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AGROECOLOGICAL ASPECTS OF RARE ENERGY CROPS GROWING IN ORDER TO PRODUCE SUSTAINABLE PLANT BIOMASS

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INTRODUCTION

Today, the problem of reducing Ukraine's energy dependence on nonrenewable energy sources remains unresolved. In fact, Ukraine imports part of its electricity and gets some from expired nuclear power plants. Other nonrenewable energy sources derived from natural gas and oil are mainly imported and produced in short supply in our country. Besides, renewable energy sources such as alternative energy of plant resources, solar, wind and geothermal energy are not fully used. Therefore, the issue of rational use of natural resources remains relevant and insufficiently studied. This problem needs to be substantiated.

In this regard, it is important to find ways of obtaining cheap biomaterials from energy crops under current conditions. Because plant biomass is a good raw material for the production of biofuel, which is an alternative to fossil fuels. Which in the future will reduce the energy dependence of European countries, in particular Ukraine.The development of bioenergy sector will strengthen the economy and create new employment opportunities[1]. The introduction of bioenergy projects will make it possible to obtain a significant amount of energy from plant raw materials[2]. It is necessary to take into account the impact on the environment: soil fertility, their water and air regimes, biodiversity. Moreover, the complete cycle from biofuel producer to biofuel consumer will increase the effectiveness of biomass production and reduce the

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[1] Kulyk Maksym, Kalinichenko Oleksandr, Dekovetz Vitalii. Efficiency of energy crops cultivation for business development in Ukraine. *Organization and management in the services' sphere on selected examples* / Editors : Tetyana Nestorenko, Tadeusz Pokusa. Monograph. Opole: The Academy of Management and Administration in Opole, 2020: 36–45. ISBN 978-83-66567-02-3. http://pedagogika.wszia.opole.pl/ebook/3_2020.pdf

[2] Kulyk M. I., Padalka V. V. (2020) Rozvytok bioenerhetyky na osnovi roslynnoho enerhetychnoho resursu (na prykladi Poltavskoi oblasti) [Development of bioenergy based on plant energy resources (on the example of Poltava region)]. Upravlinnia stratehiiamy vyperedzhaiuchoho innovatsiinoho rozvytku: monohrafiia / za red. k.e.n., dotsenta N. S. Illiashenko. Sumy : Trytoriia, pp. 109–118. (in Ukrainian)

environmental impact [3]. It is necessary to pay attention to the purification of contaminated soils. In this case energy crops can successfully perform phytoremediation function. But the areas of contaminated land in Ukraine are growing every year. This is connected with pesticide load, unreasonable doses of mineral fertilizers, migration of polutants, radioactive pollution, etc [4].

In this publication we made an attempt to give a biological description of rare energy crops, peculiarities of ecological aspects of their cultivation on marginal lands in Ukraine. The biological and morphological characteristics and illustrative material of energy crops from the Poaceae family were given. Understanding the morphological and biological characteristics and the relationship between energy crops and environmental conditions will make it possible to select the optimal elements of their cultivation technology. And the mutual cultivation of energy crops with different combinations of these crops in the phytocenosis will increase the yield of biomass as a raw material for biofuel production

1. The problem prerequisites emergence and the problem formulation

A large number of scientific works are devoted to the study of energy crops in the environment of our country: M. V. Roik, V. L. Kurylo, M. Ya. Humentyk[5], O. M. Hanzhenko[6], D. B. Rakhmetov[7], D. B. Rakhmetov, O. M. Verhun, and S. O. Rakhmetova[8], H. H. Heletukha, T. A. Zhelezna, O. V. Tryboy[9], V. L. Kurylo,

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[3] Kulyk M. I., Kurylo V. L., Kalinichenko O. V., Galytska M. A. (2019) Plant energy resources: agroecological, economic and energy aspects. Monograf. 160 p.

[4] Kulyk M., Galytska M., Samoylik M., & Zhornyk, I. (2019) Phytoremediation aspects of energy crops use in Ukraine. Agrology, vol. 2(1), 65–73. DOI: https://doi.org/10.32819/2617-6106.2018.14020

[5] Роїк М. В. Ефективність вирощування високопродуктивних енергетичних культур / [М. В. Роїк, В. Л. Курило, М. Я. Гументик та ін.] // Вісник Львівського національного аграрного університету. 2011. № 15(2). С. 85–90.

[6] Курило В. Л. Біоенергетика в Україні: стан та перспективи розвитку / В. Л. Курило, М. В. Роїк, О. М. Ганженко // Біоенергетика. 2013. Вип. № 1. С. 5–10.

[7] Рахметов Д. Б. Міскантус в Україні: інтродукція, біологія, біоенергетика / Д. Б. Рахметов, Т. О.Щербакова, С. Д. Рахметов. Київ : Фітосоціоцентр, 2015. 158 с.

[8] Рахметов Д. Б. Panicum virgatum L. – перспективний інтродуцент у Національному ботанічному саду ім. М. М. Гришка НААН України / Д. Б. Рахметов, О. М. Вергун, С. О. Рахметова // Інтродукція рослин. Вип. 3(63), 2014. С. 4–12, 24.

[9] Гелетуха Г. Г. Перспективи вирощування та використання енергетичних культур в Україні / Г. Г. Гелетуха, Т. А. Железна, О. В. Трибой. Київ, 2014. 33 с.

D. B. Rakhmetov and M. I. Kulyk[10], N. V. Pryshliak[11] and others. The most widespread energy crops are switchgrass, miscanthus and willow[12].. Indiangrass, big bluestem and sorghum perennial are also of great scientific interest. But a thorough study of the morphological and biological characteristics of these crops, their yield potential and energy productivity in their mutual cultivation has not been given proper attention. These are the issues we have studied in this publication.

Therefore, the development of bioenergy in Ukraine requires searching ways to reduce the cost of various types of bio-raw materials in the economic justification of their production[13]. This involves a comprehensive study of energy crops, as well as the development of management and logistics of their cultivation on the basis of technical and economic concepts [14, 15]. It is necessary to upgrade the infrastructure of territorial communities systematically, to develop processing facilities for biofuel production. In addition, the involvement of energy service companies to supply consumers with alternative energy is promising.

The main components of the bioenergy production potential in Ukraine are primary agricultural residues (cereal straw, corn and sunflower

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[10] Курило В. Л., Рахметов Д. Б., Кулик М. І. Біологічні особливості та потенціал урожайності енергетичних культур родини тонконогових в умовах України. *Вісник Полтавської державної аграрної академії*. Вип. 1(88), 2018. С. 11–17.

[11] Kulyk M., Kalynychenko O., Pryshliak N., Pryshliak V. (2020). Efficiency of using biomass from energy crops for sustainable bioenergy development. *Journal of Environmental Management and Tourism*, [S.l.], v. 11, n. 5, p. 1040–1053, aug. 2020. ISSN 2068-7729 doi: https://doi.org/10.14505//jemt.v11.5(45).02

[12] Міскантус в Україні : колективна монографія / авторський колектив М. В. Роїк, В. М. Сінченко, О. О. Іващенко, та ін. К. : ТОВ «ЦП «Компрінт», 2019. 256 с.

[13] Кулик М. І., Курило В. Л., Калініченко О. В. Урожайність та енергетична ефективність виробництва відновлюваної рослинної сировини енергетичних культур. *Оптимальні енергетичні системи з урахуванням наявного потенціалу відновлюваних джерел енергії у Лісостепу України : колективна монографія* / За заг. ред. М. І. Кулика, О. В. Калініченка. Полтава: ПП «Астрая», 2019. С. 30–48.

[14] Kulyk M. I., Kurylo V. L., Kalinichenko O. V., Galytska M. A. Plant energy resources: agroecological, economic and energy aspects. *Monograf*. 2019. 119 p.

[15] Писаренко П. В., Курило В. Л., Кулик М. І. Агробіомаса та фітомаса енергетичних культур для виробництва біопалива. *Розробка та вдосконалення енергетичних систем з урахуванням наявного потенціалу альтернативних джерел енергії : колективна монографія* / за ред. О. О. Горба, Т. О. Чайки, І. О. Яснолоб. П. : ТОВ НВП «Укрпромторгсервіс», 2017. С. 258–266.

residues, etc.)[16] as well as industrial cultivation of energy crops and the processing of household solid waste[17, 18].

Energy crops are able to provide a significant amount of plant material. They produce significant yields, which implies a large amount of biomass for biofuel production each year[19]. Moreover, energy crops have a number of advantages of biomass growing and using (Figure 1).

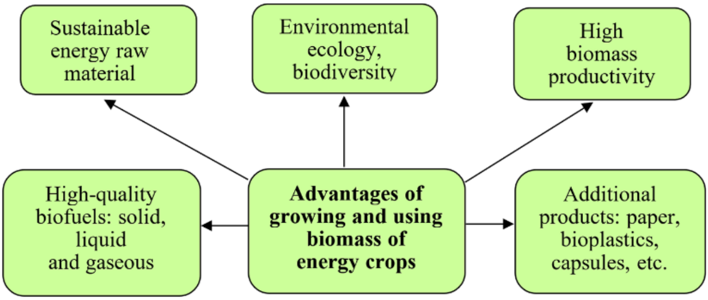

Figure 1. Advantages of growing and using biomass of energy crops

Scientists[20] identified weather and climate and environmental factors as the most influential factors in determining the yields and quality of agricultural products and energy crops, and only afterwards anthropogenic effects[21].

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[16] Тараненко А. О., Цьова Ю. А., Середа М. С., Кузенко Л. Ю., Солодовник М. А. Потенціал біомаси відходів сільського господарства для виробництва біоенергетики в Полтавській області. Вісник ПДАА. 2021. № 4. С. 142–153.

[17] Taranenko, A. O., Kulyk, M. I., & Popov, S. I. (2020). Ahroekolohichne obgruntuvanniavyroshchuvannia enerhetychnykh kultur. *Ekolohichni innovatsii u pidvyshchenni ekonomichnoi ta prodovolchoi bezpeky Ukrainy: kolektyvna monohrafiia*. Poltava: PP «Astraia».

[18] Morozov, R. V., & Fedorchuk, Ye. M. (2015). Otsinka bioenerhetychnoho potentsialu roslynnykhvidkhodiv ta enerhetychnykh kultur u silskomu hospodarstvi. *Naukovyi Visnyk Khersonskoho Derzhavnoho Universytetu*, 10(3), 111–117.

[19] Taranenko, A. O., Kulyk, M. I., & Popov, S. I. (2020). Ahroekolohichne obgruntuvanniavyroshchuvannia enerhetychnykh kultur. *Ekolohichni innovatsii u pidvyshchenni ekonomichnoi ta prodovolchoi bezpeky Ukrainy: kolektyvna monohrafiia*. Poltava: PP «Astraia».

[20] Польовий А. М., Божко Л. Ю. Вплив кліматичних змін на режим зволоження вегетаційного періоду в Україні. Український гідрометеорологічний журнал. 2015. № 16. С. 128–139.

[21] Korenko, M., Bulgakov, V., Kurylo, V., Kulyk, M., Kainichanko, A., Ihnatiev, Y., & Matušeková, E. (2021). Formation of Crop Yields of Energy Crops Depending

Increased air temperature and an uneven distribution of rainfall, characterised by heavy rainfall during the warm season, preventing efficient moisture storage in the soil and leading to an increase in the frequency and intensity of droughts[22]. As the authors[23] point out, the physical and geographical location of Ukraine greatly determines its rather complex nature in changing climatic conditions, which causes instability and crop losses in some years that can be as high as 45–50 %.The European Green Deal defines a set of measures that will guide EU policy for the coming years. This relates to climate, energy, biodiversity, industrial policy, trade, etc[24, 25, 26, 27, 28, 29].

Global greenhouse gas emissions by sector were found to be distributed as follows: three quarters of emissions come from the energy sector, almost a fifth from agricultural production, and the remaining 8.4%

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on the Soil and Weather Conditions. Acta Technologica Agriculturae, 24(1), 41–47. doi: 10.2478/ata-2021-0007

[22] Польовий А. М., Божко Л. Ю. Вплив кліматичних змін на режим зволоження вегетаційного періоду в Україні. Український гідрометеорологічний журнал. 2015. № 16. С. 128–139.

[23] Білявський Ю. В., Білявська Л. Г. Аналіз агро-кліматичних та грунтових умов Лісостепу України для вирощування сільськогосподарських та енергетичних культур. Оптимальні енергетичні системи з урахуванням наявного потенціалу відновлюваних джерел енергії у Лісостепу України : колективна монографія / За заг. ред. М. І. Кулика, О. В. Калініченка. Полтава : ПП «Астрая», 2019. С. 7–17.

[24] Brodny J., Tutak M. The analysis of similarities between the European Union countries in terms of the level and structure of the emissions of selected gases and air pollutants into the atmosphere. Journal of Cleaner Production. 2021. Vol. 279. N123641. DOI: 10.1016/j.jclepro.2020.123641

[25] Kardung M., Cingiz K., Costenoble O., Delahaye R. at. al. Development of the Circular Bioeconomy: Drivers and Indicators. Sustainability. 2021. Vol. 13. Iss. 1. N413. DOI: 10.3390/su13010413

[26] Ossewaarde M, Ossewaarde-Lowtoo R. The EU's Green Deal: A Third Alternative to Green Growth and Degrowth. Sustainability. 2020. Vol. 12. Iss. 23. N9825. DOI: 10.3390/su12239825

[27] Ronzon T., Piotrowski S., Tamosiunas S., Dammer L., at. al. Developments of Economic Growth and Employment in Bioeconomy Sectors across the EU. Sustainability. 2020. Vol. 12. Iss. 11. N4507. DOI: 10.3390/su12114507

[28] Scown M.W., Brady M.V., Nicholas K.A. Billions in Misspent EU Agricultural Subsidies Could Support the Sustainable Development Goals. One Earth. 2020. Vol. 3. Iss. 2. P. 237–250. DOI: 10.1016/j.oneear.2020.07.011

[29] Tsakalidis A., Gkoumas K., Pekar F. Digital Transformation Supporting Transport Decarbonisation: Technological Developments in EU-Funded Research and Innovation. Sustainability. 2020. Vol. 12. Iss. 9. N3762. DOI: 10.3390/su12093762

from industry and waste[30], [31]. Integrated and innovative approaches are needed to achieve zero CO^2 emissions in many sectors. This is particularly important in the energy and agribusiness sectors. Therefore, to build a low-carbon economy, Ukraine needs to pay more attention to the development of renewable energy sources, in particular bioenergy. In this regard, the development of bioenergy is a prerequisite for solving energy and environmental challenges and is closely connected to the mitigation of global climate change.

2. Morphological and biological characteristics and yield potential of energy crops

Switchgrass *(Panicum virgatumL.)* is a perennial herbaceous plant of Poaceae family with a well leafy upright stem (figure 2).

Figure 2. Switchgrass

(Panicum virgatum L.)

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[30] Khan Z., Ali S., Umar M., Kirikkaleli D., Jiao Z. L. Consumption-based carbon emissions and International trade in G7 countries: The role of Environmental innovation and Renewable energy. Science Of The Total Environment. 2020. Vol. 730. N138945. DOI: 10.1016/j.scitotenv.2020.138945

[31] Neves A., Godina R., Azevedo S. G., Matias J. C. O. A comprehensive review of industrial symbiosis. Journal Of Cleaner Production. 2019. Vol. 247. N119113. DOI:10.1016/j.jclepro.2019.119113

Switchgrass plants reach a height of up to 250 cm. The number of productive shoots per plant is 12–35. The plants are straight or semi-branched depending on their shape. The panicles are 30–40 cm long and 20–30 cm wide. The seeds are divided into three groups according to the weight of 1000 pieces: small seeds up to 1.5 g, medium seeds from 1.5 to 1.8 g, large seeds over1.8 g[32].

The perennial rhizomes of switchgrass can be divided into several parts during vegetative propagation. Therefore, switchgrass is characterized by generative and vegetative propagation.

Switchgrass dry phytomass is harvested in late winter – early spring period on frozen soil provided the stems are dry and low in moisture and microelements. Yield: above-ground plant phytomass in the period of panicles emergence is 42–64 t/ha, in flowering period is 42.7–70.2 t/ha; dry weight is 10–15 t/ha; seed is 500–600 (sometimes up to 1000) kg/ha[33].

Herbaceous crops introduced into Ukraine include the following rare energy crops: indiangrass, big bluestem and sorghum perennial.

Indiangrass *(Indiangrass, Sorghastrum nutans, Sorghastrum nutans L.Nash)* is a perennial plant of Poaceae family, with tall (up to 8 m) upright stems. The minimum depth of root penetration reaches 60–70 cm. The plants are characterized by rapid growth and development of the above-ground vegetative mass. The flowering period is from August to October. The plant is propagated both in generative and vegetative ways (Figure 3).

Sorghum is used to control soil erosion and is widely used in landscaping. The plants are tolerant to an extremely wide range of soil conditions and have a moderate drought and salt tolerance. However, the plants grow better in deep, well-drained soils with a pH of 4.0–7.8[34].

Seeding rate of the single-species crops of indiangrass is 4–5 kg/ha; in mixtures is10–50%. The duration of indiangrass cultivation on a plot is up

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[32] Курило В. Л., Рахметов Д. Б., Кулик М. І. Біологічні особливості та потенціал урожайності енергетичних культур родини тонконогових в умовах України. *Вісник Полтавської державної аграрної академії*. Вип. 1(88), 2018. С. 11–17.

[33] Курило В. Л., Кулик М. І., Калініченко О. В. Енергетичні культури : підручник. Полтава : ПП «Астрая», 2019. 320 с.

[34] Кулик М. И. Энергетические культуры для очищения почв от тяжелых металлов и получения биотоплива. Современные энерго- и ресурсосберегающие экологически устойчивые технологии и системы сельскохозяйственного производства : сборник науч. тр. / под ред. Н. В. Бышова. Вып. 12. Рязань : ФГБОУ ВО РГАТУ, 2016. С. 364–367.

to 15 years. It takes two years to obtain the highest yield of biomass per hectare. Biomass yields of indiangrass are 12–15 t/ha [35].

Figure 3. Indiangrass

(Indiangrass, Sorghastrum nutans (L.) Nash)

Big bluestem (*Big Bluestem, Andropogon gerardii Vitman*) is a perennial herbaceous plant. This herb is used to control soil erosion. It has phytoremediation properties. The natural habitat of big bluestem phytocenosis is open fields and meadows. Plant height is 1.8–2.5 m; the minimum root penetration depth is 50 cm (Figure 4).

Figure 4. Big bluestem

(Big Bluestem, Andropogon gerardii Vitman)

[35] Henning, J. (1993) Big bluestem, Indiangrass, and switchgrass. Bulletin G4673. University of Missouri Cooperative Extension. University of Missouri. Columbia, MO. Internet-resurs. Retrieved from: https://extension.missouri.edu/ publications/g4673

Big bluestem is used as raw material for the biofuel industry and can be used as quality livestock feed, improving biodiversity [36].

Big bluestem is a drought-tolerant cereal, and it requires sufficient moisture for seed germination and plant establishment during the initial periods of growth and development. The plant does not require fertile soils and is resistant to salinization. The optimum soil acidity is in the range of a pH 6.0–7.5. The plants are moderately salt-tolerant.

Seeding rates for natural conditions are 4.5–6 kg/ha; in mixture of 10–50%, about 288,000 seeds per kg. The biomass yield is 10–12 t/ha. The number of years of cultivation on a plot is 12–14; the number of years to the maximum biomass yield per 1 ha is three years.

Sorghum perennial (*Columbus Grass, Sorghum almum Parodi*) is a perennial herbaceous plant of Poaceae family (Figure 5). The crop is characterized by a high biomass and seed yield, frost-resistance and a well-established cultivation technology[37].

Figure 5. Sorghum perennial, Columbus grass

(Columbus Grass, Sorghum almum Parodi)

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[36] Paul W. Barnes. Adaptation to Water Stress in the Big Bluestem-Sand Bluestem Complex. Ecology Vol. 66, No. 6 (Dec., 1985), pp. 1908–1920. https://doi.org/10.2307/2937387

[37] Chable, V., Nuijten, E., Costanzo, A., Goldringer, I., Bocci, R., Oehen, B., Rey, F., Fasoula, D., Feher, J., Keskitalo, M., Koller, B., Omirou, M., Mendes-Moreira, P., Van Frank, G., Kader, A., Jika, N., Mathieu, T., and Adanella Rossi. (2020). Embedding Cultivated Diversity in Society for Agro-Ecological Transition. Sustainability, 12, 784. doi:10.3390/su12030784

The plant height is 2.8–3.5 m; minimum root penetration is 70–80 cm. Plants are characterized by high drought-resistance and moderate salt tolerance. Seeding rates of sorghum for natural conditions are 8.5–10 kg/ha; in mixture have not been studied. The biomass yield is 18–20 t/ha. Number of years of cultivation on a plot is up to 7; the number of years to the maximum biomass yield per 1 ha is two years[38].

Thus, in terms of biology, the energy crops listed above are typical members of Poaceae family. The plants by their morphological traits are capable to form a powerful aboveground vegetative mass in 2–3 years of vegetation with a lifetime of energy plantations of 7 to 15 years. Which fully corresponds to the criteria of sustainable production of plant biomass as a raw material for biofuel production. In addition, it was determined that the biological and adaptive characteristics of energy crops are quite suitable for cultivation in Ukraine.

3. Environmental aspects of optimising the cultivation of energy crops

The use of fossil fuels as the main source of energy in recent decades has had a huge impact on the environment. Meanwhile, the level of CO_2 emissions into the atmosphere has increased, significantly contributing to global warming and climate change[39]. Therefore, with the depletion of fossil fuel production, ever-increasing fossil fuel prices and environmental pollution, it is important to research and implement the use of renewable energy sources on a national scale.[40].

Biomass is a major source of bioenergy. The global trend (2000–2018) of renewable energy sources shows an increasing share of biomass use for

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[38] Дьомін Д. Г., Щербак Є. Ю., Кулик М. І. Потенціал біомаси малопоширених енергетичних культур. Матеріали науково-практичної інтернет-конференції «Сучасні напрями та досягнення селекції і насінництва сільськогосподарських культур» / Ред. кол.: Тищенко В. М. (відп. ред.) та ін. Полтавська державна аграрна академія, 2021. С. 43–47.

[39] Peni, D.; Dębowski, M.; Stolarski, M. J. Influence of the Fertilization Method on the Silphium perfoliatum Biomass Composition and Methane Fermentation Efficiency. Energies 2022, 15, 927. https://doi.org/10.3390/en15030927

[40] Paolini, V.; Petracchini, F.; Segreto, M.; Tomassetti, L.; Naja, N.; Cecinato, A. Environmental impact of biogas: A short review of current knowledge. J. Environ. Sci. Health A 2018, 53, 899–906. [Google Scholar] [CrossRef] [PubMed]

energy production[41]. Thus, since 2000, the percentage of biomass usage has increased by 13.1% (Figure 7).

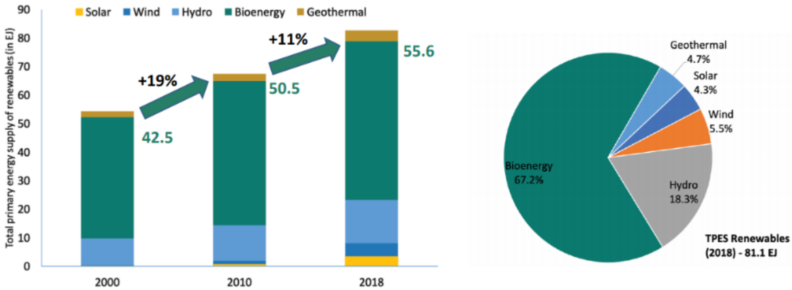

Figure 7. Development of bioenergy in the world [42]

Today, energy crop biomass is considered to be a key element in achieving climate change mitigation. Strategies such as carbon sequestration and bioenergy with carbon capture and storage (BECCS) are increasingly developing[43,44].

In terms of sustainable development and environmental management, the cultivation of energy crops should provide not only an economic but also a socio-ecological contribution (biodiversity increase, landscape aesthetics). In the context of food crisis and increasing demand for agricultural land, energy crops should be grown on marginal agricultural land to reduce competition with food crop production.

Cultivation of energy crops must be sustainable within the context of climate change effects. Planning for these crops should be introduced systematically, using integral and systematic approaches. Further research and policy incentives should consider not only the economic potential of energy crop cultivation, but also environmental issues. Biodiversity, plant

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[41] Rosch C. & Skarka J. (2008). European Biofuel Policy in a Clobal Context: Trade-Offs and Strategies. GAIA-ecological perspectives for science and society, 17(4), 378–386.

[42]Global bioenergy statistics 2020. Retrieved from: http://www.worldbioenergy.org/uploads/201210%20WBA%20GBS%202020.pdf

[43] Karp, A.; Shield, I. Bioenergy from plants and the sustainable yield challenge. New Phytol. 2008, 179, 15–32. [CrossRef]

[44] Canadell, J. G.; Schulze, E. D. Global potential of biospheric carbon management for climate mitigation. Nat. Commun. 2014, 5, 5282. [CrossRef] [PubMed]

fertility and adaptation to climate change as well as social issues for the area are also included.

All this allows existing agricultural systems to adapt to the changing world and encourage the development of a more sustainable bioeconomy[45].

Biomass production of renewable plant material from energy crops depends on many factors that determine the feasibility of their cultivation. They also ensure the ecological and energy effectiveness of energy crop cultivation (Fig. 8).

Factors affecting energy crops cultivation

- Equipment and facilities for cultivation
- Environmental factors
- Social factors
- Natural resources (soils, water), greenhouse effects
- New markets, subsidies, labour force
- Economy, globalisation, new product
- Energy needs, new energy sources
- Plants (genetic engineering, breeding)

Figure 8. Factors affecting energy crops cultivation and biomass production

Environmental influences on energy crops cultivation are mainly reflected in its effect on seed germination and the initial stages of plant growth. It also affects photosynthesis intensity and the formation and development of the above-ground vegetative mass, thereby influencing plant yields. Air temperature and rainfall are key environmental factors.

Changes in temperature can both increase the growing season and impair plant growth and development. The amount and distribution of precipitation is generally the most important factor in fluctuating production levels. Limited water availability during the growing season can reduce crop yields. Mild and dry winter can have a negative effect and promote the development of pests and diseases in energy crops plantations. Heavy snowfalls can lead to lodging of plants during the

[45] Moritz Von Cossel, Moritz Wagner, Jan Lask, Elena Magenau, Andrea Bauerle, Viktoria Von Cossel, Kirsten Warrach-Sagi, Berien Elbersen, Igor Staritsky, Michiel Van Eupen, Yasir Iqbal, Nicolai David Jablonowski, Stefan Happe, Ana Luisa Fernando, Danilo Scordia, Salvatore Luciano Cosentino, Volker Wulfmeyer, Iris Lewandowski 1 and Bastian Winkler 1 Prospects of Bioenergy Cropping Systems for A More Bioeconomy. Social-Ecologically Sound Agronomy 2019, 9, 605; doi:10.3390/agronomy9100605

winter period. On the other hand, the cultivation of energy crops can have its effects on the environment. Possible environmental effects on biomass can be: water and mineral resources usage, soil quality and erosion, spread of minerals and pesticides into the soil and groundwater, formation and use of biomass waste, changes in the existing landscape and biodiversity.

Therefore, in order to achieve balanced cultivation and use of energy crops as plant material, ecological aspects must be taken into account. To reduce the pressure on the environment, it is recommended to establish energy plantations and grow energy crops on marginal lands that have low fertility, show signs of degradation and require reclamation[46]. The emphasis should be placed on energy-saving agricultural technologies with minimum use of plant protectants and fertilizers, the use of mechanical method of weed control in energy crops as an alternative to chemical weed control. The optimal sowing date of the crop, pre-sowing preparation of seeds with bio-preparations, and the selection of resistant varieties to the environmental conditions should be followed.

Positive ecological aspects of growing and using energy crops can be their use for phytoremediation (cleaning) of soils[47]. The cultivation of energy crops in mutual crops is effective for increasing the biomass productivity, improving the quality of marginal lands by raising the organic matter content of the soils. This has been proven by our previous research [48].

4. The analysis of existing methods for solving the problem and formulating a task for the research

The aim of the research is to determine the impact of the diverse composition of energy crops on the yield and biomass energy productivity.

The object of the research is the yield and energy output of energy crops biomass depending on the components of agrophytocenoses.

The subject of the research is energy crops: switchgrass, big bluestem, indiangrass and sorghum perennial, their mutual cultivation in phytocenosis, and biomass yields.

In the experiment we used *general scientific methods* and *special methods,* namely: field – to determine the interaction of the subject with

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[46] Писаренко П. В., Горб О. О., Кулик М. І., та ін. 2017. Науково-практичні рекомендації до вирощування енергетичних культур та використання фітомаси. Полтава, 34 с.

[47] Kulyk M., Galytska M., Samoylik M. & I. Zhornyk. 2019. Phytoremediation aspects of energy crops use in Ukraine. Agrology. Vol. 2(1). P. 65–73. URL: https://doi.org/10.32819/2617–6106.2018.14020

[48] Taranenko A., Kulyk M., Galytska M., Taranenko S., Rozhko I. 2021. Dynamics of soil organic matter in *Panicum virgatum* sole crops and intercrops. *Zemdirbyste-Agriculture.* Vol. 108(3): 255–262. DOI: 10.13080/z-a. 2021.108.033

the object of research; weight – to determine the yield of energy crops biomass, laboratory and analytical – to determine the energy output of energy crops biomass, calculation – to establish the energy productivity of crops. Mathematical and statistical analysis of the obtained results (method of dispersion) was also applied. The analysis determined a significant difference between the experiment variants according to the LSD at a 5% level of significance.

The field experiments were established and carried out in accordance with the requirements of the agronomic research methodology. Experimental variants combined: Sw – single-species switchgrass crops (variant 1, control), Sw+Ig – mutual crops of switchgrass and indiangrass (variant 2), Sw+Bb – mutual crops of switchgrass and big bluestem (variant 3), Sw+Sa – mutual crops of switchgrass and perennial sorghum (variant 4), Ig+Bb – mutual crops of indiangrass and big bluestem (variant 5), Ig+Sa – mutual crops of indiangrass and sorghum perennial (variant 6), Bb+ Sa – mutual crops of big bluestem and perennial sorghum (variant 7). The variants in each repetition were arranged in a randomised way (Figure 6).

var5	var2	var7	var2
var3	var6	var1	var5
var1	var4	var4	var3
var7	var5	var3	var7
var2	var1	var6	var4
var6	var7	var5	var1
var4	var3	var2	var6
1 repetition	2 repetition	3 repetition	4 repetition

Fig. 6. Arrangement of the variants in the field experiment

Note: Sw – single-species switchgrass crops (var1, control), Sw+Ig – mutual crops of switchgrass and indiangrass (var2), Sw+Bb – mutual crops of switchgrass and big bluestem (var3), Sw+Sa – mutual crops of switchgrass and sorghum perennial (var4), Ig+Bb – mutual crops of indiangrass and big bluestem (var5), Ig+Sa – mutual crops of indiangrass and sorghum perennial (var6), Bb+ Sa – mutual crops of big bluestem and sorghum perennial (var7).

In our research, energy crops were counted and analysed according to generally accepted and specific scientific methods and recommendations for production[49].

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[49] Kulyk M., Elbersen W. Methods of calculation productivity phytomass for switchgrass in Ukraine. Poltava, 2012. 10 p.

Yields of the so-called “raw” (green mass) and “dry” plant biomass of energy crops were measured at the end of the plant vegetation [50].

The effectiveness of energy crop cultivation was assessed using the author’s methodology [51].

Thus, the establishment and performance of the field experiment was in accordance with the methodology of scientific research in agronomy. The laboratory experiment was carried out in accordance with the scientific guidelines.

5. Results of experiments

Observations of the weather conditions of three years of the research determined that air temperature and precipitation during the growing season of energy crops varied within a wide range. The year 2019 was characterised by average temperatures against a decrease in precipitation at the end of the summer period. The air temperature increase and even distribution of precipitation during the spring-summer period was recorded during 2021 (Figs. 9–11).

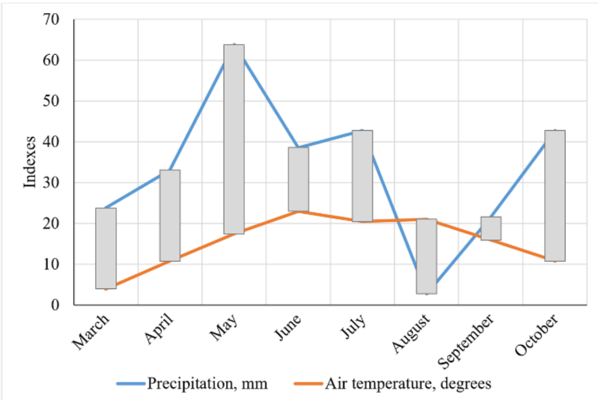

Figure 9. Air temperature and precipitation during the growing season of energy crops, 2019

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[50] Кулик М. І., Рахметов Д. Б., Курило В. Л. Методика проведення польових та лабораторних досліджень з просом прутоподібним *(Panicum virgatum L.)*. Полтава : РВВ ПДАА, 2017. 24 с.

[51] Калінченко О. В., Кулик М. І. Науковий твір «Методичні засади оцінки енергетичної ефективності вирощування енергетичних культур в умовах Лісостепу України» (Свідоцтво про реєстрацію авторського права на твір № 93177 від 18.10.2019).

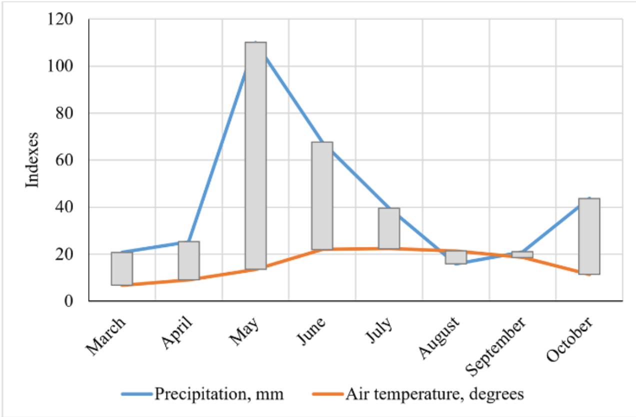

Figure 10. Air temperature and precipitation during the growing season of energy crops, 2020

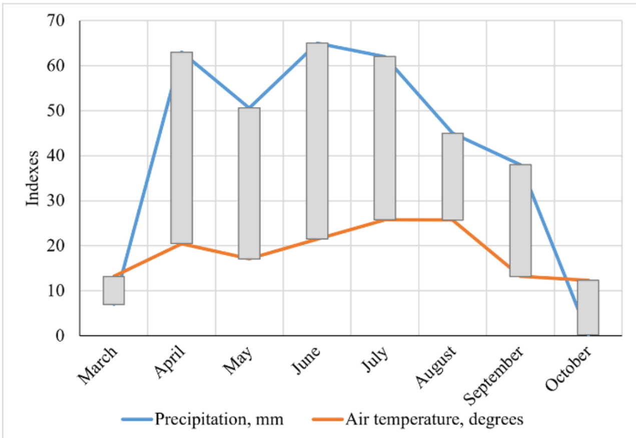

Figure 11. Air temperature and precipitation during the growing season of energy crops, 2021

Research of foreign authors determined the effectiveness of growing energy crops in mutual single-species crops. The ecological effect of growing energy crops and increasing of yields[52,53], and energy productivity of energy crops[54] for different growth of vegetative components in phytocenoses were noted[55]. Our previous research found a significant influence of plant biometrics in terms of stem height and density on the biomass yields of rare energy crops. Sorghum perennial and switchgrass formed the highest yield of dry biomass. This index was significantly lower for big bluestem[56]. Our research also shows that in single-species crops, dry biomass yield of indiangrass was 8.9 t/ha in the first year, 10.1 t/ha in the second year and 14.9 t/ha in the third year. Biomass yields of big bluestem ranged between 4.4 and 9.3 t/ha. Dry biomass yields of Columbus grass increased from 11.4 t/ha (1st year) to 14.9 t/ha (2nd year) and to 18.0 t/ha (3rd year). The model we have developed for creating artificial phytocenoses allows for reclamation using energy crops based on agro-ecological monitoring and agronomic justification for the cultivation of rare energy crops[57].

Based on the results of new original research, it was found that the mutual cultivation of energy crops optimises the phytocenosis structure and makes the best use of the marginal land area. This contributes to an

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[52] McKone, M. J., Lund C. P. and J. M. OíBrien. 1998. Reproductive biology of two dominant prairie grasses (Andropogon gerardii and Sorghastrum nutans, Poaceae): male-biased sex allocation in wind-pollinated plants. Am. J. Bot. 85: p. 776–783.

[53] Weik L., Kaul H.-P., Kübler E., Aufhammer W. (2002). Grain Yields of Perennial Grain Crops in Pure and Mixed Stands *Journal of Agronomy and Crop Science*. https://doi.org/10.1046/j.1439-037X.2002.00580.x

[54] Jungers J. M., Lee R. DeHaan, Kevin J. Betts, Craig C. Sheaffer, and Donald L. Wyse (2017). Intermediate Wheatgrass Grain and Forage Yield Responses to Nitrogen Fertilization. Agron. J. 109:462–472. doi:10.2134/agronj2016.07.0438

[55] Рожко І., Дьомін Д., Кулик М. Вивчення сортів проса прутоподібного вітчизняної та іноземної селекції за продуктивністю та схожістю насіння. *Генетика та селекція сільськогосподарських рослин – від молекули до сорту:* матеріали ІІ Інтернет-конференції молодих вчених (м. Київ, 30 серпня 2018 р.). НААН, СГІ-ННЦ, М-во аграр. політики та прод. України, Укр. Ін-т експертизи сортів рослин. 2018. С. 23.

[56] Рожко І. І., Дьомін Д. Г., Кулик М. І. Вплив біометричних показників рослин на врожайність біомаси інтродукованих малопоширених енергетичних культур. *Вісник Полтавської державної аграрної академії*. 2021. Вип. (2), С. 114–123. DOI: https://doi.org/10.31210/visnyk2021.02.14

[57] Kulyk Maksym, D'omin Dmytro, Rozhko Ilona. Reclamation of marginal lands using rare energy crops. *European vector of development of the modern scientific researches: collective monograph* / edited by authors. 2nd ed. Riga, Latvia : Baltija Publishing, 2021: 136–157. ISBN: 978-9934-26-077-3 DOI: https://doi.org/10.30525/978-9934-26-077-3–27

even distribution of plants in the field plane, more intensive growth and development of energy crops, shading and weed displacement. Ultimately, this affects the level of biomass yield of the plant components.

We first determined the yield of different energy crop mixtures by raw biomass (only harvested from the field). The results show that the yield of raw biomass varied from 40.4 to 46.6 t/ha in the third vegetation year for the variants of the experiment (Fig. 12).

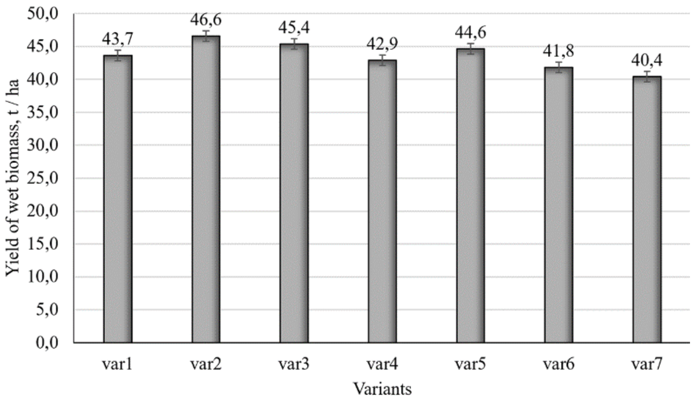

Figure 12. Raw biomass yields from different cultivation variants of energy crops

Note: Sw – single-species crops of switchgrass (var1, control), Sw+Ig – mutual crops of switchgrass and indiangrass (var 2), Sw+Bb – mutual crops of switchgrass and big bluestem (var3), Sw+Sa – mutual crops of switchgrass and sorghum perennial (var4), Ig+Bb – mutual crops of indiangrass and big bluestem (var5), Ig+Sa – mutual crops of indiangrass and sorghum perennial (var6), Bb+Sa – mutual crops of big bluestem and sorghum perennial (var7).

It was found that in comparison with single-species crops of switchgrass (Sw), the biomass yield significantly increased under mutual cultivation with other energy crops. Thus, the yield increase in variant 2 (Sw+Ig) was 2.9 t/ha, in variant 3 (Sw+Bb) was 1.7 t/ha, in variant 5 (Ig+Bb) was 0.9 t/ha, and in variant 4 (Sw+Sa) was at a level of LSD (least significant difference)$_{0.95}$ (–0.8 t/ha). In all other variants of the experiment, a significant decrease of wet biomass yield (by 1.9–3.3 t/ha) was obtained compared to the control.

Moisture content in phytomass, which varied from 28.0 to 29.2% had a significant impact on dry biomass yield of energy crops by the trait approximation coefficient (R 0.45) (Fig. 13).

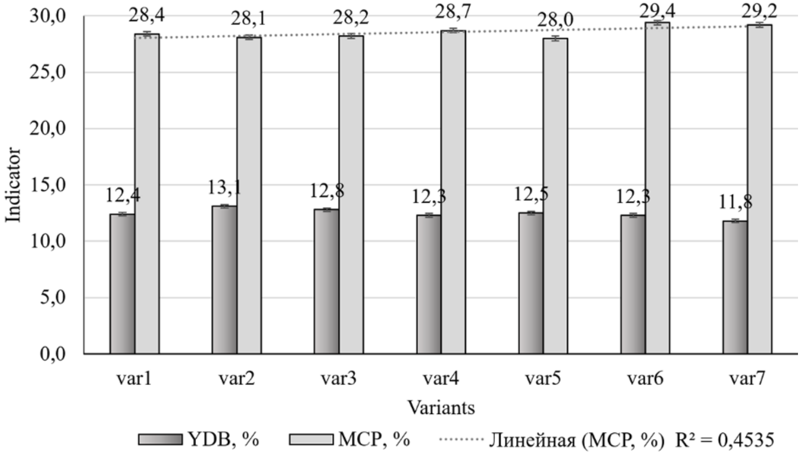

Figure 13. Moisture content in phytomass (MCP) and dry biomass yield (YDB) in different variants of energy crops cultivation.

Note: Sw – single-species crops of switchgrass (variant 1, control), Sw+Ig – mutual crops of switchgrass and indiangrass (variant 2), Sw+Bb – mutual crops of switchgrass and big bluestem (variant 3), Sw+Sa – mutual crops of switchgrass and sorghum perennial (variant 4), Ig+Bb – mutual crops of indiangrass and big bluestem (variant 5), Ig+Sa – mutual crops of indiangrass and sorghum perennial (variant 6), Bb+Sa – mutual crops of big bluestem and sorghum perennial (variant 7).

The lowest moisture content was found in the phytomass of mutual crops of indiangrass and big bluestem (variant 5), switchgrass and indiangrass (variant 2), switchgrass and big bluestem (variant 3). This index was the highest in the variants of mutual cultivation of indiangrass and sorghum perennial (variant 6), big bluestem and sorghum perennial (variant 7). Other variants had intermediate (average) value of moisture content in phytomass.

After drying phytomass, its dry matter yield was determined. This index varied from 11.8 to 13.1 t/ha (Fig. 14).

The variants Sw+Ig (0.7 t/ha), Sw+Bb (0.4 t/ha) and Ig+Bb (0.1 t/ha) provided the greatest yields increase in comparison with the control. At a level of the standard, yield of dry mass was in the variants: Sw + Sa (0.7 t/ha), Ig + Sa (–0.1 t/ha), significantly less in the variant Bb + Sa (–0.6 t/ha). After measuring the energy content in dry biomass (in the range of 16.9 and 17.2 MJ/kg), we calculated the energy productivity of the crops in different variants of the experiment (Fig. 15).

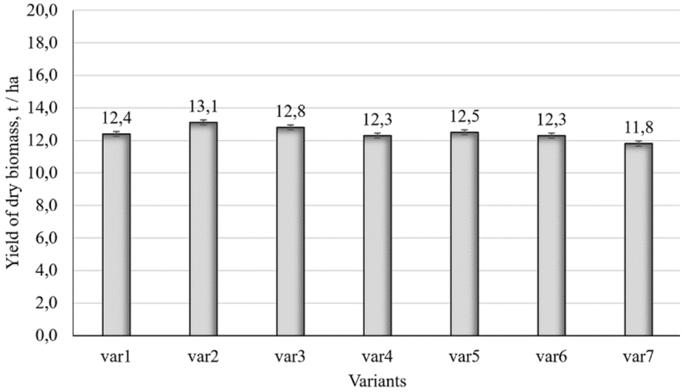

Figure 14. Dry biomass yield from different cultivation variants of energy crops

Note: Sw – single-species crops of switchgrass (variant 1, control), Sw+Ig – mutual crops of switchgrass and indiangrass (variant 2), Sw+Bb – mutual crops of switchgrass and big bluestem (variant 3), Sw+Sa – mutual crops of switchgrass and sorghum perennial (variant 4), Ig+Bb – mutual crops of indiangrass and big bluestem (variant 5), Ig+Sa – mutual crops of indiangrass and sorghum perennial (variant 6), Bb+Sa – mutual crops of big bluestem and sorghum perennial (variant 7).

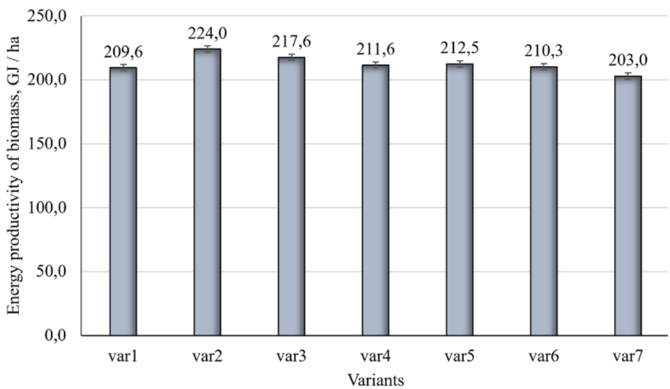

Figure 15. Energy productivity of crops in different variants of energy crops cultivation.

Note: Sw – single-species crops of switchgrass (variant 1, control), Sw+Ig – mutual crops of switchgrass and indiangrass (variant 2), Sw+Bb – mutual crops of switchgrass and big bluestem (variant 3), Sw+Sa – mutual crops of switchgrass and sorghum perennial (variant 4), Ig+Bb – mutual crops of indiangrass and big bluestem (variant 5), Ig+Sa – mutual crops of indiangrass and sorghum perennial (variant 6), Bb+Sa – mutual crops of big bluestem and sorghum perennial (variant 7).

The research results clearly prove that mutual cultivation of switchgrass and indiangrass (Sw+Ig) in comparison with a single-species crop (Sw) significantly increases the amount of energy obtained per hectare by 14.4 GJ/ha, by 8.0 GJ/ha in variant 3 (Sw+Bb) and by 2.9 GJ/ha in variant 5 (Ig+Bb). Other variants of the experiment with mutual cultivation of energy crops provided energy productivity at a level of control, or significantly less.

CONCLUSIONS

The morphometric characteristics of plants of rare energy crops allow them to form strong stems. This provides the basis for high biomass yields. In addition, the adaptive properties of energy crops correspond to Ukrainian conditions. The plants are not demanding to growing conditions. They are salt resistant, drought resistant and have phytoremediation properties.

According to the research results, it was found that a high level of yield of conditionally humid biomass, in comparison with single-species crops of switchgrass, is formed by mutual crops of switchgrass and indiangrass (46.6 t/ha), mutual crops of switchgrass and big bluestem (45.4 t/ha), mutual crops of indiangrass and big bluestem (44.6 t/ha). The yields obtained on the combined cultivation of switchgrass and sorghum perennial according to $LSD_{0.5}$ were at a control level (42.9 t/ha), while in the other variants, this index was significantly lower.

The most productive grass mixtures of rare energy crops in terms of dry biomass yield were identified: switchgrass and indiangrass (13.1 t/ha), switchgrass and big bluestem (12.8 t/ha), indiangrass and big bluestem (12.5 t/ha). At a level of the standard, dry matter yield was in the variants of mutual cultivation of switchgrass and sorghum perennial (variant 4) and indiangrass and sorghum perennial (variant 6) – received equal indices (12.3 t/ha). Mutual cultivation of big bluestem and sorghum perennial provided significantly lower dry biomass yield(11.8t/ha) in comparison with the control and other variants of the experiment.

Among the studied variants, the highest energy productivity was provided by mutual crops of switchgrass and indiangrass (224.0 GJ/ha), switchgrass and big bluestem (217.6 GJ/ha. In the variants of mutual cultivation of switchgrass and sorghum perennial, indiangrass and big bluestem, and indiangrass and sorghum perennial, the energy yield was almost a level of control (211.6–212.5 GJ/ha). The lowest energy yield from the field area was obtained in the variants of mutual cultivation of big bluestem and sorghum perennial.

SUMMARY

The current issue is to find ways of obtaining cheap energy and additional product from energy crops. This can be achieved by cultivating known energy crops and studying rare energy crops. Therefore, in order to determine the impact of the diverse composition of energy crops on biomass yields and energy productivity, original research was performed in the forest-steppe conditions of Ukraine.The general scientific and special methods were used in the research. The experimental variants combined single-species crops of switchgrass and a diverse co-cultivation of energy crops: switchgrass, indiangrass, big bluestem and sorghum perennial.

The results showed that certain mutual crops (Sw+Ig, Sw+Bb and Ig+Bb) can increase the yield of conditionally humid biomass (up to 44.6–46.6 t/ha) and dry biomass (up to 12.5–13),1 to t/ha). Energy content of biomass was determined to be between 16.9 and 17.2 MJ/kg, which depended on moisture content in phytomass at harvest time. The energy productivity of each experiment variant was calculated. It was found that the greatest amount of energy can be obtained from mutual cultivation of switchgrass and indiangrass, switchgrass and big bluestem.

References

1. Kulyk Maksym, Kalinichenko Oleksandr, Dekovetz Vitalii. Efficiency of energy crops cultivation for business development in Ukraine. *Organization and management in the services' sphere on selected examples* / Editors: Tetyana Nestorenko, Tadeusz Pokusa. Monograph. Opole: The Academy of Management and Administration in Opole, 2020: 36–45. ISBN 978-83-66567-02-3. http://pedagogika.wszia.opole.pl/ebook/3_2020.pdf

2. Kulyk M. I., Padalka V. V. (2020) Rozvytok bioenerhetyky na osnovi roslynnoho enerhetychnoho resursu (na prykladi Poltavskoi oblasti) [Development of bioenergy based on plant energy resources (on the example of Poltava region)]. Upravlinnia stratehiiamy vyperedzhaiuchoho innovatsiinoho rozvytku: monohrafiia / za red. k.e.n., dotsenta N. S. Illiashenko. Sumy: Trytoriia, pp. 109–118. (in Ukrainian)

3. Kulyk M. I., Kurylo V. L., Kalinichenko O. V., Galytska M. A. (2019) Plant energy resources: agroecological, economic and energy aspects. Monograf. 160 p.

4. Kulyk M., Galytska M., Samoylik M., & Zhornyk, I. (2019) Phytoremediation aspects of energy crops use in Ukraine. Agrology, vol. 2(1), 65–73. DOI: https://doi.org/10.32819/2617-6106.2018.14020

5. Роїк М. В. Ефективність вирощування високопродуктивних енергетичних культур / [М. В. Роїк, В. Л. Курило, М. Я. Гументик та ін.] // Вісник Львівського національного аграрного університету. 2011. № 15(2). С. 85–90.

6. Курило В. Л. Біоенергетика в Україні: стан та перспективи розвитку / В. Л. Курило, М. В. Роїк, О. М. Ганженко // Біоенергетика. 2013. Вип. № 1. С. 5–10.

7. Рахметов Д. Б. Міскантус в Україні: інтродукція, біологія, біоенергетика / Д. Б. Рахметов, Т. О.Щербакова, С. Д. Рахметов. Київ : Фітосоціоцентр, 2015. 158 с.

8. Рахметов Д. Б. Panicum virgatum L. – перспективний інтродуцент у Національному ботанічному саду ім. М. М. Гришка НААН України / Д. Б. Рахметов, О. М. Вергун, С. О. Рахметова // Інтродукція рослин. Вип. 3(63), 2014. С. 4–12, 24.

9. Гелетуха Г. Г. Перспективи вирощування та використання енергетичних культур в Україні / Г. Г. Гелетуха, Т. А. Железна, О. В. Трибой. Київ, 2014. 33 с.

10. Курило В. Л., Рахметов Д. Б., Кулик М. І. Біологічні особливості та потенціал урожайності енергетичних культур родини тонконогових в умовах України. *Вісник Полтавської державної аграрної академії*. Вип. 1(88), 2018. С. 11–17.

11. Kulyk M., Kalynychenko O., Pryshliak N., Pryshliak V. (2020). Efficiency of using biomass from energy crops for sustainable bioenergy development. *Journal of Environmental Management and Tourism*, [S. l.], v. 11, n. 5, p. 1040–1053, aug. 2020. ISSN 2068-7729 doi: https://doi.org/10.14505//jemt.v11.5(45).02

12. Міскантус в Україні: колективна монографія / авторський колектив М. В. Роїк, В. М. Сінченко, О. О. Іващенко, та ін. К. : ТОВ «ЦП «Компрінт», 2019. 256 с.

13. Кулик М. І., Курило В. Л., Калініченко О. В. Урожайність та енергетична ефективність виробництва відновлюваної рослинної сировини енергетичних культур. *Оптимальні енергетичні системи з урахуванням наявного потенціалу відновлюваних джерел енергії у Лісостепу України : колективна монографія* / За заг. ред. М. І. Кулика, О. В. Калініченка. Полтава: ПП «Астрая», 2019. С. 30–48.

14. Kulyk M. I., Kurylo V. L., Kalinichenko O. V., Galytska M. A. Plant energy resources: agroecological, economic and energy aspects. *Monograf*. 2019. 119 p.

15. Писаренко П. В., Курило В. Л., Кулик М. І. Агробіомаса та фітомаса енергетичних культур для виробництва біопалива. *Розробка та вдосконалення енергетичних систем з урахуванням наявного потенціалу альтернативних джерел енергії : колективна монографія* / за ред. О. О. Горба, Т. О. Чайки, І. О. Яснолоб. П. : ТОВ НВП «Укрпромторгсервіс», 2017. С. 258–266.

16. Тараненко А. О., Цьова Ю. А., Середа М. С., Кузенко Л. Ю., Солодовник М. А. Потенціал біомаси відходів сільського господарства для виробництва біоенергетики в Полтавській області. Вісник ПДАА. 2021. № 4. С. 142–153.

17. Taranenko, A. O., Kulyk, M. I., & Popov, S. I. (2020). Ahroekolohichne obgruntuvanniavyroshchuvannia enerhetychnykh kultur. *Ekolohichni innovatsii u pidvyshchenni ekonomichnoi ta prodovolchoi bezpeky Ukrainy: kolektyvna monohrafiia*. Poltava: PP “Astraia”.

18. Morozov, R. V., & Fedorchuk, Ye. M. (2015). Otsinka bioenerhetychnoho potentsialu roslynnykhvidkhodiv ta enerhetychnykh kultur u silskomu hospodarstvi. *Naukovyi Visnyk Khersonskoho Derzhavnoho Universytetu*, 10(3), 111–117.

19. Taranenko, A. O., Kulyk, M. I., & Popov, S. I. (2020). Ahroekolohichne obgruntuvanniavyroshchuvannia enerhetychnykh kultur. *Ekolohichni innovatsii u pidvyshchenni ekonomichnoi ta prodovolchoi bezpeky Ukrainy: kolektyvna monohrafiia*. Poltava: PP “Astraia”.

20. Польовий А. М., Божко Л. Ю. Вплив кліматичних змін на режим зволоження вегетаційного періоду в Україні. Український гідрометеорологічний журнал. 2015. № 16. С. 128–139.

21. Korenko, M., Bulgakov, V., Kurylo, V., Kulyk, M., Kainichanko, A., Ihnatiev, Y., & Matušeková, E. (2021). Formation of Crop Yields of Energy Crops Depending on the Soil and Weather Conditions. Acta Technologica Agriculturae, 24(1), 41–47. doi: 10.2478/ata-2021-0007

22. Польовий А. М., Божко Л. Ю. Вплив кліматичних змін на режим зволоження вегетаційного періоду в Україні. Український гідрометеорологічний журнал. 2015. № 16. С. 128–139.

23. Білявський Ю. В., Білявська Л. Г. Аналіз агро-кліматичних та грунтових умов Лісостепу України для вирощування сільськогосподарських та енергетичних культур. Оптимальні

енергетичні системи з урахуванням наявного потенціалу відновлюваних джерел енергії у Лісостепу України : колективна монографія / За заг. ред. М. І. Кулика, О. В. Каліченка. Полтава: ПП “Астрая”, 2019. С. 7–17.

24. Brodny J., Tutak M. The analysis of similarities between the European Union countries in terms of the level and structure of the emissions of selected gases and air pollutants into the atmosphere. Journal of Cleaner Production. 2021. Vol. 279. N123641. DOI: 10.1016/j.jclepro.2020.123641

25. Kardung M., Cingiz K., Costenoble O., Delahaye R. at. al. Development of the Circular Bioeconomy: Drivers and Indicators. Sustainability. 2021. Vol. 13. Iss. 1. N413. DOI: 10.3390/su13010413

26. Ossewaarde M, Ossewaarde-Lowtoo R. The EU's Green Deal: A Third Alternative to Green Growth and Degrowth. Sustainability. 2020. Vol. 12. Iss. 23. N9825. DOI: 10.3390/su12239825

27. Ronzon T., Piotrowski S., Tamosiunas S., Dammer L., at. al. Developments of Economic Growth and Employment in Bioeconomy Sectors across the EU. Sustainability. 2020. Vol. 12. Iss. 11. N4507. DOI: 10.3390/su12114507

28. Scown M.W., Brady M.V., Nicholas K.A. Billions in Misspent EU Agricultural Subsidies Could Support the Sustainable Development Goals. One Earth. 2020. Vol. 3. Iss. 2. P. 237–250. DOI: 10.1016/j.oneear.2020.07.011

29. Tsakalidis A, Gkoumas K., Pekar F. Digital Transformation Supporting Transport Decarbonisation: Technological Developments in EU-Funded Research and Innovation. Sustainability. 2020. Vol. 12. Iss. 9. N3762. DOI: 10.3390/su12093762

30. Khan Z., Ali S., Umar M., Kirikkaleli D., Jiao Z.L. Consumption-based carbon emissions and International trade in G7 countries: The role of Environmental innovation and Renewable energy. Science Of The Total Environment. 2020. Vol. 730. N138945. DOI: 10.1016/j.scitotenv.2020.138945

31. Neves A., Godina R., Azevedo S.G., Matias J.C.O. A comprehensive review of industrial symbiosis. Journal Of Cleaner Production. 2019. Vol. 247. N119113. DOI:10.1016/j.jclepro.2019.119113

32. Курило В. Л., Рахметов Д. Б., Кулик М. І. Біологічні особливості та потенціал урожайності енергетичних культур родини тонконогових в умовах України. *Вісник Полтавської державної аграрної академії*. Вип. 1(88), 2018. С. 11–17.

33. Курило В. Л., Кулик М. І., Калініченко О. В. Енергетичні культури : підручник. Полтава : ПП "Астрая", 2019. 320 с.

34. Кулик М. И. Энергетические культуры для очищения почв от тяжелых металлов и получения биотоплива. Современные энерго- и ресурсосберегающие экологически устойчивые технологии и системы сельскохозяйственного производства : сборник науч. тр. / под ред. Н. В. Бышова. Вып. 12. Рязань : ФГБОУ ВО РГАТУ, 2016. С. 364–367.

35. Henning, J. (1993) Big bluestem, Indiangrass, and switchgrass. Bulletin G4673. University of Missouri Cooperative Extension. University of Missouri. Columbia, MO. Internet-resurs. Retrieved from: https://extension.missouri.edu/ publications/g4673

36. Paul W. Barnes. Adaptation to Water Stress in the Big Bluestem-Sand Bluestem Complex. Ecology Vol. 66, No. 6 (Dec., 1985), pp. 1908–1920/ https://doi.org/10.2307/2937387

37. Chable, V., Nuijten, E., Costanzo, A., Goldringer, I., Bocci, R., Oehen, B., Rey, F., Fasoula, D., Feher, J., Keskitalo, M., Koller, B., Omirou, M., Mendes-Moreira, P., Van Frank, G., Kader, A., Jika, N., Mathieu, T., and Adanella Rossi. (2020). Embedding Cultivated Diversity in Society for Agro-Ecological Transition. Sustainability, 12, 784. doi:10.3390/su12030784

38. Дьомін Д. Г., Щербак Є. Ю., Кулик М. І. Потенціал біомаси малопоширених енергетичних культур. Матеріали науково-практичної інтернет-конференції «Сучасні напрями та досягнення селекції і насінництва сільськогосподарських культур» / Ред. кол.: Тищенко В. М. (відп. ред.) та ін. Полтавська державна аграрна академія, 2021. С. 43–47.

39. Peni, D.; Dębowski, M.; Stolarski, M.J. Influence of the Fertilization Method on the Silphium perfoliatum Biomass Composition and Methane Fermentation Efficiency. Energies 2022, 15, 927. https://doi.org/10.3390/en15030927

40. Paolini, V.; Petracchini, F.; Segreto, M.; Tomassetti, L.; Naja, N.; Cecinato, A. Environmental impact of biogas: A short review of current knowledge. J. Environ. Sci. Health A 2018, 53, 899–906. [Google Scholar] [CrossRef] [PubMed]

41. Rosch C. & Skarka J. (2008). European Biofuel Policy in a Clobal Context: Trade-Offs and Strategies. GAIA-ecological perspectives for science and society, 17(4), 378–386

42. Global bioenergy statistics 2020. Retrieved from: http://www.worldbioenergy.org/uploads/201210%20WBA%20GBS%20 2020.pdf

43. Karp, A.; Shield, I. Bioenergy from plants and the sustainable yield challenge. New Phytol. 2008, 179, 15–32. [CrossRef]

44. Canadell, J.G.; Schulze, E.D. Global potential of biospheric carbon management for climate mitigation. Nat. Commun. 2014, 5, 5282. [CrossRef] [PubMed]

45. Moritz Von Cossel, Moritz Wagner, Jan Lask, Elena Magenau, Andrea Bauerle, Viktoria Von Cossel, Kirsten Warrach-Sagi, Berien Elbersen, Igor Staritsky, Michiel Van Eupen, Yasir Iqbal, Nicolai David Jablonowski, Stefan Happe, Ana Luisa Fernando, Danilo Scordia, Salvatore Luciano Cosentino, Volker Wulfmeyer, Iris Lewandowski 1 and Bastian Winkler 1 Prospects of Bioenergy Cropping Systems for A More Social-Ecologically Sound Bioeconomy. Agronomy 2019, 9, 605; doi: 10.3390/agronomy9100605

46. Писаренко П. В., Горб О. О., Кулик М. І., та ін. 2017. Науково-практичні рекомендації до вирощування енергетичних культур та використання фітомаси. Полтава, 34 с

47. Kulyk M., Galytska M., Samoylik M. & I. Zhornyk. 2019. Phytoremediation aspects of energy crops use in Ukraine. Agrology. Vol. 2 (1). P. 65–73. URL: https://doi.org/10.32819/2617–6106.2018.14020

48. Taranenko A., Kulyk M., Galytska M., Taranenko S., Rozhko I. 2021. Dynamics of soil organic matter in *Panicum virgatum* sole crops and intercrops. *Zemdirbyste-Agriculture*. Vol. 108(3): 255–262. DOI: 10.13080/z-a.2021.108.033

49. Kulyk M., Elbersen W. Methods of calculation productivity phytomass for switchgrass in Ukraine. Poltava, 2012. 10 p.

50. Кулик М. І., Рахметов Д. Б., Курило В. Л. Методика проведення польових та лабораторних досліджень з просом прутоподібним *(Panicum virgatum L.)*. Полтава : РВВ ПДАА, 2017. 24 с.

51. Калінченко О. В., Кулик М. І. Науковий твір «Методичні засади оцінки енергетичної ефективності вирощування енергетичних культур в умовах Лісостепу України» (Свідоцтво про реєстрацію авторського права на твір № 93177 від 18.10.2019).

52. McKone, M. J., Lund C. P. and J. M. OíBrien. 1998. Reproductive biology of two dominant prairie grasses (Andropogon gerardii and Sorghastrum nutans, Poaceae): male-biased sex allocation in wind-pollinated plants. Am. J. Bot. 85: p. 776–783.

53. Weik L., Kaul H.-P., Kübler E., Aufhammer W. (2002). Grain Yields of Perennial Grain Crops in Pure and Mixed Stands *Journal of Agronomy and Crop Science*. https://doi.org/10.1046/j.1439-037X.2002.00580.x

54. Jungers J. M., Lee R. DeHaan, Kevin J. Betts, Craig C. Sheaffer, and Donald L. Wyse (2017). Intermediate Wheatgrass Grain and Forage Yield Responses to Nitrogen Fertilization. Agron. J. 109:462–472 doi:10.2134/agronj2016.07.0438

55. Рожко І., Дьомін Д., Кулик М. Вивчення сортів проса прутоподібного вітчизняної та іноземної селекції за продуктивністю та схожістю насіння. *Генетика та селекція сільськогосподарських рослин – від молекули до сорту:* матеріали ІІ Інтернет-конференції молодих вчених (м. Київ, 30 серпня 2018 р.). НААН, СГІ-ННЦ, М-во аграр. політики та прод. України, Укр. Ін-т експертизи сортів рослин. 2018. С. 23.

56. Рожко І. І., Дьомін Д. Г., Кулик М. І. Вплив біометричних показників рослин на врожайність біомаси інтродукованих малопоширених енергетичних культур. *Вісник Полтавської державної аграрної академії*. 2021. Вип. (2), С. 114–123. DOI: https://doi.org/10.31210/visnyk2021.02.14

57. Kulyk Maksym, D'omin Dmytro, Rozhko Ilona. Reclamation of marginal lands using rare energy crops. *European vector of development of the modern scientific researches: collective monograph* / edited by authors. 2nd ed. Riga, Latvia: Baltija Publishing, 2021: 136–157. ISBN: 978-9934-26-077-3 DOI: https://doi.org/10.30525/978-9934-26-077-3-27

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