EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology 2022, 23(2), 162–172
https://doi.org/10.12912/27197050/145731
ISSN 2719-7050, License CC-BY 4.0

Received: 2021.12.25
Accepted: 2021.01.10
Published: 2022.02.01

Productivity Model of Herbal Bioenergy Cultures Depending on Biometric Indicators of Overhead Mass

Vasyl Lopushniak[1], Oxana Tonkha[1], Halyna Hrytsuliak[2*], Halyna Lopushniak[3], Miroslava Polutrenko[2], Lyuba Poberezhna[2], Valentina Gamayunova[4], Olena Pikovska[1], Tomasz Jakubowski[5], Yulia Kotsyubynska[6]

[1] National University of Life and Environmental Sciences of Ukraine, Heroiv Oborony Str. 15, Kyiv, 03041, Ukraine
[2] Ivano-Frankivsk National Technical University of Oil and Gas, Karpatska Str. 15, Ivano-Frankivsk, 76000, Ukraine
[3] Kyiv National University named after Vadym Hetman, Peremohy Ave. 54/1, Kyiv, 03057, Ukraine
[4] Mykolayiv National Agrarian University, Mykolaiv, Heorhiia Honhadze Str. 9, Mykolaiv, Mykolaiv Oblast, 54000, Ukraine
[5] University of Agriculture in Krakow, Al. Adama Mickiewicza 21, 31-120 Kraków, Poland
[6] Ivano-Frankivsk National Medical University, Halytska Str. 2, Ivano-Frankivsk, 76018, Ukraine
* Corresponding author's e-mail: gritsulyaka@ukr.net

ABSTRACT
The research was carried out on the territory of c. Tsenzhiv of Yamnytsya territorial community of Ivano-Frankivsk region on sod-podzolic degraded soils according to the generally accepted research methods. The productivity of miscanthus and switchgrass depends on the biometric indicators of plants, namely the height of plants and the number of stems. Correct models of miscanthus and switchgrass productivity are calculated depending on the dose of sewage sludge. For miscanthus, the correlation coefficient r = 0.952 and for switchgrass r = 0.951, which indicates a high linear relationship between plant height, number of stems and productivity. The dry matter yield in grass energy crops varies according to fertilizer application. The productivity of the agrophytocenosis of miscanthus is much higher than that of switchgrass. With the addition of sewage sludge at a dose of 40 t/ha, the dry matter yield under the same growing conditions in the agrophytocenosis of miscanthus is 12.2 t/ha, or 3.3 t/ha higher than the productivity of agrophytocenosis switchgrass. The use of composts based on SS + straw (3: 1)) – 30 t/ha + $N_{30}K_{55}$, has a significant impact on yield, providing the highest productivity of miscanthus – 13.0 t/ha, and switchgrass – 9.6 t/ha. In order to obtain stable biomass productivity of grass energy crops (miscanthus and switchgrass), it is advisable to use compost of sewage sludge and straw in a ratio of 3: 1 at a dose of 30 t/ha. Thus, two important problems are partially solved, namely increasing the productivity of energy crops and utilizing municipal waste (sewage sludge).

Keywords: miscanthus, switchgrass, sewage sludge, compost.

INTRODUCTION

Today, humanity is facing new challenges that need to be addressed urgently: the depletion of traditional energy sources, the rising cost of their production, pollution at an increasing rate due to their extraction, transportation and consumption; formation of excessive amounts of organic waste of industrial, agricultural and household origin [Atlas 2016, Domaratskiy et al. 2019, Hrytsuliak & Lopushniak 2017, Kulik 2016, Pysarenko et al. 2017, Persykova & Blokhyna 2018, Panfilova et al. 2020a, Turhollow 1991]. All of this has reached alarming proportions and is a factor in the impact on global climate change.

One of the ways to partially overcome such problems is to increase the share of renewable energy sources in the overall balance of energy resources, in particular raw bioenergy resources. For Ukraine, bioenergy is one of the directions of the renewable energy sector [Clifton-Brown et al. 2007, Hetmanenko 2016, Humentyk 2019, Kahle et al. 2001, Turhollow 1991]. A large number of plants are studied in terms of their use for energy purposes to determine the possibility of their probable spread as energy crops [Batsmanova et al. 2020, Humentyk 2019, Hrytsuliak & Lopushniak 2017, Kabak 2014, Kurylo et al. 2013, Roik et al. 2011]. Miscanthus and switchgrass are becoming widespread among many promising species. Growing them on degraded soils can create the conditions for slowing down the degradation processes and stabilizing the ecological condition of such soils for a long period up to 20–25 years, followed by revitalization, which will increase the stability of soil systems and partially improve their basic agro-, bio-, physico-chemical, as well as environmental properties [Hrytsuliak & Lopushniak 2017, Kulyk 2017, Lopushniak et al. 2021a, Persykova & Blokhyna 2017, Roik et al. 2015, Panfilova et al. 2020b, Sanderson et al. 1996].

Ukraine has significant resource potential for biomass production for energy purposes, which can allow the country to become a platform for innovative solutions in this area and attract investment. This encourages new approaches and the development of integrated technologies in the cultivation of bioenergy crops, which will make a significant contribution to strengthening energy security, improving soil condition and improving the environmental situation in the country [Enerhetychna... 2017, Lopushniak et al. 2021b, Lopushniak & Hrytsuliak 2021, Pysarenko et al. 2017, Roik et al. 2015].

Analysis of recent research and publications

Almost 200 million tons of conventional fuel are consumed annually in Ukraine, while the production from natural sources is only 80 million tons. With such an imbalance between the consumption of energy raw materials from different sources, biofuels constitute the potential energy resource [Pysarenko et al. 2017, Kahle et al. 2001, Kholodna 2016, Lopushniak & Hrytsuliak 2021, Weindorf et al. 2012]. By 2035, the Energy Strategy of Ukraine is planning to increase the volume of renewable energy sources in the total primary energy supply to 25%, and biomass energy production is planned to increase to 11 million tons in oil equivalent, or 4 times compared to the existing volumes [Kabak 2014, Lopushniak & Hrytsuliak 2021, Turhollow 1996, Van Loocke 2012].

Herbaceous miscanthus and switchgrass, which are relatively new for Ukraine bioenergy cropsare characterized by a height of more than 1.5–2.5 m, a strong root to a depth of 2.0 m and more, and leave a large number of root and postharvest residues in the soil. This allows growing such crops in the areas that are not used in traditional crop production, degraded and marginalized soils, including those with low groundwater levels, ensuring not only rational land use, but also stabilizing the soil cover, preventing the spread of its degradation processes. and man-made pollution [Lopushniak & Hrytsuliak 2021, Pysarenko 2017, Weindorf et al. 2012]. Researchers also note that miscanthus and switchgrass crops are undemanding to the soil, so they can be grown on degraded, disturbed, unproductive and sloping lands [Batsmanova et al. 2020, Lopushniak et al. 2021a, Turhollow1996, Van Loocke 2012, Weindorf et al. 2012].

In the initial periods of vegetation, the need of miscanthus and switchgrass plants in the application of mineral fertilizers is relatively low, due to the root system, which is significantly branched and penetrates quite deep into the soil. This allows intensively absorbing nutrients, including from deeper layers of soil. In addition, the nutrients that accumulate in the rhizomes of miscanthus can be recycled in subsequent vegetation cycles [Lopushniak & Hrytsuliak 2021, Lopushniak et al. 2021b, Pysarenko, 2017, Panfilova et al. 2020a, Panfilova et al. 2020b]. However, due to high productivity and biomass yield, these crops need nutrients in an accessible form during the growing season. Given the long-term cycles of use of plantations of such crops, the system of their mineral nutrition in agrophytocenoses should include fertilizers in stock, in particular in the form of organic compounds, which minimizes the risk of agrochemical contamination of soil [Lopushniak et al. 2017a, Lopushniak & Hrytsuliak 2021, Sanderson et al. 1996, Van Loocke 2012].

Under the current conditions of agricultural production in Ukraine, given the lack of organic fertilizers for traditional crop production, non-traditional types of organic raw materials can be sources of increasing organic matter resources in the soil under bioenergy crops. The waste from public utilities, namely sludge from wastewater treatment plants, which is accumulated in excess in Ukraine, can be used as fertilizer provided their environmental safety and permissible content of heavy metals, pollutants and other pollutants [Lopushniak & Hrytsuliak 2021, Van Loocke 2012].

The introduction of sewage sludge under bioenergy crops has significant prospects and allows solving the problem of utilization of its accumulated significant reserves in municipal utilities, as well as helps to provide plants with the necessary macro-and micronutrients. After all, sewage sludge itself contains a significant amount of essential nutrients for plant growth and development [Lopushniak et al.2021a, Van Loocke 2012, Weindorf et al. 2012]. Therefore, this raw material should be considered as an important link for environmentally friendly technologies for growing energy crops. Composting sewage sludge with other organic materials, including sawdust, cereal straw, etc., is also a promising way. Straw compost with sewage sludge enhances the humus-forming ability of the soil by intensifying the development of beneficial microflora, which promotes mineral nutrition of plants, which in turn increases the bioproductivity of agrophytocenoses [Batsmanova et al. 2020, Kalenska 2019, Lopushniak et al. 2021b, Lopushniak & Hrytsuliak 2021, Mazurenko et al. 2020].

It is important to study the patterns related to the productivity formation of bioenergy crops for the introduction of various types of sewage sludge to further increase biomass production and stabilize the energy balance of the country.

The aim of the research was to study the patterns of formation of productivity of bioenergetic grass crops under different fertilizer systems in combination with sewage sludge (SS) and compost based on them, applied on degraded soils under conditions of sufficient moisture.

MATERIALS AND METHODS

The research was carried out on the territory of c. Tsenzhiv of Yamnytsya territorial community of the Ivano-Frankivsk region on sod-podzolic degraded soils according to generally accepted research methods. The content of humus in the soil was determined using the Turin method, the hydrolytic acidity and the amount of absorbed bases were determined with the Kappen method and Kirsanov's method, respectively, the content of mobile compounds of phosphorus and potassium, whereas the content of ammonium and nitrate forms of nitrogen compounds were determined according to the method of Cornifield [Batsmanova et al. 2020, Lopushniak & Hrytsuliak 2021, Lopushniak et al. 2021a, Lopushniak et al. 2021b].

Trace elements and heavy metals in the plant were determined using standard methods (atomic absorption). The chemical composition of the studied soil and composts with SS and straw was determined using devices based on X-ray fluorescence and magneto-optical effects. EXPERT 3L analyzer was used, which allowed controling all studied indicators with an accuracy of 0.005% [Lopushniak & Hrytsuliak 2021, Lopushniak et al. 2021a, Kholodna 2016, Mazurenko et al. 2020].

Biometric indicators were determined during the growing season every three weeks on selected 20 plants: a) the height of the main shoot; b) the number of leaves.

The agrochemical parameters were determined at the experimental site: the humus content was 1.90% in the arable layer (0–20 cm) of soil and 1.78% in the subsoil (20–40 cm) layer, the total nitrogen content of 0.07 and 0.08%. The indicators of nitrogen content of mineral compounds, phosphorus compounds and potassium compounds were 67.0, 174.0 and 172.0 mg/kg in the arable (0–20 cm) layer of soil and 56.8, 131.0 and 139, 0 mg/kg in the subsoil (20–40 cm) layer of soil. The content of alkaline hydrolyzed nitrogen compounds, mobile phosphorus compounds and potassium metabolic compounds decreased significantly with depth [Lopushniak & Hrytsuliak 2021, Mazurenko et al. 2020].

The schemes of field experiments with culture of miscanthus and switchgrass were the same and included the following options:

1) Without fertilizers – control;
2) $N_{60}P_{60}K_{60}$;
3) $N_{90}P_{90}K_{90}$;
4) SS – 20 t/ha + $N_{50}P_{52}K_{74}$;
5) SS – 30 t/ha + $N_{30}P_{33}K_{66}$;
6) SS – 40 t/ha + $N_{10}P_{14}K_{58}$;
7) Compost (SS + straw (3: 1)) – 20 t/ha + $N_{50}P_{16}K_{67}$;
8) Compost (SS + straw (3: 1)) – 30 t/ha + $N_{30}K_{55}$ [Lopushniak & Hrytsuliak 2021, Lopushniak et al. 2021a].

Options 3–8 are balanced for the introduction of basic nutrients – the introduction of nitrogen, phosphorus and potassium was 90 kg/ha.

Sewage sludge, which was used in the research, was taken from overflowing silt maps of Ivano-Frankivsk «Ekotechprom» in the village Yamnytsia, Ivano-Frankivsk region. Its acidity was pH -8.1. Nitrogen content – 0.66%; phosphorus – 2.51; potassium – 2.16% (based on dry matter), and trace elements in mobile form: copper – 14.9 mg/kg; cobalt – 3.9; zinc – 7.2 mg/kg of dry mass of sewage sludge [Lopushniak & Hrytsuliak 2021, Lopushniak et al. 2021a].

In addition to the direct use of sewage sludge as fertilizer, studies used the compost made from straw. Composting SS with organic raw materials, such as straw, helps to bind excess nutrients, conversion of mobile compounds of pollutants into a strongly bound form, humification of organic residues, release of excess moisture from raw materials, improving sanitation and hygiene [Batsmanova et al. 2020, Clifton-Brown et al. 2007, Lopushniak & Hrytsuliak 2021, Mazurenko et al. 2020].

Composts were prepared in the immediate vicinity of the experimental plots in the field. During the laying of composts, SS were mixed with straw of cereals. The compost pile was formed 4 m wide and 5–6 m long. First, 50 cm thick organic material (straw) was spread on the bottom of the burta, SS and organic material 0.3–0.4 m thick were alternately placed in layers. The top layer was covered with 0.4–0.5 m thick soil layer. average samples were taken and its agrochemical parameters were determined (Table 1).

Under the conditions of the experiment, miscanthus was planted manually according to the scheme of 0.5×0.7 m. At the same time, rhizomes with 5–6 growth buds were used for better rooting. The depth of earning rice was 0.12–0.15 m. During the first 16–18 months, the plant usually forms a strong root system, but the closure of plants in rows does not occur. At plant heights of 0.15–0.20 m, loosening between rows was carried out to control the spread of weeds. The following year, owing to a good root system, a significant increase herbage was formed. During this period, the energy crop is very competitive with weeds and does not require additional cultivation between rows. Plant development takes place within three years [Clifton-brown et al. 2007, Lopushniak & Hrytsuliak 2021, Mazurenko et al. 2020, Lopushniak et al. 2021b]. After the third year of vegetation, the vegetative mass was collected. The period of harvesting the vegetative mass of miscanthus is December. During this period, the humidity of the stems decreases to 17%. It was in December that the plants were mowed, weighed and samples were taken for laboratory analysis.

Switchgrass was sown by hand with a distance between rows of 0.5 m to a depth of 0.04–0.05 m. The plant is characterized by slow shoots. Many weeds have sprouted during this time, so it was necessary to control weeds manually. Three inter-row treatments were carried out at the sites every 8 to 10 days. After the switchgrass plants reached a height of more than 0.3 m, no cultivation was carried out. The most desirable period for harvesting switchgrass as well as miscanthus is December–February. In December, the plants were mowed, productivity records were taken and samples were collected for laboratory experiments [Lopushniak et al. 2021a, Lopushniak et al. 2021b].

Table 1. Agrochemical parameters of compost used for experiments

Agrochemical indicators	Gross content	Error, %
Organic matter, %	78	0.1
pH	7.2	0.01
Nitrogen of alkaline hydrolyzed compounds, mg/kg	453.23	11.1
Nitrogen of nitrate compounds ($N\text{-}NO_3$), mg/kg	752.1	7.2
Phosphorus of mobile compounds, mg/kg of soil	401.3	6.9
Potassium metabolic compounds, mg/kg of soil	224.3	6.9
Mn, mg/kg	0.094	0.001
Zn, mg/kg	0.153	0.04
Fe, mg/kg	0.025	0.02
Cu, mg/kg	0.107	0.01
Ca^{2+}, mg/kg	1491.4	12.08
Mg^{2+}, mg/kg	0.126	0.03

In the early spring, after the cessation of late frosts, aisles were treated and SS were applied according to the experimental scheme.

The area of the accounting area is 35 m^2, the total area is 63 m^2. The experimental plots are placed in triplicate. Plant development was observed for three years [Lopushniak & Hrytsuliak 2021, Lopushniak et al. 2021b].

The computer program Statistica 6.0 was used for statistical processing of research results.

On average, in 2016–2019, weather conditions were characterized by typical deviations from long-term averages. Compared to the long-term average for 2016–2017, precipitation was 494.1–546.8 mm, in 2018–2019 is equal to 389.5–321.5 mm [Lopushniak et al. 2021b].

Depending on the weather conditions of the growing season and the use of fertilizers, the biometric indicators of miscanthus and switchgrass plants were marked by certain changes (Fig. 1).

Over the years of research, the average height of miscanthus plants ranged from 1.33 to 2.04 m. In the options where sewage sludge was added at a dose of 20–40 t/ha, plant height increased, compared to the control, by 0.17–0.42 m, respectively. With the addition of a mixture of sewage sludge and straw (3: 1)) – 20 t/ha + $N_{50}P_{16}K_{67}$ plant height increased by 0.57 m compared to option 1, and was 1.9 m. For all years of research, the highest rate of stem height miscanthus provided a option where a mixture was used (SS + straw (3: 1)) – 30 t/ha + $N_{30}K_{55}$ (variant 8), which averaged 2.04 m, which is 0.7 m higher than the control option [Lopushniak & Hrytsuliak, 2021, Lopushniak et al. 2021b].

During the years of research, the average height of switchgrass plants varied from 1.10

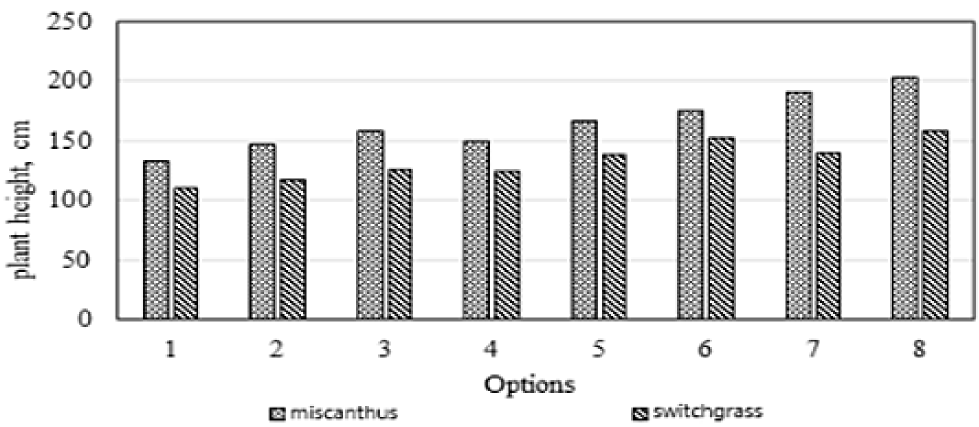

Figure. 1. Height of miscanthus and switchgrass plants depending on the regime of mineral nutrition on degraded soils, 2016–2019

Table 2. Productivity of bioenergy crops on degraded soils (2016–2019)

Options	Switchgrass					Miscanthus				
	Harvest raw mass			Dry matter yield		Harvest raw mass			Dry matter yield	
	t/ha	Increase		t/ha	Increase %	t/ha	Increase		t/ha	Increase %
		±t/ha	%				±t/ha	%		
Without fertilizers - control	15.3	-	100	7.1	100	22.1	-	100	10.0	100
$N_{60}P_{60}K_{60}$	16.1	0.8	105	7.5	106	23.0	0.9	104	10.4	104
$N_{90}P_{90}K_{90}$	17.0	1.7	111	7.7	108	23.8	1.7	108	11.0	110
SS – 20 t/ha + N_{50} $P_{52}K_{74}$	16.8	1.5	110	8.2	106	23.5	1.4	106	10.6	106
SS -30 t/ha + $N_{30}P_{33}K_{66}$	17.5	2.2	114	8.5	120	24.4	2.3	110	11.7	117
SS – 40 t/ha + N_{10} $P_{14}K_{58}$	18.3	3.0	120	8.9	125	25.1	3.0	113	12.2	122
Compost (SS + straw (3:1)) – 20 t/ha + $N_{50}P_{16}K_{67}$	19.0	3.7	124	9.2	129	26.0	3.9	118	12.8	128
Compost (SS + straw (3:1)) – 30 t/ha + $N_{30}K_{55}$	19.7	4.4	129	9.6	135	26.9	4.8	122	13.0	130
SSD $_{05}$	0.2	0.2	5	0.2	2	0.3	0.3	2	0.2	4

m to 1.58 m. In variants 2 and 3, where mineral fertilizers were used in doses $N_{60}P_{60}K_{60}$ and $N_{90}P_{90}K_{90}$, plant height increased by 0.07 and 0.16 m, respectively. With the use of sewage sludge at a dose of 20–40 t/ha (options 4 – 6) the height of plants increased compared to the control by 0.14–0.42 m, respectively. With the addition of a mixture based on SS + straw (3: 1)) – 20 t/ha + $N_{50}P_{16}K_{67}$ plant height increased by 0.30 m compared to option 1 and was 1.40 m. mixtures based on SS + straw (3: 1)) – 30 t/ha + $N_{30}K_{55}$ (option 8) is 1.58 m, which is 0.48 m higher than the results of the control option 1 [Lopushniak & Hrytsuliak 2021, Lopushniak et al. 2021b].

On average, over the years of research with the use of organic fertilizers and composts based on them, the differences in the productivity of the vegetative mass of bioenergy crops were noted in the studied results (Table 2).

On average, during 2016–2020 studies, the productivity of the vegetative mass of miscanthus in the options with the addition of sewage sludge (options 4–6) was 23.5–25.1 t/ha, which is 0.5–2.1 t/ha increased by of options where fertilizers were applied at a dose of $N_{60-90}P_{60-90}K_{60-90}$ (options 2 and 3). Application of a mixture based on SS and straw (options 7–8) productivity of vegetative mass was 26.0–26.9 t/ha, which is 3.9–4.8 t/ha more than the results of studies of control option 1. The dry yield of miscanthus plants were 10.0–13.0 t/ha, depending on fertilizer options. With the addition of sewage sludge (options 4–6) to the soil, the dry plant yield was 10.6–12.2 t/ha, which is 0.6–2.2 t/ha more than in the result of the studied option 1. SS together with straw (options 7–8) in the soil; the yield of dry mass of the plant was at the level of 12.8–13.0 t/ha, which is 2.2–2.4 t/ha more than in the options where only sewage sludge was added [Lopushniak & Hrytsuliak 2021, Lopushniak et al. 2021a].

For four years of research, the productivity of switchgrass was 16.8–18.3 t/ha in the options with the addition of sewage sludge (options 4–6), which is 0.7–2.2 t/ha more than in the options,

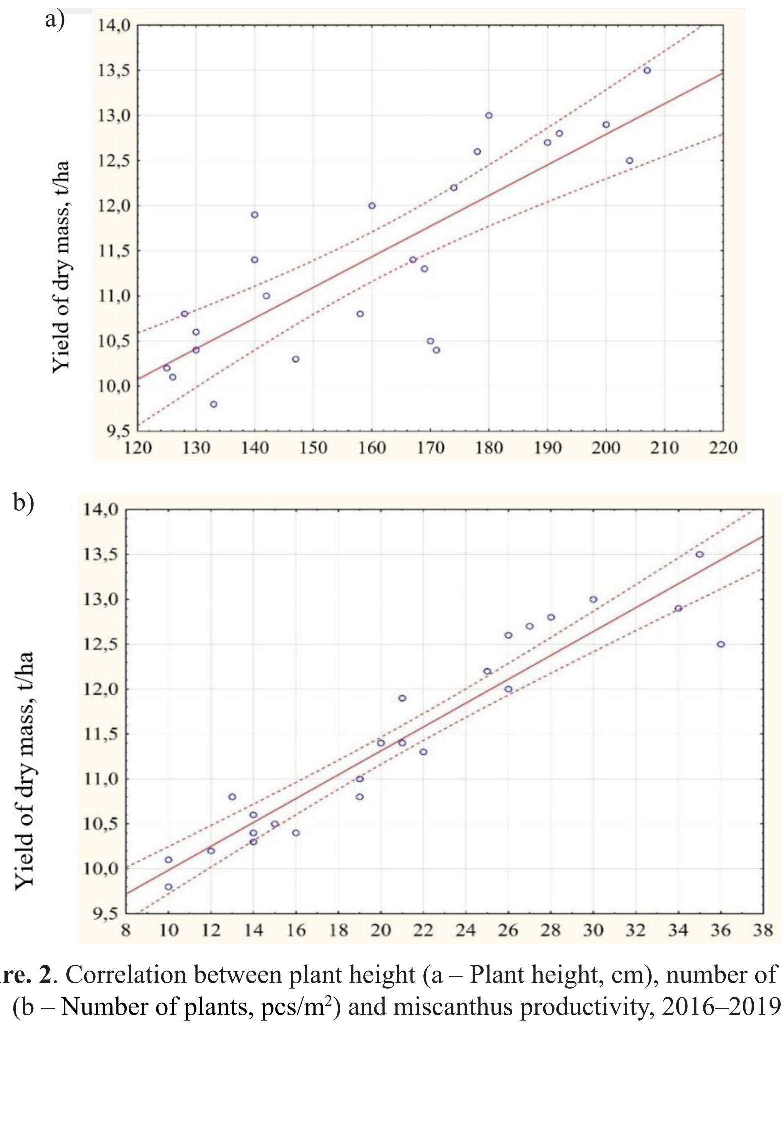

Figure. 2. Correlation between plant height (a – Plant height, cm), number of stems (b – Number of plants, pcs/m^2) and miscanthus productivity, 2016–2019

where only mineral fertilizers were added at a dose of $N_{60-90}P_{60-90}K_{60-90}$ (options 2 and 3). The use of a complex mixture of sewage sludge and straw (options 7–8) productivity of the vegetative mass of switchgrass was 19.0–19.7 t/ha, which is 3.7–4.4 t/ha more than the in results of the studies of option 1, i.e. control [Clifton-Brown et al. 2007, Lopushniak & Hrytsuliak, 2021, Lopushniak et al. 2021b]. The productivity of switchgrass depends not only on the weight of each plant and the number of plants per unit area, but also on the moisture content of the plant at the time of harvest. The dry matter yield of switchgrass at the time of harvest was 7.1–9.6 t/ha, depending on the application of fertilizers. With the addition of sewage sludge (options 4–6) the yield of dry productivity was 8.2–8.9 t/ha, which is 1.1–1.8 t/ha higher than the indicators of option 1. The use of a mixture of fertilizers based on sewage sludge of water and straw (options 7–8) dry matter yield was higher by 1.0 – 1.4 t/ha compared to the options where only sewage sludge was added and amounted to 9.2–9.6 t/ha [Lopushniak & Hrytsuliak 2021, Lopushniak et al. 2021a, Lopushniak et al. 2021b].

The analysis of the main indicators of productivity indicates that the correlations of quantitative indicators of plants (height and density of stems) have a significant impact on the yield of agrophytocenoses of bioenergy crops (Fig. 2) [Lopushniak & Hrytsuliak 2021, Lopushniak et al. 2021a].

According to the results of correlation-regression analysis, it was found [Lopushniak & Hrytsuliak 2021, Lopushniak et al., 2021b] that the productivity of miscanthus depends mostly on the height of plants with coefficients of determination and correlation $R^2 = 0.80$, $r = 0.81$, as well as the number of stems ($R^2 = 0.77$, $r = 0.88$)

The multiple regression equation can have the following form:

$$y = 8.6563 + 0.1328x \quad (1)$$

where: x is the height of plants, cm; y – yield of dry plant, t/ha; and

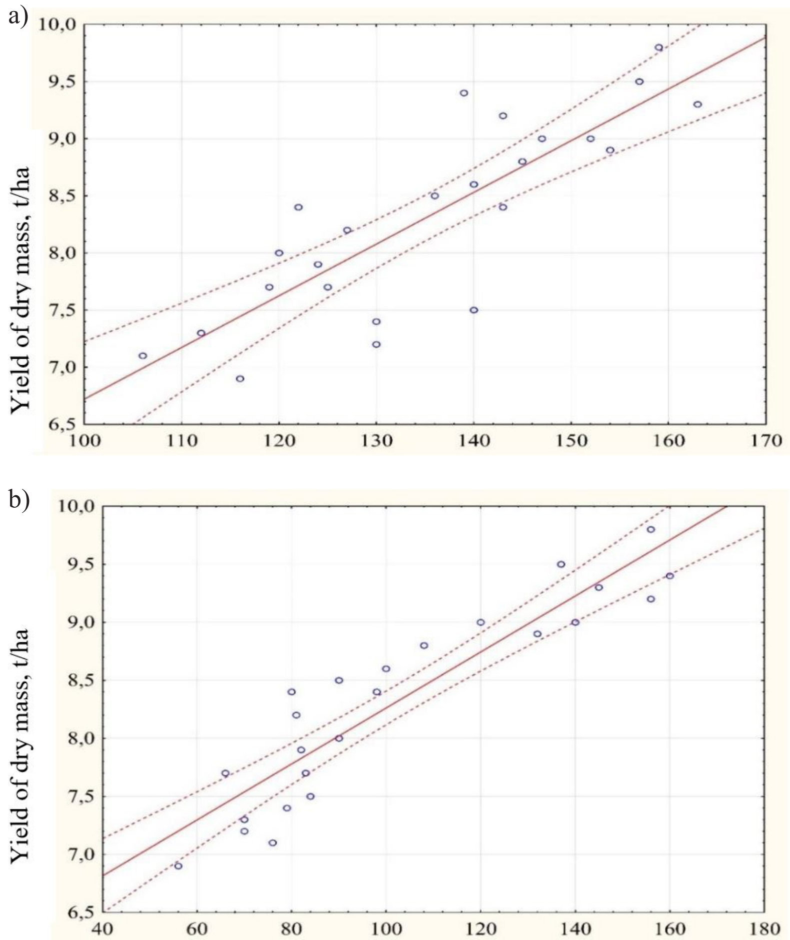

Figure 3. Correlation between plant height (a – Plant height, cm), number of plants (b – Number of plants, pcs/m^2) and switchgrass productivity, 2016–2019

$$y = 5.9968 + 0.034x \quad (2)$$

where: x is the number of plants, pcs/m^2; y – yield of dry plant, t/ha [Lopushniak & Hrytsuliak 2021, Lopushniak et al. 2021b].

The connection between the dry mass yield of the plant, plant height and the number of miscanthus stems was proven; it was determined that these indicators are interdependent, i.e. the dry plant mass yield increases along with plant height and the dry plant mass yield increases with the number of stems per m^2 [Lopushniak & Hrytsuliak 2021, Lopushniak et al. 2021b, Weindorf et al. 2012].

The results obtained during the study suggest that the height of the switchgrass plant is 1.45–1.56 m in the variants with the addition of sewage sludge at a dose of SS – 40 t/ha + $N_{10}P_{14}K_{58}$ (option 6) and with the addition of a mixture of SS + straw (3: 1)) – 30 t/ha + N_{30} K_{55} (option 8).

According to the results of correlation-regression analysis, it was determined that the yield of switchgrass depends on the height of the plant for the coefficient of determination R^2 = 0.86 and the correlation coefficient r = 0.83 and the number of stems for the coefficient of determination R^2 = 0.89 and correlation coefficient r = 0.94 [Lopushniak & Hrytsuliak 2021, Lopushniak et al. 2021b]. The regression equations can have the following form:

$$y = 0.04524x + 2.1964 \quad \text{(plant height and productivity)} \quad (3)$$

where: x is the height of plants, cm; y – yield of dry plant, t/ha (Fig. 3a).

$$y = 0.13284x + 8.6563 \quad \text{(number of stems and productivity)} \quad (4)$$

where: x is the number of plants, pcs/m^2; y – yield of dry plant, t/ha (Fig. 3b).

In order to determine the nature of multiple correlation, the methods of multiple linear regression analysis were used, the results of which are shown in Figures 4 and 5.

Thus, close correlations have been established between plant productivity, plant height and number of plants per m^2 [Clifton-Brown et al. 2007, Lopushniak & Hrytsuliak 2021, Lopushniak et al. 2021b].

The yield of dry mass of switchgrass plants from plant height and number of plants can be expressed by the equation:

$$z = 6.2494 + 0.034x + 0.057y \quad (5)$$

where: z is the dry matter yield of switchgrass, t/ha; x – height of plants, cm; y – number of plants, pcs/m^2.

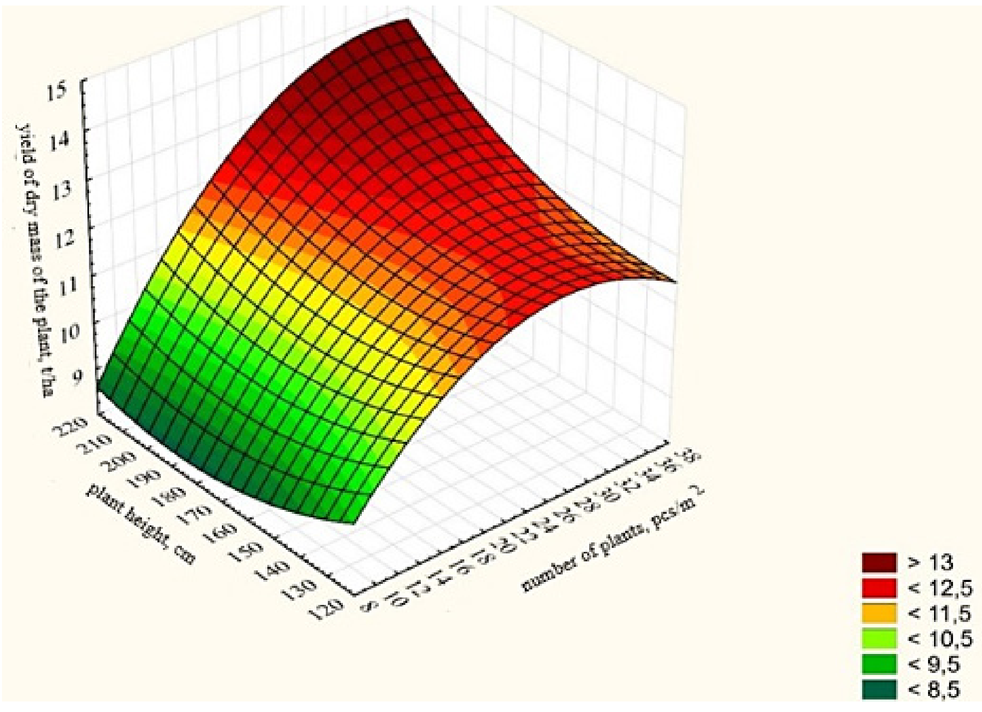

Figure 4. Model of miscanthus productivity depending on plant height and number of plants per m^2

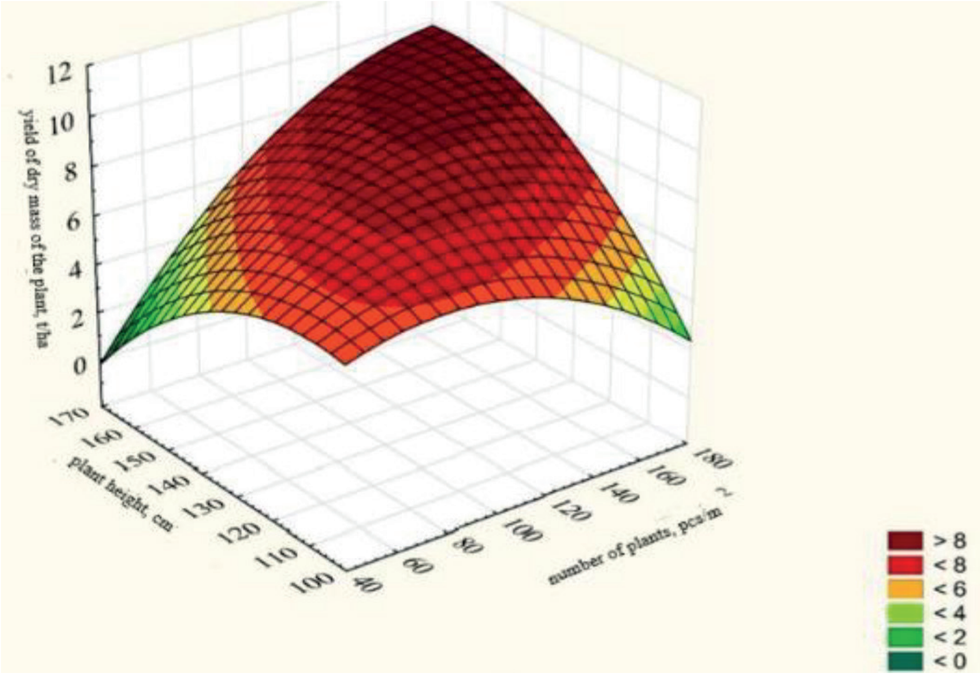

Figure. 5. Switchgras productivity model depending on plant height and number of plants per m^2

The dependence of the productivity of miscanthus plants on plant height and number of stems can be represented by the equation:

$$z = 9.2014 + 0.1496x + 0.0056y \quad (6)$$

where: z is the dry matter yield of miscanthus, t/ha; x – height of plants, cm; y – number of plants, pcs/m^2.

The mathematical models for determining the productivity of switchgrass and miscanthus, as well as multiple regression coefficients are significant, because the actual value of the t-criterion exceeds the theoretical value at 5% level of significance [Lopushniak & Hrytsuliak 2021, Lopushniak et al. 2021b].

As can be seen from Table 3, the coefficient of determination R^2 for the model of switchgrass productivity depending on the dose of sewage sludge is 0.903, and for miscanthus – 0.905, which indicates that these mathematical models explain about 90 – 91% variability [Lopushniak & Hrytsuliak 2021, Lopushniak et al. 2021]. The level of statistical significance (significance) is equal to p = 0.002, which corresponds to the given framework of high statistical reliability, namely $p < 0.05$. One of the most important indicators in the presented table is the average relative absolute error, which shows how much the mathematical model could be wrong when estimating performance. The absolute value of this error is 2.7% for switchgrass and 3.5% for miscanthus, which is quite an acceptable result.

Table 3. Coefficients of multiple regression of dry matter yield of switchgrass and miscanthus

The dry matter yield of switchgrass ($F = 98.544 > F_{0,05} = 2.21$)						
Regression coefficient	Values of regression coefficients	Standard error	Materiality criterion	Correlation coefficient, R	Coefficient of determination, R^2	Absolute error p, %
z	6.249376	0.633062	7.934575	0.951	0.903	2.7489
x	0.005727	0.006981	0.820389			
y	0.003356	0.000505	6.646094			
The dry matter yield of miscanthus ($F = 100.67 > F_{0,05} = 2.21$)						
z	9.201403	0.787613	14.53475	0.952	0,905	3.543
x	-0.005585	0.06115	0.91333			
y	0.149565	0.020576	7.26906			

CONCLUSIONS

1. The productivity of miscanthus and switchgrass depends on the biometric indicators of plants, namely the height of plants and the number of stems. The correct models of miscanthus and switchgrass productivity are calculated depending on the dose of sewage sludge. For miscanthus, the correlation coefficient r = 0.952 and for switchgrass r = 0.951, which indicates a high linear relationship between plant height, number of stems and productivity.
2. Dry matter yield in grass energy crops varies according to fertilizer application. The productivity of the agrophytocenosis of miscanthus is much higher than that of switchgrass. With the addition of sewage sludge at a dose of 40 t/ha, the dry matter yield under the same growing conditions in the agrophytocenosis of miscanthus is 12.2 t/ha, or 3.3 t/ha higher than the productivity of agrophytocenosis switchgrass.
3. The use of composts based on SS + straw (3: 1) – 30 t/ha + $N_{30}K_{55}$, has a significant impact on yield, providing the highest productivity of miscanthus – 13.0 t/ha, and switchgrass – 9.6 t/ha.
4. In order to obtain stable biomass productivity of grass energy crops (miscanthus and switchgrass), it is advisable to use compost of sewage sludge and straw in a ratio of 3: 1 at a dose of 30 t/ha. Thus, two important problems are partially solved – increasing the productivity of energy crops and utilizing municipal waste (sewage sludge).

REFERENCES

1. Atlas enerhetychnoho potentsialu netradytsiinykh ta vidnovliuvanykh dzherel enerhii. 2016. K, 54.
2. Batsmanova L., Taran N., Konotop Y., Kalenska S., Novytska N. 2020. Use of a colloidal solution of metal and metal oxide-containing nanoparticles as fertilizer for increasing soybean productivity. Journal of Central European Agriculture, 21(2), 311–319. https://doi.org/10.5513/JCEA01/21.2.2414
3. Clifton-brown J.C., Breuer J., Jones M.B. 2007. Carbon mitigation by the energy crop, Miscanthus. Glob. Chang. Biol., 13, 2296–2307.
4. Domaratskiy Y., Berdnikova O., Bazaliy V., Shcherbakov V., Gamaynova V., Larchenko O., Domaratskiy A., Baychuk I. 2019. Dependence of winter wheat yielding capacity an mineral nutrition in irrigation Conditions of Southern Steppe of Ukraine. Indian Journal of Ecology, 46(3), 594–598.
5. Hetmanenko V. 2016. Efektyvnist dii kompostiv na osnovi osadiv stichnykh vod na orhanichnu rechovynu chornozemu opidzolenoho. Visnyk ahrarnoi nauky, 71–73
6. Humentyk M.Y. 2019. Osoblyvosti tekhnolohii zmishanoho vyroshchuvannia bioenerhetychnykh zlakovykh kultur dlia vyrobnytstva biopalyva. Bioenerhetyka, 1(13), 16–18.
7. Hrytsuliak H., Lopushniak V. 2017. Osad stichnykh vod u systemi udobrennia verby enerhetychnoi : monohrafiia. Lviv: Prostir-M, 180.
8. Enerhetychna stratehiia Ukrainy do 2035 roku, Bezpeka, enerhoefektyvnist, konkurentospromozhnist», skhvalena rozporiadzhenniam Kabinetu Ministriv Ukrainy vid 18 serpnia 2017 r. № 605-r. [elektronnyi resurs]. – Rezhym dostupu: http://mpe.kmu.gov.ua/minugol/control/uk/doccatalog/list?currDir=50358 (data zvernennia: 27.12.2019 r.).
9. Kabak O.O. 2014. Ekonomichna ta ekoloho-enerhetychna otsinka vyrobnytstva ta vykorystannia bioenerhetychnykh resursiv u silskohospodarskykh pidpryiemstvakh: avtoref. dys. k. e. n.: spets. 08.00.04. Ekonomika ta upravlinnia pidpryiemstvamy, Mykolaiv, 21.
10. Kalenska S., Yeremenko O., Novictska N., Yunyk A., Honchar L., Cherniy V., Stolayrchuk T., Kalenskyi V., Scherbakova O., Rigenko A. 2019. Enrichment of field crops biodiversity in conditions of climate changing. Ukrainian Journal of Ecology, 9(1), 19–24.
11. Kahle P., Beuch S., Boelcke B., Leinweber P., Schulten H.R. 2001. Cropping of Miscanthus in Central Europe: biomass production and influence on nutrients and soil organic matter. Eur. J. Agron., 15, 171–184.
12. Kholodna A.S. 2016. Soil factors of floodplain soils that limit growth of energy crops. Gruntoznavstvo, 17(4), 43–49.
13. Kurylo V.L., Rakhmetov D.B., Kulyk M.I. 2013. Biological features and potential of yield of energy crops of the thin-skinned family in the conditions of Ukraine bulletin of Poltava state agrarian academy, 1(88), 11–17. URL: http://journals.pdaa.edu.ua/visnyk/article/view/13/3
14. Kulik M.I. 2016. Energeticheskiye kul'tury dlya ochishcheniya pochv ot tyazhelykh metallov i polucheniya biotopliva. Sovremennyye energo- i resursosberegayushchiye ekologicheski ustoychivyye tekhnologii i sistemy sel'skokhozyaystvennogo proizvodstv: sb. nauch. tr. Pod red. N.V. Byshova. Vyp, Ryazan': Fgbou Vo Rgatu, 12, 364–367.

15. Kulyk M., Kalinichenko O.V., Halytska M.A., et al. 2017. Fitoenerhetychni kultury: navch. posib. Poltava, 150.
16. Kurylo V.L., Roik M.V., Hanzhenko O.M. 2013. Bioenerhetyka v Ukraini: stan ta perspektyvy rozvytku. Bioenerhetyka, 1, 5–10.
17. Kukharets S.M., Holub H.A. 2012. Zabezpechennia enerhetychnoi avtonomnosti ahroekosystem na osnovi vyrobnytstva biopalyva. Visnyk Zhytomyrskoho natsionalnoho ahroekolohichnoho universytetu: nauk.-teoret. zb. Zhytomyr, 1(1), 345–352.
18. Lopushniak V., Hrytsuliak H. 2021, The intensity of the heavy metals by topinambur in the conditions of the oil polluted areas. Iraqi Journal of Agricultural Sciences, 52(6), 1334–1345. https://doi.org/10.36103/ijas.v52i6.1473
19. Lopushnyak V.I., Hrytsulyak G.M., Bikin A.V., Polutrenko M.S., Kotsyubynska Y.Z. 2021. Prognostic Models of Panicum virgatum L. Using Artificial Neural Networks. Journal of Environmental Engineering, 22(11), 62–71. https://doi.org/10.12911/22998993/142958
20. Lopushniak V., Hrytsuliak H., Kotsiubynsky A., Lopushniak H. 2021. Forecasting the Productivity of the Agrophytocenoses of the Miscanthus Giganteus for the Fertilization Based on the Wastewater Sedimentation Using Artificial Neural Networks Ecological Engineering & Environmental Technology. 22(3), 11–19. https://doi.org/10.12912/27197050/134867
21. Pysarenko P.V., Kurylo V.L., Kulyk M.I. 2017. Ahrobiomasa ta fitomasa enerhetychnykh kultur dlia vyrobnytstva biopalyva. Rozrobka ta vdoskonalennia enerhetychnykh system z urakhuvanniam naiavnoho potentsialu alternatyvnykh dzherel enerhii: monohrafiia. Za red. O. O. Horba, T. O. Chaiky, I. O. Yasnolob. Poltava: Ukrpromtorhservis, 258–266.
22. Persykova T.F., Blokhyna E.A. 2018. Produktyvnost hybrydov sorho zernovoho v zavysymosty ot uslovyi pytanyia na dernovo-podzolystoi lehkosuhlynystoi pochve severo-vostoka Belarusy. Ekolohycheskoe sostoianye pryrodnoi sredы y nauchno-praktycheskye aspektы sovremennыkh ahrotekhnolohyi: materyalы Mezhdunarodnoi nauchno-praktycheskoi konferentsyy (22–23 marta 2018 hoda, h. Riazan). Riazan: Yzdatelstvo Riazanskoho hosudarstvennoho ahrotekhnolohycheskoho unyversyteta. Chast I., 297–302.
23. Roik M.V., Kurylo V.L., Humentyk M.Y. 2011. Efektyvnist vyroshchuvannia vysokoproduktyvnykh enerhetychnykh kultur. Visnyk Lvivskoho natsionalnoho ahrarnoho universytetu, 15(2), 85–90.
24. Roik M.V., Yaholnyk O.H. 2015. Ahropromyslovi enerhetychni plantatsii – maibutnie Ukrainy. Bioenerhetyka, 2, 4–7.17.
25. Mazurenko B., Kalenska S., Honchar L. and Novytska N. 2020. Grain yield response of facultative and winter triticale for late autumn sowing in different weather conditions. Agronomy Research 18(1), 183–193, https://doi.org/10.15159/AR.20.008
26. Panfilova A., Gamajunova V., Smirnova I. 2020. Influence of fertilizing with modern complex organic-mineral fertilizers to grain yield and quality of winter wheat in the Southern Steppe of Ukraine. Journal of Agricultural Science 2(31), 196–201.
27. Panfilova A., Mohylnitska A., Gamayunova V., Fedorchuk M., Drobitko A., Tyshenko S. 2020. Modeling the impact of weather and climatic condition and nutration variants on the yield of spring barley varieties (*Hordeum vulgare* L.) Agronomy Research, 18(S2), 1388–1403.
28. Sanderson M.A., Reed R.L., Mc Laughlin S.B., Wohlschlaeger S.D., at el. 1996. Switchgrass as a sustainable bioenergy crop. Bioresource Technology, 56, 83–93.
29. Turhollow A.F. 1991. Screening herbaceous lignocellulosic energy crops in temperate regions of the USA. Bioresource Technology, 36, 247–252.
30. Van Loocke A., Twine T.E., Zeri M., Bernacchi C.J. 2012. A regional comparison of water use efficiency for miscanthus, switchgrass and maize Agric. For. Meteorol., 164, 82–95.
31. Weindorf D.C., Zhu Y., Chakraborty S., Bakr N., Huang B. 2012. Use of portable X-ray fluorescence spectrometry for environmental quality assessment of peri-urban agriculture. Environmental Monitoring and Assessment, 184(1), 217–227.