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THE POTENTIAL OF ORGANIC WASTE AS A SUBSTRATE FOR ANAEROBIC DIGESTION IN UKRAINE: TREND DEFINITIONS AND ENVIRONMENTAL SAFETY OF THE PRACTICES

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Abstract. This article is devoted to the analysis and prospects of using different types of organic waste to achieve environmental goals. Due to the unique climate and natural resources, Ukraine has significant potential for biomass, the processing of which should solve urgent problems with the disposal of waste, as well as the production of alternative energy sources and biofertilizers. The preferred substrates for anaerobic digestion in Ukraine, considering the technological feasibility, availability, and volume are animal manure (cattle, pigs), bird droppings, plant residues, industrial sludge, common sludges. After analyzing the statistics for 2015-2019, the groups of dominant wastes were identified, and with the help of the built-in function "TREND", the forecast of the waste potential with an organic component for 2021–2026 was constructed. Examining the obtained indicators for different types of waste, the reasons for the tendency of decrease or increase in their formation in the next five years were revealed. The direction of enhancing the sustainability of bioenergy, achieving environmental goals through the bioprocessing of organic waste associated with the ecological safety of production processes were discussed.

Keywords: organic wastes, anaerobic digestion, waste potential forecast, biofuels, biofertilizers, digestate.

1. Introduction

Dependence on fossil fuels, such as oil, coal, and natural gas, is growing alarmingly, leading to the depletion of such resources and requiring a new sustainable approach to bioenergy production (Dhanya et al., 2020). The use of biomass in the world is a long-recognized trend that replaces the use of exhaustible minerals, as well as reduces carbon emissions, which cause global warming. Modern biotechnological approaches to the utilization of organic waste into biofuels and biofertilizers have become a priority mechanism for the eco-modernization of enterprises.

Due to the unique climate and natural resources, Ukraine has significant biomass potential, which has strong market prospects for the country in terms of energy production and environmental goals (Zelenaja energetika, 2019). Today, consideration and resolution of these issues are quite relevant for Ukraine, as it will overcome energy dependence on other countries, produce competitive goods for the foreign market, solve

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the problem of waste disposal, as well as improve soil bioproductivity.

The largest segment in the biofuel market is solid biofuel in the form of firewood, wood chips, pellets (granules), and briquettes from biomass, baled straw. Fuel briquettes in Ukraine are produced in smaller quantities than pellets, with wood, husks, straw, and reeds mainly used as raw materials. An additional source of biomass can be the cultivation of energy crops (willow, poplar, and miscanthus) on low-fertile lands, which in Ukraine are about 4 million hectares. As for the production of liquid biofuels, the potential of Ukrainian biomass and the availability of production facilities are already suitable for the profitable production of bioethanol and biodiesel (Geletukha et al., 2018).

Biogas projects in Ukraine are developing rapidly. At the beginning of 2019, there were 18 projects, at the end of 2020 – 27 projects (SAF, 2020). Sustainable biogas technologies contribute to the healing of soils and ecosystems. Digestate, which is formed in the process of biogas production, is rich in organic compounds and organic carbon and can be used as a biofertilizer replacing mineral fertilizers. The use of digestate as an organic fertilizer activates such an important property of the soil as the absorption of greenhouse gases and increases the supply of organic carbon (UABIO, 2020).

The European Union has become the key driver in reducing the impact of industry on nature. At present, Ukraine is only taking the first steps towards achieving environmental goals, but cooperation with the EU encourages Ukraine to implement tools that make the industry cleaner.

2.1. Review of the previous research

Reviewing the publication activity in the international scientific databases Scopus and Web of Science on the topic “organic waste as a substrate for anaerobic digestion” over 20 years shows a growing interest in the relevance of this research. The first scientific publications in these databases appeared already in 1990. Their focus was on the kinetics of the anaerobic digestion process, including a kinetic model for the anaerobic digestion of organic substrates (Barthakur et al., 1991). Over the last 20 years, the research topics have broadened a lot. The year 2020 is seen to be the peak year for research over the past 20 years, as shown in Fig. 1. Based on several studies, current research has focused on waste-to-energy processes, improving various methods of producing biogas and hydrogen from organic waste involving the dark fermentation phase.

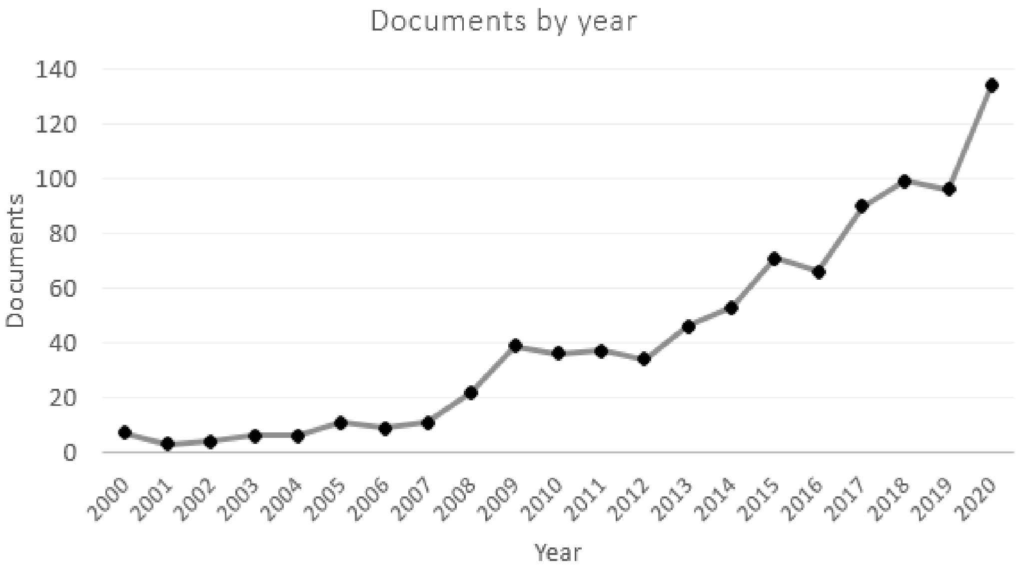

Fig. 1. Analysis of search results by year

Comparing the research interest of different countries based on index journals' publications, Fig. 2 shows that China leads with 222 publications (as an advanced research country). The USA, the European countries (Italy, Poland, Germany, Spain), and India are also active and have published around 50-60 papers each in the last 20 years.

The study (Rocamora et al., 2020) of operational parameters and their impact on the process performance of dry anaerobic digestion of organic waste as a substrate, sweet potato vine, organic fraction of municipal solid waste, corn stover, stritchgrass, wheat straw and chicken manure were compared. Co-digestion of organic wastes increases methane production compared to the digestion of a single feedstock. The work (Thanarasu et al., 2018) evaluated the applicability of tea powder waste as an alternative supplementary substrate to increase biogas production in the anaerobic digestion of organic solid waste with the presence of methanogens in the activated sludge. Various kinds of approaches are being explored in food processing. By the study (Paritosh et al., 2017), the anaerobic digestion approach has proven to be one of the cleanest and most promising solutions for food waste management and energy production. There is a known method (China, 2011), intensification of the process of anaerobic digestion of chicken manure by supplying an additional source of carbon as plant residues (straw). The given method of biogas production shows the feasibility of co-fermentation of organic waste of animal and plant origin.

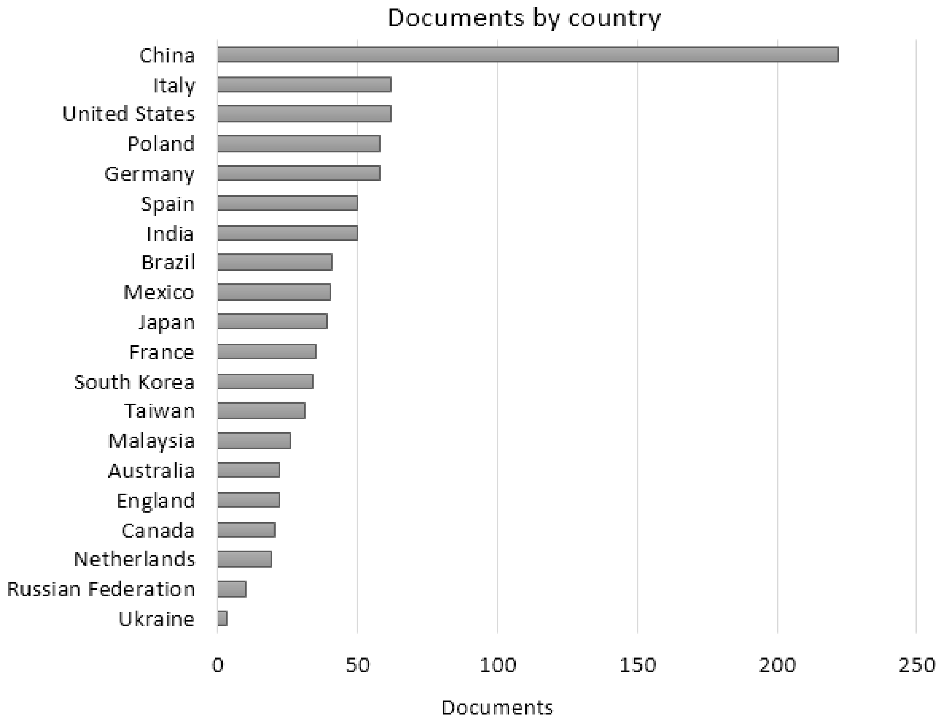

Fig. 2. Analysis of search results by country

Ukraine is so far represented in the metrics database by 3 published papers in 2020. In summary, the published Ukrainian studies cover the topics of optimising the process of anaerobic digestion of organic animal waste and increasing the biogas yield: optimisation of dry anaerobic digestion of chicken manure (Shapovalov et al., 2020), an increase in the biogas output during fermentation of manure of cattle with winemaking waste (Polishchuk et al., 2020) and by adding substandard flour to a cow manure-based substrate (Polishchuk et al., 2020).

According to the study (Skliar, 2021) agro-industrial complex of Ukraine, producing large amounts of organic waste, such as waste from sugar factories, breweries, cattle, pig farms, and poultry farms, has enough resources to produce biogas. The study (Voytovych et al., 2020) shows that the potential of biogas production from sewage sludge by the value of the average specific biogas production is 5.1 times higher compared to chicken manure on examples of biogas plants of family type in Ukraine.

The study aims to assess the potential of using organic waste in Ukraine for anaerobic digestion to obtain various bioproducts, respectively, making forecasts for individual groups of organic waste with the selection of dominant species for bioenergetic utilization and optimization of environmental safety of food industry and agricultural enterprises to improve the efficiency of bioenergy potential of organic waste.

2.2. Materials and Methods

The prospect of using various types of waste for energy purposes is confirmed by the predicted values of the potentials of their formation. The forecast is built using the built-in “TREND” function in MS Excel, taking into account two variables: the amount of waste generated and the time. The time interval was selected considering statistical data. The starting point of the forecast is 2020, which is due to the availability of the latest actual data for 2019 only. At the same time, data for 5 years preceding 2020 were used to obtain a "retrospective forecast" for 2020–2026 (State Statistics Service of Ukraine, 2019).

The choice of the confidence interval for constructing an accurate forecast was carried out separately for each type of waste. At the same time, the relative linear deviation was taken into account, taking into account the value of the average linear deviation of the annual volumes of waste from the average annual level of waste generation over the last 5 years, Table 1.

The confidence interval defined the range around each predicted value in which, according to the forecast (with a normal distribution), the data related to the forecast for the next 5 years is expected to fall. The size of the confidence interval, namely its lower and upper boundaries, are taken as possible forecast scenarios. At the same time, the lower limit of the confidence interval acted as a negative forecast – a decrease in the rate of waste generation while the upper limit of the confidence interval was taken as a positive forecast of an increase in the rate of waste generation.

To predict the volume of bird droppings production, the polynomial trend was calculated for the analyzed data and future periods using the trend equation:

$$y = 85.262x^2 - 525.55x + 8184.9 \ (R^2 = 0.9968)$$

Table 1

Forecast of waste generation in Ukraine for the period of 2021–2026

WASTE TYPE	Years(n)					Mean	Average linear deviation	Relative linear deviation (forecast confidence interval), %
	2015	2016	2017	2018	2019	$\bar{x} = \frac{\sum x_i}{n}$	$\bar{l} = \frac{\sum \lvert x - \bar{x} \rvert}{n}$	$V = \frac{\bar{l}}{\bar{x}} \cdot 100$
The siege of industrial drains	3209.90	3919.80	3648.70	3630.30	3346.10	3550.96	218.368	±6
Sludge waste coming from the treatment facilities	249.80	838.30	971.70	793.90	792.20	729.18	191.752	±26
Animal wastes and mixed food wastes	897.00	990.60	587.60	607.50	441.00	704.74	191.248	±27
Wastes of plant origin	7742.30	8606.00	8782.30	7829.30	8068.60	8205.7	390.760	±5
Animal excrement	4938.00	4288.70	3653.40	3233.80	3612.90	3945.36	534.392	±14
Ordinary sediment	397.60	693.60	515.10	643.50	563.30	562.62	85.016	±15
Sorting remnants	35.60	81.90	63.2	63.60	69.20	62.7	10.840	±17

The time series of chicken litter formation is formed by years with two variables: year (x), the volume of chicken litter in thousand tons per year (y).

When building the forecasts, a time scale with equal intervals of one year between data points was selected. The annual intervals are selected according to the statistical data state on the first day of each year. The year 2021 was selected as the initial year from which the forecast was made. In this case, to build a forecast for 2021–2025, the data for 6 years preceding 2021 were used. This allowed us to build a "retrospective forecast".

A confidence interval of 95 % was selected. Which allowed us to establish a range around each predicted value, which according to the forecast (with normal distribution) was expected to get 95 % of the points related to the forecast for the next 5 years.

Taking into account the size of the confidence interval, the lower and upper limits were chosen and accepted as possible forecast scenarios. At the same time, the lower boundary of the confidence interval was used as a negative projection – a decrease in the rate of chicken dung formation. Likewise, the upper boundary of the confidence interval is accepted as a positive forecast – an increase in the rate of chicken droppings formation.

3. Results and Discussion

3.1. Organic waste potential in Ukraine: analysis and forecast

The substrate used in Ukraine can be divided into paid and free types.

Paid raw materials usually include plant waste that must be previously grown, collected, and harvested. In Ukraine, such raw materials are represented by silage corn with an average yield of green mass of less than 25 tons per hectare. The demand for corn for silage has increased significantly in recent years but attempts to find a worthy alternative is ongoing. The paid raw materials include such types of substrates as silage corn, sweet sorghum, sugar beet, and cereal straw.

Such a substrate is usually not used as a mono-substrate because it is uneconomical in biogas production and economic costs. It is used as an additive to the main substrate to stabilise free raw material, stabilise and enhance yield.

Raw materials that are free of charge or paid for by the producer as a waste disposal fee are classified as free raw materials. These raw materials include animal waste, food industry waste, organic fraction of municipal solid waste, sewage sludge from wastewater treatment plants, and organic fractions from landfills (Ecobusiness, 2019).

Therefore, the preferred substrates for anaerobic digestion in Ukraine, considering the technological feasibility, availability, and volume, could be animal manure (cattle, pig, chicken), sugar beet pulp, crop residues.

Estimates of by-product generation and biomethane production potential are presented on the SAF platform of Ukraine based on the data from the State Statistics Service as of 2018–2019.

The calculation assumes that the share of the biomass of crop residues (straw, maize, and sunflower stalks) that can be withdrawn for biogas production is 30–40 % of the technically available mass. Simultaneously, the digested mass from crop residues returns to the fields, balancing the need for nutrients.

The total estimated potential for methane production from the considered by-products and maize silage is 7800000000 nm³ CH_4 per year, as of 2018, which is almost 40 % of Ukraine's natural gas production or practically 25 % of total natural gas consumption in 2018.

Crop residues can provide almost half of the biogas production potential. Manure and dung together cover only 11 % of the potential.

Among crop residues, wheat straw (36.4 %) and maize stalks (34.6 %) contribute considerably to the biogas production potential. There is a trend towards an increase in the total potential of crop residues in Ukraine, which is related to the rise in crop yields (SAF, 2020).

In Fig. 3 we have compiled a block diagram of the classification of various types of waste containing organic components in accordance with the data (State Classifier of Inputs, 1996; Law of Ukraine "On Waste", 1998) for utilization for energy purposes. At the same time, with a rational approach to the disposal of such wastes, many useful products can be obtained, among which digestate deserves special attention, in a form suitable after a certain treatment for use as fertilizer and dietary supplement.

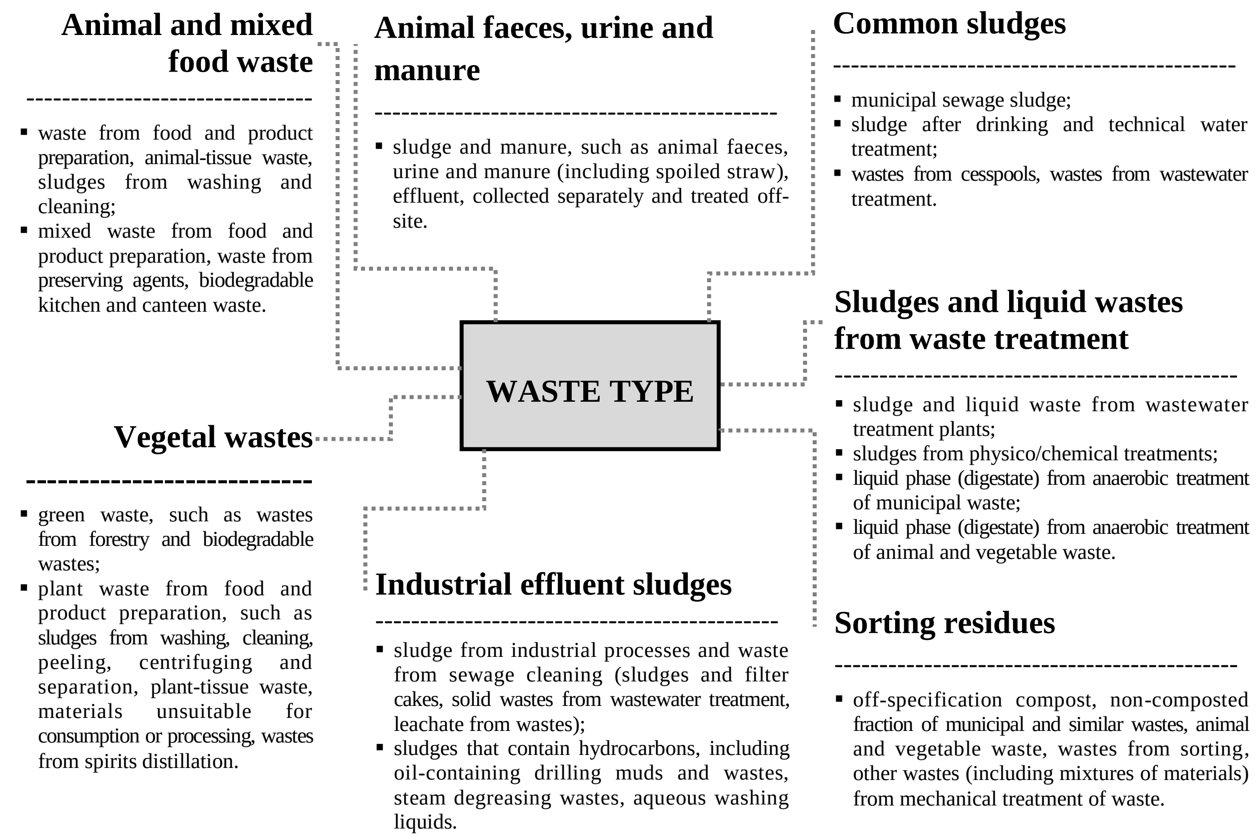

Fig. 3. Model for the classification of organic waste

According to (Wąs et al., 2020), the analysis of the potential of agricultural biogas production in Ukraine indicates that approximately 1.14 million heads of cattle, 3.4 million heads of pigs, and 118.9 million heads of poultry may be assumed as suppliers of the substrate for the biogas plants. It is possible to reach 2.9 billion m^3 of agricultural biogas from animal manure. Although the fragmentation of the Ukrainian agricultural sector into small farms and enterprises means that much of the potential is hardly useable in practice. For small farms, there are problems of profitability and lack of substrate supply even for small digestion plants. The study also noted that over 50 % of the total potential (enterprises) is located in five regions: Cherkasy, Kyiv, Vinnytsia, Dnipropetrovsk, Poltava, due to the level of agricultural development (animal production). The estimated potential for biogas production from manure could cover 3.17 % of Ukraine's total electricity demand or 2.28 % of natural gas demand.

The average annual share of waste containing an organic component is 5 % of the total amount of waste generated in Ukraine (State Statistics Service of Ukraine, 2019). However, taking into account the multi-tonnage of this type of waste (17761.26 thousand tons), the high potential of using this waste for energy purposes should be noted. In addition, the most promising are plant waste, animal faeces, urine, and manure, as well as industrial effluent sludge, which accounts for 2.3, 1.1, and 1 %, respectively, of the total average annual amount of waste generated in Ukraine, Fig. 4.

The results of the constructed forecast are shown in Fig. 5, where the lines represent the central trend between the lower and upper limits of the confidence interval.

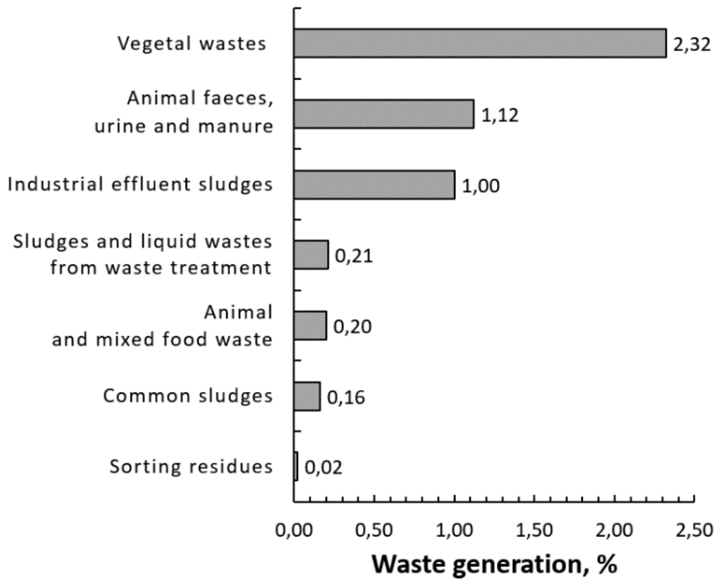

Fig. 4. Percentage of waste containing organic components of the total amount of waste generated in Ukraine

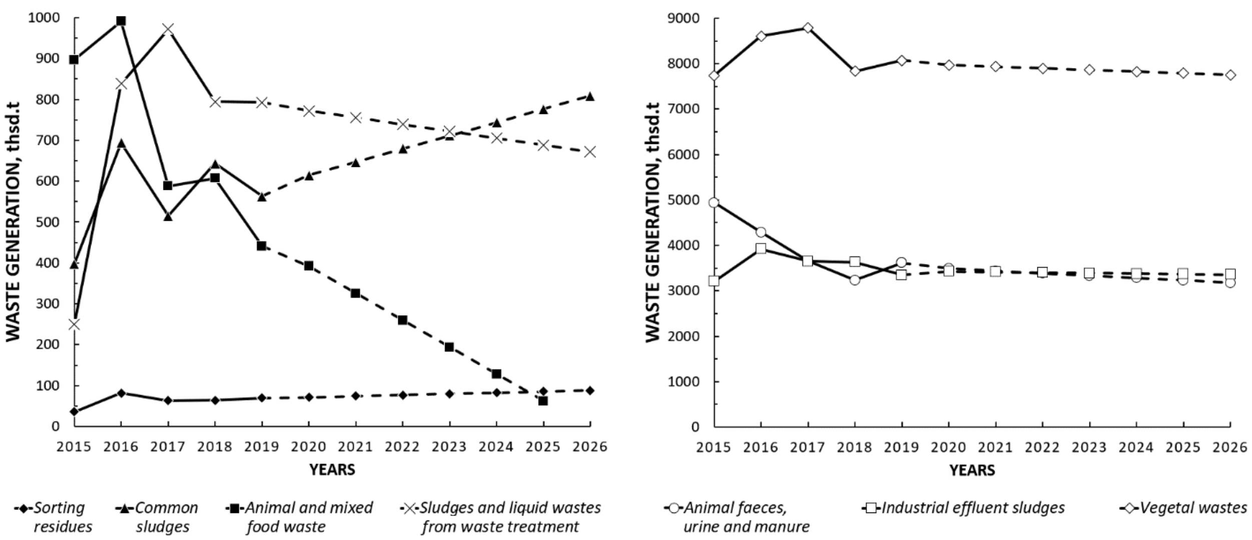

Fig. 5. Predictions of the potential for the formation of different types of waste containing organic components

Despite the significant variation in the actual indicators of waste generation for the period from 2015 to 2019, forecasts until 2026 indicate a relatively stable annual level of waste generation of plant origin, animal faeces, urine, and manure, as well as industrial sewage sludge. Focusing in more detail on each of the analyzed indicators, we note that animal and mixed **food** waste since 2019 has a rapid tendency to decrease due to new technologies in the processing of food of animal origin, its physical reduction, and processing of animal waste. Focusing on the analysis of sludges and liquid wastes from waste treatment, we note that the dynamics of reduction of these types of waste is much slower, which adequately reflects the critical situation in Ukraine with processing and disposal of household waste, sludge, and liquid waste from sewage treatment plants and more. Animal faeces, urine, and manure show a slight reduction in absolute volume over the next five years (2021–2026), but this is due not so much to waste reduction as to a reduction in livestock in Ukraine’s agricultural sector. The volume of vegetal wastes and industrial effluent sludges is almost unchanged in the forecast period, which is quite understandable, as forestry and industrial enterprises in Ukraine do not pay enough attention to the environmental component of their activities.

Of particular interest are waste common sludges which have a high tendency to increase the rate of their formation. This problem is relevant for all regions of Ukraine as the modernization of public utilities is not carried out, and every year the wear of municipal water treatment facilities increases, which reflects the projected values of waste. The growth is also observed for sorting residues, although it is not as critical as the previous indicator but also needs attention from the state, businesses, and the public.

Note that considering the reasons for the reduction of the above types of waste by 2026, one of the factors in their reduction is the active development of environmentally friendly technologies, including the use of anaerobic digestion processes. It is innovative developments that should be the impetus for reducing all types of waste in the next five years (2021–2026).

According to the analysis of statistical reporting data of enterprises, the development of poultry farming in the period from 1990 to the present day can be divided into two stages – the decline in poultry production from 1990 to1997 and the revival of production from 1998 to the present day (Buriak, 2017).

It is established in the Poultry Market (2018) (Poultry Market, 2013) that during 2016–2018 the total projected demand for poultry eggs in Ukraine will decrease from 16990 million eggs in 2015 (by domestic production – 16920 million eggs) to 14260 million eggs in 2018 (by domestic production – 14220 million eggs) or by 2.73 billion eggs (by 16.1 %) of the probable decline in purchasing power of the Ukrainians. The analysis of changes in the animal population and production volumes suggests that the general trend is characterized by an increase in indicators (Consortium Resources..., 2016; Ryabukha, 2019). Among the reasons for the increase in volumes, it is possible to define the increase in the economic efficiency of the activity of the enterprises of poultry farming branch at the expense of modernization of manufacture, creation of new links of vertically integrated structures, and introduction of control systems of production quality. The results of the study showed that the current state and potential of the poultry industry have prospects for development.

Therefore, the issue of chicken manure utilization is becoming more and more relevant for Ukraine, and biogas technology can be an energy-efficient and environmentally friendly solution.

3.2 Environmentally safe trends of increasing the efficiency of bioenergy potential of organic waste in the agricultural enterprise functioning

An important area of effective implementation of organic waste bioprocessing, particularly in biofuel production, is countering the emergencies that occur in the action of various factors of technogenesis. The existing technologies and measures of emergency response at industrial and agricultural enterprises operate according to the following principle: detect negative impact – install equipment – decontaminate (Fig. 6). The main drawback of such a system algorithm is that in the period from detection of hazardous substances to decontamination, people, animals, or territory can be affected (as in the Chernobyl disaster) and technological processes can also be stopped. Enterprises with no direct contamination are also at risk of contamination through water, air, transport, or raw materials (Fig. 7).

In this case, it is difficult to calculate the latent long-term effects on the environment and human health. It also affects the ecological characteristics of the waste of the food industry and agro-industrial complexes. Therefore, the proper approach to the organization of the environmental safety system of agricultural enterprises is a very important task.

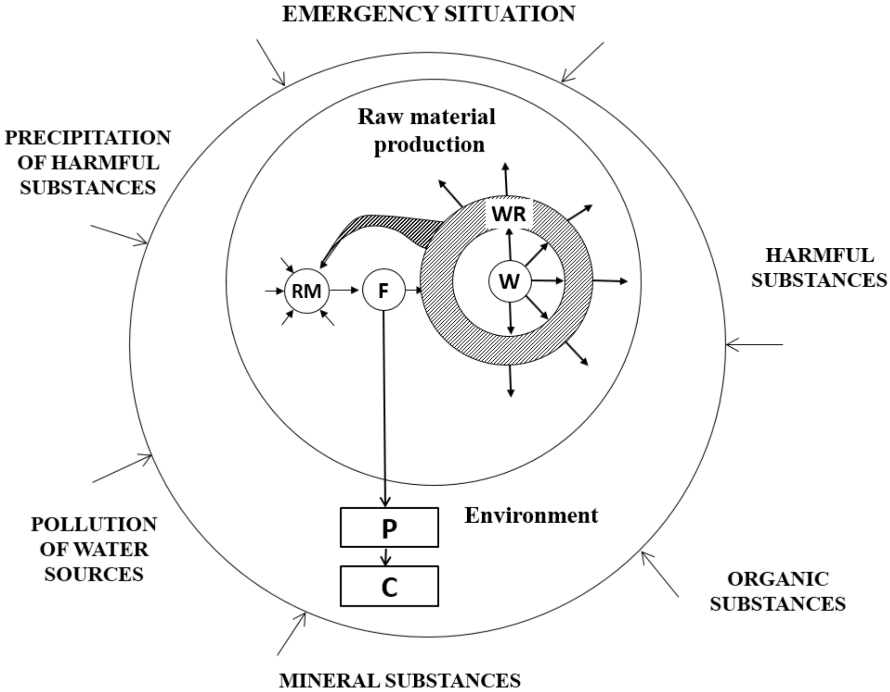

Fig. 6. Traditional algorithm of emergency counteraction at agricultural enterprises through the "water supply" line: C – raw material; F – farm; PR – products; CP – consumer; W – waste; W – waste recycling (water solutions)

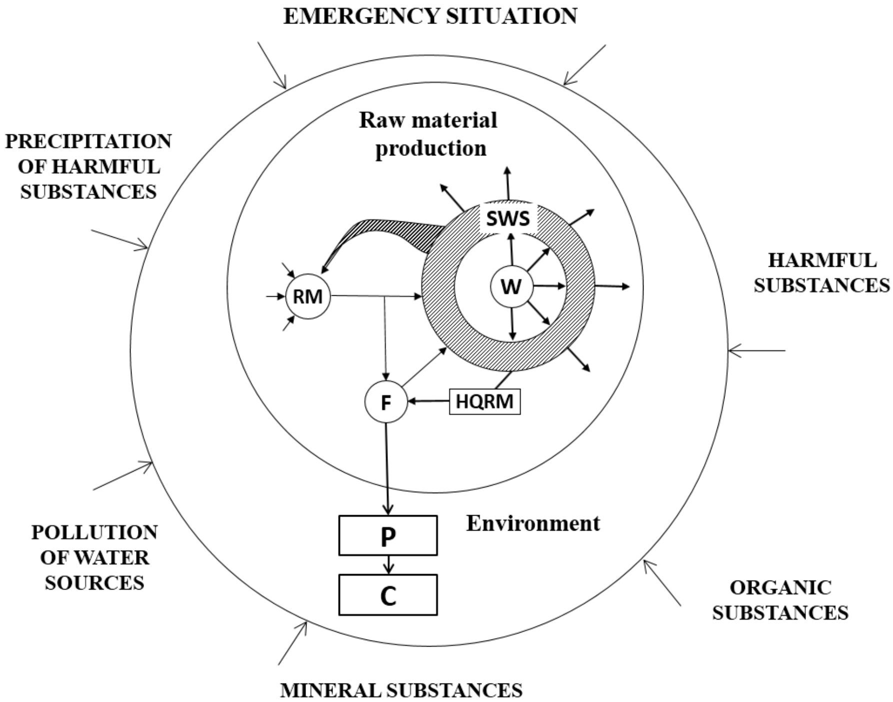

Fig. 7. Environmentally safe algorithm of emergency counteraction at agricultural enterprises through the "water supply" line: HQRM – high-quality raw materials; SWS – safe water system

Obviously, in the modern environmental situation, it is necessary to change the functional structure of food industry enterprises fundamentally. It has to counteract emergencies proactively. If new technological equipment is installed, it should be a better resource- and energy-efficient than the previous one. At the same time, the implementation of an integrated system of waste management, as a valuable secondary resource with its bio-energy potential, acquires strategic importance in the context of the sustainable development of Ukraine. Likewise, integrated waste management system complies with the Directive on Energy Efficiency and Renewable Energy approved in 2018 by the EU Transport, Telecommunications and Energy Council, precisely in the area of sustainability of bioenergy, directly linked to the environmental safety of the production processes and the use of various types of organic substrates for the development.

4. Conclusions

Rational utilization of all types of waste in the world and Ukraine is an important task to solve problems of environmental pollution. An important issue today is not only the disposal of various types of waste but also the production of useful products in the form of bioenergy, biofuels, biofertilizers, bioadditives, etc. According to the assessment of the prospects and forecast of the use of waste with an organic component as a substrate for anaerobic digestion in Ukraine, the dominant types of waste that tend to increase or are almost unchanged during this period have been identified. They include sewage sludge, industrial sewage sludge, animal faeces, urine and manure, plant wastes. In the future, this will make it possible to focus on solving the problems of waste disposal and the achievement of environmental goals, as well as to counteract emergencies at agricultural enterprises by using the efficient bioenergetic potential of organic waste.

References

Barthakur, A., Bora, M., & Singh H. D. (1991). Kinetic model for substrate utilization and methane production in the anaerobic digestion of organic feeds. *Biotechnology Progress*, 7(4), 369-376. doi:10.1021/bp00010a012

Biogas projects in Ukraine 2020. Infographics. (2020). *SAF: Sustainable Agribusiness Forum*. Retrieved from https://saf.org.ua/news/1042/

Buriak, R. I. (2017). Research and forecasting of conditions of Ukraine poultry products market. *Scientific Journal of NUBiP. Series: Economy, Agrarian Management, Business*, 260. Retrieved from http://journals.nubip.edu.ua/index.php/Economica/article/view/8824

Dhanya, B., Mishra, A., Chandel, A. K., & Verma, M. L. (2020). Development of sustainable approaches for converting the organic waste to bioenergy. *Science of The Total Environment*, 723, 138109. doi:10.1016/j.scitotenv.2020.138109

Dynamics of poultry production in Ukraine since 1990 and forecasts of industry development till 2020. (2013). *Poultry Market: Poultry farming of Ukraine and the world management, analytics, reforms, standards*. Retrieved from http://market.avianua.com/?p=48

China. (2011). *CN Patent No. 102173895*. Jiangsu Cascade Clean Energy, Inc.

Consortium Resources and Waste Advisory Group Limited, UK and COWI A/S, Denmark. (2016). *Programme to Support the Green Modernization of the Ukrainian Economy. National Waste Management Strategy for Ukraine. Annex 5: Agricultural Waste. Working document preliminary draft.* Retrieved from https://eco.kiev.ua/assets/files/Dod.5.-Vidhodi-silskogo-gospodarstva.pdf

Geletukha, G. G., Zheluzna, T. A., & Dragnev, S. V. (2018). Analysis of the possibilities of production and distribution of briquettes from agricultural production in Ukraine. *Analytical note of BAU*, 20, 5-6. Retrieved from https://saf.org.ua/wp-content/uploads/2018/05/position-paper-uabio-20-ua.pdf

Healthy soils with sustainable biogas and biomethane value chains – 3 arguments to World Soil Day. (2020). *UABIO: Bioenergetic Association of Ukraine*. Retrieved from: https://uabio.org/news/9351/

Law of Ukraine "On Waste": Zakon Ukraine 1998, №187/98-VR (1998). Retrieved from: https://zakon.rada.gov.ua/laws/show/187/98- %D0 %B2 %D1 %80#Text

Paritosh, K., Kushwaha, S. K., Yadav, M., Pareek, N., Chawade, A., & Vivekanand, V. (2017). Food Waste to Energy: An Overview of Sustainable Approaches for Food Waste Management and Nutrient Recycling. *BioMed research international*, 2370927. doi:10.1155/2017/2370927

Polishchuk, V. M., Shvorov, S. A., Krusir, G. V., & Davidenko, T. S. (2020). Increase of the biogas output during fermentation of manure of cattle with winemaking waste in biogas plants. *Problemele energeticii regionale*, 2(46), 123–134. doi:10.5281/zenodo.3898326.

Polishchuk, V. M., Shvorov, S. A., Tarasenko, S. Y., & Antypov, I. O. (2020). Increasing the biogas release during the cattle manure fermentation by means of rational addition of substandard flour as a cosubstrate. *Science and innovation*, 16(4), 23-33. doi:10.15407/scin16.04.023

Prospects for the development of the biomass market in the EU and Ukraine. Impact of biomass utilization on climate change. (2019). *Zelenaja energetika*. Retrieved from https://uspp.ua/assets/doc/uspp-biomass.pdf

Rocamora, I., Wagland, S. T., Villa, R., Simpson, E. W., Fernandez, O., & Bajón-Fernández, Y. (2020). Dry anaerobic digestion of organic waste: A review of operational parameters and their impact on process performance. *Bioresource Technology*, 299, 122681. doi:10.1016/j.biortech.2019.122681

Ryabukha, G. (2019). State regulation and forecasting of pultry breeding as a prospective livestock industry. *Problems And Prospects Of Economic And Management*, 1(17), 107-113. doi:10.25140/2411-5215-2019-1(17)-107-113 (Ukrainian)

Shapovalov, Y., Zhadan, S., Bochmann, G., Salyuk, A., & Nykyforov, V. (2020). Dry anaerobic digestion of chicken manure: a review. *Applied Sciences*, 10(21), 7825. doi:10.3390/app10217825

Skliar R. (2021). *Potential of energy production from agricultural waste*. Obukhov Readings: XYI International Scientific and Practical Conference. Kiev, Ukraine : NUBiP.

Statistical yearbook. Environment of Ukraine 2015–2019. (2019). *State Statistics Service of Ukraine*. Retrieved from https://ukrstat.org/en/druk/publicat/kat_e/publ1_e.htm

State Classifier of Inputs: Classification of inputs on the basis of a system and infrastructure. DK 005-96. Order № 89. (1996). Retrieved from: https://zakon.rada.gov.ua/rada/show/vb089217-96#Text

Substrate for biogas. (2019). *Ecobusiness*. Retrieved from https://ecolog-ua.com/news/syrovyna-dlya-biogazu

Thanarasu, A., Periyasamy, K., Devaraj, K., Periyaraman, P., Palaniyandi, S., & Subramanian, S. (2018). Tea powder waste as a potential co-substrate for enhancing the methane production in Anaerobic Digestion of carbon-rich organic waste. *Journal of Cleaner Production*, 199, 651–658. doi: 10.1016/j.jclepro.2018.07.225

The potential of biomethane production in Ukraine. (2020). *SAF: Sustainable Agribusiness Forum*. Retrieved from https://saf.org.ua/news/590/

Voytovych, I., Malovanyy, M., Zhuk, V., & Mukha, O. (2020). Facilities and problems of processing organic wastes by familytype biogas plants in Ukraine. *Journal of Water and Land Development*. 45 (IV–VI), 185–189. doi: 10.24425/jwld.2020.133493

Wąs, A., Sulewski, P., Krupin, V., Popadynets, N., Malak-Rawlikowska, A., Szymańska, M., Skorokhod, I., & Wysokiński, M. (2020). The potential of agricultural biogas production in Ukraine–impact on GHG emissions and energy production. *Energies*, 13(21), 5755. doi:10.3390/en13215755