced technology for growing switchgrass (the bean component in the row spacing is meadow clover).

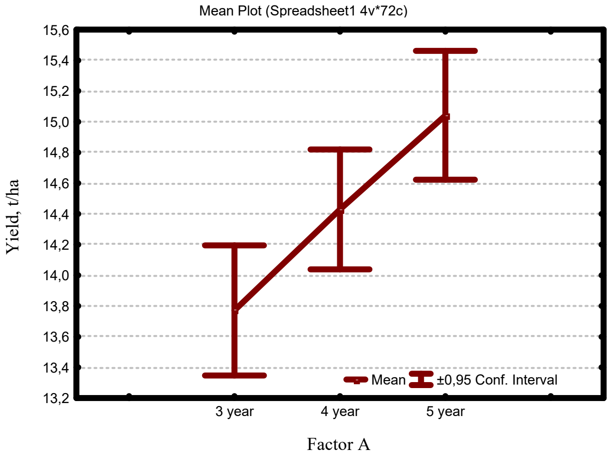
It has been established that the years of crop vegetation do not have a significant effect on the yield level of switchgrass for dry biomass. Under conditions of 3 years, the yield variation limit was from 13.3 to 14.2 t / ha, for 4 years – from 14.1 to 14.8 t / ha, and for 5 years – from 14.6 to 15.5 t / ha.

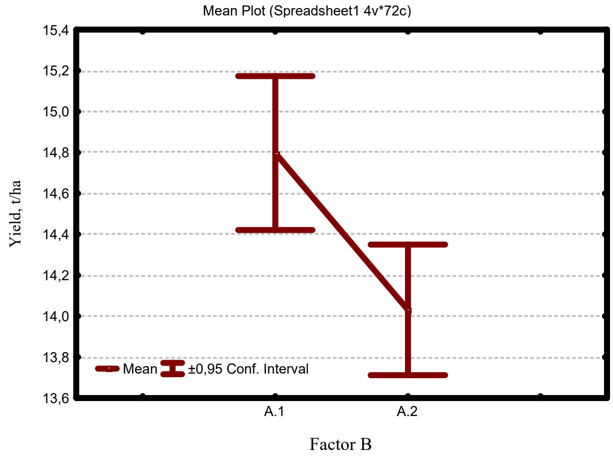
At the same time, it was determined that growing conditions have a more significant impact on the yield of switchgrass biomass (A.2 – the yield varied from 13.7 to 14.3 t / ha, or A.1 – from 14.4 to 15.2 t / ha), as well as the cultivation technology (in variants B.3 they got the highest yield - from 15.1 to 15.7 t / ha).

*The influence of optimized growing technology and growing conditions on the energy efficiency of switchgrass biomass production.*

To determine the energy efficiency of growing switchgrass, we used the following indicators described in the methodology with an energy intensity of raw materials of 16.5 MJ / kg. These indicators for the variants of experiments in the conditions of Polissia (A.1) had different values (Table 3).

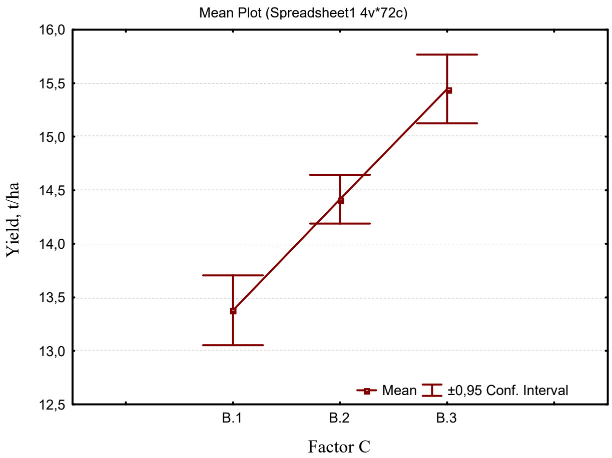
Figure 6. Dependence between the year of vegetation (a), growing conditions (b), technology (c) and the yield of switchgrass biomass, 2015-2019

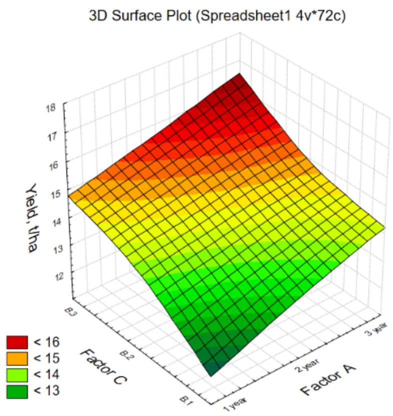



A

B




C

Ac

*Source*: formed by the authors

Table 3. Energy efficiency of biomass production depending on the cultivation technology on A.1, 2015 – 2019

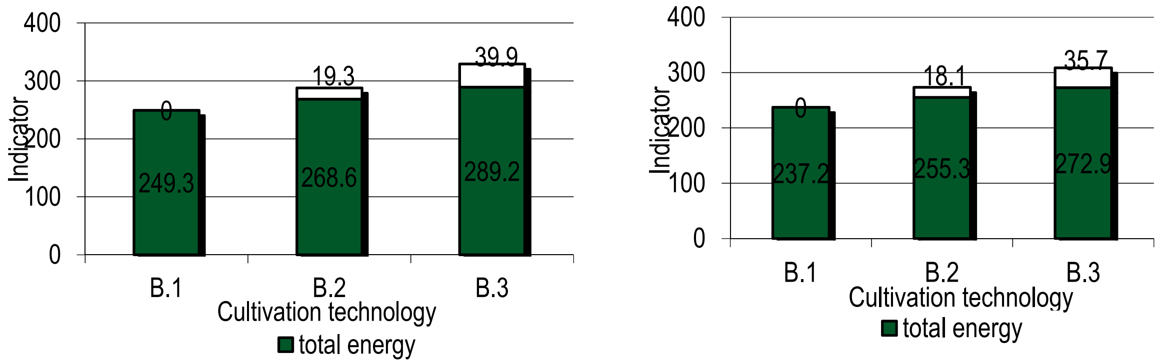
| Technology | Vegetation year | Yield, t/ha | Energy efficiency indicators* | | | | |
|---|---|---|---|---|---|---|---|
| | | | B, t/ha | $E_{aa}$, GJ/ha | $E_c$, GJ/ha | $EP_c$, GJ/ha | $K_{ee}$ |
| B.1 | the third | 12,9 | 14,2 | 234,1 | 55,7 | 3,9 | 4,2 |
| | the fourth | 13,8 | 15,2 | 250,5 | 57,4 | 3,8 | 4,4 |
| | the fifth | 14,5 | 16,0 | 263,2 | 60,4 | 3,8 | 4,4 |
| Average for years | | 13,7 | 15,1 | 249,3 | 57,8 | 3,8 | 4,3 |
| B.2 | the third | 14,2 | 15,6 | 257,7 | 60,4 | 3,9 | 4,3 |
| | the fourth | 14,9 | 16,4 | 270,4 | 61,5 | 3,8 | 4,4 |
| | the fifth | 15,3 | 16,8 | 277,7 | 63,2 | 3,8 | 4,4 |
| Average for years | | 14,8 | 16,3 | 268,6 | 61,7 | 3,8 | 4,4 |
| B.3 | the third | 15,1 | 16,6 | 274,1 | 60,8 | 3,7 | 4,5 |
| | the fourth | 15,8 | 17,4 | 286,8 | 62,1 | 3,6 | 4,6 |
| | the fifth | 16,9 | 18,6 | 306,7 | 65,6 | 3,5 | 4,7 |
| Average for years | | 15,9 | 17,5 | 289,2 | 62,8 | 3,6 | 4,6 |

* Note: B – output of solid biofuel, t/ha; Eaa – aggregate energy accumulated in switchgrass biomass, GJ/ha, Ec otal energy expenditures on switchgrass biomass cultivation, GJ/ha; EPc – energy profit of switchgrass biomass cultivation, GJ/ha; Kee – coefficient of energy efficiency of switchgrass biomass cultivation.

On average, over three years, the highest coefficient of energy efficiency in conditions A.1 (Polissia) was obtained with optimized cultivation technology variants - at the level of 4.6.

The data in Figure 7 shows the change in energy output, and the coefficient of energy efficiency depending on the technology of growing switchgrass.

Figure 7. Energy output (a) and energy efficiency coefficient (b) depending on the technology of growing switchgrass in conditions A.1 (Polissia), 2015-2019




A b

The application of the optimized switchgrass growing technology (B.3), compared with the conventional (B.2), on average over the years of research allowed to increase the energy yield by 20.6 GJ / ha, and increase the energy efficiency coefficient by 0.2 – from 4 , 4 to 4.6 (average efficiency). Technology B.3 allowed to increase energy efficiency indicators in comparison with B.1 (control), respectively – by 39.9 GJ / ha and 0.3 units.

Another situation was noted in experiments in the Forest-steppe (table 4). Under these conditions, switchgrass on variants of conventional technology without herbicides, compared with conventional and optimized technology, provided a significant reduction in energy efficiency.

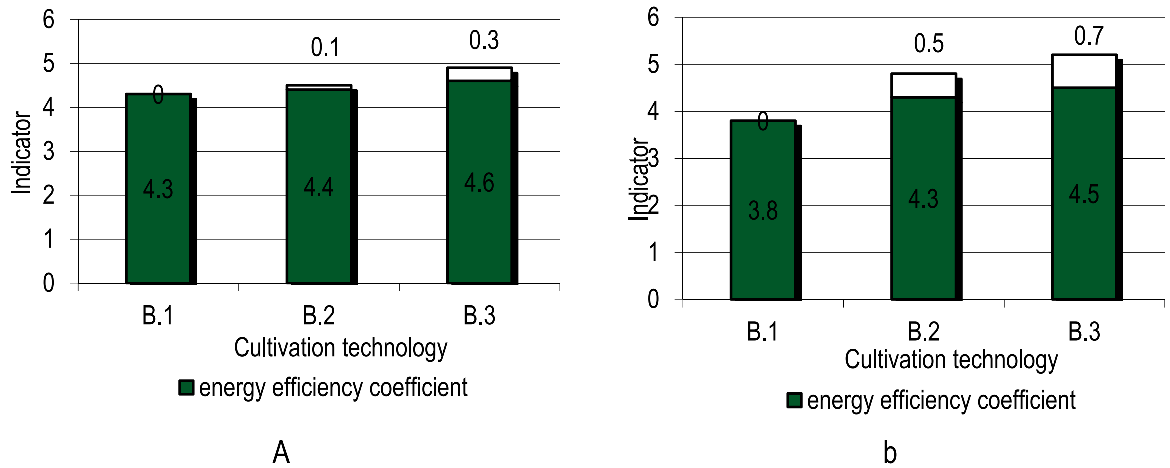
Table 4. Energy efficiency of biomass production depending on the cultivation technology on A.2, 2015–2019

| Technology | Vegetation year | Yield, t/ha | Energy efficiency indicators* | | | | |
|---|---|---|---|---|---|---|---|
| | | | B, t/ha | $E_{aa}$, GJ/ha | $E_c$, GJ/ha | $EP_c$, GJ/ha | $K_{ee}$ |
| B.1 | the third | 12,2 | 13,4 | 221,4 | 59,4 | 4,4 | 3,7 |
| | the fourth | 13,1 | 14,4 | 237,8 | 60,7 | 4,2 | 3,9 |
| | the fifth | 13,9 | 15,3 | 252,3 | 66,3 | 4,3 | 3,8 |
| Average for years | | 13,1 | 14,4 | 237,2 | 62,1 | 4,3 | 3,8 |
| B.2 | the third | 13,8 | 15,2 | 250,5 | 59,0 | 3,9 | 4,2 |
| | the fourth | 14,0 | 15,4 | 254,1 | 59,5 | 3,9 | 4,3 |
| | the fifth | 14,4 | 15,8 | 261,4 | 60,3 | 3,8 | 4,3 |
| Average for years | | 14,1 | 15,5 | 255,3 | 59,6 | 3,9 | 4,3 |
| B.3 | the third | 14,5 | 16,0 | 263,2 | 60,2 | 3,8 | 4,4 |
| | the fourth | 15,1 | 16,6 | 274,1 | 61,3 | 3,7 | 4,5 |
| | the fifth | 15,5 | 17,1 | 281,3 | 62,1 | 3,6 | 4,5 |
| Average for years | | 15,0 | 16,5 | 272,9 | 61,2 | 3,7 | 4,5 |

*Note: B – output of solid biofuel, t/ha; $E_{aa}$ – aggregate energy accumulated in switchgrass biomass, GJ/ha, $E_c$ total energy expenditures on switchgrass biomass cultivation, GJ/ha; $EP_c$ – energy profit of switchgrass biomass cultivation, GJ/ha; $K_{ee}$ – coefficient of energy efficiency of switchgrass biomass cultivation.

Figure 8 shows the change in energy output, and the energy efficiency coefficient depending on the technology of growing switchgrass in the forest-steppe for three years. The technology for growing switchgrass using a herbicide (B.2), compared with control (B.1), increases the energy yield by 18.1 GJ / ha and increases the energy efficiency coefficient by 0.5 units – from 3.8 (low efficiency) up to 4.3 (average efficiency). Optimized technology (with legumes) also increases these indicators compared to the control, respectively – by 35.7 GJ / ha and 0.7 units.

Figure 8. Energy output (a) and energy efficiency coefficient (b) depending on the technology of growing switchgrass in conditions A.2 (Forest-steppe), 2015-2019




Versions of optimized switchgrass growing technology, compared to the control, provided a significant increase in energy yield by 35.7 GJ/ha, and an increase in energy efficiency coefficient by 0.7 units – from 3.8 (low efficiency) to 4.5 (average efficiency).

This trend is consistent with the results of Sami *et al.* (2001), who found that the energy yield for switchgrass biomass was 16694 kJ/kg (16.7 MJ/t).

Along with this, the authors Farrell A. et al (2006) argue that the energy requirement for switchgrass energy plantations is 7.5 GJ/ha. Similar results were confirmed by the results of Sokhansanj S. *et al*. (2009), according to which the energy consumption of switchgrass is 7.2 GJ / ha. According to Wang M. (2001), the energy requirement for switchgrass is much greater at around 12 GJ/ha.

## Conclusion

1. It has been established that growing conditions affect the yield level of Cave-in-rock switchgrass. Higher productivity of switchgrass biomass is formed under the conditions of Polissia (13.7-15.9 t/ha), less – under the conditions of the Forest-Steppe (13.1-15.0 t/ha).

2. Yield of switchgrass biomass significantly depends on the technology of cultivation. The optimized cultivation technology, in comparison with the control and existing technology, provides greater productivity. This feature is characteristic of two research points.

3. Compared with conventional technology, the application of optimized switchgrass growing technology has allowed increasing the energy efficiency indicators of crop cultivation. This set of measures increases the output of solid biofuel and energy by 1ha and increases the coefficient of energy efficiency. This feature is characteristic both for Polissia and for the Forest-steppe.

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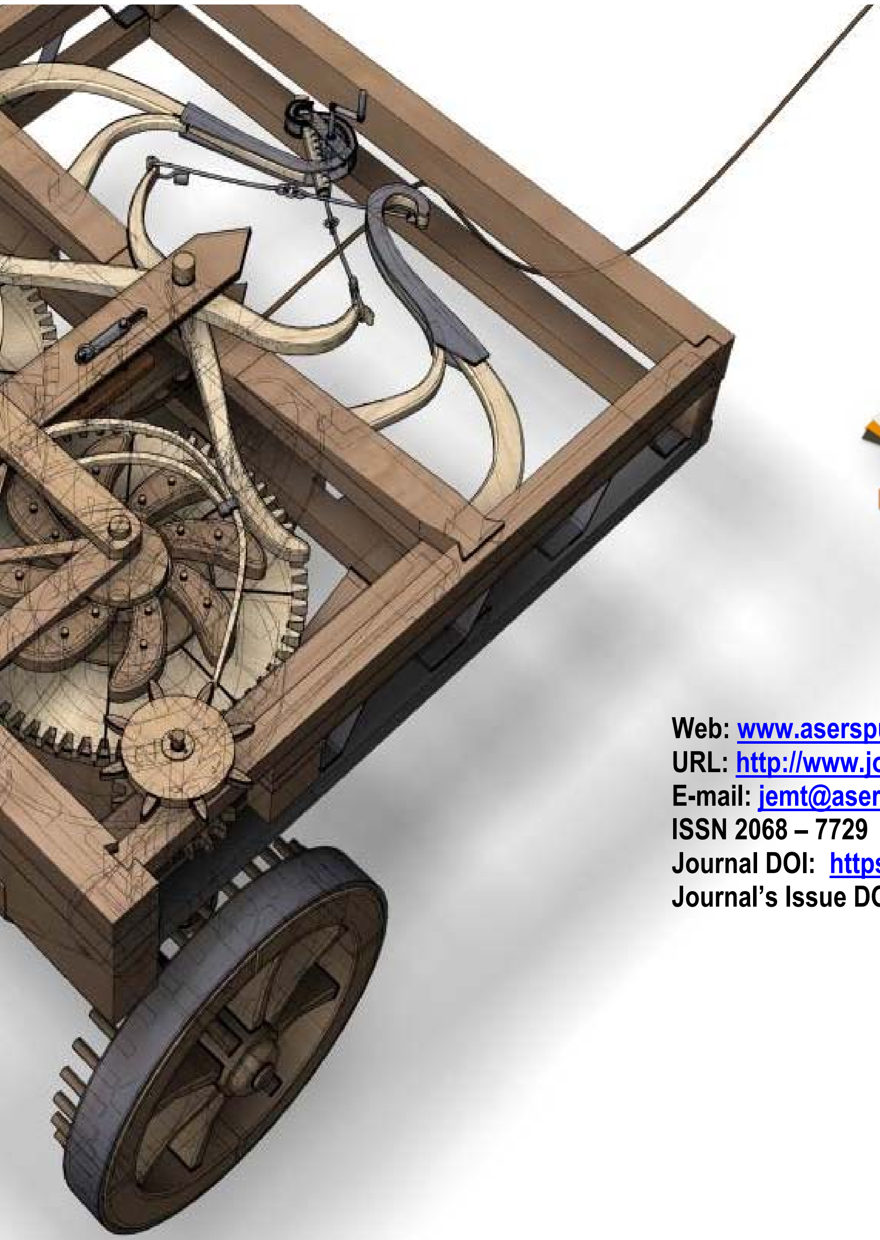

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