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TECHNICAL AND TECHNOLOGICAL ASPECTS OF BIOLOGICAL RECLAMATION USING ANTHROPOGENIC ORGANIC WASTE IN COMPOSITION WITH SEWAGE SLUDGE

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Abstract. A systematic modern analysis of the state of waste management in the country encourages the search for more rational, efficient and cost-effective ways of processing and recycling solid waste. The inclusion of sewage sludge as a raw material in technologies for processing substrates makes it possible to solve the problems of accumulation and negative environmental impact of this hazardous waste, in addition to the problems of recycling. Promising strategies for the use of sewage sludge in combination with other components for reclamation purposes are considered: the production of substrates by direct mixing without any physical and chemical transformation of the substrate before application for reclamation purposes; composting to obtain reclamation compost; preliminary anaerobic biodegradation with the formation of biogas and subsequent use of digestate for reclamation purposes. The conditions for the application of the strategies, their advantages and disadvantages are analyzed.

Keywords: organic waste, composting, sewage sludge, direct mixing, biodegradation.

1. Introduction

The systemic modern analysis of waste management practices in the country urges the search for more rational, efficient, and economically viable ways of processing and disposing of solid municipal waste (SMW). This primarily involves improving the normative and legal framework for waste management regulation, taking into account the functions and responsibilities of executive authorities, and strict compliance with existing legislation in this field. It also entails ensuring funding for the implementation and popularization of new environmentally safe methods of disposal, including the implementation of a separate collection system for SMW and the promotion and preference of biotechnological methods of disposal (Just et al., 2007).

Modern approaches to handling organic waste can be divided into three groups of methods: burial and landfilling, incineration, and utilization. An analysis of the environmental pollution problem and the deterioration of public health allows us to draw conclusions about the most environmentally safe, economical, and efficient waste management methods. Comparative analysis (Just et al., 2007, Carlsson et al., 2002) leads to the conclusion that waste utilization is the most environmentally efficient method. Directive on waste (Directive 2008/98/EC of the European Parliament and of the Council, 2008) provides the following waste management priorities:

1. Waste prevention.
2. Preparation for reuse.
3. Recycling.
4. Other types of recovery, such as energy recovery.
5. Disposal.

A similar priority structure that places the utilization of organic waste as the top priority is

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declared in the Law of Ukraine "On Waste Management" (Law of Ukraine, 1998). Utilization is the processing of waste resulting in products that can be used in other industries, thereby incorporating them into a continuous production cycle – recycling. Addressing waste management issues in this way is rational, resource-saving, environmentally safe, and economically viable. The utilization of solid waste requires a well-organized waste collection system throughout the country, and the success of this method depends to a large extent on the overall culture and responsibility of the population.

In the case of waste utilization, biotechnology is of great interest. The viability and effectiveness of biotechnological processes are determined by their compactness and scalability, as well as high labor productivity. These processes can be controlled and regulated, implemented under "gentle" conditions, at normal pressure and low environmental temperatures. They generate fewer waste and by-products, have minimal dependence on climate and weather conditions, do not require large land areas, and do not require the use of pesticides, herbicides, or other foreign agents detrimental to the environment. Therefore, biotechnology as a whole and its individual branches are among the most priority directions of scientific and technological progress and serve as a prominent example of "high technologies" associated with the prospects of development in various industries. Biological technologies are currently undergoing rapid development, and the level of their advancement largely depends on the scientific and technological potential of the country. All highly developed countries consider biotechnology as one of the most important contemporary fields, considering it a key method for industrial reconstruction in line with the needs of the time, and take measures to stimulate its development (Struchok, 2023).

From an ecological standpoint, biotechnological measures have no competitors because they are natural and therefore not accompanied by side effects that are difficult, and often impossible, to predict in the development of nature conservation technologies when using chemical, physicochemical, physical measures, as well as certain biological measures based on the use of organisms that are not representatives of natural ecosystems.

Among the biotechnological methods that can be used for the effective utilization of organic waste, the most researched and promising ones from an eco-economic perspective are:

- Anaerobic fermentation (biomethanogenesis)
- Aerobic fermentation
- Composting
- Vermicomposting

Anaerobic fermentation (biomethanogenesis, bioconversion) is the most widespread method of waste utilization that meets modern ecological requirements and serves as an alternative energy source. Biomethanogenesis is of great importance in conditions of gradual depletion of traditional energy resources (oil, gas, coal, etc.) and the increasing fuel shortage, as well as the complications in centralized natural gas supply (Krucir et al., 2016; Elizarov, Nikiforov, 2008).

The main advantage of composting as a component of low-waste or zero-waste production is the environmental friendliness of this method. In addition to reducing the burden on the natural environment by excluding waste from entering it, which significantly affects the environment and introduces pollutants and toxic substances, composting yields a valuable secondary resource – vermicompost. Given the current state of soils, vermicompost can help solve the problem of rapid decline in land fertility. Vermicompost is a concentrated organic fertilizer, consisting of fine granules with a size of 1–3 mm, and is formed during processes inherent in nature. Plants easily absorb the fertilizer throughout their development cycle, and it is a component in preventing the accelerated degradation of the environment. The fertilizer contains a complex of essential nutrients and micronutrients, soil antibiotics, vitamins, enzymes, growth hormones, and plant development. Vermicompost is inhabited by a unique community of microorganisms that ensure soil fertility (Barrena et al., 2008; Gorodniy et al. ; 1990, Garmash, 2003;Atiyeh et al., 2000).

Vermicomposting using earthworms, including rainworms and other species, is an effective and environmentally safe method for organic waste disposal (animal husbandry, household, and industrial waste). This method allows the transformation of various types of waste, which were previously the main pollutants of the environment, into a complete animal protein suitable for animal feeding and human consumption, as well as for the pharmaceutical industry (worm biomass). On the other hand, it also yields granular humus fertilizer (vermicompost) (Kulyk, Garmash, 2000). Earthworms are even capable of processing waste that is challenging to dispose of, such as waste from the cellulose-paper industry.

2. Theoretical part

2.1. Classification of organic waste

Organic waste includes food waste, agricultural plant waste, agricultural animal waste, technogenic waste from industries and wastewater treatment technologies (wastewater sludge, waste from agroindustrial enterprises, waste from industries utilizing organic raw materials). All these wastes are classified based on their different chemical composition and various physicochemical properties. Using these wastes as the sole raw material for the aforementioned biotechnological processes is impractical because they have an inconsistent composition that is not optimal for implementing the aforementioned processes. Therefore, they are practically always used in combination to balance the composition for the subsequent implementation of biotechnological processes under optimal conditions. We were interested in a composition that would include a large-volume waste from wastewater treatment - wastewater sludge (WS). If they were included in the raw material composition for implementing biotechnological processes, it would be possible to utilize this large-volume waste, the uncontrolled accumulation and uncontrolled biodegradation of which pose a significant environmental threat. To analyze the prospects of using WS in biotechnologies related to material preparation for reclamation, we used information on the accumulated and continuously obtained WS from the sewage treatment plants of Lviv's wastewater treatment facilities. Laboratory research was conducted using certified equipment in the laboratory of agrochemical, toxicological-radiological studies of soil ecological safety and product quality at the Lviv branch of the State Institution "State Soil Protection Service". The qualitative composition of fresh wastewater sludge (WS) from the city of Lviv was determined based on the results of these laboratory studies, as presented in Table 1.

Table 1

Qualitative composition of fresh wastewater sludge

Parameter	Unit of Measurement	Actual Value	
		Dry Matter	As Is
1	2	3	4
Acidity: Salt pH	*pH*	–	6.4
Water pH	*pH*	–	6.1
Moisture	*%*	–	73.6
Ash	*%*	23.8	–
Total Phosphorus	*%*	1.6	0.42
Total Potassium	*%*	0.3	0.08
Total Nitrogen	*%*	3.56	0.93
Ammonium Nitrogen	*%*	0.28	0.073
Nitrate Nitrogen (in peat)	*mg/100g*	11.75	–
Calcium (as soil)	*mmol/100g*	11.75	–
Magnesium (as soil)	*mmol/100g*	4.12	–
Sulfur (extractable in soil)	*mg/kg*	14.8	–
Trace Elements: Copper (Cu)	*mg/kg*	–	4.0
Zinc (Zn)	*mg/kg*	–	17.6
Manganese (Mn)	*mg/kg*	–	45.1
Cobalt (Co)	*mg/kg*	–	2.86
Iron (Fe)	*mg/kg*	–	65.0
Lead (Pb)	*mg/kg*	–	1.56
Cadmium (Cd)	*mg/kg*	–	0.2
Boron (B)	*mg/kg*	–	4.01

As seen from the table, the collected fresh wastewater sludge from Lviv wastewater treatment plants contains an adequate amount of phosphorus, potassium, and nitrogen according to DSTU 7369:2013 (Ukrainian State Standard 7369:2013), while heavy metals do not exceed the maximum permissible concentrations (MPC).

To assess the quantity of accumulated sludge in the Lviv wastewater treatment plants, topographic and geodetic surveys were conducted, based on which a map of the sludge field was created with precise localization to local coordinates (Tymchuk et al., 2020a; Shkvirko et al., 2021). A three-dimensional model of the sludge field surface morphology (excluding the lower protrusions of the sludge field) is presented in Fig. 1.

As observed from Fig. 1, the surface of the sludge field is uneven. This irregularity may be attributed to the fact that during the sludge deposition process on the sludge field, they were dumped only from one side, resulting in such uneven distribution. Based on the analysis of research data, the area of the sludge field was determined to be 12.9006 hectares or 129.006 square meters, and the volume of sludge on the sludge field amounts to 407.659 cubic meters. Such significant volumes of accumulated sludge pose a considerable environmental threat, necessitating the development of a strategy for their utilization. It should be noted that the situation with accumulated wastewater sludge in Lviv is typical for Ukraine. In Ukraine, over 1 billion tons of sludge have already been accumulated, with an additional 40–50 million cubic meters of high-moisture wastewater sludge (97 % moisture content) being added each year, equivalent to 1.2–1.5 million tons of sludge in terms of dry matter. This emphasizes the importance of wastewater sludge utilization in technologies that ensure their large-scale utilization, including in the reclamation technologies of disturbed lands.

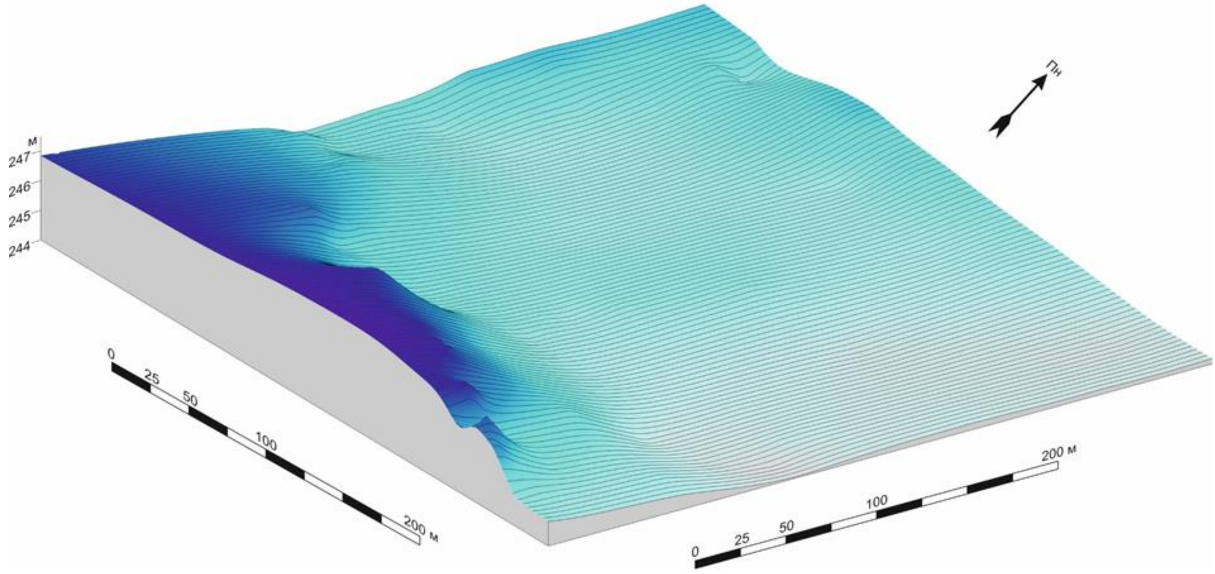

Fig. 1. Three-dimensional model of the sludge field surface morphology (excluding the lower protrusions of the sludge field)

Other components of the composition used (when necessary) together with wastewater sludge for preparing materials for reclamation were food and wood waste, the characteristics of which are not provided here.

2.2. Optimal strategies for utilizing organic waste in compositions with wastewater sludge through their use in reclamation technologies

The strategy for utilizing organic waste in compositions with wastewater sludge, in our opinion, should be developed for each sludge localization object and vary depending on the characteristics of the sludge localization object, the amount of accumulated sludge on the sludge fields, the productivity of their formation, the technical capabilities of organizing technological processes for creating substrates for reclamation, the efficiency ranking of substrates in reclamation technologies, and the priority ranking of different forms of these substrates in terms of achieving the goals of the European Green Deal (European Interest, 2020).

From our perspective, considering the localization and volume of wastewater sludge, three strategies for their use in compositions with other components for reclamation purposes are possible:

1. Creation of substrates through direct mixing without any physicochemical transformations of the substrate before application for reclamation purposes.
2. Composting to obtain reclamation compost.
3. Pre-anaerobic decomposition with biogas production and subsequent use of digestate for reclamation purposes.

Regarding the prioritization in accordance with the European Green Deal, whose main idea is that all greenhouse gas emissions should be absorbed by ecosystems, the analysis of the proposed strategies allows us to draw the following conclusions:

- In the case of uncontrolled biodegradation of organic waste, all CO_2 that was absorbed during biomass synthesis is released into the atmosphere, causing secondary pollution.

- In the case of anaerobic decomposition (Strategy 3) as the first stage of substrate preparation for reclamation, renewable energy in the form of biogas is additionally obtained, reducing the use of traditional energy sources and thus decreasing CO_2 emissions into the atmosphere.
- Strategies 1 and 2 are considered equivalent from the perspective of the European Green Deal.

Thus, from the perspective of the European Green Deal, priority is given to Strategy 3 compared to Strategies 1 and 2.

From the perspective of substrate efficiency in reclamation technologies, more favorable options are the application of Strategies 2 and 3 since the substrates obtained through these technologies are more homogenized, balanced in terms of nutrient elements, and sterilized from pathogenic microflora.

Considering the amount of accumulated sludge on sludge fields, the productivity of their formation, and the technical possibilities of organizing technological processes for creating substrates for reclamation, the following aspects should be taken into account:

- For the implementation of anaerobic decomposition as the first stage of substrate preparation (Strategy 3), a sufficient amount of accumulated wastewater sludge is required, proportional to the capacity of the facility to ensure its continuous operation for a sufficiently long period. Additionally, the installation and the entire technological line of its support should be prepared. Not all sludge localization sites, even those with large volumes of accumulated and newly formed wastewater sludge, have the possibility of constructing and operating such a facility. For example, thanks to investments from the European Bank for Reconstruction and Development, such a facility is being developed for the Lviv wastewater treatment plants.
- For the implementation of Strategy 2, a sufficient amount of accumulated and newly formed wastewater sludge is also required to ensure the composting technology.
- Wastewater sludge from all sludge localization sites that do not meet the criteria mentioned above can be utilized according to Strategy 1.

The choice of a specific strategy needs to be made for each individual case, taking into account the aforementioned criteria, requirements, and priorities. Below, we will discuss the features of implementing the aforementioned strategies for utilizing wastewater sludge in combination with other organic waste in the technologies of reclaiming degraded lands.

2.3. Creation of substrates for direct mixing without any physicochemical transformations of the substrate prior to application for the purpose of reclamation

Qualitative indicators of substrates based on “freshly collected” and “aged” sludge were determined using the method of bioindication during previous studies on the creation of substrates for direct mixing without any physicochemical transformations of the substrate prior to application for the purpose of reclamation (Shkvirko et al., 2018; Shkvirko et al., 2019). The influence of different substrate compositions on the similarity, growth, and development of plants was investigated.

Laboratory tests for assessing the quality of substrates revealed that the addition of “aged” sewage sludge to the substrate results in the suppression of growth and development of bioindicator plants due to the presence of pathogenic microflora, fungi, and mold. On the other hand, when “freshly collected” sewage sludge is added to the substrate, plant germination only occurs in samples where the sludge content does not exceed 40 %.

Laboratory tests for assessing the quality of substrates based on soil, sewage sludge, and natural sorbents showed that the addition of natural zeolite to the substrate has a positive effect on the germination of bioindicator plants. The best results were observed in samples with a sludge content of 40 % and zeolite content of 7.5 % and 10 %.

Based on the results of phenological observations and measurements of plant parameters, dependencies of their growth and development, which can be used for biological reclamation, were established depending on different types of substrate. It was found that when using a substrate based on sewage sludge and glauconite for growing barley, the mass of a single plant is 4.4 % higher than in the control sample, and when using a substrate based on sewage sludge and glauconite for growing ryegrass, the average stem height of ryegrass is 3.2 % higher compared to the control sample.

It has been established that the optimal composition for conducting biological reclamation is a substrate with a component ratio of 50 % soil, 40 % sludge, and 10 % natural sorbent.

2.4. Composting for the production of reclamation compost

Laboratory investigations were conducted on composting using sewage sludge as a raw material, both “aged” (collected from sludge fields) and “freshly collected" (directly from wastewater treatment plants after dewatering). The results of the studies are described in (Tymchuk et al., 2020b, Storoshchuk et al., 2022). The research has demonstrated the potential of using sewage sludge in the raw material composition for composting. It has also been confirmed that the addition of wood chips and active compost stimulates the assimilation of ammonia, improves the structure and porosity of the composting mixture, and enhances the free air space, which affects ventilation and nutrient transformation. The changes in key parameters of composting during the process were experimentally investigated and graphically interpreted, including temperature profiles, oxygen content, carbon dioxide, and ammonia levels in the composting mixtures, as well as changes in compost moisture content during composting.

According to the results of sanitary-microbiological studies, the following has been established:

- "Freshly collected" sewage sludge is moderately contaminated with thermophilic microorganisms that play a crucial role in the composting process as they are responsible for the breakdown of organic matter. The highest population of these microorganisms was found in a compost sample consisting of 50 % "freshly collected" and 50 % "aged" sewage sludge.
- Both "aged" and "freshly collected" sewage sludge samples contained bacteria of the Salmonella genus. However, no traces of these bacteria were found in the composting mixtures.
- The highest population of phytopathogenic bacteria was observed in 2–3 year-old sewage sludge samples, but the number of these microorganisms in the composting mixtures was 16–25 times lower compared to the samples of 2–3 year-old sewage sludge.

Based on the analysis of the results of bioindication studies, it has been determined that an optimal universal component for creating a growth substrate is a mixture of "freshly collected" and "aged" sewage sludge in a ratio of 1:1. In this mixture, the above-ground part of the plant is not highly developed, but the root system is extensively branched, allowing for adaptation to various environmental factors. When combined with a small portion of natural sorbents, this mixture can be effective for the reclamation of solid waste disposal sites, minimizing the need for fertile soil layers.

2.5. Preceding anaerobic biodegradation with biogas production for subsequent utilization in digested sludge reclamation

The issues related to the utilization of digested sludge for reclamation purposes were investigated by us in (Malovanyy, Storoshchuk, 2022; Malovanyy et al., 2020). In the fermentation process, an inoculum was used to intensify the biodegradation. The inoculum was selected from the anaerobic reactor of "Enzyme" LLC. It was found that the composition of the inoculum significantly affects the quality indicators of the resulting digested sludge during the fermentation process. The excess moisture was reduced by approximately 22 % before the bioindication studies. It was observed that samples with a higher inoculum content exhibited better moisture reduction compared to samples with a lower content.

The analysis of the digested sludge obtained from the methane fermentation process using thermogravimetric method revealed that the quantity of the inoculum has a significant influence on the decomposition of the organic component. It should be noted that samples containing a higher amount of fermenting inoculum exhibited less thermal stability. The onset of destructive and thermo-oxidative processes in these samples was shifted to lower temperatures during the third stage of thermolysis. Evidently, the increased susceptibility of these samples to thermo-oxidative degradation during the third stage of thermolysis is due to the presence of a greater amount of biologically decomposed products formed during anaerobic fermentation.

The studies regarding the utilization of digested sludge for reclamation purposes have demonstrated that in all investigated variants with digested sludge content, a positive effect on the growth of cultivated plants was observed compared to the control and sterile control. In this case, the limiting factor for digested sludge utilization is its high moisture content (95–98 %), which requires prior dewatering.

3. Conclusions

✓ The most effective methods that can be used for the efficient utilization of organic waste are biotechnological methods, including anaerobic digestion (biogas production), aerobic digestion, composting, and vermicomposting.

✓ In the case of utilizing sewage sludge as a raw material for implementing biotechnological processes, this large-scale waste, which poses a significant environmental threat due to uncontrolled accumulation and uncontrolled biodegradation, could be effectively utilized. Other components of the composition, used as needed along with sewage sludge for preparing materials for reclamation, included food and wood waste.

✓ From the perspective of sewage sludge localization and volumes, there are three strategies for their utilization in compositions with other components for reclamation purposes: creating directly mixed substrates without any physical or chemical transformations of the substrate before application for reclamation; composting to obtain reclamation compost; preceding anaerobic biodegradation with biogas production for subsequent utilization in digested sludge reclamation. We believe that the strategy of organic waste utilization in compositions with sewage sludge should be developed for each sewage sludge localization site and vary depending on the peculiarities of the sewage sludge localization site, the amount of accumulated sewage sludge on sludge fields, the productivity of their formation, the technical possibilities for organizing technological processes of substrate creation for reclamation, the efficiency ranking of substrates in reclamation technologies, and the priority ranking of different forms of these substrates in terms of achieving the goals of the European Green Deal.

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