Technium Vol. 14, pp.94-99 (2023)
ISSN: 2668-778X
www.techniumscience.com

Agricultural biomass feedstock for biofuels production in Ukraine

Oleksandra Tryboi, Tetiana Zheliezna, Semen Drahniev

Department of Thermophysical Problems of Heat Supply Systems
Institute of Engineering Thermophysics, NAS of Ukraine
Kyiv, Ukraine
tryboi@secbiomass.com

Abstract. **Ukraine has a large potential of biomass available for the production of solid, gaseous and liquid biofuels. According to 2021 data, the bioenergy potential is about 25 Mtoe, of which 49% is agricultural residues and 30% is energy crops (in case of growing on 2 mln ha). Of the agriresidues, only sunflower husk is now widely used for energy, while the potential of straw, corn stalks and sunflower stalks is practically untapped for this purpose. For Ukraine, one of the promising directions is priority use of corn stalks for the production of energy and solid biofuels such as briquettes and pellets. Another prospective area is growing energy crops. Ukraine has 3-4 mln ha of unused (marginal) agricultural land, which can be engaged for growing energy crops such as willow, poplar, miscanthus (for solid biofuels) and corn silage for biogas. Growing energy crops as biomass feedstock and its further use for the production of heat and power becomes competitive in light of growing prices of natural gas and issues with providing security of its supply. An important but less-developed sector of Ukraine's bioenergy is motor biofuels. Having such a big potential of agribiomass, the country could produce bioethanol and biodiesel including the advanced biofuels from lignocellulosic feedstock. It is necessary to create favourable conditions for the development of domestic production of motor biofuels. This may include a reduction in the excise tax, the abolition of compulsory tax bill for the full rate of excise duty when transporting bioethanol, the introduction of an export duty on rapeseed, and some other measures.**

Keywords: bioenergy, biomass potential, biofuels, agriresidues, energy crops

I. Introduction

Bioenergy is dynamically developing in Ukraine with the average annual growth of 11%. This rate is assessed based on statistical data on the production of biofuels and energy supply from biofuels in 2010-2020 (Fig. 1). According to Ukraine's Energy Balance for 2020, the share of biofuels in the total primary energy supply (TPES) was nearly 5%. At that, the bioenergy potential of the country can cover nearly 30% of TPES and replace about 4 billion/y of natural gas until 2030. The latter is especially important considering urgent necessity to completely reject the consumption of Russian natural gas.

The existing bioenergy installations in Ukraine include hundreds of boiler plants, more than 20 CHP plants/power plants running on solid biomass, about 30 biogas cogeneration plants, and more than 25 landfill gas power plants. Lately, the issue of biomethane production and use has become very topical in the country. Development of motor biofuels market is also of high importance in the view of necessity to decarbonize the transport sector.

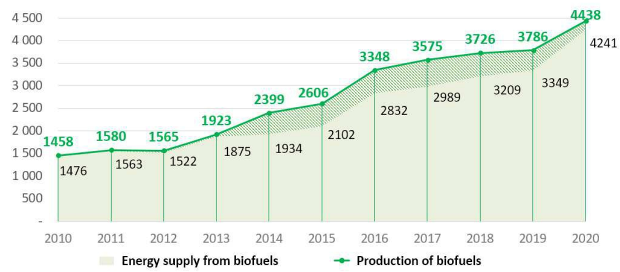

Fig. 1. Dynamics of bioenergy development in Ukraine, ktoe.

II. Assessment of Biomass Potential

Ukraine has a large potential of biomass available for the production of solid, gaseous and liquid biofuels. According to 2021 data, the bioenergy potential is about 25 Mtoe/y, of which 49% is agricultural residues and 30% is energy crops in case of growing on 2 million ha (Fig. 2). Of the agriresidues, only sunflower husk is now widely used for energy, while the potential of straw, corn stalks and sunflower stalks is practically untapped for this purpose.

Now, more than 70% of the available amount of sunflower husk is utilized for the production of pellets/briquettes and for direct combustion at boiler plants and CHP plants to generate heat and power. At that, only about 3-4% of the cereal straw potential is consumed for energy, mainly at boiler plants in rural areas. In addition, there are some rare examples of solid biofuels or energy production from corn stover. Residues and byproducts of sunflower production (stalks, heads) are not used for energy at all due to several reasons, one of which is an undeveloped harvesting technology. The same reason explains current little use of corn stalks for energy.

III. CORN RESIDUES

Corn stover is considered the most prospective type of agricultural residues in Ukraine to be involved in energy production. The reasons for this are its big annual amount, less use as organic fertilizer and feed for animals and better fuel characteristics as compared with cereal straw.

Though the technology for stalks harvesting is not introduced and worked out yet in Ukraine, national experts has already studied the question and developed some preliminary recommendations. There are several technological schemes for harvesting grain corn: a) using corn combines with further stationary treatment of ears (with or without peeling of ears); b) using combine harvesters equipped with corn reapers; c) collecting a mixture of grain and cobs with combines. Currently, the mostly used method for commercial corn harvesting is combine threshing of ears in the field, shredding and spreading of the comminuted biomass with the use of combine harvesters equipped with corn reapers. This method of harvesting grain corn is the most economically feasible.

Pressing biomass into bales contributes to increased logistics efficiency and reduces the required area of warehouses. Technological schemes for harvesting corn stover (corn residues) in bales can be divided into four main types:

- A single-pass scheme is based on a combine harvester connected with a baler, which forms bales simultaneously with corn grain threshing.
- A two-pass scheme includes a combine harvester with a special reaper that forms corn residues windrows, which are further baled with a baler attached to a tractor.
- In a three-pass scheme, a combine harvester spreads corn residues, which are windrowed by a tractor with a windrower shredder; then a tractor with a baler presses the residues in large square bales (round bales).
- In a multi-pass scheme, a combine harvester spreads corn residues, then a tractor with a shredder shreds them, following which a tractor with a rake makes windrows from the biomass, and a tractor with a baler presses the residues.

According to [1], of the technologies above, the three-pass system is recommended for Ukraine due to the possibility to use standard agricultural machinery and due to less contact of biomass with the soil. As mentioned, the three-pass system includes the usage of combine harvester + tractor with stalk-shredding windrower + tractor with a baler to form large square bales or round bales (Fig. 3). An alternative to making bales may be shredding corn residues to obtain a mixture of different fractions or some selected fractions such as cobs. Another option could be the collection of a part of residues after threshing grain with a combine harvester. Different models of equipment can be used at different stages of the harvesting process. Not all types of the required equipment are available in Ukrainian market, but they can be ordered and imported through dealers into Ukraine.

Various technologies based on different machinery can be used for corn residues harvesting. However, taking into account equipment available on the market and results of field trials in the USA and in the EU, it is reasonable to perform feasibility study of five corn stover supply chains. They are: the three-pass system based on using a large square baler (1) or a round baler (2); forage harvester system (3); forage wagon system (4); corn cob harvesting technology based on Vermeer CCX770 cob harvester (5).

The obtained results show that the most economically feasible technology of corn stover harvesting is forming large square bales that will allow having biomass at the central storage facility at a distance of 25 km from the field at a cost of 22.3 EUR/t d.m. (dry matter). The system of harvesting shredded corn residues based on a forage loader wagon is also economically feasible with a simple payback period of 4.6 years and IRR of 26.0%.

However, a field research is required to evaluate the feasibility of technology using a forage loader wagon under Ukrainian conditions. For biomass processing, it is important to perform techno-economic assessment of the full value chain, including storage. Further processing of corn stover into briquettes and pellets will increase the benefit of biomass for energy.

For the global trade of solid biofuels, international standards have been developed, which are gradually being harmonized in Ukraine. The national standard DSTU EN 15234-6:2017 “Solid biofuels – Fuel quality assurance – Part 6: Non-woody pellets for nonindustrial use” was harmonized with European EN 15234-6:2012 and came into force from in 2017. Quality requirements for non-woody pellets and briquettes are set by the international standards ISO 17225-6:2014 “Solid biofuels – Fuel specifications and classes – Part 6: Graded non-woody pellets” and ISO 17225-7:2014 “Solid biofuels – Fuel specifications and classes – Part 7: Graded non-woody briquettes”. These standards have not been harmonized in Ukraine yet. However, some briquettes and pellet producers developed their own specifications for solid biofuels from corn stover. Certification lets the producers to sell their high-quality product at a higher price.

Main characteristics that affect biomass densification process are the initial condition of the biomass such as particles size, presence of inclusions and moisture content. When processing crop residues, sunflower husks, reed residues and similar biomass types it is possible to use a typical scheme designed for the production of straw briquettes and pellets without intermediate drying.

Fig. 3. The three-pass system for making corn bales.

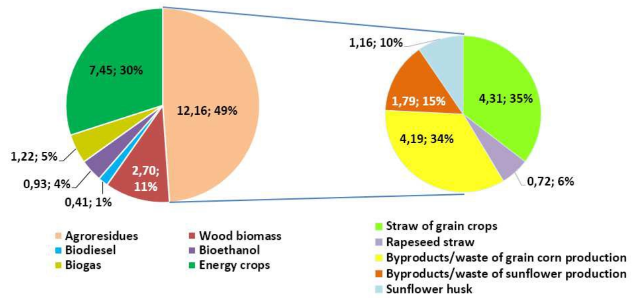

Fig. 2. Structure of biomass for energy potential in Ukraine, ktoe.

Technium Vol. 14, pp.94-99 (2023)
ISSN: 2668-778X
www.techniumscience.com

Results of the feasibility study show that corn briquettes and pellets can be competitive in the biofuel market of Ukraine, and their production may be a profitable business project. The selling price of briquettes, the productivity of the briquetting equipment, as well as the price of the feedstock for briquettes production, have the most significant influence on the basic economic indicators. In case of briquettes, that applies for a briquetting line of 2-4 t/h productivity, IRR being >25% (Table 1). For pellets, productivity of the line should be more than 4 t/h to achieve IRR >25%.

TABLE I. FEASIBILITY STUDY OF PRODUCING BRIQUETTES FROM CORN STOVER

Indicators	Productivity of a briquetting line, t/h		
	0.5	*2.0*	*4.0*
Annual briquettes production, t/y	3000	12000	24000
Capital costs, 1000 EUR	147.5	598.8	1572.0
Operating costs, 1000 EUR/y	193.4	677.5	1319.5
Loan (the share of equipment costs), %	70		
Loan rate, %	7		
Term of loan, y	5		
Corn stover bales costs at the plant, EUR/t d.m. without VAT	36.4		
Net cost of briquettes, EUR/t	70.6	62.7	63.2
Selling price for corn stover briquettes, EUR/t with VAT	90		
Annual revenue from selling of the briquettes, 1000 EUR	270.0	1080.0	2160.0
NPV, 1000 EUR	39.2	677.9	1214.1
Simple payback period, y	6.0	3.7	4.4
Discounted payback period (under the discount rate of 7%), y	7.8	4.2	5.2
IRR, %	13.9	34.7	26.1

IV. ENERGY CROPS

Ukraine has significant land potential for growing energy crops, which can become a feedstock for production of heat and power, biofuels, and further biomaterials in the future. Large areas of underutilized and marginal agricultural land in Ukraine allow producing energy crops without competition with food and feed production. According to different estimates, there are about 3-4 million hectares of marginal land in Ukraine where the production of food crops is not feasible. Cultivating less demanding crops for energy production can bring economic viability to these lands and regions. Additionally, a number of energy crops proved their phytoremediation ability to clean certain types of contaminated land [2, 3] still producing a non-contaminated biomass.

Energy crops can be cultivated in all three agro-ecological zones of Ukraine: Polissia, Forest-steppe and Steppe zones. A big gene pool of energy crops was created at the National Botanic Garden of Ukraine consisting of 522 taxons [4]. Energy crop species of willow, paulownia, Miscanthus, and switchgrass are already cultivated in Ukraine. There are 36 varieties of energy crops registered in the State Register of Plant Varieties Suitable for Distribution in Ukraine approved for bioenergy utilisation [5]. Energy crops recommended for cultivation under Ukrainian climate conditions include Salix Viminalis L., Paulownia Sieb. et Zucc., Populus sp. L. for solid biofuels and Miscanthus x giganteus, Panicum virgatum L., Silphium perfoliatum L., Arundo donax L. that can be used either for solid biofuels or in case of early harvest for biogas production (Table II).

Energy crops can provide a security of biomass fuels supply to energy facilities. Today, there are about 5.4 ha of lands under energy crops plantations in Ukraine. The largest areas of plantations belong to willow, second place is occupied by Miscanthus. Economic potential of energy crops in case of growing on 1 mln ha of unused agricultural land amounts 4.88 Mtoe. Additionally, 2.58 Mtoe can be obtained from growing corn or other promising energy crops for biogas on another million ha.

Cultivation of all energy crops can be conditionally divided into three stages: 1) soil preparation; 2) direct cultivation (planting, plantation care); 3) harvesting (the final operation is the liquidation of the plantation after the end of its existence). Depending on the type of energy crop, the growing process has its characteristic features. That is, Miscanthus is planted with rhizomes, poplar and willow are planted with seedlings, and rapeseed, sorghum, and flax are sown with seeds.

TABLE II. SRC* AND PERENNIAL GRASSES RECOMMENDED FOR CULTIVATION UNDER UKRAINIAN CLIMATE CONDITIONS

Scientific name	LHV, MJ/kg	Plantation lifetime, years	Harvest cycle for biomass, years	Biomass yield, t/ha/year (d.m.)
Salix Viminalis L.	16.7…18.4	20…25	2…3	7.2…10,1 [6]
Paulownia Sieb. et Zucc.	16.67	45…50	3	3.6…8 [7, 8]
Populus sp. L.	17.7…18.7	20…25	2	4…10
Miscanthus x giganteus	16.8...20.4	20…25	1	16,4…28 [9]
Panicum virgatum L.	15.9…17.7 [10]	10…15	1	8.5…15 [11, 12]
Silphium perfoliatum L.	14.6…17.9 [13]	15…20	1	11.6…21.9 [13, 14]
Arundo donax L.	16…18 [15]	30…50	1	25…50 [16]

* Short rotation coppice

The energy crop biomass value chain has the following components:

- Use of land plots (own/leased);
- Planting material (own/purchased/multiplied under a license agreement);
- Machinery for tillage, planting, care, harvesting (own / rented / purchased);
- Selection of means of protection and fertilizers in accordance with the conditions of the land plot;
- Marketing/processing of biomass.

The incorporation of energy crop plantations takes place depending on the type of plant:

- Seedlings (willow, poplar, paulownia);
- Rhizomes (Miscanthus);
- Seeds (perennial Sorghum, Switchgrass, Sylphium perfoliatum).

Calculation of the economic efficiency of the energy willow plantation was carried out for two options of typical projects for the regions of Ukraine.

The first option — the Amalgamated territorial community (ATC) establishes a plantation of energy willow in order to meet its own needs for biofuel for heating public sector institutions. Energy willow will be grown on 120 hectares of rented land. With a yield of 20 t/(ha · year), the plantation will allow to obtain 2,400 t of chips with a moisture content of about 50%, which will be sufficient for operation during the heating period of solid fuel boilers with a total capacity of more than 2 MW. Taking into account the 3-year wood cutting cycle, the plantation is divided into three plots each with an area of 40 hectares with a three-year yield of 60 t/ha (fresh biomass).

The second option is a commercial plantation of energy willow with a total area of 1,200 hectares, which is divided into three plots of 400 hectares each with a three-year yield of 60 t/ha. It is assumed that the wood chips obtained from the plantation will be sold at the market price.

We assume the term of the total existence of a single plantation of energy willow is 25 years. With a 3-year growing cycle, 5-8 crops can be harvested during this period. It should be noted that the yield of the first and last cuts will be 60% of the base yield. After the last biomass harvest, the energy willow plantation is subject to uprooting.

Given the area of a single plantation (40 hectares), the first option will use rented machinery, except for a re-equipped disc cultivator and a soil cutter with special protective elements to avoid damage to the willow during inter-row maintenance operations. For the second option of the standard project, all the necessary machinery will be purchased. The results of the preliminary feasibility study of the specified options of the projects of growing energy willow plantations are given in Table III.

TABLE III. FEASILITY STUDY OF GROWING ENERGY CROPS

Indicators	Case 1 (at ATC)	Case 2 (commercial plantation)
Plantation area, ha	120	1200
Total harvest of chips, 1000 t	51.84	518.4
Investments in machinery, 1000 EUR	7.5	1266.0
Investments in seedlings, 1000 EUR	81.2	744.4
Capital costs (total), 1000 EUR	**88.7**	**2010.4**
Capital costs (specific), EUR/ha	**739.2**	**1675.3**
Soil preparation costs, EUR/ha	782.5	802.0
Costs for pre-planting soil treatment, planting and care, EUR/ha	403.0	240.8
Costs for the first harvest, EUR/ha	571.3	179.9
Costs for the 2-7 harvests, EUR/ha	675.5	152.0
Costs for the last harvest, EUR/ha	512.1	88.1
Costs for grubbing with rented machinery, EUR/ha	564.0	
Specific costs for land rent, EUR/ha	1879.7	
Specific operating costs for the entire willow growing cycle, EUR/ha	**8765.4**	**4969.5**
Loan (share of capital costs), %	70	
Loan rate, %	7	
Term of loan, y	5	
Selling price for willow chips, EUR/t without VAT	30.0	30.0
Simple payback period, y	**12.8**	**11.7**
Discounted payback period (under the discount rate of 7%), y	19.9	17.8
NPV, 1000 EUR	24.3	739.8
IRR,%	8.3	9.3

The results of the calculations show that under the selected typical conditions, the simple payback period in both cases is more than 10 years. An increase in the selling price of willow chips can lead to a certain reduction in the payback period, but this is not enough for the attractiveness of the business project. Providing state support to producers of energy crops in Ukraine can improve the economic performance of such projects. Thus, with a subsidy at the level of UAH 25,000/ha, the simple payback period of the energy willow cultivation project will be 8.8 years for both options, with an IRR of 16.9% for option 1 (ATC plantation) and an IRR of 14.4% for option 2 (commercial plantation) with a selling price of willow chips of 30 EUR/t excluding VAT. In addition, it is necessary to reduce capital / operational costs (for example, to make the most of existing machinery) and to look for additional income for the project (for example, to rent out the purchased equipment to other users).

V. Production of Biofuels

An important but less-developed sector of Ukraine's bioenergy is motor biofuels. Having such a big potential of agribiomass, the country could produce a lot of bioethanol and biodiesel including the advanced biofuels from lignocellulosic feedstock. However, in recent years, bioethanol has been produced only in very limited volumes in Ukraine, and there has been no production of biodiesel at all [17]. Nevertheless, according to the draft National Renewable Energy Action Plan until 2030 [18], it is planned to significantly increase the consumption of motor biofuels, including advanced ones, by 2030 (Table IV).

TABLE IV. Consumption of Bioethanol and Biodiesel in Ukraine

Years	Bioethanol, ktoe	Biodiesel, ktoe
Actual data [17]		
2014	42.4	-
2015	35.1	-
2016	38.4	-
2017	47.0	-
2018	37.2	-
2019	88.1	-
2020	51.1	-
Forecast [18]		
2025	184 (37[a])	26 (5)
2030	238 (48)	87 (17)

[a] The amount of advanced biofuels is indicated in brackets.

Currently, a number of barriers hinders the development of motor biofuels market in Ukraine. The major of them are as follows:

- High rate of excise tax (100 EUR/1000 l) on biodiesel and its mixtures (30-100% in the mixture with oil products), as well as on motor gasoline with a content of at least 5 wt. % of bioethanol or ethyl tert-butyl ether or their mixture.

- Compulsory tax bill for the full excise duty required for the transportation of bioethanol.
- Absence of legally established requirements for the mandatory share of bioethanol in gasoline and biodiesel in diesel fuel.
- Absence of export duty on rapeseed.
- Lack of domestic production of methanol and difficulties in meeting the requirements for handling methanol.
- Absence of a system for collecting used cooking oil.
- Absence of a domestic laboratory for testing all quality indicators of fatty acid methyl ethers in accordance with State Standards of Ukraine 6081:2009 and EN 14214:2019.

In 2021-2022, two draft laws regarding biofuels were passed in the first reading in Ukrainian Parliament. One of them envisaged introduction of a requirement to have at least 5% (vol.) of liquid biofuels (bio-components) in motor gasoline sold in Ukraine from May 2022. The other envisaged this share to be at least 10%. Unfortunately, both draft laws did not have any further progress in their adoption.

It is urgently necessary to create favourable conditions for the development of domestic production of motor biofuels. This may include a reduction in the excise tax, the abolition of compulsory tax bill for the full excise duty when transporting bioethanol, the introduction of an export duty on rapeseed, setting compulsory targets for the consumption of bioethanol and biodiesel, and some other measures/incentives.

Analysis of the biomass potential structure in Ukraine indicates large volumes of lignocellulosic raw materials such as wood biomass of different origins, various agricultural residues, woody and herbaceous energy crops – about 20 Mtoe/y in total. According to Roadmap for bioenergy development in Ukraine until 2050 [19], the bioenergy potential may double by 2050 due to a number of reasons. They include increase in the yield of cereal crops; considerable increase in the economic potential of biogas obtained from different types of feedstock; doubling areas under energy crops and an increase in their yield; certain growth of forest felling and some others. Accordingly, the potential of lignocellulosic raw materials will rise to over 30 Mtoe/y in 2050.

A part of this raw material can be consumed to obtain advanced biofuels. Assessment performed in [19] shows that the production of advanced biofuels may range from about 25 ktoe/y in 2025 to 430 ktoe/y in 2050. At that, the total production of biofuels is expected to be 260 ktoe/y in 2025 and more than 850 ktoe/y in 2050. It means that the share of advanced biofuels in the total production volume might increase from nearly 10% to 50% during that period.

EU RED II defines biofuels obtained from food/feed raw materials that do not compete with food/feed production as biofuels with a low risk of indirect land use change. The possibility to produce biofuels from the excess amount of food/feed feedstock is a relevant option Ukraine’s case. This is because Ukraine has large areas of agricultural land and the amounts of harvested crops are more than enough to provide the country with food and livestock feed. In addition, there are up to 4 million hectares of unused agricultural land in Ukraine. This land has not been used for cultivating crops for years, so it can be partly engaged in growing energy crops for the production of all types of biofuels – solid, liquid, and gaseous.

It is important to note that of Ukraine’s conditions regarding the total area of agricultural land, including that not used for agricultural production, are significantly different from the situation in the EU countries. In the latter, the area of agricultural land is quite limited, and the possibility of its expansion is practically non-existent. Therefore strict sustainability criteria are applied to prevent competition between the production of biofuels and food/feed.

We believe that for Ukraine, as a country with special conditions, some exceptions can be made regarding the criteria of land use sustainability. For example, this could be a permit to use up to 1% of arable land for growing crops for the production of biofuels, which will not be subject to the restrictions specified in EU RED II on the inclusion of biofuels in meeting renewable energy targets in transport sector. For Ukraine, 1% of arable land is about 300,000 hectares. If they are used to grow grain corn (150,000 ha) and rapeseed (150,000 ha), it will make it possible to obtain approximately 165 ktoe/y of bioethanol and 104 ktoe/y of biodiesel.

VI. Conclusions

Ukraine has a large potential of biomass available for the production of solid, gaseous and liquid biofuels. According to 2021 data, the bioenergy potential is about 25 Mtoe, of which 49% is agricultural residues and 30% is energy crops (in case of growing on 2 mln ha). Corn stover is considered the most prospective type of agricultural residues in Ukraine to be involved in energy production. The most economically feasible technology of corn stover harvesting is forming large square bales that will allow having biomass at the central storage facility at a distance of 25 km from the field at a cost of 22.3 EUR/t d.m. (dry matter). Further processing of corn stover into briquettes and pellets will increase the benefit of biomass for energy.

Energy crops are already cultivated in Ukraine on the area of about 5.4 ha of lands. The largest areas of plantations belong to willow, followed by plantations of Miscanthus. Energy crops can be cultivated in all three agro-ecological zones of Ukraine and there are 36 varieties registered in the State Register approved for bioenergy utilisation. Energy crops recommended for cultivation under Ukrainian climate conditions include Salix Viminalis L., Paulownia Sieb. et Zucc., Populus sp. L. for solid biofuels and Miscanthus x giganteus, Panicum virgatum L., Silphium perfoliatum L., Arundo donax L. that can be used either for solid biofuels or in case of early harvest for biogas production. Typical projects for energy crop cultivation can be cultivation on marginal lands of amalgamated territorial communities on rented equipment or the establishment of a commercial plantation with the machinery purchase. The simple payback period in both cases is more than ten years, and state support to producers of energy crops in Ukraine can improve the economic performance of such projects. Production of motor biofuels is the less developed sector of Ukraine's bioenergy. Still, the country could produce a lot of bioethanol and biodiesel, including advanced biofuels from lignocellulosic feedstock from its enormous potential of agro biomass.

Acknowledgment

We are grateful to Georgii Geletukha, Head of the Bioenergy Association of Ukraine, for expressing his opinion on sustainability issues regarding the production of biofuels in Ukraine's conditions.

References

[1] G. Geletukha, S. Drahniev, T. Zheliezna, and A. Bashtovyi, "Analysis of pellets and briquettes production from corn residues," UABio Position Paper N 23, April 2020, 42 p.

[2] R. Lord, J. Atkinson, A. Lane, J. Scurlock and G. Stree, "Biomass, Remediation, re-Generation (BioReGen Life Project): Reusing brownfield sites for renewable energy crops," Proceedings of GeoCongress 2008: Geotechnics of Waste Management and Remediation, March 9-12, 2008, New Orleans, Louisiana, USA.

[3] M. I. Kulyk, M. A. Galytska, M. S. Samoylik, and I. I. Zhornyk, "Phytoremediation aspects of energy crops use in Ukraine," Agrology, 1(4), 2018, pp. 373–381.

[4] N.V. Zaimenko, D.B. Rakhmetov, S.D. Rakhmetov, "Application outlook on new and rare energy crops as raw material for solid biofuel in Ukraine," «Bioenergy» journal, 2016, 1(7), pp. 4 -10.

[5] State Register of Plant Varieties Suitable for Distribution in Ukraine, valid as of 08.09.2022. Access: https://sops.gov.ua/derzavnij-reestr

[6] Ya. D. Fuchylo, I.V. Gnap, O. M. Ganzhenko, "Growth and productivity of some foreign cultivars of energy willow in Volyn Opillia. Plant Varieties Studying and Protection," 14(2), 2018, pp. 230–239.

[7] M. Jakubowski, "Cultivation Potential and Uses of Paulownia Wood: A Review," Forests 2022, 13, 668 p.

[8] J. B. Berdón, A. J. Montero Calvo, L. Royano Barroso, A. I. Parralejo Alcobendas, J. González Cortés, "Study ofPaulownia's Biomass Production in Mérida (Badajoz),Southwestern Spain," Environment and Ecological Research, Vol.5, No.7, 2017, pp. 521-527.

[9] V. M. Vir'ovka, O. G. Opanasenko, S. V. Perets', "Features of growing Miscanthus large on sewed organogenic soils of Left-bank Forest-steppe, Bulletin of Agricultural Science," 2019-08, N10, pp. 60-66.

[10] Database for the physico-chemical composition of (treated) lignocellulosic biomass, micro- and macroalgae, various feedstocks for biogas production and biochar. https://phyllis.nl/

[11] O. Kalinichenko and M. Kulyk, "Economic efficiency of rod-shaped millet (switchgrass) cultivation within the forest-steppe of Ukraine," Ekonomika APK, 2018, pp. 19-28.

[12] M. Kulyk, "Energy potential and economic efficiency of switchgrass phytomass production for biofuels. Scientific reports of NUBiP of Ukraine," 0(4 (61), 2016.

[13] D. Peni, M.J. Stolarski, A. Bordiean, M. Krzyżaniak, M. Dębowski, "Silphium perfoliatum—A Herbaceous Crop with Increased Interest in Recent Years for Multi-Purpose Use," Agriculture, 10, 2020, 640 p.

[14] V.H. Kurhak, S. Sliusar, "Productivity of perennial herbal plants when grown for energy needs," Bulletin of Agricultural Science, V99, N11, 2021, pp. 48-54.

[15] L.G. Angelini, L. Ceccarini, E. Bonari, "Biomass yield and energy balance of giant reed (Arundo donax L.) cropped in central Italy as related to different management practices," European Journal of Agronomy, V22, Iss.4, 2005, pp. 375-389.

[16] V.L. Kurylo, D.B. Rakhmetov, M.I. Kulyk, "Biological features and potential of yield of energy cultures of the family of thin-skinned in the conditions of Ukraine," Bulletin of Poltava State Agrarian Academy, No 1, 2018, pp. 11–17.

[17] Report on the promotion and use of energy from renewable sources in Ukraine in 2019-2020. State Agency on Energy Efficiency and Energy Saving of Ukraine, 2021, 33 p.

[18] Draft National Renewable Energy Action Plan until 2030. State Agency on Energy Efficiency and Energy Saving of Ukraine, 2022, unpublished.

[19] Georgii Geletukha, Tetiana Zheliezna, Yuri Matveev, Petro Kucheruk, Volodymyr Kramar. Roadmap for bioenergy development in Ukraine until 2050. Bioenergy Association of Ukraine, Position paper N 26, November 2020.