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Bioenergy recycling of household solid waste as a direction for ensuring sustainable development of rural areas

Abstract: Current practice of waste generation and management in Ukraine has led to an increase in the area of landfills and a loss of the beneficial potential of waste. Today, territorial communities in Ukraine have received enormous new powers within the framework of decentralization, in particular, waste management is now under their jurisdiction. In order to implement the National Waste Management Strategy in Ukraine 2030 and the National Waste Management Plan 2030, communities need to activate the areas of effective disposal of household solid waste (HSW), and for this purpose it is necessary to take into account European norms and standards in this area, as well as share successful Ukrainian and foreign experience. The aim of the study is to analyze a successful case of waste management of a separate community in Ukraine (Illintsi United Territorial Community) as an example for other communities, as well as to develop guidelines for bioenergy recycling

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of waste in the community under the study with the production of RDF fuel and biogas in order to provide energy resources and improve the condition of the environment. To achieve this goal, there were used the following methods: monographic, deductive, inductive, analysis and synthesis, economic analysis, graphic and tabular, statistical, as well as the case-study method. The conducted research confirmed the growth of waste generation volumes in Ukraine and their limited beneficial use. The developed recommendations on the improvement of the household solid waste management based on the successful case of Illintsi Territorial Community and proposals for organizing the production of RDF fuel and biogas can become a strong basis for the development of communities on the basis of sustainability.

Keywords: biogas, waste, recycling, energy resources, RDF fuel

Introduction

One of the most urgent global environmental problems is inefficient waste management; the volumes of waste are constantly growing due to the influence of population growth and a number of other factors. Nowadays, humanity violates one of the main ecological laws, namely the cycle of substances in nature, by introducing synthetic substances into circulation. In Ukraine, to solve this problem, out of date technologies of waste disposal in landfills are mainly used. The main disadvantage of using this method of disposal is a significant negative impact on the ecological state.

Waste management in Ukraine has certain features, namely:

- a focus on the disposal of waste, its placement in landfills and/or spontaneous landfills, most of which do not meet the requirements for environmental safety;
- an extremely low technological level and state of management information support;
- a lack of practical implementation of innovative waste-processing technologies.

The volume of waste generation in Ukraine, despite the gradual decrease in the population of Ukraine, is increasing annually (State Statistics Service of Ukraine 2021), and according to all forecasts, this trend is set to continue in the future. All powers in the field of household waste management have been transferred to local self-government bodies as part of the decentralization process. This decision is justified by various local conditions in settlements (income level, composition of waste, type of building, availability of processing/disposal facilities, etc.). Regardless of these differences, the principles of waste management are the same and are consistent with international requirements. Today, the priority task should be the construction of the local effective waste-management system. In accordance with the Law of Ukraine "On Waste" (1998, 2020), local self-government bodies must: ensure compliance with the requirements of the legislation on waste; organize the collection and disposal of household waste; monitor compliance by legal entities and individuals with requirements in the field of industrial and household-waste management in accordance with current legislation; exercise other powers in accordance with

the laws of Ukraine; make decisions on the allocation of land plots for the placement of waste and the construction of waste-management facilities.

In most regions of the country, efforts in this area are focused only on improving the sanitation system (ensuring the greatest possible coverage and the timely removal of HSW to landfills) and arranging landfills on a more or less acceptable level. Other methods of waste management, such as waste sorting and separate collection (with further processing), in Ukrainian settlements are not sufficiently used, although every year, an increasing number of heads of local self-government bodies are aware of the need for such measures.

With the above points in mind, it can be concluded that the issue of waste recycling within the sustainable development of rural areas is an extremely urgent task.

1. Literature review

In EU countries, the issue of household-solid-waste management is extremely relevant, since a circular model of economic development has been applied. In accordance with this, the following goals concerning waste have been set:

- achieving the recycling of 65% of household waste by 2035;
- achieving the recycling of 75% of packaging waste by 2035;
- achieving a reduction of household-waste disposal to a maximum of 10% by 2030;
- the prohibition of landfilling of selectively collected waste (Directive (EU) 2018/851).

Not all EU countries are ready to implement such plans. In particular, the studies by Wielgosiński et al. (2021) show that for the Polish composition of municipal waste, even if the assumed levels of recycling of individual streams are met, achieving the overall target level of 65% recycling in 2025/30 may not be possible.

Switzerland is the leader among EU countries in terms of effective waste management. Today, half of all HSW generated in the country is collected separately and recycled – this indicator has more than doubled over the past twenty years (Waste management: National Reporting to CSD 18/19 by Switzerland, 2020).

There are widespread studies on the generation and management of HSW on the example of some countries and cities. In particular, Dikole and Letshwenyo (2020) conducted a study on the generation rate, composition and characteristics of solid waste of households with low, middle and high income in Palapye, Botswana. Their results showed that households with a higher level of income generated more waste per person, food waste was predominant in the composition of HSW and was mostly generated in high-income households.

Fadhullah et al. (2022) studied the practice of household-solid-waste segregation in the east coast of Malaysia and confirmed the need to design waste-separation programs that suit the needs of the targeted population of the region.

Zikali et al. (2022) investigated solid-waste-management practices and the importance of recycling for integrated solid-waste management (SWM) in a developing city of Zimbabwe using a case study. The results of their research confirmed that municipalities in developing countries were unable to cope with the large volumes of solid waste generated by the rapid growth of urban populations.

Nanda and Berruti (2021) made a review of the composition of solid wastes according to income of the population in different countries and studied different landfilling technologies.

Bozhanova et al. (2022) studied the logistics of household waste and proposed both methodological approaches, and practical recommendations for improving the management system of waste-collection enterprises engaged in preparation for the disposal of paper, cardboard and partly plastic, which would have both economic and social effects.

Today, the bioenergy recycling of waste is an important direction, as it enables the obtaining of both energy and organic fertilizers, the need for which is significant in Ukraine (Berezyuk et al. 2021).

The energy potential of the waste of various origins and energy crops have been researched by: Pryshliak et al. (2019), specifically the waste of agricultural enterprises and prospects for their use as energy carriers for energy autonomy; Kaletnik et al. (2021), who focused on willow, poplar, miscanthus in particular as energy crops; Adeniran et al. (2019) who studied domestic solid waste on the example of a separate business entity (university) and its energy potential.

Today, waste remains an environmental problem in Ukraine (Tokarchuk et al. 2021). There is an urgent need for the development of waste-free technologies with the production of energy carriers (biogas) (Kaletnik et al. 2020), the identification of socio-economic factors related to household-waste generation (Kala et al. 2020) and the development of the economy on the basis of sustainability (Kaletnik and Lutkovska 2020).

The development of an effective system of processing and disposal of HSW in Ukraine and their use as alternative sources of energy in conditions of rising prices for energy carriers on the world market and the refusal to supply hydrocarbons from the aggressor country (Russia) is extremely necessary today, and these factors determine the relevance of this research.

The purpose of the study is to develop recommendations for the effective management of community waste in Ukraine based on the successful case of the Illintsi community as well as to develop guidelines for bioenergy recycling of waste to provide communities with energy resources.

2. Materials and methods

Structural, functional and systemic approaches were the methodological basis for the study of the effectiveness of community waste processing as the base for its sustainable development. A set of general scientific and special methods was used in the research process:

- monographic – the analysis of scientific elaborations on the research problem, which made it possible to establish cause-and-effect relationships of the development of phenomena and processes occurring in the HSW-management system and to identify innovative and progressive ways of solving current problems;
- deductive – during the theoretical comprehension of the problem and the clarification of individual concepts; movement from the general to the partial made it possible to project the situation with HSW-generation and management in Ukraine in general at the local level, i.e. individual communities;
- inductive – research from individual to general allowed the development of recommendations on waste management for communities of Ukraine based on the successful experience of the Illintsi community;
- economic analysis – when collecting, systematizing and processing information on the generation and management of waste of various origins and types in Ukraine and when determining the efficiency of the functioning of individual enterprises in the field of HSW processing;
- analysis and synthesis – when combining the constituent economic phenomena in a single process;
- graphic and tabular – for the visual display of individual indicators of HSW generation and disposal;
- statistical – in the process of processing information for the analysis and assessment of waste generation and management.

The research methodology involves the achievement of the following tasks:

1) the analysis of the state of waste generation in Ukraine in dynamics;

2) research on waste management in Ukraine;

3) an analysis of a successful case of HSW management in one of the communities of the Vinnytsia region of Ukraine;

4) the development of guidelines for bioenergy recycling of waste of the selected community to ensure energy security as well as full or partial energy autonomy;

5) the development of guidelines for using the experience of the Illintsi community in the field of HSW management, which can be used by other territorial communities as a successful case.

The basis of the research is the case-study method, specifically qualitative research in the social sciences, which involves the study of a single social object (situation, event, incident, person, social group) or several demonstrative objects in order to understand a wider class of similar cases (class of events). The basis is a successful case, in particular, the practice of HWS management in the Illintsi community, Vinnytsia region, Vinnytsia oblast, which is recommended for implementation by other territorial communities of Ukraine. The design method was used for the development of proposals for bioenergy recycling of waste from the specified community.

The study included the processing of statistical materials of the State Statistics Service of Ukraine regarding waste generation and waste management, as well as documentation of the Illintsi community and communal enterprise (CE) "Dobrobut", which is located on the territory of

the community and is engaged in waste management (waste-processing complex) as the object of the study.

The obtained results include a set of measures aimed at the deep processing of HSW by territorial communities as a means of ensuring their sustainable development.

The research was carried out as part of the implementation of the applied research "Bioenergy Recycling of Waste in the System of the Rational Use of Natural Resources and the Sustainable Development of Agriculture", state registration number 0122U000849 performed at the expense of the state budget of Ukraine at Vinnytsia National Agrarian University.

3. Results and discussion

Currently, there is a problem with the accumulation and disposal of various types of waste in Ukraine, which harm not only the environment, but people as well. According to the data of the State Statistics Service of Ukraine, in 2020 compared to 2018, the amount of generated waste increased by 110,039.6 thousand tons, while the amount of disposed waste decreased by 3,133.5 thousand tons during the same period (Table 1). The accumulation of waste causes the release of pollutants and greenhouse gases into the environment. Thus, according to the report submitted to the UN FCCC in 2020 and the environmental indicators listed by the Ministry of Environmental Protection and Natural Resources of Ukraine regarding production outputs, the total emissions into the atmosphere from all types of economic activity and households in 2018 were as follows: hydrofluorocarbons – 1,349,257.6 tons of CO_2-equivalent, sulfur hexafluoride – 33,290.9 tons of CO_2-equivalent, nitrous oxide – 129,690.1 tons, methane – 2,700,797.1 tons, carbon dioxide – 231,694.1 thousand tons, carbon dioxide from biomass used as fuel – 7,348.8 thousand tons. Unfortunately, there is a disappointing tendency of increases in emissions (Ministry of Environmental Protection and Natural Resources of Ukraine 2020).

The Ministry of Development of Communities and Territories of Ukraine reports that in 2020, more than 54 million m^3 of household waste was generated. In absolute terms, this is more than 10 million tons, which are concentrated in 6,000 landfills occupying an area of around 9,000 hectares. Of all landfills, 4.3% are overloaded, and 14% do not meet environmental standards. The area of unauthorized landfills with household solid waste is also increasing, especially in the private sector of rural territorial communities. Due to the introduction of the separate collection of waste, up to 10% of HSW was processed, of which about 2% was incinerated, and the rest was disposed of with the help of waste-processing facilities.

When implementing modern technologies of HSW management in territorial communities, the main part of this raw material (waste) can be used for energy purposes. It is the authorities of the communities that the legislator entrusted with the authority to control the state of HSW management (Ministry of Development of Communities and Territories of Ukraine 2020).

Table 1. The volume of waste generated and disposed in Ukraine [thousand tons]

Tabela 1. Objętość odpadów generowanych i usuwanych na Ukrainie [tysiąc ton]

Indicators	Years			Absolute deviation [+,–]
	2018	2019	2020	
Waste generated, total	352,333.9	441,516.5	462,373.5	110,039.6
Waste from economic activity	346,790.4	435,619.8	456,423.8	109,633.4
Household waste	5,543.5	5,896.7	5,949.7	406.2
Waste disposed, total	103,658.1	108,024.1	100,524.6	–3,133.5
Disposal/regeneration of solvents	103.9	137.1	111.2	7.3
Recycling/disposal of organic substances that are not used as solvents	397.6	474.8	320.0	–77.6
Composting of organic waste	671.6	619.8	549.8	–121.8
Fermentation of organic waste	88.5	77.7	63.5	–25.0
Paper and cardboard processing	0.3	0.3	0.3	0
Recycling/utilization of metals and their compounds	5,798.9	5,592.7	5,356.2	–432.7
Recycling/utilization of other inorganic materials	55,930.2	58,763.3	43,068.9	–12,861.3
Regeneration of acids and bases	0.8	1.0	2.1	1.3
Recovery of components used to reduce pollution	26,649.4	27,348.7	36,553.7	9,904.3
Re-distillation of used petroleum products or their other reuse	12.5	14.7	13.5	1.0
Soil tillage that has a positive effect on agriculture or improves the ecological situation	12,320.3	13,263.0	13,501.3	1,181.0
Use of waste obtained from any of the above-mentioend operations	1,684.1	1,731.0	984.1	–700.0
Totally prepared for disposal	3,193.6	2,810.4	2641,3	–552.3
Exchange of waste for further disposal	14.2	17.1	2,578.4	2,564.2
Waste sorting	28.2	28.3	32.3	4.1
Mechanical and biological processing of waste at MBP installations	65.6	38.1	15.3	–50.3
Dismantling of unusable vehicles	0.1	0	0	–0.1
Collection and preliminary processing of scrap metal and waste containing metals	3,085.5	2,726.9	15.3	–3,070.2

Source: formed by the authots according to the State Statistics Service of Ukraine (2021).

Household waste or household solid waste has a great potential for recycling, which is not fully realized in the conditions of Ukraine and is often simply lost.

There is a clear hierarchy of waste management in EU countries (Fig. 1). The highest priority is the prevention of waste generation, the least desirable is disposal.

Fig. 1. Hierarchy of waste management in EU countries (Waste Framework Directive)

Rys. 1. Hierarchia zarządzania odpadami w krajach UE

Unfortunately, in Ukraine, waste management based on this principle is rather an exception than a rule for communities. However, there are communities that pay a lot of attention to effective waste management, and their activities can become a successful example for others. One of these is the Illintsi urban territorial community of the Vinnytsia region, which has started a number of projects on waste management since 2016 and is successfully implementing them now (Fig. 2).

In 2017, the implementation of the project "Construction of the waste sorting complex on the territory of the household solid waste landfill" and establishment of CE "Dobrobut" in the town of Illintsi in the Illintsi district, Vinnytsia region, Ukraine, became an important step for the community.

The estimate of the project was UAH 11.756 million, of which the regional budget allocated UAH 10.5 million. In parallel with the construction of the complex, on June 6, 2018, a Memorandum on cooperation in the field of waste management was signed between the Illinetska, Orativska, and Dashivska united territorial communities to ensure the creation of conditions for waste collection and sorting.

The structure of the enterprise, in addition to the waste-sorting complex, also includes a contact zoo, a landscape nursery as well as a material and technical base focused on the provision of

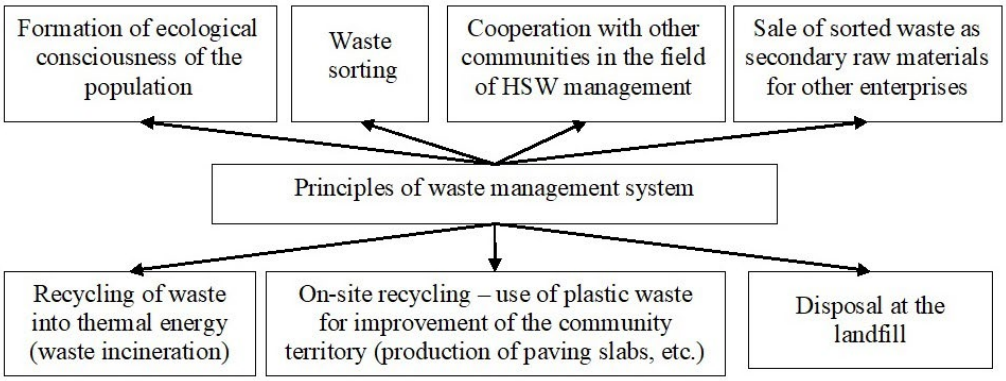

Fig. 2. Principles of the waste management system implemented in Illintsi community, Vinnytsia region
Source: generalized and systematized by the authors

Rys. 2. Zasady systemu gospodarowania odpadami wdrożonym w gminie Illintsi w regionie Vinnytsia

services for the improvement of the territory of the community and the contact zoo. The contact zoo is mostly used for the social tasks of Illintsi Town Council, including conducting excursions, maintaining the image of an ecologically oriented community and bringing up eco-friendly youth.

The complex of measures aimed at creating a positive image of CE "Dobrobut" involves the constant provision of services by the Illintsi territorial community in the field of community improvement under the brand "Illintsi – Everything Takes Place Here" and the implementation of educational activities in the field of the environmentally safe development of the relevant territories.

A key to the rational use of a community's waste is its high-quality sorting. The morphology of household solid waste entering the waste-sorting complex of CE "Dobrobut" is represented mainly by organic waste – 28% (leaves, tree chips, organic household waste, etc.), 18% – unclaimed HSW that cannot be sold and can be burned to ensure heating of the enterprise itself and, in the future, the heating of the zoo in winter. More than 40% of the sorted waste is sold for processing. During 2020, CE "Dobrobut" sorted 20,500 m^3 of HSW, of which 40% was sold, 14% was sent for processing, and 46% was sent to landfill (Fig. 3).

Among the enterprises to which CE "Dobrobut" sells sorted secondary raw materials are: LLC "Kozyatynska Sewing Factory" in the city of Kozyatyn, Vinnytsia region (sorted washed plastic for the production of fillers for outerwear), LLC "Ekopodillia" in the city of Vinnytsia (waste paper, ferrous and non-ferrous metal and partly plastic).

About 14% of HSW is used for recycling within the community as a component for the production of paving slabs. In the paving slab production workshop, sand and plastic agglomerate are combined into the following mixture: 30% plastic waste and 70% sand (the technology requires the use of river sand) (Fig. 4).

The appropriate mixture enters a special machine, which heats it up to 180°C and turns it into a hot mass. This mass is weighed in portions and placed in a press, in which the final formation

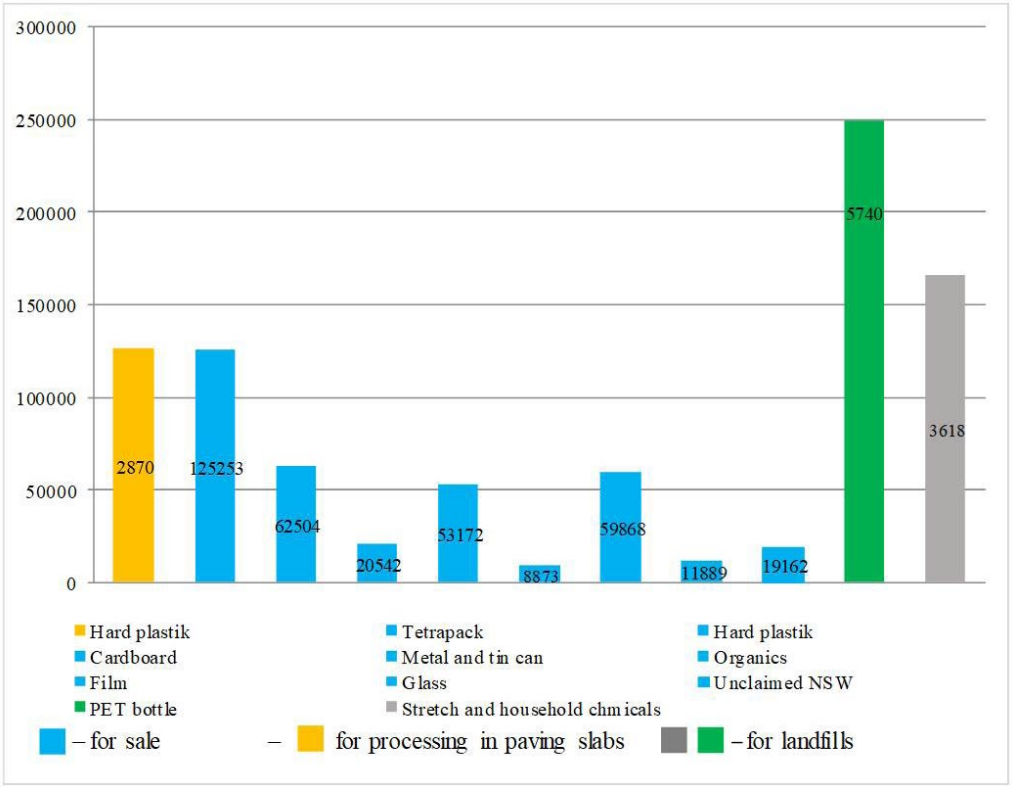

Fig. 3. The morphology of solid waste and directions of their use in the CE "Dobrobut" of Illintsi community, 2021 [thousand tons]
Source: (Honcharuk et al. 2022)

Rys. 3. Morfologia odpadów stałych i kierunków ich użycia w „Dobrobut" w gminie Illintsi, 2021 [tysiąc ton]

(a) (b)

Fig. 4. Production process (a) and appearance (b) of paving slabs produced by CE "Dobrobut" of Illintsi community
Source: formed on the basis of data of CE "Dobrobut"

Rys. 4. Proces produkcyjny (A) i wygląd (B) płyt brukowania wyprodukowany przez CE „Dobrobut" gminy Illintsi

of the paving slabs is executed. The paving slabs are produced at a basic size of 17 × 12 × 3 cm (0.02 m^2) with an average weight of 1.15 kg. Paving slabs of this type are cheaper and of better quality than concrete slabs. These products are practically unaffected by salt solutions or temperature changes, and their service life is unlimited, and what is important is that they can be recycled. During an eight-hour shift, CE "Dobrobut" produces up to 250 m^2 of paving slabs. Today, the entire volume of production is used to meet the needs of the city and the community; it was also used for the improvement of the waste-sorting complex, namely the area around the utility company and more than 10,000 m^2 of pavement in the town of Illintsi.

If appropriate dyes are added to the mixture from which the paving slabs are made during the production process, then it can be produced in any required color, which improves the visual characteristics. Currently, only dark gray paving slabs are produced in the Illintsi territorial community to save costs. This technology makes it possible to produce paving slabs resistant to the effect of chemical reagents that have a negative effect on competitive products, e.g. paving slabs produced on the basis of the sand-concrete mixture.

The company's individual technological line ensures production with the supplementation of the cement-concrete mixture with 30% of plastic.

Based on the sale price of plastic of UAH 9.75/m^2, costs for sand and labor, the paving slabs costs UAH 280/m^2 (Table 2).

Table 2. The structure of the cost of 1 m^2 of paving slabs produced by CE "Dobrobut" in Illintsi community

Tabela 2. Struktura kosztu 1 m^2 płyt nawierzchniowych wyprodukowanych przez CE „Dobrobut" w gminie Illintsi

Item No.	Cost items	Weight (volume) [kg (kW)]	Price [UAH/kg (kW)]	Price [UAH]
1	Material costs, including:			
2	plastic	17.25	9.75	168.19
3	sand	40.25	0.10	4.03
4	electricity	8.00	6.00	48.00
5	Labor costs	–	–	59.78
6	Total	X	X	280.00

Source: formed on the basis of data of CE "Dobrobut".

Based on the HSW structure, it is possible to determine the potential volumes of plastic that can be used to produce this paving slab. According to the data in Figure 4, almost 25% of all household waste is plastic, which amounts to approximately 5,125 m^3. Under the complete processing of the available amount of plastic at landfill, more than 341,000 m^2 of paving slabs with a cost price of more than UAH 95.5 million can be obtained.

Comparing analogues of the corresponding products with the prices of Epicenter LLC (Ukraine), it can be stated that, taking into account competitive advantages in durability and the possibility of recycling when selling the corresponding products with a markup of UAH 56/m^2 (20%),

the products of CE "Dobrobut" are competitive on the market (Table 3). Among the competitive advantages of paving slabs of CE "Dobrobut", it is also possible to include lower weight, which reduces logistics costs during transportation, and larger unit sizes, which facilitates its installation and reduces the cost of relevant works.

Table 3. Comparison of the main competitive indicators of paving slabs of CE "Dobrobut" of Illintsi community with the cost of the close analogues

Tabela 3. Porównanie głównych wskaźników konkurencyjnych płyt brukowania „Dobrobut" z gminy Illintsi z kosztami ich odpowiedników

No.	Indicator	CE "Dobrobut"	"Avenue Stare misto grey H4" (nearest analogue)	"Brukland H = 60 mm grey" (analogue 2)	"Zolotoy Mandaryn Tsehla black" (analogue 3)
1	Size [cm]	17 × 12 × 3	6 × 12 × 4	10 × 20 × 6	20 × 10 x 4
2	Weight of 1 m^2 [kg]	57.5	91.4	131.5	50.0
3	Price [UAH/m^2]	336.0	365.5	500.0	465.0

Source: formed on the basis of data of CE "Dobrobut" and Epicenter Site (2022).

Based on the possible volume of sales and a markup of 20%, CE "Dobrobut" can get a net profit from the sale of this product to the amount of UAH 19.3 million (341,662.3 × 56). This will provide an opportunity to develop the company's material base, provide potential buyers with a product that is of higher quality in terms of its characteristics compared to those of analogues, and create additional jobs in the community.

These products can be reused. Paving slabs that have defects can be crushed and remelted with the help of a special shredder. When the useful life of the paving slabs comes to an end, it can be crushed in the same way, then some more agglomerated film is added and the film is reused.

Today, organic waste and unclaimed waste (a mixture of mostly organic waste that cannot be divided into fractions) is not used beneficially in Illintsi community. Currently, they are still disposed of in landfill; however, the community is searching for ways of their further use. In particular, the organic fraction of waste is planned to be processed into organic fertilizers by means of vermicomposting. This technology is new for Ukraine and only some preliminary studies of its effectiveness have been conducted.

In view of the shortage of energy resources in Ukraine caused by military actions, we believe that the energy use of waste is more relevant.

A promising direction for communities is the organization of RDF production from waste. RDF fuel is fuel in the form of granules formed from the dry residue that remains after all cycles of solid waste sorting by grinding and pressing. For the Illintsi community, it is proposed to use residues of sorting for the production of this type of fuel.

The composition of waste used for the production of RDF includes cellulose materials, wood and derivatives, leather and rubber waste, etc., the proportion of which may vary (Table 4).

Table 4. Typical morphological composition of RDF fuel

Tabela 4. Typowy skład morfologiczny paliwa RDF

No.	Component	Content [%], not more
1	Polyethylene	33
2	Textiles of various types	22
3	Paper, cardboard, other types of cellulosic materials	15
4	Polyethylene terephthalate	13
5	Wood, its derivatives	7
6	Plastic, synthetic fibers, multilayer packaging	6
7	Polypropylene	5
8	Leather, leather substitutes, leather and rubber products (natural and synthetic)	3

Source: Alternative RDF-fuels for the energetics 2018.

The percentage content of residues that can be used to produce RDF fuel ranges from 18 to 35% of the total mass of HSW (in the Illintsi community, it was 18%). This amount may not be sufficient to meet the community's energy needs, so there is a possibility in which not only unsortable residues, but also all potentially combustible materials from HSW are used to produce RDF fuel (it may reach 45% of the total mass). Comparing the caloric content of RDF fuel, it is 4,200–5,200 kcal/kg in the first variant, and 5,200–5,400 kcal/kg in the second variant. Thus, it is possible to obtain fuel with a higher heat of combustion (up to 20–22 MJ/kg) under the forced enrichment of household solid waste, which will result in a higher output of energy resources.

Among the EU countries, the Netherlands, Italy, Belgium and Finland are the leaders of RDF fuel production. This has been facilitated by a balanced state policy aimed at promoting its production: the fuel is referred to in the local policy, and investmentx in the industry is stimulated. The experience of our close neighbor – Poland – seems to be interesting, since its government promoted commercial production of RDF fuel due to administrative measures (e.g. banning the disposal to landfills of waste that has high energy potential that is more than 6 MJ/kg of calorific value) and economic measures (introduction of a monthly tax on waste per person).

On average, one ton of waste can produce 350 kg (35%) of RDF fuel, which will have a moisture content of 12–14% (Alternative RDF Fuel for Energy 2018).

The priority measures for the implementation of such a project in the Illintsi community are:

1) gaining advanced European experience on the production and use of RDF fuel by communities;

2) the assessment of the HSW potential for the production of RDF fuel;

3) the retrofitting of the waste-processing plant of Illinetsk urban territorial community with the line for RDF fuel production.

In order to use the energy potential of organic waste, which makes up 28% of the HSW structure of the Illintsi community and is currently directed to landfill, bioenergy recycling is proposed, i.e. the organization of biogas production at the HSW landfill.

Morphological composition of the organic part of HSW at the landfill of CE "Dobrobut" (area of 15 ha) is shown in Table 5.

Table 5. Morphological composition of the organic part of solid waste at the landfill of CE "Dobrobut"

Tabela 5. Skład morfologiczny organicznej części odpadów stałych na składowisku CE „Dobrobut"

No.	Morphological composition of the organic part of HSW	Landfill		Content of the main chemical elements in the dry matter of the organic components of HSW [%]					
		content by the mass of HSW [%]	content in the organic part of HSW [%]	C	H	O	N	S	ash
1	Paper	21.0	44.5	45.40	6.10	42.10	0.30	0.12	6.00
2	Food waste	12.0	25.4	41.70	5.80	27.60	2.80	0.25	21.90
3	Wood	2.1	4.5	48.30	6.00	42.40	0.30	0.11	2.90
4	Textiles	2.6	5.5	46.20	6.40	41.80	2.20	0.20	3.20
5	Leather, rubber	4.6	9.5	59.80	8.30	19.00	1.00	0.30	11.60
6	Plastic	3.4	7.2	67.90	8.57	10.30	1.13	0.05	12.02
7	Bones	1.6	3.4	59.60	9.50	24.70	1.02	0.19	4.99
8	Mixture of components	47.2	0	48.10	6.53	33.30	1.18	0.15	10.74

Source: formed by the authors based on the data of CE "Dobrobut".

In the case of the availability of a percentage content of HSW in the organic matter and atomic weight of carbon, hydrogen, oxygen, nitrogen, sulfur, the number of gram-moles of these elements per 1 kg of HSW is determined (Table 6).

In the process of HWS storage at the landfill, the anaerobic process of the decomposition of organic matter takes place, during which, new chemical compounds are formed including carbon dioxide (CO_2), methane (CH_4), ammonia (NH_3) and hydrogen sulfide (H_2S). These are gaseous substances that form biogas when mixed. Knowing the molecular masses of the formed compounds of CO_2 (44), CH_4 (16), NH_3 (17), H_2S (34) and water H_2O (18), it is possible to determine the mass of substances formed during the decomposition of 1 kg of HSW (Analytical Note of BAU 2019).

Based on the above-mentioned details, the volume of biogas generation (Gmax) at an average landfill, for example CE "Dobrobut" in Illintsi (currently processing and sorting household solid waste), can be calculated using the formula:

$$G = M \cdot V\ [\mathrm{m}^3] \tag{1}$$

where:

M – annual amount of HSW that enters the landfill,

V – the volume of biogas produced per 1 kg of HSW ($V = 0.218\ \mathrm{m}^3/\mathrm{kg}$).

Table 6. The mass of the starting substances during anaerobic decomposition of organic substances of 1 kg of HSW in CE "Dobrobut"

Tabela 6. Masa początkowej substancji podczas beztlenowego rozkładu substancji organicznych 1 kg HSW w „Dobrobut"

Input chemical elements		Output compounds				
Chemical sign	mass [g]	chemical formula	mass [g]	mass fraction [%]	volume [m^3]	volume fraction [%]
C	102.00	CO_2	162.20	66.70	0.0923	42.36
H	13.78	CH_4	77.20	31.80	0.1210	55.53
O	70.70	NH_3	3.06	1.36	0.0044	2.02
N	2.50	H_2S	0.34	0.14	0.0002	0.09
S	0.32					
H_2O	53.50					
	242.80		242.80	100	0.2179	100

Source: formed by the authors based on the data of CE "Dobrobut".

$$M = N \cdot R \tag{2}$$

where:

N – the norm of accumulation of HSW per citizen per year (N = 300 kg),

R – number of residents in the town.

Thus, for example, for the Illintsi TC (population is approximately 20,000 people), the volume of biogas generated at the landfill per year is:

$$G = 300 \cdot 20000 \cdot 0{,}218 = 1308000 \text{ m}^3.$$

According to the calculation, it is possible to obtain significant volumes of biogas for the production of both thermal and electrical energy.

Based on the relevant calculations, it should be noted that in terms of biomethane and carbon dioxide, according to the data in Table 6, the volumes will be 726,000 m^3 of biomethane and 582,000 m^3 of carbon dioxide (9,720 tons).

The capacity of the available landfill exceeds 60,000 tons of HSW per year, so the project cost will be about 7.2 million euros. The cost of the project is extremely high for the community, so the development of such a project is possible only if investors are involved.

Based on the calculations, the production volumes will make it possible to sell biomethane at a cost of UAH 49,104/thousand m^3 and carbon dioxide at 2,196 UAH/t (61 Euros). Therefore,

the total revenue will amount to UAH 35.6 million – biomethane; UAH 21.3 million – sale of carbon dioxide (total of UAH 56.8 million annually).

Possible ways of using biomethane by the community include:

1) obtaining thermal energy and using it for heating social infrastructure facilities;

2) heating of the landscape nursery of CE "Dobrobut" in order to minimize the cost of community improvement services;

3) use of liquefied biomethane by the sugar factory as a substitute for natural gas, which will make it possible to reduce the cost of the final products.

Summarizing this successful case of the Illintsi community, it is possible to outline the following measures in the field of solid-waste management, which should be implemented in other communities (Table 7).

Table 7. Guidelines for effective HSW management based on the successful case of Illintsi community and the authors' proposals

Tabela 7. Wytyczne dotyczące skutecznego zarządzania HSW w oparciu o udany przypadek gminy Illintsi i propozycji autorów

No.	Content of the events
1	Taking measures to form ecological awareness of the population, promotion of ecological solid waste management.
2	Implementation of HSW sorting in the community.
3	Organization of cooperation with other communities regarding HSW management if the community is small (an example of the Illints community cooperating with Dashkiv and Orativ regional territorial communities).
4	Participation of communities in the international grants and competitions on energy efficiency to obtain preferential financing of waste management projects.
5	Construction of a waste processing plant, which will generate streams of sorted waste for further beneficial use.
6	Sale of sorted waste (glass, metal, paper, etc.) to specialized enterprises outside the community for the production of secondary products.
7	Recycling of sorted waste within the community (following the example of the Illintsi community – production of pavement slabs from secondary plastic).
8	Use of unclaimed waste (a mixture that cannot be sorted) for the production of RDF fuel.
9	Organization of biogas production from community organic waste.

Source: generated by the authors.

Thus, it is possible to ensure the beneficial use of almost 100% of waste generated in the communities. This practice meets the European requirements for SWM and allows the community to solve environmental problems and provide itself with its own energy resources.

Conclusions

Sustainable development of rural areas and communities is impossible without energy-efficient and environmentally safe components. Effective waste management occupies an important role in this process since it enables the combination of the specific components of sustainable development. The research results can be summarized as follows:

1. Analysis of the volume of waste generated as a result of economic activity and in households in Ukraine showed a tendency towards an increase, particularly in 2020, there was more waste than during any other period under the research.

2. Beneficial use of waste in Ukraine is limited, obtaining energy from waste is an exception rather than a rule.

3. There are successful cases of waste management in Ukraine, in particular, the Illintsi Territorial Community of the Vinnytsia region. Components of the community's success are as follows: the implementation of activities aimed at forming environmental awareness of the population, cooperation with other communities in the field of HSW management, waste sorting, operation of a waste processing plant. A unique practice of the community is the recycling of plastic waste by its own efforts in the production of paving slabs from crushed polyethylene bags and a mixture of sand. The experience of the Illintsi community in the field of HSW management can be used by other communities to improve the environmental situation and obtain secondary raw materials.

4. Organic and unclaimed waste, which should be used for bioenergy recycling, has not been beneficially used in the Illintsi community. It is advisable to process unclaimed waste into RDF fuel, but for this purpose, it is important to master successful cases of such production in European communities. It is proposed to use organic waste for the production of biogas, which will have the following effect on the economy: it will increase the energy independence of the community, reduce utility companies' expenses on energy carriers, improve ecological condition of the territorial community, reduce the amount of greenhouse gas emissions and provide agricultural producers with organic fertilizers. The main restraining factor for the development of biogas production in household solid waste landfills is, first of all, the lack of state incentives and a necessary amount of investment. By means of state stimulation of the development of alternative energy and subsidies from local budgets for the relevant utility companies, it is possible to achieve a solution to the tasks set in the short-term prospect.

5. For the successful implementation of the practice of the effective management of community waste, guidelines have been developed taking into account the successful Ukrainian case of the Illintsi community. In the context of energy, there is the production of RDF fuel and biogas – which is especially relevant today when there is a shortage of energy resources in communities due to attacks of Russian troops on the energy infrastructure of Ukraine.

From October 10, 2022, the Russian Federation began to use the destruction of energy infrastructure as one of the main methods of waging war against Ukraine. According to the Center for Economic Strategy (Ukraine), in the first month and a half (October-November),

approximately 1,500 missiles already hit the energy system. The configuration of the energy system changes after each impact. According to the Energy Research Center (Ukraine), if we take the situation as of October 10 as 100%, then 15% of stability remains in the energy system until now. There are two ways to increase the stability of the system: 1) to search for and quickly deliver all available equipment to Ukraine, primarily transformers; 2) to equip the critical infrastructure of communities with alternative generation. For the implementation of the second direction, it is the use of waste as an energy carrier to generate the required electrical and *thermal* energy that is very promising.

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Bioenergetyczny recykling odpadów stałych z gospodarstw domowych jako kierunek zapewnienia zrównoważonego rozwoju obszarów wiejskich

Streszczenie

Obecna praktyka wytwarzania i zarządzania odpadami na Ukrainie doprowadziła do wzrostu obszaru składowisk i utraty korzystnego potencjału odpadów. Dzisiaj społeczności terytorialne na Ukrainie otrzymały nowe uprawnienia w ramach decentralizacji, w szczególności zarządzania odpadami. Aby wdrożyć krajową strategię zarządzania odpadami na Ukrainie 2030 i krajowy plan zarządzania odpadami 2030, społeczności muszą aktywować obszary skutecznego usuwania odpadów stałych gospodarstw domowych (HSW), a w tym celu konieczne jest uwzględnienie norm europejskich oraz standardów w tej dziedzinie, a także dzielenie się doświadczeniem narodowym, ukraińskim oraz światowym. Celem opracowania jest analiza udanego przypadku zagospodarowania odpadów wydzielonej gminy na Ukrainie (Zjednoczona Wspólnota Terytorialna Illintsi) jako przykładu dla innych gmin, a także opracowanie wytycznych dotyczących bioenergetycznego recyklingu odpadów w badanej społeczności z produkcją paliwa RDF i na zamówienie biogazu w celu zapewnienia zasobów energetycznych i poprawy stanu środowiska. Aby osiągnąć ten cel, zastosowano metody: monograficzną, dedukcyjną, indukcyjną, analizy i syntezy, analizy ekonomicznej, graficznej i tabelarycznej, statystycznej oraz metody studium przypadku. Przeprowadzone badania potwierdziły wzrost ilości wytwarzania odpadów na Ukrainie i ich ograniczone korzystne zastosowanie. Opracowane zalecenia dotyczące poprawy gospodarki odpadami stałymi w gospodarstwach domowych w oparciu o udany przypadek społeczności terytorialnej Illintsi oraz propozycje organizowania produkcji paliwa RDF i biogazu mogą stać się silną podstawą dla rozwoju społeczności na podstawie zrównoważonego rozwoju.

Słowa kluczowe: biogaz, odpady, recykling, zasoby energetyczne, paliwo RDF