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PARAMETERS OF AEROBIC BIOCOMPOSTING OF VARIOUS AGE WASTEWATER SLUDGE WITH THE ADDITION OF PLANT RAW MATERIALS

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Abstract. Decades of accumulated wastewater sludge (WWS) at Ukrainian sewage treatment plants (STP) represent a significant environmental hazard. In European countries, the predominant methods for managing sludge at STPs are thermal drying and sludge incineration, both of which come with substantial initial and ongoing expenses. In Ukraine, a more cost-effective and energy-efficient solution is aerobic biocomposting of WWS, resulting in the production of an organo-mineral mixture. Depending on the input sludge, this mixture can be utilized for land restoration and landfill rehabilitation. The capital costs associated with the implementation of biocomposting are 3-5 times lower than for drying and 8-10 times lower than for incineration. The resulting compost contains a sufficient amount of nutrients necessary for plant growth and development. Extensive research has shown that the use of organo-mineral fertilizers derived from WWS increases the humus content and boosts crop yields. Nevertheless, the optimal methods for implementing biocomposting to produce versatile substrates for various biological reclamation projects remain very relevant.

Keywords: aerobic biocomposting, biocompost, biological reclamation, C/N ratio, gas detector-analyzer, thermophilic mode, wastewater sludge (WWS).

1. Introduction

Recently, there has been a significant surge in the production and buildup of industrial waste containing organic components, resulting in the encroachment upon new territories and environmental contamination. Among the types of waste experiencing alarming growth is WWS (wastewater sludge), generated at sewage treatment plants following the biological wastewater treatment phase.[1-3] Consequently, the issue of managing and utilizing this waste is of utmost importance in today's global context. Over the years, untreated WWS has accumulated in overloaded silt areas, landfills, and quarries, causing harm to environmental safety and deteriorating living conditions. An essential aspect of sewage sludge disposal lies in the pre-treatment processes applied to these sludges. These processes encompass stages such as stabilization through lime addition, composting, aerobic/anaerobic conversion, as well as dehydration and drying procedures.[4,5]

The total amount of WWS generated as a result of urban wastewater treatment at the STP is 0.5–1.0% of the total amount of treated wastewater with a sludge moisture content of 97–98%, respectively. During the year, about 1 m^3 of sediment with a moisture content of 97% per equivalent inhabitant is formed. Based on the total actual productivity of STP, about 40–50 million m^3 of WWS with a moisture content of 97% or 1.2–1.5 million tons of sludge in terms of dry matter are generated annually in Ukraine. According to DSTU 8727: 2017,[6] the total amount of accumulated "old" sewage sludge in Ukraine is estimated at 1 billion tons.

Unreclaimed industrial sites such as landfills and dumps represent a considerable environmental hazard when they remain in an unsafe condition. To enhance wastewater treatment, it is advisable to incorporate cutting-edge technologies, with a particular focus on adsorption methods.[7,8] In Ukraine, there is a rising demand for biological reclamation of these spent industrial sites but this undertaking entails substantial resource and financial investments. Consequently, exploring ways to minimize costs and preserve natural resources holds great promise.

Biocomposting of agricultural organic waste derived from animals has gained widespread adoption in Ukraine. In contrast, biocomposting of WWS (wastewater

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sludge) is less prevalent due to lower energy content and potential complications in selling the final product, stemming from the potential presence of various toxic contaminants in WWS. Conversely, many European countries have embraced WWS composting methods, including Hungary, where approximately 78% of sludge is treated using this technology, the Czech Republic at 39%, Germany at 12%, and Poland at 9%.[9,10]

The likelihood of elevated levels of heavy metal compounds and other chemical and biological contaminants in sludge makes it unsuitable for agricultural use. However, it remains suitable for the biological reclamation of disturbed lands.[11,12] Currently, there are no prohibitions on using WWS for agricultural purposes in Ukraine. Nevertheless, in accordance with Regulation EU 2019/1009,[13] which outlines rules for access to the EU fertilizer market, digestate obtained from materials containing WWS is restricted from agricultural use as a fertilizer. Consequently, the primary and promising avenues for the disposal of such products involve their utilization in the biological reclamation of disturbed lands or in forestry.

The management and proper handling of wastewater sludge (WWS) to reduce its negative impact on the environment is a key environmental issue. Nevertheless, the chemical composition of WWS contains a significant amount of organic matter, accounting for approximately 70% of the dry matter weight of the sludge. It also boasts significant concentrations of both macro- and micronutrients. According to Hryshko and Korinovska[14] typical sewage sludge contains roughly 1-3 % nitrogen (N), 1-4 % phosphorus (P), and 0.2-0.7 % potassium (K). However, the precise quantities of these elements can vary based on wastewater composition.[15-17] In addition, WWS contains trace elements such as cobalt (Co), iron (Fe), zinc (Zn), and manganese (Mn), which are important for healthy plant growth and development.[18,19]

These characteristics give grounds to consider MSW as a component of organic-mineral fertilizers for various purposes. An integrated approach to the WWS disposal not only solves environmental problems but also offers economic benefits through the production of secondary raw materials.

As of the year 2022, Ukraine has already established key regulatory documents that promote the widespread use of recycled WWS as components of organo-mineral mixtures. This regulatory framework has been in place in Ukraine since 2014 and is specifically set out in DSTU 7369:2013.[20] In addition, a more specialized DSTU 8727:2017 came into force on April 1, 2018.[6] These regulatory documents define the basic requirements for the preparation, processing, and decontamination of WWS through biothermal composting. They also specify the methodology for calculating the permissible doses of organo-mineral mixtures containing WWS as fertilizers, with a focus on pollutant content.

Furthermore, the utilization of biothermal composting facilities is exceptionally rare in the operational procedures of Ukrainian sewage treatment plants (STP).

Therefore, it becomes necessary to develop more comprehensive scientific and practical recommendations for the WWS processing through aerobic composting. These guidelines should take into account many factors, including moisture level, chemical and bacteriological composition of WWS, age of WWS (especially relevant for the disposal of old sludge accumulated in sludge sites), type and parameters of available plant-based materials, conditions governing the biocomposting process, type of aeration, its frequency and intensity, humidification level, and dosage and concentration of specialized additives. These additives may include thermophilic microorganisms to intensify the process and enhance biodegradation, as well as specific chemicals designed to convert heavy metal ions into complex, inert compounds.

2. Experimental

2.1. Materials and Methods

The initial material for this study consisted of mechanically dehydrated WWS, which was obtained at the mechanical dehydration plant of Lviv STP through the centrifugation of a mixture containing raw sludge and excess activated sludge. Subsequently, this sediment was called “new WWS” (abbreviated as WWS_{new}). The impact of old WWS (WWS_{old}) on the biocomposting process was investigated for one of the feedstock mixtures. An old WWS sample was collected from the existing sludge site at Lviv STP, with an indicated age of 2.5 ± 0.5 years based on the logbook records. Wood chips were employed as plant-based fillers in these experiments. To expedite the development of the biocomposting process in all experimental formulations, actively composting material aged around 2 weeks was incorporated, sourced from the middle section of compost piles at the biocomposting station LCE “Green City”.

For laboratory composting, four different feedstock mixtures were prepared (Table 1): three mixtures (№1 – №3) with different volume fractions of WWS and mixture №4 – control mixture of active compost.

In laboratory experiments, the initial approach was to use whole values of the filler (wood chips) to WWS volume ratio. In particular, two compositions were tested, one with a ratio of 1:1 and another with a ratio of 2:1. To assess the influence of old WWS on the biocomposting process, a mixture with a filler : WWS" ratio of 1:1 (referred to mixture №3) was chosen, wherein half of the sediment consisted of new WWS, and the other half was composed of old WWS.

Table 1. Mass and mass fractions of the mixture components at the beginning of process in the laboratory conditions

Mixture number	Mass, kg					mass fraction			
	WWS_{new}	WWS_{old}	Wood chips	Active compost	Total	WWS_{new}	WWS_{old}	Wood chips	Active compost
1	2.760	0	0.9426	1.712	5.414	0.510	0	0.174	0.316
2	3.680	0	0.628	2.282	6.590	0.558	0	0.095	0.346
3	1.840	1.840	0.628	2.282	6.590	0.279	0.167	0.095	0.346
4	0	0	0	6.846	6.846	0	0	0	1.000

Table 2. Initial humidity of mixtures at the beginning of composting in laboratory conditions

Mixture number	Density, kg/m^3	The mixture weight, kg	The water weight in the mixture, kg	The DC mixture weight, g	Humidity of the mixture, wt%	Part of DC, %
1	443.2	5.492	3.387	2045	63.1	37.8
2	555.1	6.576	4.294	2225	67.0	33.8
3	550.7	6.627	4.356	2225	66.1	33.8
4	571.6	6.912	4.088	2739	60.8	40.0

The initial temperature of the mixtures prepared for composting was 27.0 °C. The initial humidity of the mixtures was within the range of 60.8-67 wt% (Table 2).

All mixtures were thoroughly mixed to homogenize their structure and intensify the composting process. In Table 3 the distribution of dry compounds' (DC) weight by components of the mixtures is shown.

Critical parameters under observation throughout the experiment included the levels of organic carbon and nitrogen, along with their computed quantities in the four examined mixtures. The calculated C/N ratios at the beginning of the biocomposting process are shown in Table 4. Estimated concentrations of organic carbon and nitrogen in WWS and wood chips were obtained on the basis of average values established in previous studies on similar raw material.[21,22]

The laboratory biocomposting unit consists of a TCP-0105 thermostatic device equipped with a tubular electric heater with a maximum power of 3.0 kW, a temperature controller, a stirrer, and a resistance thermocouple. The working space of the thermostat is 250 dm^3 (Fig. 1).

The aerobic composting experiment lasted 60 days and was carried out in four sealed plastic bioreactors with a volume of 20 dm^3 each, tightly closed with lids. Initially, the volume of the compost mixture in each bioreactor was set at 12 dm^3, which is 60% of their total capacity. To minimize energy consumption, the four reactors were placed inside a temperature-controlled tank filled with water. The temperature of the water bath was regulated by a thermostat to ensure uniform temperature distribution in the tank by means of a stirring mechanism. Temperature and humidity sensors (3 in total) were attached to the inside of the bioreactor lids. These sensors were connected to a digital eight-channel temperature and humidity meter VTV-118-4.

Table 3. Distribution of mixtures' dry matter at the beginning of composting by components

Mixture number	Weight of dry compounds, kg			
	WWS	Active compost	Wood chips	Total
1	0.612	0.690	0.768	2.070
2	0.795	0.928	0.499	2.222
3	0.795	0.944	0.499	2.238
4	0	2.811	0	2.811

Table 4. Estimated values of the carbon and nitrogen ratio (C/N, w/w) in the mixtures before their biocomposting

Mixture number	Carbon weight, kg				Nitrogen weight, kg				C/N ratio of compound
	WWS	Active compost	Wood chips	Total	WWS	Active compost	Wood chips	Total	
1	0.1523	0.2043	0.3576	0.7142	0.0192	0.0129	0.0019	0.034	21.005
2	0.2032	0.2743	0.2392	0.7167	0.0249	0.0179	0.0013	0.0441	16.252
3	0.2020	0.2751	0.2392	0.7162	0.0256	0.0191	0.0014	0.0461	15.536
4	0.0	0.8302	0.0	0.8302	0.0	0.0551	0.0	0.0551	15.067

Fig. 1. Photo of experimental laboratory unit

To facilitate air circulation inside the bioreactor, the bioreactor lids have two equidistant holes with a diameter of 5 mm. The mounting frame inside the thermostat ensured complete immersion of the test objects. Aeration was achieved by intensive stirring of the compost in the reactors for 20 seconds once a day. The composting process was carried out with the windows open to ensure natural aeration.

The temperature of the compost mixture was measured once a day, immediately after measuring the composition of the gas mixture, by inserting laboratory thermometers (TL-4 and TGL 11998) into the mixture at the same depth from the bottom of the bioreactor. To avoid the rapid temperature decrease observed in small-volume reactors,[23] we fixed the set temperature to implement the thermophilic composting regime by modeling the corresponding temperature dynamics inside the full-scale compost pile. The thermophilic mode of biocomposting lasted 5-7 days, which is sufficient to destroy most pathogenic microorganisms, after which the temperature was gradually reduced.

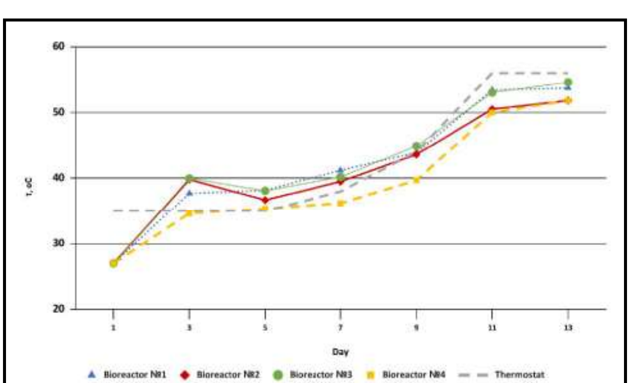
Gas analysis within the bioreactors involved daily measurements using a gas detector-analyzer known as DOZOR-C-M-5. This analyzer has the capability to determine the presence of five gases in the air, including oxygen (O_2), methane (CH_4), carbon dioxide (CO_2), ammonia (NH_3), and hydrogen sulfide (H_2S). The time required for measurements in the different channels was as follows: NH_3 and H_2S - 3 minutes, CO_2, O_2, and CH_4 - 1.5 minutes. To determine the O_2 content, its minimum value is recorded in bioreactors (to ensure the necessary conditions for aerobic composting), and the maximum value of CO_2 is recorded. It is believed that for the composting process, the oxygen concentration should be in the range of 15-20%. Adequate aeration at an early stage of composting reduces the process time, which leads to the oxidation of carbon (C) to carbon dioxide (CO_2) and reduces methane emissions.[24]

3. Results and Discussion

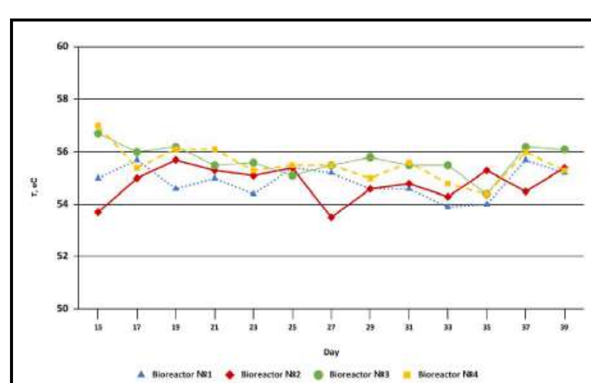
3.1. Temperature Indicators

Temperature is one of the main factors affecting the anaerobic composting process. In Fig. 2 one can observe the temperature profiles for the different compost mixtures tested in the four bioreactors. The experiment started at a water temperature of 35°C in the thermostatically controlled tank, which corresponds to the average temperature for mesophilic aerobic composting.

Initially, the temperature of the compost mixture was significantly lower than the thermostat temperature. However, starting on the second day of the experiment, the temperature in the test mixtures (No.1, 2, and 3) exceeded the water temperature in the thermostat. This shift indicates a rapid acceleration of organic materials decomposition by aerobic microorganisms, accompanied by significant local release of heat.



a



b

Fig. 2. Change in temperature of compost mixtures in bioreactors: a) from 1 to 14 days; b) from 15 to 40 days

After 2 days from the beginning of the experiment, the inside temperature was 37.7 ^oC in mixture No.1, 39.8 ^oC in No. 2, 40.0 ^oC in No. 3, and 34.6 ^oC in No.4, which corresponds to a significant positive temperature difference ΔT in mixtures 1–3 ($\Delta T1$ = +2.7 ^oC; $\Delta T2$ = +4.8 ^oC; $\Delta T3$ = +5.0 ^oC); only in the control mixture No. 4 the temperature difference of active compost was negative ($\Delta T4$ = -0.4 ºC), which is an indirect evidence that the most intensive phase of aerobic composting in the control active compost has already taken place in nature, in the biocomposting station.

3.2. Oxygen Content in Bioreactors

The minimum concentration of O_2 in biocompost mixtures decreased slightly in the first week of the experiment (Fig. 3) but then increased and remained constant, which indicates and confirms the aerobic conditions of biocomposting.

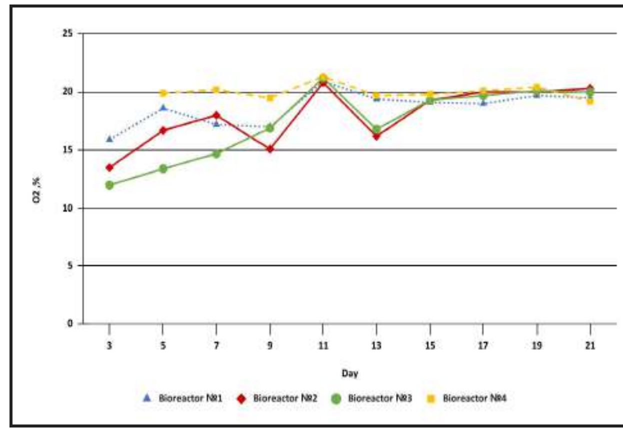


Fig. 3. Changes in the volume fraction of oxygen in the gaseous medium of bioreactors

Figs. 4-7 show the correlation of changes in the temperature of compost mixtures (No. 1, No. 2, No. 3, and No. 4) and the oxygen content in them over time.

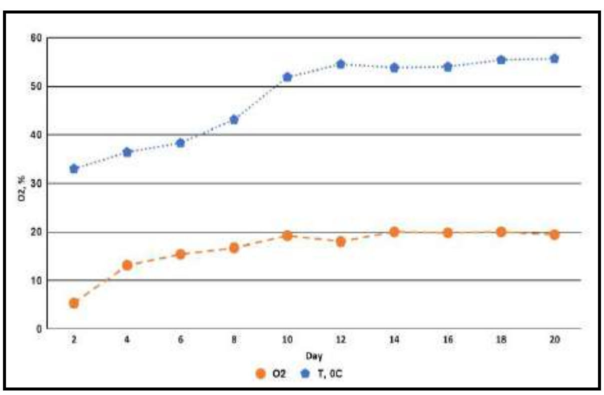


Fig. 4. Change in temperature and O_2 content of compost mixture No.1 over time

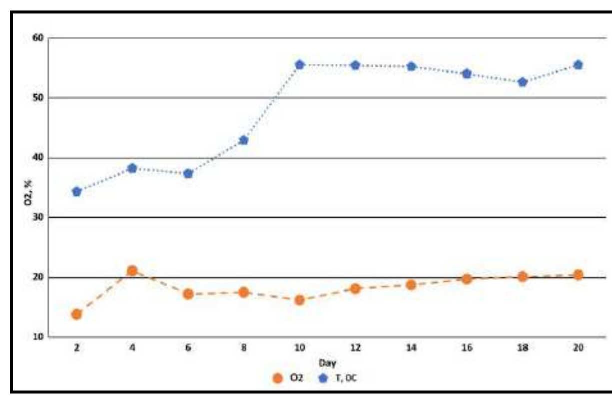


Fig. 5. Change in temperature and O_2 content of compost mixture No.2 over time

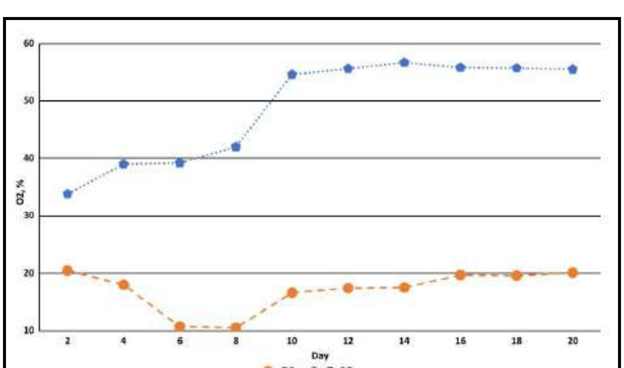


Fig. 6. Change in temperature and O_2 content of compost mixture No.3 over time

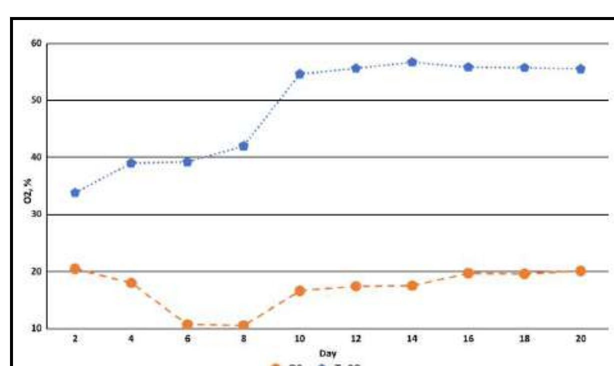


Fig. 7. Change in temperature and O_2 content of compost mixture No.4 over time

3.3. The Content of Carbon Dioxide in Bioreactors

The change in CO_2 content (% vol.) inside the bioreactors 1–4 is presented in Fig. 8. In the first bioreactor with the highest wood chip content, the maximum CO_2 content of 6.7 vol. % is observed in the period from 1 to 5 days of research. The bioreactor No.2 shows maximum CO_2 content of 6.7 vol. % after the first 3 days.

From the 15th day, stable values of CO_2 content (0.5–1.5 vol. %) were observed in all bioreactors.

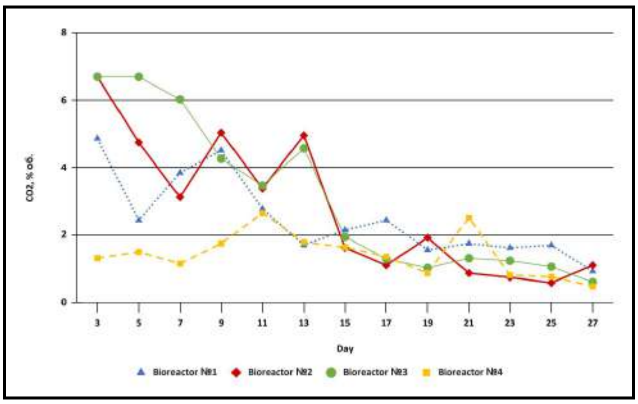


Fig. 8. Changes in CO_2 content in bioreactors

3.4. Ammonia Concentration in Bioreactors

Fig. 9 shows that NH_3 content increased in the bioreactors No.2 and No.1 on the 7th and 9th day of composting, respectively, and reached a maximum on the 15th day.

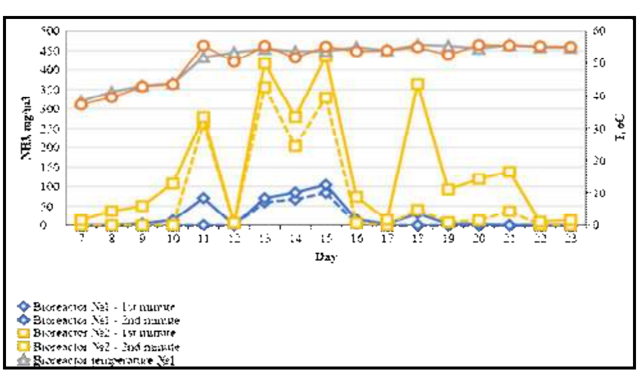


Fig. 9. Changes in NH_3 content in bioreactors №1 and №2

The increase in NH_3 concentration indicates the initial phase of decomposition of organic nitrogen compounds during composting. After reaching the peak, the NH_3 level began to decrease.

In bioreactors No.3 and No.4, no NH_3 content was recorded, indicating that the addition of wood chips and active compost improved ammonia absorption and improved the structure and porosity of the compost mixture.

3.5. Moisture Content of Compost Mixtures

Typically, moisture levels decrease during the thermophilic phase due to the combined effects of elevated temperatures and aeration. In this case, the initial moisture content (equivalent to 68% wet weight) decreased. To assess the degree of water evaporation in the bioreactors, a practical approach was used, involving drying the samples in a thermostat. In addition, periodic watering was carried out to maintain an optimal level of moisture in the compost mixture.

4. Conclusions

The results of laboratory experiments on biocomposting of sewage sludge show promising possibilities of including WWS in the feedstock mixture. Furthermore, the results indicate that the addition of wood chips and active compost improves ammonia absorption and promotes microbial nitrification. This improvement leads to an improved compost structure, increased porosity, and increased free air space, which has a positive effect on ventilation and nutrient transformation. The compost produced by this method can be used for the biological reclamation of disturbed industrial areas such as landfills, abandoned quarries, *etc*.

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ПАРАМЕТРИ АЕРОБНОГО БІОКОМПОСТУВАННЯ ОСАДІВ СТІЧНИХ ВОД РІЗНОГО ВІКУ З ДОДАВАННЯМ РОСЛИННОЇ СИРОВИНИ

Анотація. *Десятиліттями накопичені осади стічних вод (ОСВ) на каналізаційних очисних спорудах (КОС) України становлять значну екологічну небезпеку. У європейських країнах переважними методами поводження з осадом на очисних спорудах є термічне висушування та спалювання осаду, які потребують значних початкових і поточних витрат. В Україні економічно вигіднішим та енергоефективнішим рішенням є аеробне біокомпостування осадів стічних вод, у результаті якого утворюється органо-мінеральна суміш. Залежно від вхідного осаду, ця суміш може бути використана для рекультивації земель і рекультивації полігонів. Капітальні витрати, пов'язані з впровадженням біокомпостування, у 3-5 разів нижчі, ніж при сушінні, й у 8-10 разів нижчі, ніж при спалюванні. Отриманий компост містить достатню кількість поживних речовин, необхідних для росту і розвитку рослин. Широкі дослідження показали, що використання органо-мінеральних добрив, отриманих із ОСВ, збільшує вміст гумусу та підвищує врожайність сільськогосподарських культур. Тим не менш, пошук оптимальних методів впровадження біокомпостування для виробництва універсальних субстратів для різних проектів біологічної рекультивації залишається дуже актуальним.*

Ключові слова: *аеробне біокомпостування, біокомпост, біологічна рекультивація, співвідношення C/N, газовий детектор-аналізатор, термофільний режим, осад стічних вод (ОСВ).*