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Assessment of the Agronomic Value of Organic Fertilizer Made of Composted Sludge

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ABSTRACT

The study presents data on changes in the chemical composition of sludge in Astana (Republic of Kazakhstan) during composting with the addition of wheat straw and microbial biological preparations. The purpose of this study was to evaluate the agronomic value of sludge compost as a fertilizer. The specific hypotheses tested in this study were: (1) the addition of different biological preparations will improve the quality of the compost, enhancing its nutrient content (nitrogen, phosphorus, potassium), and (2) the incorporation of wheat straw will reduce nitrogen losses during composting by increasing the carbon-to-nitrogen ratio. Quantitative changes in the chemical components of compost from a mixture of sludge and wheat straw during composting were studied. The pH of the sludge increased during the first 10 days of composting and then decreased. In almost all samples, the amount of total phosphorus and potassium increased up to 2 times during composting. Losses reached up to 35% of the initial nitrogen, as a result of nitrogen volatilization. The addition of straw helped to reduce nitrogen losses during the active phase by increasing the carbon-to-nitrogen ratio in the initial mixtures.

1. INTRODUCTION

Sustainable environmental development allows the conservation of natural resources and biodiversity [1] and ensures the stability of ecosystems and the viability of the environment on a long-term basis [2]. Considering environmental challenges, the principles of sustainable development have become increasingly relevant in recent years. Thus, considerable attention is paid to the processing of organic waste as an environmentally friendly disposal and an alternative to chemical fertilizers [3].

One of these alternatives is the byproducts of urban wastewater treatment, i.e., sludge. Considering that sludge deposits are rich in organic matter, they are a good raw material for composting.

Composting is a complex procedure involving a sequence of different chemical processes. This is an aerobic process in which microorganisms use organic substances for metabolism and biologically decompose waste into stable humic components [4]. Composting is becoming a more attractive alternative to wastewater sludge disposal due to its advantages over traditional methods such as burial, incineration, and discharge into the ocean, which allows for reuse of the resources contained in the sludge and is consistent with the principles of sustainable development [5]. Composting sludge can effectively break down decomposing organic matter into a stable end product, which can then be used as a fertilizer for the soil.

The material obtained after composting sludge has the necessary content of phosphorus (P), nitrogen (N), and potassium (K) in amounts not less than traditional organic fertilizers. Compost mixtures can be used for land reclamation, fertilizing industrial crops, and long-term pastures. Due to the versatility of the use of fertilizers from sludge, the resulting material is already actively used in agriculture.

There are the following features of the use of sludge compost:

(1) Untreated sludge contains pathogenic organisms and toxic substances. However, the metabolic heat released during the thermophilic phase of the composting process effectively destroys them, and the final product can be safely used for application to the soil [6];

(2) The resulting compost has positive effects on growing crops, like stimulating plant growth, retaining moisture, increasing the amount of organic matter in the soil, and controlling erosion [7].

The applicability of sludge compost for agricultural use is limited by the content of heavy metals [8]. Domestic, commercial, and industrial discharges contain metals, which subsequently enter the sludge through wastewater. The high content of heavy metals, especially those obtained from industrial sources, can cause their accumulation and toxicity to plants growing in soils enriched with sludge. There are various approaches to reducing biologically available fractions of heavy metals. Thus, soil pH is the main factor regulating the availability of heavy metals and the rate of their absorption by plants [9]. Therefore, before applying to the soil, it is necessary to carry out full quality control of compostable materials.

For aerobic composting of sludge, the choice of filler is important. According to research [10], fillers affect the final mineral composition of the resulting compost.

Moisture-absorbing organic materials are used as the base filler of composting (most often this is waste from the wood processing industry and agriculture, like sawdust, bark, and straw of cereals). These materials simplify the supply of oxygen to the compostable mass, which is crucial in the intensification of the processes of mineralization of organic substances [11]. The choice of straw as a filler increases the flowability of the compost and its uniformity during the pre-grinding of the filler.

The present study was conducted to study the agronomic qualities of the final product of aerobic composting of sludge with straw as a filler. The purpose is to determine the effectiveness of using the thermophilic composting method for organic waste processing.

2. MATERIALS AND METHODS

A concrete platform located on the territory of the Astana Su Arnasy Republican State Enterprise with the Right of Economic Management was used to form the heaps under evaluation. Dehydrated sludge and crushed wheat straw were used as raw materials.

We used the aerobic method of composting sludge, and the parameters of the compost mixture and the speed of the composting process were determined depending on the type of biological preparation.

With the help of special equipment, eight heaps were formed (1.5m wide, 1m high, and 10m long), the total dry weight of each heap was 12-15t, and the moisture content of the heap was 60%. According to the experiment design, wheat straw and biological preparations were added and mixed. A BELARUS-80.1 tractor and a trailed agitator were used to mix the heaps.

The experiment was conducted according to the following scheme:

Variant 1. The control variant (sludge without biological preparations);

Variant 2. Sludge+straw (10%) + biological preparation Trichodermin SS (1 l/t);

Variant 3. Sludge+straw (20%) + biological preparation Trichodermin SS (1.5 l/t);

Variant 4. Sludge+straw (10%) + biological preparation Agromix SS (2 l/t);

Variant 5. Sludge+straw (20%) + biological preparation Agromix SS (2 l/t);

Variant 6. Sludge+straw (10%) + Consortium B (1 l/t);

Variant 7. Sludge+biological preparation Micromix (1 l/t);

Variant 8. Sludge+straw (10%) + Consortium A (1 l/t).

The specific combinations and concentrations of sludge, straw, and biological preparations were chosen based on preliminary studies and literature reviews that indicated their potential effectiveness in enhancing compost quality (Tables 1 and 2).

Table 1. Chemical composition of compost raw materials before composting

Name	Moisture, %	Organic Matter, %	Name of the Chemical, %		
			N	P	K
Straw	13.02	92.7	0.56	0.3	1.53
Sludge	65	43	6.2	0.8	0.2

The use of biological preparations in composting has been widely documented to enhance the breakdown of organic matter and improve nutrient retention [12].

Table 2. Composition of biological preparations

Name of the Biological Preparation	Composition
Trichodermin SS	*Tr. lignorum, Tr. alb.*
Agromix SS	*Streptomyces sindenensis* strain PM9, *Streptomyces griseus* strain PM25, *Bacillus aryabhattai* strain PM62, *Bacillus aryabhattai* strain PM68, *Bacillus aryabhattai* strain PM69, *Bacillus megaterium* strain PM80B, *Lentzea violacea* strainPM86B
Micromix	*Streptomyces pratensis, Bacillus mesentericus, Azotobacter chroococcum*
Consortium A	*Bacillus cereus* strain No.8, *Bacillus megaterium* strain No.10, *Rhizobium pusense* strain No.25, *Sphingomonas paucimobilis* strain No.49, *Streptomyces graminearus* strain *No.61*, *Pseudomonas protegens* strain No. 62, *Pseudomonas marginalis* strain No. 64, *Streptomyces albidoflavus* strain No. 81, *Pseudomonas fluorescens* strain No. 83 *Pseudomonas putida* strain No. 87
Consortium B	*Pseudomonas protegens* strain No. 62, *Pseudomonas marginalis* strain No. 64, *Pseudomonas fluorescens* strain No. 83, *Pseudomonas putida* strain No. 87, *Bacillus cereus* strain No. 8, *Bacillus megaterium* strain No. 10

Studies have shown that adding carbon-rich materials, such as straw, can significantly reduce nitrogen losses and improve the stability of compost [13, 14].

The heaps were treated with several biopreparations with a titer of 10^6 colony-forming units (CFU)/ml mixed with water in a ratio of 1:4. Biological preparation solutions were used in the amount of 5 l/1 t of sludge. A sprayer mounted on the agitator was used to apply the biological preparations. The temperature and pH of the heaps were measured daily, and the humidity and chemical composition of the composted mass were monitored once every ten days.

Temperature changes in compost heaps were monitored using a mercury thermometer. The pH of the compost sample was determined using a pH meter using a suspension in a sample-to-water ratio of 1:10. The compost samples were dried and sieved to a size of less than 0.25mm. The organic matter content was determined by measuring the dry matter mass loss in a muffle furnace at 550°C for 6 hours. The total N content was determined using the Kjeldahl method. The total P content was determined using the colorimetric method with vanadomolybdophosphoric acid, and the total K content was determined by photometry with flame emission after wet digestion [15, 16]. Atomic absorption spectrophotometry using flame was used to determine the available fraction of heavy metals in the final compost. All experiments were carried out in a three-fold repetition. Humidity was determined by drying: the sample was kept at a temperature of 70±5°C for 24 hours [17].

3. RESULTS

3.1 Temperature, pH, humidity

During the composting process, changes in color, volume, humidity, odor, and texture of the contents of the heaps were monitored. Changes in the temperature of compost mixtures showed different results depending on their composition. The heaps passed three stages of composting: mesophilic, thermophilic, and maturation stage.

In the composting process, temperature variability plays an important role in the formation of microbial communities, improving sanitation, biological degradation rates, and microbial diversity. During the first week of composting, a rapid increase in temperature was observed. Significant differences in the average daily temperature were observed between the studied variants (Figure 1).

When composting sludge, the pH of the heaps was determined every 10 days. The initial pH values for all variants were neutral. During the first 10 days, the pH increased to a maximum of 8.0. By the 20th day, the pH had gradually decreased and stabilized at 6.5-6.7.

During composting, the moisture level in all the heaps gradually decreased to 20 days; on the 10th day, water was added to the heaps to maintain humidity within the recommended values (40-50%). At the end of composting, a significant decrease in volume and weight was recorded in all heaps. The fully matured compost had a low moisture content (about 10%), which is necessary to stabilize the compost material.

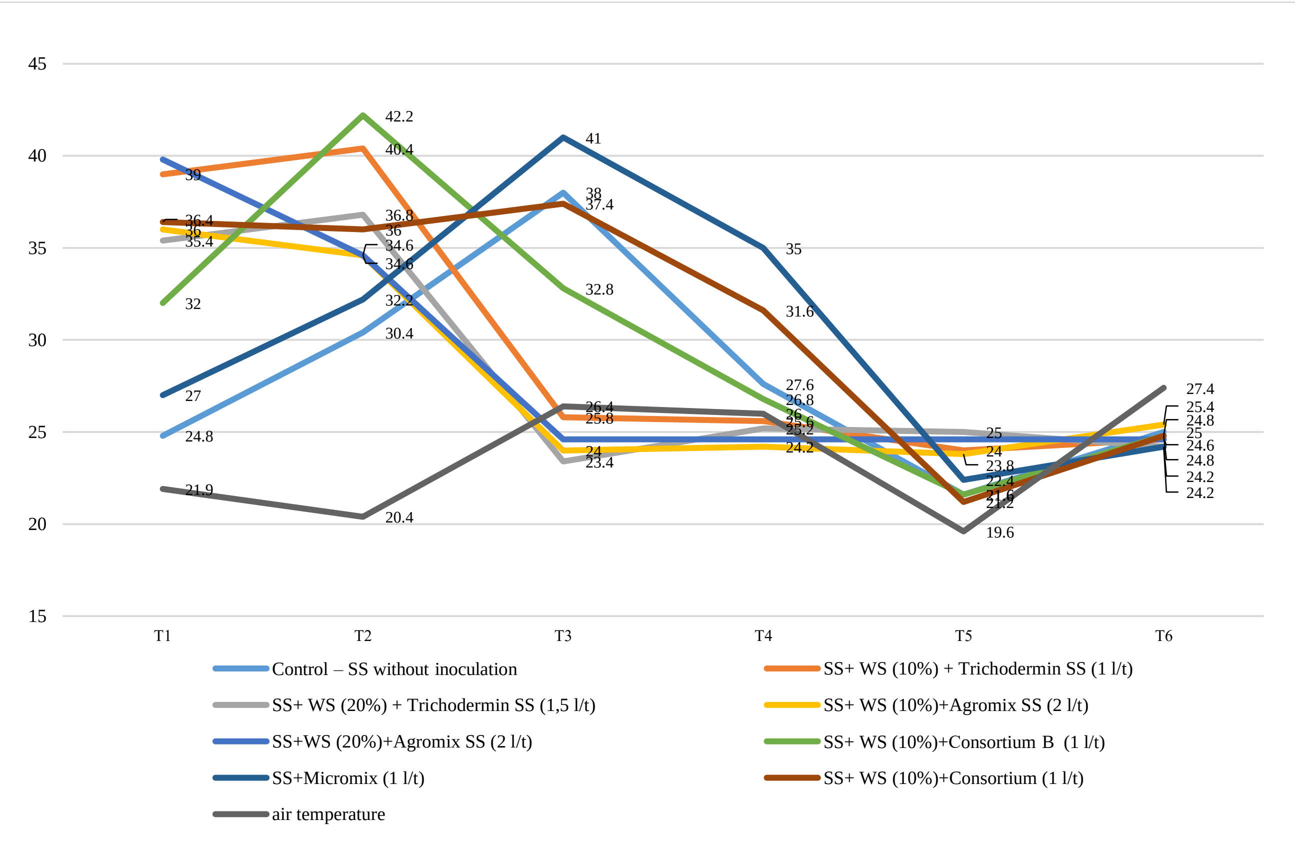

Figure 1. Temperature change in the study variants during the composting period

Table 3. The resulting amount of N and C in sludge

Version	N, %			C, %		
	10 Days	20 Days	30 Days	10 Days	20 Days	30 Days
Control variant (sludge without biological preparations)	2.361	2.115	1.461	36.85	36.54	36.076
Sludge +straw (10%) + biological preparation Trichodermin SS (1 l/t)	2.541	1.4396	1.2026	38.8	39.833	36.573
Sludge +straw (20%) + biological preparation Trichodermin SS (1.5 l/t)	2.824	0.8663	1.3516	40.76	37.86	37.766
Sludge +straw (10%) + biological preparation Agromix SS (2 l/t)	2.361	1.31	0.85	40.00	39.726	38.553
Sludge +straw (20%) + biological preparation Agromix SS (2 l/t)	2.954	0.71	0.9573	38.685	37.243	37.8493
Sludge +straw (10%) + Consortium B (1 l/t)	2.541	0.9033	1.123	39.88	38.136	37.466
Sludge +biological preparation Micromix (1 l/t)	2.371	2.4366	2.2383	40.825	36.406	36.302
Sludge +straw (10%) + Consortium (1 l/t)	2.364	1.282	1.1413	37.15	38.063	36.603
Least significant difference (LSD)	0.23	0.17	0.16	2.96	2.5	2.34

3.2 N and C

Sludge deposits before composting were characterized by a high content of organic matter (48%). The N and P content was also high. Their content was 5.2 and 1.1%, respectively. The K content did not exceed 0.2%, and this type of fertilizer is characterized by a low K content. When using sludge as a fertilizer, the lack of K is compensated by enriching it with mineral fertilizers.

The N and carbon (C) content after sludge composting are shown in Table 3.

During the first 10 days, a large loss of N was observed, from 35.4 to 54.6%. The greatest losses were found in the variants using biological preparations Agromix SS, Trichodermin SS, Consortium A, and Consortium B. N losses had a high rate as the temperature of the heaps increased to 50-60℃. The total N content increased from 22 to 75% after 30 days of composting in experimental variants using 20% straw and microbial Consortium B. In the control variant, a decrease in the total N content by 28.5% was observed after 20 days, which is because the thermophilic phase in this variant occurred much later than in the other variants.

The main C loss also occurred in the first 10 days due to the high activity of aerobic and anaerobic microbes. Initially, large emissions of CH_4 may occur due to the presence of anaerobic microflora in the compost raw materials. Initially, the compost mass accumulates and compacts, preventing the penetration of O_2. At this time, an optimal anaerobic environment for CH_4 emissions is created. In the process of mixing the heaps, enrichment with O_2 promotes the growth of aerobic microorganisms, increases CO_2 emissions, and reduces CH_4 emissions. A decrease in CO_2 emissions is observed during the cooling of the heaps and their maturation, which indicates the stability of mature compost.

3.3 P and K

The P concentration in all variants increased at the end of the storage process due to the mineralization of organic matter. The proportion of total P after composting ranged from 0.721 to 1.683%. The maximum concentration values of this element were observed in the variant using the biological preparation Micromix. In the variant with the biological preparation Micromix, the increase equaled 2.4 times, in the control variant 2 times, in compost with microbial consortia A and B 25%, and the smallest amount was recorded in the variant with Agromix SS+straw (20%). Besides, the total K content corresponded to the trend of changes in the total P content in all variants (Table 4).

Table 4. The resulting P and K content in compost

Variant	P, %			K, %		
	10 Days	20 Days	30 Days	10 Days	20 Days	30 Days
Control variant (sludge without biological preparations)	0.668	1.284	1.459	0.434	0.556	0.530
Sludge +straw (10%) +biological preparation Trichodermin SS (1 l/t)	0.807	0.847	0.824	0.430	0.461	0.293
Sludge +straw (20%) +biological preparation Trichodermin SS (1.5 l/t)	0.499	0.699	0.933	0.438	0.506	0.387
Sludge +straw (10%) +biological preparation Agromix SS (2 l/t)	0, 627	0.720	0.961	0.529	0,511	0.441
Sludge +straw (20%) +biological preparation Agromix SS (2 l/t)	0.852	0.730	0.721	0.706	0.560	0.381
Sludge +straw (10%) +Consortium B (1 l/t)	1.446	0.593	0.944	0.639	0.983	0.368
Sludge +biological preparation Micromix (1 l/t)	1.409	1.256	1.683	0.618	0.647	0.789
Sludge +straw (10%) +Consortium (1 l/t)	0.972	0.609	0.947	0.620	0.448	0.595
LSD	0.134	0.135	0.078	0.73	0.09	0.103

Table 5. The resulting heavy metal content in compost

Variant	Ni, mg/kg	Cu, mg/kg	Zn, mg/kg	Cd, mg/kg	Hg, mg/kg	Pb, mg/kg
Maximum permissible concentration (MPC) for the Republic of Kazakhstan	200.0	750.0	1,750.0	15.0	7.5	250.0
MPC for the European Union	300.0	1,000.0	2,500.0	20.0	16.0	-
Control variant (sludge without biological preparations)	46.81	115.35	769.94	0.55	0	13.62
Sludge +straw (10%) +biological preparation Trichodermin SS (1 l/t)	17.16	82.9	575.58	0.77	0.9	10.28
Sludge +straw (20%) +biological preparation Trichodermin SS (1.5 l/t)	17.47	105.87	739.43	0.59	0.33	12.98
Sludge +straw (10%) +biological preparation Agromix SS (2 l/t)	38.28	93.47	703.13	1.07	0	13.75
Sludge +straw (20%) +biological preparation Agromix SS (2 l/t)	36.81	105.10	720.94	0.69	0	13.71
Sludge +straw (10%) +Consortium B (1 l/t)	44.29	104.95	735.19	0.53	0.95	12.41
Sludge +biological preparation Micromix (1 l/t)	61.47	122.78	916.65	0.65	0.64	16.42
Sludge +straw (10%) +Consortium (1 l/t)	60.4	101.16	679.91	0.53	0.87	19.78
LSD	3.95	4.5	30.79	0.17	0.08	1.73

At the beginning of composting, the amount of total P increased by 27% from the initial value in the variants using microbial consortium B and Micromix biological preparation. In other versions of the experiment, a decrease in total P was observed. Over the next 10 days, the amount of P in the control variant increased by 92%, in the variants using biological preparation Trichodermin SS + 20% straw and biological preparation Agromix SS + 10% straw, the increase equaled 40 and 15%, respectively. As the total weight of the heaps decreased after composting, an increase in the total P content from 14 to 34% was observed in most experiments.

3.4 Heavy metals

Before composting into the soil, it becomes necessary to determine the concentration of toxic metals in the final compost. The values obtained as a result of the study are presented in Table 5.

According to the total heavy metal content, the compost meets the requirements for the content of sludge used for fertilizing crops, according to standard 2578-2014 of the Republic of Kazakhstan [18]. The requirements for the content of heavy metals in sludge used to fertilize agricultural land in the Republic of Kazakhstan differ from the requirements of the Directive for the EU, but the content of heavy metals in the resulting compost also does not exceed the permitted standards for the EU.

4. DISCUSSION

With biological preparations like Agromix SS, Trichodermin SS, Consortium A, and Consortium B, the temperature in the heaps increased rapidly in the mesophilic phase and reached its maximum value in the thermophilic phase that was formed as a result of the degradation of simple molecules due to the active action of microbes distributed in the compost mixture.

Temperatures below 60°C in the thermophilic phase are unsuitable from the point of view of sanitary disinfection. The American scientist P.D. Millner proved that coliform bacteria, streptococci, and salmonella were destroyed at a temperature of 60°C within 48 hours, and pathogenic microflora was preserved in variants with a composting temperature of less than 50°C [19]. The study confirms the important role of constant temperature control during the thermophilic phase to reduce pathogenicity.

Standard-compliant high temperature (>60°C) was preserved for 7 days in variants with a straw content of 10%. A similar trend of temperature change was observed in the heaps containing 20% of straw. However, in these heaps, the maximum temperature during the thermophilic period reached 55°C. Moreover, the temperature increase lasted for 9 days, which was longer than in the heaps using straw in the amount of 10%. Perhaps this is because, in heaps containing 20% of wheat straw, the decomposition of organic matter takes longer. This situation can lead to a longer thermophilic phase. During the maturation period, the temperature in the heaps gradually decreased. At the end of the experiment, the temperature in all variants had reached ambient temperature, which indicates the maturity of the compost.

The findings of this study align with previous research on sludge composting. For instance, Ajmal et al. [20] reported that maintaining high temperatures during the thermophilic phase is crucial for effective pathogen reduction and organic matter decomposition. Also, Xu et al. [21] observed that the addition of organic materials like straw can extend the thermophilic phase, enhancing compost stability and nutrient content.

The increase in pH in the compost to alkaline values in the first 10 days of the experiment is explained by the release of ammonia and mineralization of organic nitrogen as a result of microbial activity. A decrease in pH by day 20 may be caused by the evaporation of ammonia N during the thermophilic period, the transition of mesophilic microflora to thermophilic, and aeration. The pH value of the final fertilizer (6-8.5), which includes the values of 6.5-6.7 obtained in the study, indicates good compost quality from an agricultural point of view. These values have been recommended in several studies [22].

Checking the moisture content of the stored material is also very important for obtaining high-quality compost material. For the development of microorganisms, a moist, steam-filled environment is necessary. That is why it is necessary to maintain low compost humidity, which slows down the decomposition processes carried out by microorganisms and prevents the temperature in the heaps from rising. Excess moisture in the compost displaces air, creates an anaerobic environment, and leaches nutrients.

However, during the thermophilic period, as a result of the evaporation of water during microbial heat generation, the humidity level decreases to values lower than the recommended ones (40-50%). Moisture loss also occurs during the aeration of compost mixtures. Keeping the heaps moist during the composting process prevents them from drying out and reduces N losses.

The main way of N loss from compost is the evaporation of ammonia (NH_3), which leads to the loss of up to 50% of nitrogen from the initial amount in the compost [23]. In the experiment performed by Tiquia et al. [24], a researcher from the USA, 37-60% of the initial N in the compost was lost as a result of volatilization of NH_3. Some studies have also reported significantly lower N content in composted sludge (1.30%) than in stored sludge (1.98%), indicating significant losses during the thermophilic phase [25, 26]. Goyal et al. [27] noted that the decrease in the total N content at the initial stages of decomposition of organic waste was explained by its loss in the form of ammonia, which, in turn, depends on the type of material and its C-to-N ratio. In addition, some studies have examined the effect of storage temperature on NH_3 consumption. Pagans et al. [28] confirmed that NH_3 emissions increased with increasing temperature.

N losses are reduced by adding materials rich in available C. In this study, variants with a straw content of 20% by weight had the lowest proportion of total N content in the first ten days, 42%-46% of the initial values. The greatest loss of N, equal to 56%, was found in the variants of the experiment without straw, and the lowest among variants with biological preparations was found in the ones using Agromix SS.

The findings align with existing literature on nitrogen management during composting. Hoang et al. [23] reviewed strategies for mitigating nitrogen loss and highlighted that adding carbon-rich materials like straw can effectively reduce nitrogen volatilization. This aligns with our results, where higher straw content led to lower nitrogen losses. Similarly, studies by Wang et al. [29] demonstrated that carbon amendments improve the carbon-to-nitrogen ratio, thus reducing nitrogen loss through ammonia volatilization and promoting better compost stability.

An increase in the amount of total N during storage may be due to the concentration of the element as a result of mineralization of organic nitrogenous compounds and loss of total weight. N-fixing bacteria, which are part of Consortium B and Agromix SS, contributed to an increase in N content during the maturation of the compost.

The reduction of total C occurs due to the oxidation of organic substances to CO_2 and H_2O during aerobic storage. Y. Inbar noted that approximately 50% of organic matter decomposed to CO_2 and H_2O during storage. The conversion of organic substances into compost suitable for use as fertilizer depends on the ability of the microflora of the compost to secrete special enzymes [30].

The P and K content in the composting process can be increased under the influence of concentration with weight loss. Lin [31] suggested that the effect of concentration in compost occurred when organic C had a higher decomposition rate compared to organic forms of N, P, and K. The fertilizer can concentrate or dilute P, K, and trace elements in organic waste. The loss of chemical elements is manifested during alkalinization, and the decomposition of organic substances leads to their concentration [32].

Some heavy metals-in small amounts-are necessary for plant growth; however, in higher concentrations, they are likely to have negative effects. One of the main problems associated with the use of sludge compost is associated with the presence of high concentrations of heavy metals, which can have dangerous consequences for soils and crops and pose an indirect risk to human health due to the properties of biological accumulation. Thus, Du et al. [33] noted that P, Cu, Zn, and Cd increased after composting, while volatile solids, water, pH, and N decreased. He et al. [34] reported that aerobic composting processes increased the formation of heavy metal complexes in organic waste residues, which limits their solubility and potential biological availability in the soil.

In the obtained results, the highest concentrations of trace elements are represented in the form of Zn and Cu. This result is comparable to the result obtained by some scientists [35, 36], where Cu and Zn were the metals with the highest percentage of compostable materials among the measured ones [37].

The addition of straw had a diluting effect on the metal content since the values for the same types of metals in mixtures with 20% straw content were lower than in mixtures with 10% or variants without straw. The content of heavy metals in the final product was much lower than the standard limit values for compost, and therefore compost products can be safely used as a fertilizer.

5. CONCLUSIONS

The biotechnological method of thermophilic composting of sludge and wheat straw at optimal humidity provides a doubling of the organic mass with the optimization of agrochemical parameters. Under the influence of the biological product, the compost mass is heated to a temperature of 55-60°C, which allows the pathogenic microflora to be destroyed. The composting process is accelerated, thermophilic bacteria transfer N from organic to mineral form, and unpleasant odors are eliminated. This makes the resulting compost safe and suitable for application to the soil. Large N losses in the initial stages of composting are associated with the volatilization of ammonia. The amount of P in all variants increased compared to the initial value. Mixtures of sludge and plant residues of 10 and 20% were the most advantageous variants for composting, while the final compost showed a high degree of decomposition of organic substances and a low amount of heavy metals, while pH and humidity were also within acceptable limits. As for international standards, the resulting organic fertilizers do not pose a threat to the quality of soil or plants when used in agriculture or land restoration.

The long-term use of sludge compost as a fertilizer offers several benefits. It can significantly improve soil structure by enhancing aeration, water retention, and root penetration. Additionally, it increases soil fertility by boosting the levels of essential nutrients such as nitrogen, phosphorus, and potassium, leading to improved crop yields over time. The organic matter in compost also enhances microbial activity and diversity, improving nutrient cycling and overall soil health.

However, there are potential drawbacks. Continuous application of sludge compost may lead to the accumulation of heavy metals in the soil, which can pose risks to soil health and crop safety. Further research in the field of sludge composting will expand the understanding of environmentally friendly waste disposal. Experiments to optimize the composting process and research methods to reduce the content of heavy metals in the resulting compost will contribute to the development of high-quality and safe organic fertilizers.

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