Agraarteadus
2 • XXXII • 2021 169–181

Journal of Agricultural Science
2 • XXXII • 2021 169–181

ACCELERATED BIOTHERMAL COMPOSTING OF MANURE-COMPOST MIXTURE

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Saabunud: Received:	18.10.2021
Aktsepteeritud: Accepted:	12.11.2021
Avaldatud veebis: Published online:	13.11.2021
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Keywords: composting, manure-compost mixture, composting pad, mechanical aeration, parameters.

DOI: 10.15159/jas.21.30

ABSTRACT. The aim of the research was to observe the technological processes of accelerated biothermal composting of manure-compost mixture and to determine the dynamics of its temperature regime. Because of experimental research of conditions of biothermal processes of composting of manure-compost mix the mathematical laws describing dynamics of change of a temperature field in the composting pad of a different configuration for various mechanized conditions are received. It is established that mechanized composting of raw materials provides growth of internal temperatures to the maximum temperature of 65–71 °C (at height of the composting pad of 1.5 m) for 2–3 days after laying of the composting pad. In 15–17 days, the temperature is up to 50 °C, which does not correspond to the thermophilic mode of bacterial activity and the processes gradually pass into the mesophilic mode – up to 40 °C. As a result of experimental studies of biothermal processes of composting manure, it was found that during the fermentation of raw materials in the composting pad without treatment (36 days) the weight of the composting pad (at the composting pad height of 1.5 m) decreased by 20% (raw material moisture decreased by 5%). In the composting pad with mechanical treatment and addition of water, the weight of the composting pad varied from the amount of water introduced, which led to an increase in the moisture content of the raw material. There was a significant decrease in organic matter from 47–50 to 32–35% in the raw material against 50–52 to 40–41%.

Introduction

Global trends in agricultural production indicate significant changes in the technological use of organic raw materials of crop and livestock (straw, manure, droppings) for organic fertilizers. The main challenges: increasing social requirements for the ecological state of the environment (odours, pollution of water bodies, soils), restoring soil fertility, production of raw materials for organic products. One way to solve the problem is to use better organic fertilizers – compost – a mixture of animal manure or poultry droppings with plant biomass, which is produced in a shorter time of aerobic fermentation (Samarin *et al.*, 2020).

The purpose of accelerated composting is to control the processes of fermentation-decomposition of organic matter, reducing the loss of nutrients by maintaining rational living conditions of microorganisms, which reduces the time of the readiness of the product. The positive result of the measures is the reduction of environmental risks, improvement of the environment, resource conservation using non-commodity crops and processing, reduction of storage and accumulation of manure and droppings, improving the quality of fertilizers (Malik *et al.*, 2020).

Today, many organic waste composting systems are known, they have found their use in various industries for processing and further use as organic fertilizers (Huzaifah *et al.*, 2001; Rajkhowa *et al.*, 2019). Ecological and agrotechnical precautions on the release of unpleasant and greenhouse gases, phytotoxicity of components (presence of harmful substances and toxins), increase in nutrients, weed seed disposal, reduction of cultivation time, reduction of areas under sites, cost of structures and equipment, environmental factors environments (temperature, precipitation, wind, *etc.*) at the present stage have led to the development of various composting methods, which differ in shape and size, degree of perfection, use of additional components, etc. (Diacono *et al.*, 2019).

Methods of composting agricultural waste can be broadly divided into three main types, based on methods of aeration of compost materials, mechanical mixing and shovelling (Aliev *et al.*, 2018; Shevchenko *et al.*, 2021), as well as control over the release of odours and harmful gases (Sayara *et al.*, 2020).

Analysis of the state of research of bioenergetic fermentation processes of compostable raw materials allowed us to conclude that the simultaneous solution of several theoretical issues regarding changes in heat and mass balances as a function of time, and in some cases (from the point of view of practical application main states of idea) environment, shape, structure and total mass of compost material are an integral basis in the construction of most models of composting processes (Seki, 2000). In theoretical studies, most scientists use the following generalized formula for heat balance (Mason, 2006):

$$E = \Sigma E_{in} \pm \Sigma E_{trans} - \Sigma E_{out} \, , \qquad (1)$$

where

E – the accumulated energy of the compost system, MJ;

ΣE_{in} – total energy at the entrance to the system, MJ;

ΣE_{trans} – total energy of biochemical transformations, MJ;

ΣE_{out} – total energy at the output of the system (lost energy), MJ.

That is, the dynamics of the composting process depends on and changes under the influence of its input and output parameters, as well as several parameters that characterize the biochemical transformations (endogenous and exogenous) of organic matter in compost materials. Many model developers relied on deterministic approaches, *i.e.*, those that precluded the possibility of accidental influence on the studied parameters. However, some stochastic blocks are reflected in at least two of the analyzed models that have emerged in recent years (Scholwin, Bidlingmaier, 2003; Edsel, Grant, 2006).

The research (Hamelers, 2004) considers the main elements of process modelling (relative to the smallest structural component of the mixture – a single compost particle), based on the possibilities and different perspectives on the application of models.

Model developers consider a composting system at the macro level, in which attention to its analytical justification was based on the bioreactor (mainly for closed composting systems). However, several authors (Kaiser, 1996; Stombaugh, Nokes, 1996; Ndegwa *et al.*, 2000; Seki, 2000; Higgins *et al.*, 2001) have considered modelling problems based directly on the microbiological point of view of the composting process.

In some cases, the simulation was applied directly to processes occurring in the horizontal layers of the substrate (Stani, 2012; Seng *et al.*, 2016; Zhao *et al.*, 2017; Sokač *et al.*, 2021). Depending on the technological approaches to waste composting, the processes that take place in rectangular or triangular compost piles (Kim *et al.*, 2000; Petric, 2008), or concerned only individual areas of the compost substrate with uniform temperature fields (Bari *et al.*, 2000; Robinzon *et al.*, 2000; Straatsma *et al.*, 2000; Agnew, Leonard, 2003; Mironov, 2006).

The thermal balance of components in composting models was based on the rationalization of thermal energy consumption for heating the structural elements of the system, taking into account the input and output heat fluxes (thermal energy of incoming air and its water vapour, as well as any additional inputs of water vapour), losses due to heat transfer and convection losses, incoming heat fluxes and losses due to radiation, latent heat due to water evaporation and thermal energy of biological and chemical origin.

The heat released because of microbiological processes and latent heat of water evaporation were considered as the most influential parameters in the heat balance of full-scale composting systems (Weppen, 2001) and were taken into account in almost all developed models. Regression models of specific heat release were obtained from research (Kuznetsov, 2001). Simplified models for determining the specific heat of biothermal processes based on the a priori established depth of decomposition of organic matter and specific heat release based on chemical oxygen demand (HSC) have also been proposed. The proposed model (Golub, 2007; Golub *et al.*, 2017a) predicted a functional relationship between temperature and the sum of heat fluxes overtime under the conditions of heating the substrate with water vapour and heat productivity of biochemical reactions based on glucose decomposition rather than decomposition of available organic matter in general. In most cases, the latent heat of water evaporation was considered in the physical equations of gas motion due to the enthalpy of exhaust gases saturated with water vapour.

Heat loss parameters due to convection, heat transfer and radiation can be calculated using well-known dependencies and information on heat transfer processes or by heat transfer parameters determined experimentally (Weppen, 2001).

Many of the authors-developers of the models considered "mc" as a constant value (Bari *et al.*, 2000; Robinzon *et al.*, 2000; Straatsma *et al.*, 2000), which allowed to obtain the equation as follows:

$$mc\frac{dT}{dt} = GH_i + U\frac{d(BVS)}{dt}H_c - GH_o - A(T - T_a) \, , \qquad (2)$$

from which the expression for determining the rate of temperature change is as follows:

$$\frac{dT}{dt} = \frac{GH_i + U\frac{d(BVS)}{dt}H_c - GH_o - A(T - T_a)}{mc}, \quad (3)$$

where
T – the temperature, K;
H – entropy, J K^{-1};
t – time, s;
B, V, S – geometric sizes, m;
m – mass kg;
c – specific heat, J $(kg \cdot K)^{-1}$;
G – empirical coefficients, K s^{-1};
U – empirical coefficients, K m^{-3};
A – empirical coefficients, J $(s \cdot K)^{-1}$.

The presented models are theoretical and cannot fully characterize the process of bioconversion of manure-compost mixture during solid-phase composting. Therefore, the research aims to observe the technological processes of accelerated biothermal composting of manure-compost mixture and to determine the dynamics of its temperature regime.

Material and Methods

The program of experimental research provided:

- substantiation on results of research of technological and mode parameters and the basic provisions of management of processes of biothermal composting of manure-compost mix in full-scale composting pad;
- research of regularities of dynamics of a temperature mode in a full-size composting pad with their various geometrical parameters;
- study of the influence of the periodicity of mechanical aeration of manure-compost mixture in full-scale composting pads on the course of the composting process.

A closed hangar with a concrete surface, size 90 × 18 m, was used as a platform. Fresh (unloaded from the premises) litter based on sunflower husk is unloaded in tight piles onto the prepared site using a modified PRT-10 organic fertilizer spreader. Further research was conducted on four full-scale composting pads:

- composting pad №1 – composting pad 1.5 m high without further mechanical aeration and additional humidification;
- composting pad №2 – composting pad height of 1.0 m without further mechanical aeration and additional humidification;
- composting pad №3 – composting pad 1.5 m high with subsequent mechanical aerations and with additional humidification;
- composting pad №4 – composting pad 1.0 m high with subsequent mechanical aerations and with additional humidification.

Directly the process of formation of full-scale composting pads with the use of the modified spreader of organic fertilizers PRT-10 is presented in Figure 1. Further planned mechanical aeration and formation of composting pads were performed using a bucket loader T-156 and a modified spreader of organic fertilizers PRT-10.

Humidification is performed to bring the compost mixture to the technologically necessary humidity. The technical means of water delivery was a specialized car based on GAZ-53 with a capacity of 4 m^3. The amount of water (effluent) M_{water} was required to bring the manure-compost mixture to the technologically specified humidity $M_{mixture}$ and was calculated by the formula:

$$M_{water} = M_{manure}\frac{W_{mixture} - W_{manure}}{100 - W_{mixture}} \quad (4)$$

where
M_{water} – the mass of water (sewage) that must be added to the manure-compost mixture, kg;
M_{manure} – the weight of manure, kg;
W_{manure} – humidity of manure, %;
$W_{mixture}$ – humidity of manure-compost mixture, %.

Moisturizing water is supplied during mechanical aeration by spraying.

During research composting pads 3 and 4 were mechanical aerating with time intervals that are presented in Figure 2.

without additional hydration

with additional hydration

Figure 1. The process of forming full-scale composting pads using a modified spreader of organic fertilizers PRT-10

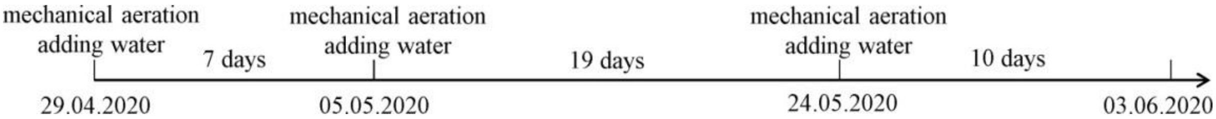

Figure 2. Time intervals of technological operations in the process of accelerated biothermal composting

During research the following parameters of technological process of the accelerated biothermal composting of litter manure on the basis of sunflower husk were defined:

- geometrical sizes of composting pads and their vertical subsidence;
- bulk density, weight, humidity;
- dynamics of temperatures in the cross section of the composting pads;
- the temperature field of the composting pads and the homogeneity of the distribution of the components of the manure-compost mixture in the composting pads.

All measurements were performed upon completion of the technological operation according to the set time interval in three repetitions.

Measurement of the geometric sizes of the composting pads and their vertical subsidence was performed using a construction tape measure (50 m) and a ruler (1.5 m) with an absolute measurement error of 1 cm. The height, width and length of the formed composting pads were determined. The vertical subsidence of the sides was measured by installing a laboratory bar in three places along their length, followed by fixing the position of the upper point of the sides.

The bulk density was determined by determining the ratio of the net weight of the manure-compost mixture poured into the tank to the volume of the specified tank (the volume of the tank was specified by the manufacturers 0.01 m^3). The mass was determined by electronic scales with an absolute measurement error of 0.001 kg.

Calculations are carried out according to the formula:

$$\gamma = \frac{m_i}{V_i} \qquad (5)$$

where

γ – is the bulk density, kg·m$^{3\ -1}$;

m_i – a mass of the bulk sample, kg;

V_i – the volume occupied by the sample of the material in bulk, m^3.

Measurement of the mass of manure-compost mixture in the composting pad was performed using SMART Life REXANT (Lin'an CF Co., Ltd, Hangzhou, Zhejiang, China) scales with an absolute measurement error of 0.1 kg.

Humidity measurement of manure-compost mixture was performed using a calibrated moisture meter VLK-01 (TOV NVF Standard-M, Zaporozhye, Ukraine). Calibration of the moisture meter was performed in the laboratory of the State Institution "State Soil Protection" (Dnipropetrovsk branch) by comparing with the results of chemical analysis according to standard methods according to GOST 26713-85, based on determining moisture loss from the mass of compost by drying it to constant weight. The absolute measurement error of the VLK-01 moisture meter for the manure-compost mixture was 0.2%.

The most important criterion for evaluating the effectiveness of the composting process is the control and maintenance of temperature. The dynamics of temperatures in the sides was studied using a personal computer to which an electronic thermometer TM-32/H-5T (TOV UKRRELE, Dnipro, Ukraine) with a system of temperature probes based on temperature sensors DS18B20 ("Dallas Manufacturing Co", Dallas, USA) was connected (Fig. 3). The absolute measurement error of the thermometer TM-32/H-5T is 0.1 °C. Temperature monitoring using the TM-32/H-5T electronic thermometer was performed every 10 minutes, and the data were recorded on a personal computer in the appropriate database file.

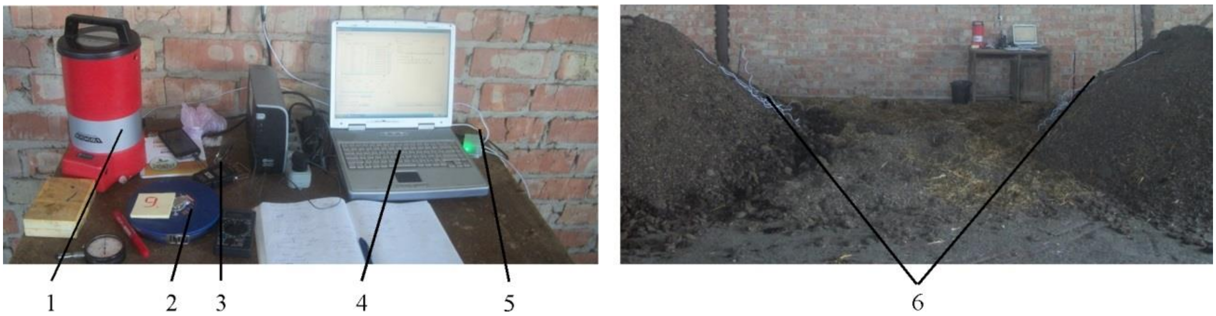

Figure 3. Measuring instruments and equipment (1 – moisture meter VLK-01; 2 – construction roulette; 3 – electronic manual scales; 4 – personal computer; 5 – electronic thermometer TM-32/H-5T; 6 – DS18B20 temperature sensors)

The scheme of arrangement of temperature probes in composting pads 1.5 m and 1.0 m high is presented in Figure 4.

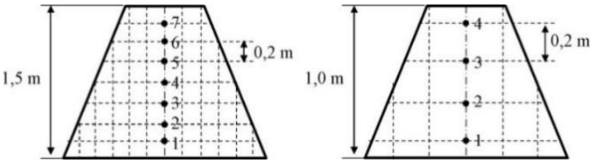

Figure 4. The layout of temperature probes

The temperature field of the surface or section of the sides was determined using a thermal imager Testo-875 (Testo SE & Co. KgaA, Lenzkirch, Germany), which allows the analysis of temperature fields with an absolute measurement error of 0.01 °C. Using the additional Testo IRSoft v. 4.1 software (Testo SE & Co. KgaA, Lenzkirch, Germany), the maximum, minimum and average values of the temperature field; build histograms and graphs of temperature distribution over a certain area and line of the temperature field was determined. The general view of the specified thermal imager and the corresponding software is presented in Figure 5.

The least Significant Difference (LSD) indicator was used for statistical evaluation of research results. LSD is a critical value that is expressed in absolute numbers and shows the limit of random deviations between the compared averages, which corresponds to a reliable interval for the absolute difference of the sample arithmetic means. If it was less than the LSD, then the samples do not differ, and if more, they are statistically different. Determine the LSD by the formula (Kiselyov *et al.*, 2017):

$$LSD_{\alpha(v)} = t_{\alpha} \cdot S_{d}\,, \quad (6)$$

where

S_d – standard error of the difference between the arithmetic means;

$t_{\alpha(v)}$ – theoretical (critical) value of Student's criterion for the level of significance α and degrees of freedom of error.

Figure 5. General view of the Testo-875 thermal imager (a), Testo IRSoft software (b) and the temperature measurement process (c)

Results

During the study, four composting pads (cross-section – triangle) were formed, the geometric sizes of which were:

- composting pad №1 – height 1.4–1.5 m, length 5.7–6.3 m, width 3.8–4.4 m;
- composting pad №2 – height 0.9–1.0 m, length 8.7–9.0 m, width 3.1–3.6 m;
- composting pad №3 – height 1.4–1.5 m, length 5.8–6.1 m, width 3.3–4.1 m;
- composting pad №4 – height 0.9–1.0 m, length 6.8–7.1 m, width 3.5–3.8 m.

Considering the time intervals of technological operations during the process of accelerated biothermal composting of full-scale composting pads, measurements of their vertical subsidence were carried out. The histogram of the above dependence is presented in Figure 6. As can be seen from the histogram, the greatest value of subsidence of the composting pad was observed in the first 7 days, which was due to the more intense process of biothermal composting. In the future, the absolute value of vertical subsidence decreases by 25–30%. $LSD_{0.5}$ for the value of the vertical subsidence of the full sides was 4.3 mm, which is lower than the difference observed in the dynamics.

By the time intervals of technological operations in the process of accelerated biothermal composting of full-scale composting pads were measured changes in their mass, taking into account the addition of water. The histogram of change of weight of full-size composting pads is presented in Figure 7. For values of weight of composting pads $LSD_{0.5}$ makes 56 kg. This figure is lower than the difference observed in the dynamics, which confirms the adequacy of the results.

The bulk density changed according to the graph in Figure 8, which shows its reduction during biothermal composting. This decrease is due to the evaporation of moisture and the chemical reaction with the release of gaseous substances. $LSD_{0.5}$ for the volume volumetric mass of full-scale composting pads was 21.3 $kg \cdot m^{3\,-1}$, which is lower than the difference observed in the dynamics.

During the observation period on the composting pads without treatment (36 days) the weight of the composting pad №1 (H = 1.5 m) decreased by 22% (moisture content of raw materials decreased by 6%), and composting pad №2 by 26% (moisture content of raw materials by 5%). In liquids with the addition of liquid – water, the weight of the composting pad №3 and the composting pad №4 varied depending on the amount of introduced water, which led to an increase in the moisture content of the raw material. For the values of moisture content in full-sized composting pads $LSD_{0.5}$ is 2.1%. Since this figure is lower than the difference observed in the dynamics, the adequacy of the results is confirmed.

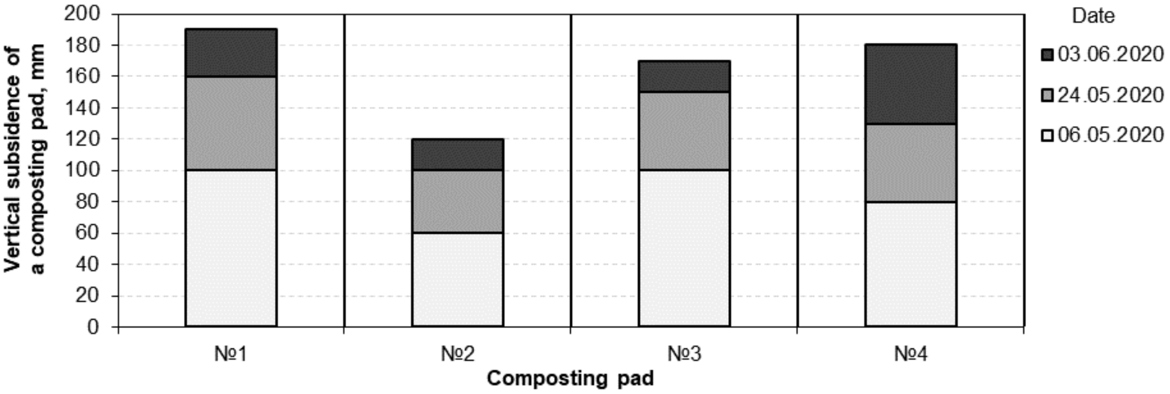

Figure 6. The dynamics of changes in the absolute value of the vertical subsidence of the full-scale composting pads

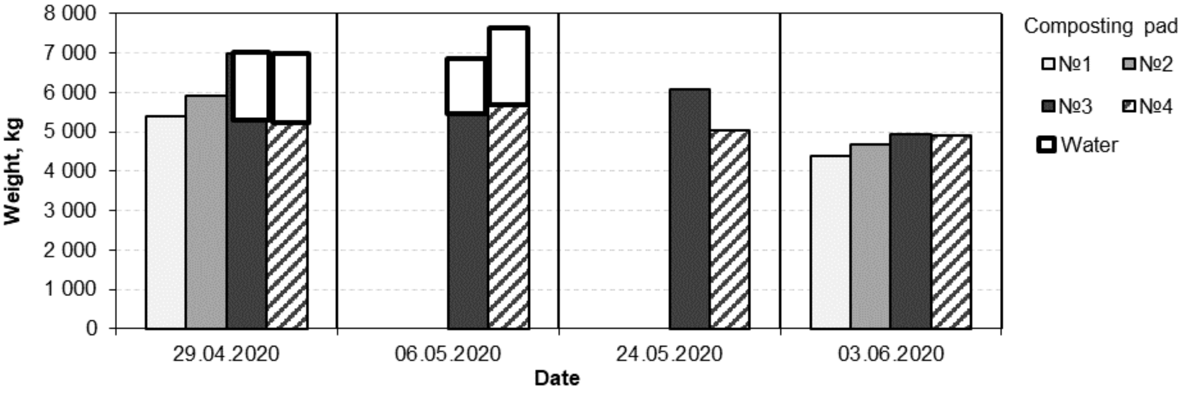

Figure 7. Changes in the mass of full-scale composting pads

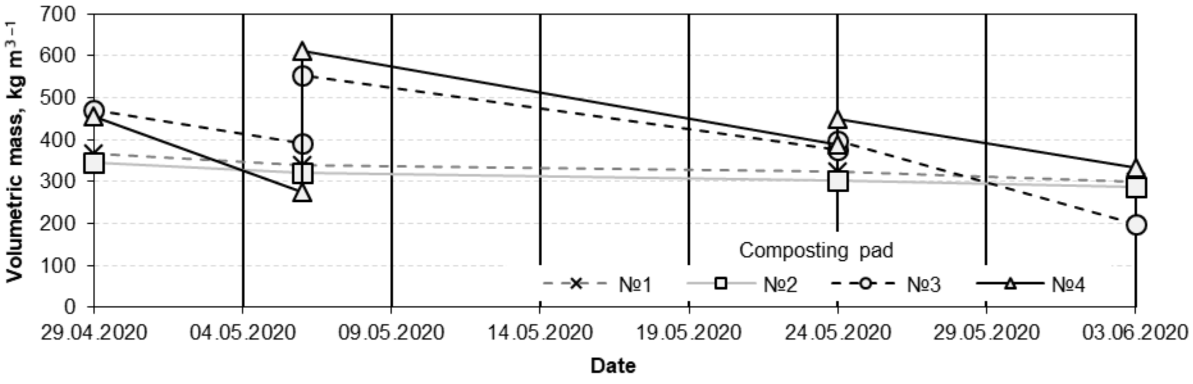

Figure 8. Changes in the volumetric mass of full-scale composting pads

Indicators of moisture content when considering changes over time relative to untreated compost has significant variations in the respective composting pads at the height of the composting pads of 1.5 m and 1.0 m (Fig. 9). It should be noted that there is a characteristic increase in moisture content and a further decline with the resumption of the rise (*i.e.,* there is an oscillating relationship).

The corresponding tendency is present also with the processed raw materials with that difference concerning discrepancy of fluctuations, which are a result of the addition of liquid – water to these composts. It should also be noted that the levels at which the values of moisture content for 36 days in untreated and treated materials are quite close to each other. The presence of fluctuations in moisture content should be considered because of the process of mineralization of organic matter: burning of carbon and oxidation of hydrogen with subsequent evaporation of moisture.

As a result of research, the dynamics of change of temperature in each point of a full-scale composting pad according to the developed technique (Figs. 10–13) is received. For the presented results of research $LSD_{0,5}$ for temperature makes 0,51 °C, that is sufficient for the statement of adequacy of the received data.

Mechanical shovelling of raw materials – aeration provides growth of internal temperatures (7 points of measurement on the height of the composting pad H = 1.5 m) to the maximum temperature of 65–71 °C and 50–58 °C at height of the composting pad of H = 1.0 on 2–3 the day after laying the composting pad. In 15–17 days, the temperature is up to 50 °C, which does not correspond to the thermophilic mode of bacterial activity and the processes gradually pass into the mesophilic mode – up to 40 °C.

By the end of the observation period (up to 36 days), the internal temperature in the composting pad №1 (H = 1.5 m), according to Figure 10, was 39–45 °C, and in the lower layers up to 30 °C.

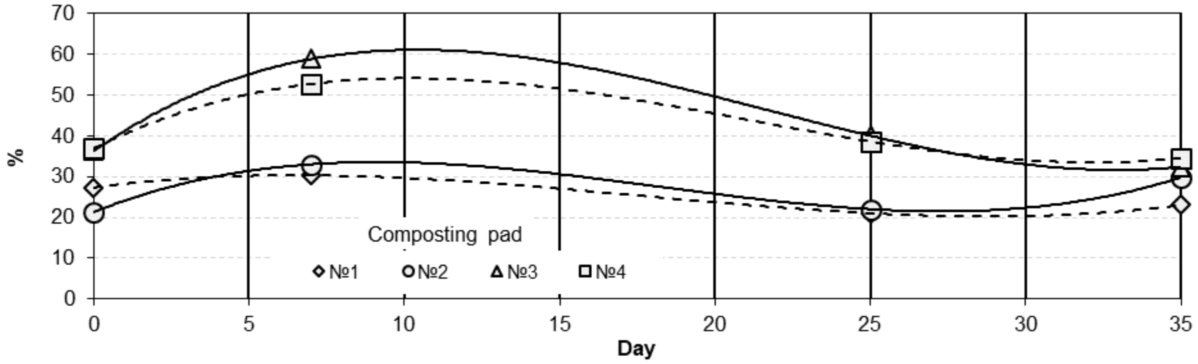

Figure 9. Dynamics of moisture content in full-sized composting pads

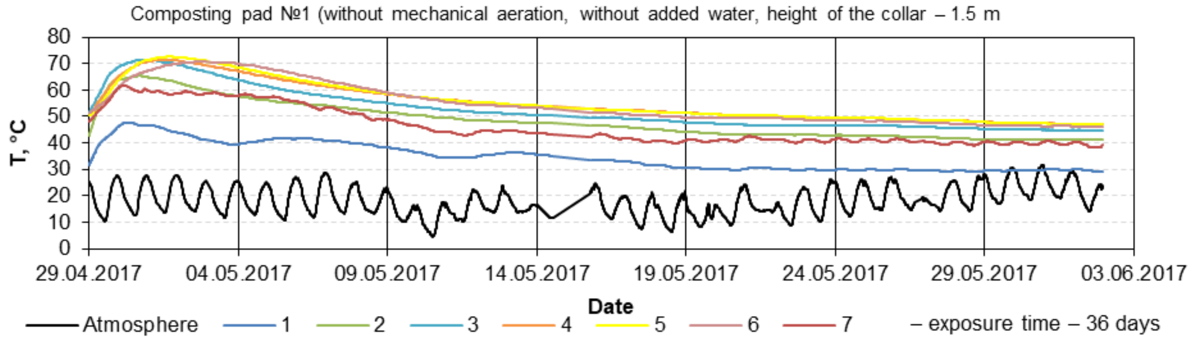

Figure 10. Dynamics of the temperature field of the composting pad №1

In the composting pad №2 (H = 1.0 m), according to Figure 11, the temperature was 5–8 °C lower in the corresponding periods. The change in ambient temperature during the day from 10 to 25 °C, during the observation period there were no significant fluctuations in the internal temperature.

In the composting pad, №3 (fig. 12) with mechanical shovelling and the addition of liquid – water, the temperature rose to 61–65 °C (H = 1.5 m) for 2–3 days at all seven measuring points, decreased by 3–5 °C and remained stable during the observation. Shovelling of raw materials without the addition of liquid for 20 days showed an increase in temperature to 70–72 °C with a gradual attenuation of thermal processes for 10 days and a decrease in temperature to 50 °C.

In the composting pad, №4 (at H = 1.0 m) and similar treatments as in the composting pad №3, thermal processes are 5–10 °C lower (Fig. 13). During aeration, the temperature of the raw material decreases to 38–44 °C, the effect of fluctuations in external temperature (10–25 °C) on the change in internal temperatures was statistically insignificant.

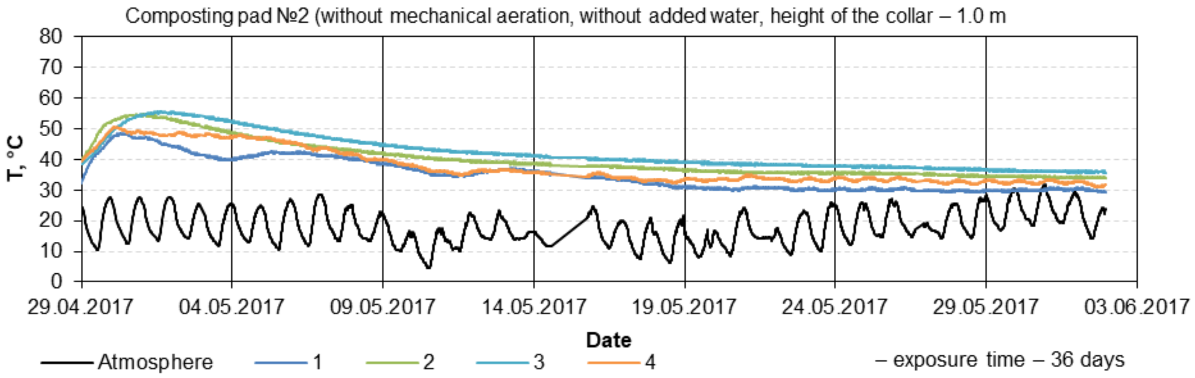

Figure 11. Dynamics of the temperature field of the composting pad №2

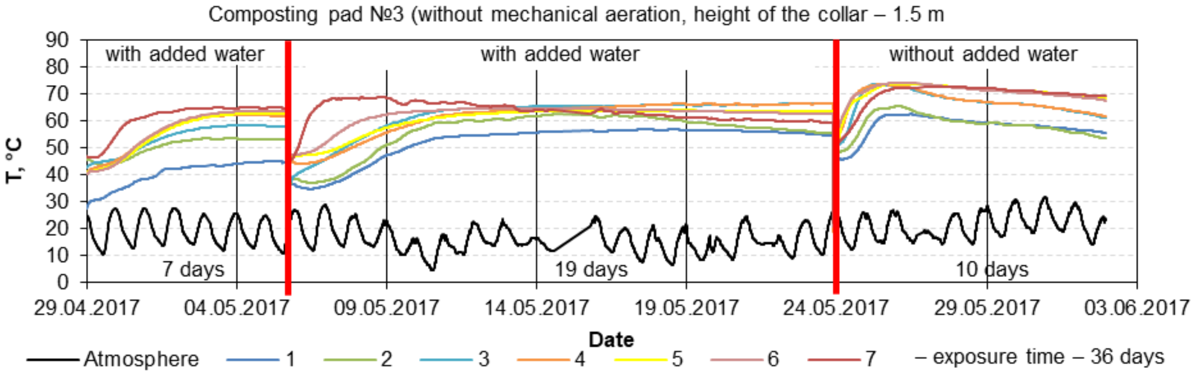

Figure 12. Dynamics of the temperature field of the composting pad №3

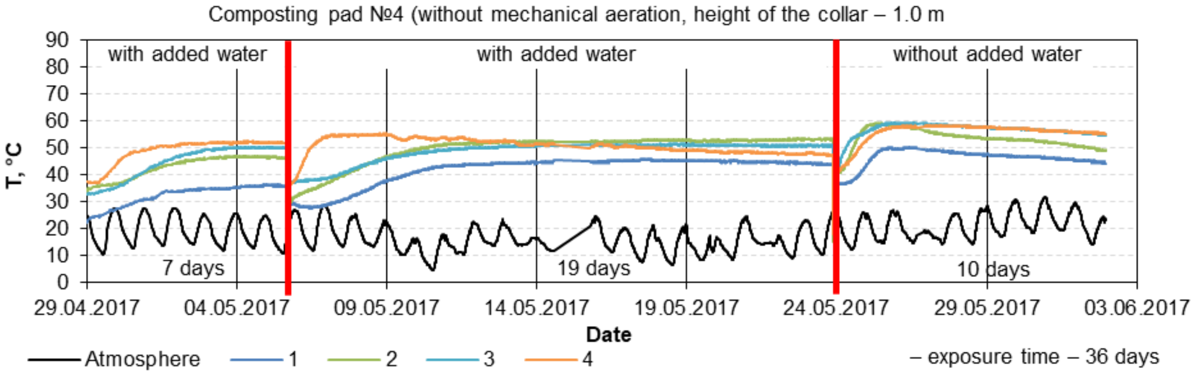

Figure 13. Dynamics of the temperature field of the composting pad №4

The results of monitoring the static temperature field of the surface of the sides with a thermal imager and a pyrometer are presented in Figs. 14–17. As can be seen from Figure 14, for the composting pad №1 there is a temperature range from 19.6 to 23.5 °C, which is practically determined by the ambient temperature, while the average value is 21.5 °C.

For composting pad №2 (Fig. 15) the temperature on the outer surface varies from 18.3 to 21.1 °C, which coincides with the ambient temperature. The average temperature is 19.9 °C, and its standard deviation is 1.2 °C.

The outer surface of the composting pad №3 (Fig. 16) is 19.0–22.3 °C. The mean value is 20.8 °C, and its standard deviation is 1.3 °C.

The composting pad №4 (Fig. 17) is quite homogeneous in terms of surface temperature, which is confirmed by the small value of the standard deviation – 0.9 °C. The average temperature is 20.9 °C.

Longitudinal and transverse sections of the composting pads №3 and №4 (Figs. 18–19) and the determination of temperatures using the above equipment indicate uniform heating of the sides within the above temperatures.

In this case, for the composting pad №3 at the cross section, the minimum and maximum temperature values are 22.7 °C and 59.4 °C, respectively, and the average value is 40.8 °C. Analysis of Figure 17 shows that in the center of the collar is a warmer mixture than outside. The standard deviation of the temperature is 8.2 °C.

A similar situation is observed for the composting pad №4: the minimum and maximum values of temperatures are 23.7 °C and 52.9 °C, respectively, and the mean value is 40.6 °C, the standard deviation is 9.1 °C.

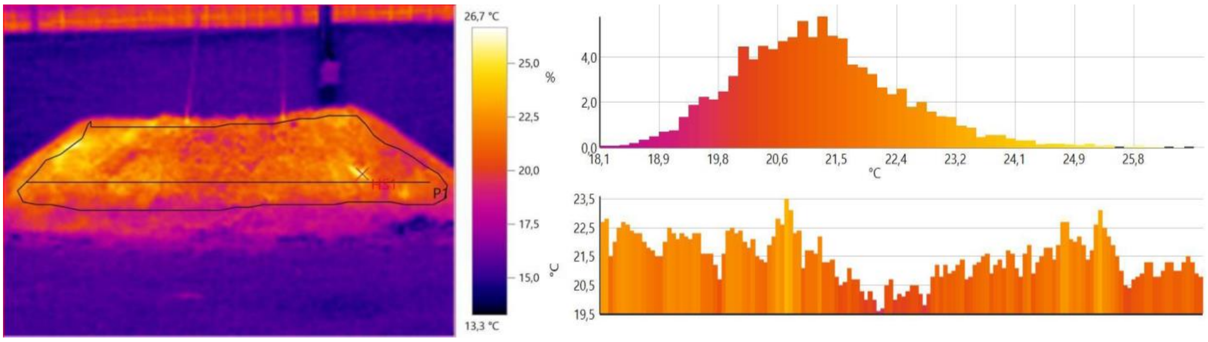

Figure 14. Static temperature field of the surface of the composting pad №1 (composting pad height of 1.5 m without further mechanical aeration and additional humidification)

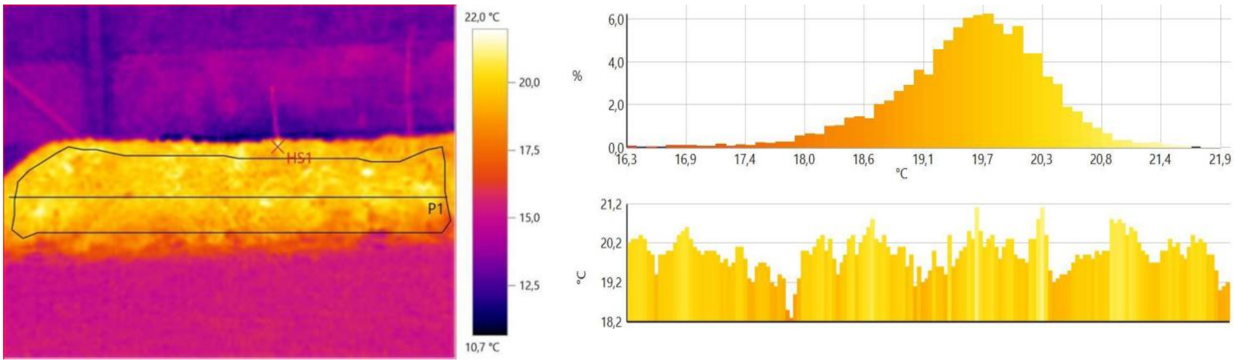

Figure 15. Static temperature field of the surface of the composting pad №2 (composting pad height of 1.0 m without further mechanical aeration and additional humidification)

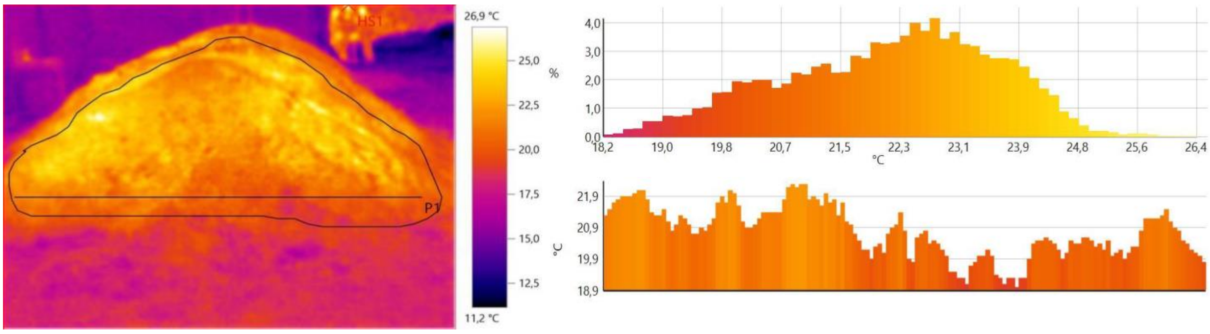

Figure 16. Static temperature field of the surface of the composting pad №3 (composting pad 1.5 m high with subsequent mechanical aeration and with additional humidification)

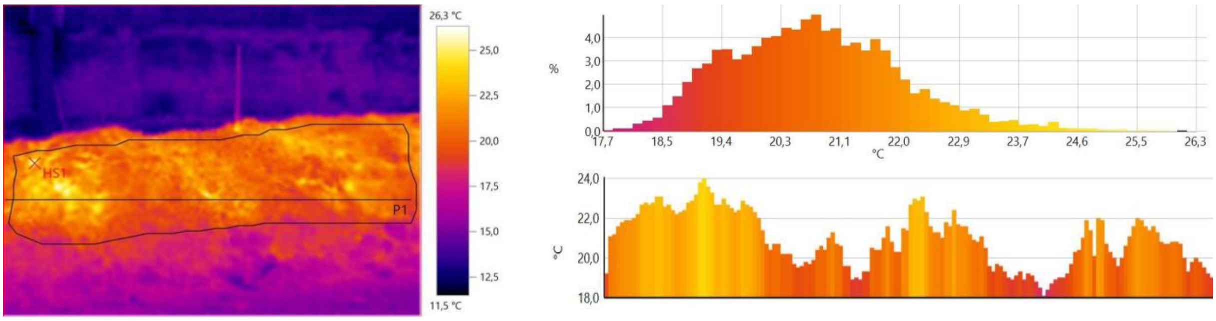

Figure 17. Static temperature field of the surface of the composting pad №4 (composting pad 1.5 m high with subsequent mechanical aeration and with additional humidification)

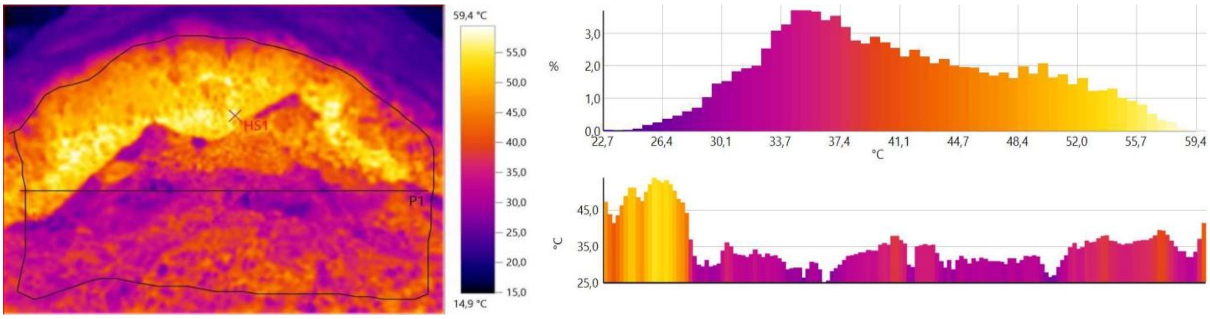

Figure 18. Static temperature field of the cross-section of the composting pad №3 (composting pad 1.5 m high with subsequent mechanical aerations and with additional humidification)

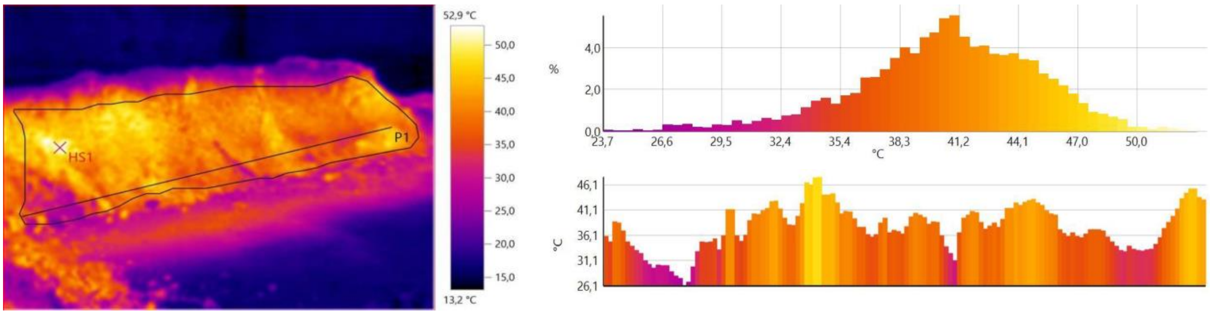

Figure 19. Static temperature field of the longitudinal section of the composting pad №4 (composting pad 1.5 m high with subsequent mechanical aeration and with additional humidification)

Discussion

As a result of the analysis of previously published sources research (Huzaifah *et al.*, 2001; Mironov, 2006; Zhao *et al.*, 2017; Diacono *et al.*, 2019; Rajkhowa *et al.*, 2019; Malik *et al.*, 2020; Samarin *et al.*, 2020; Sayara *et al.*, 2020) it was established that reduction of the negative influence of organic biomass of plant growing and animal husbandry at their accumulation on an ecological condition of environment can be reached at the expense of compost production by the accelerated fermentation technology, which is disinfected from harmful microflora and have an increased concentration of nutrients compared to the original. It was found that a multi-stage composting system with mechanized operations of mixing components, shovelling compost mixtures and simultaneous aeration is the most effective because the decomposition of the organic component of the compost mixture and water evaporation due to released heat energy leads to changes in relative water content (40–70%), ash (20–40%) and organic matter (10–40%) in the finished compost. This significantly improves its agronomic properties: the level of dry matter content increases to 40% (400 kg·t^{-1}) and the specific content of nutrients.

The state of theoretical research of bioenergetic processes of fermentation of compostable raw materials based on analytical dependences on the release of biological energy and use and preservation of the saved energy, which was applied in models of decomposition of organic matter (Bari *et al.*, 2000; Robinzon *et al.*, 2000; Straatsma *et al.*, 2000), is generalized.

The relative weight loss (due to carbon oxidation) in the storage of nutrients improves the logistics component and productivity of machine-tractor units when applying organic fertilizers. There is a significant decrease in organic matter from 47–50 to 32–35% in the raw material against 50–52 to 40–41%.

It is established that mechanical shovelling of raw materials – aeration provides growth of internal temperatures (7 measuring points on the height of the composting pad H = 1.5 m) to the maximum temperature of 65–71 and 50–58 °C at height of the composting pad H = 1.0 m on 2–3 days after laying the composting pad. In 15–17 days, the temperature is up to 50 °C, which does not correspond to the thermophilic mode of bacterial activity and the processes gradually pass into the mesophilic mode – up to 40 °C. Comparing the obtained regularities with the research data (Weppen, 2001), similar stages of biothermal composting regimes of manure-compost mixture are traced. However, our studies are more accurate and show, in addition to the dynamics of temperature change, its distribution in the composting pad. That is, we have determined the dynamics of changes in the temperature field of the composting pad as a whole.

It was found that by the end of the observation period (up to 36 days) the internal temperature in the composting pad №1 (H = 1.5 m) was 39–45 °C, and in the lower layers up to 30 °C, in the composting pad №2 (H = 1.0 m) in the corresponding periods the temperature was 5–8 °C less. Due to the changes in ambient temperature during the day from 10 to 25 °C during the observation period, no significant fluctuations in internal temperature occurred. In the composting pad №3 with mechanical shovelling and addition of liquid – water, the temperature rose to 61–65 °C (H = 1.5 m) for 2–3 days at all 7 measurement points, then decreased by 3–5 °C and remained stable during observation. Shovelling of raw materials without the addition of liquid for 20 days showed an increase in temperature to 70–72 °C with a gradual attenuation of thermal processes for 10 days and a decrease in temperature to 50 °C. In the composting pad №4 (at H = 1.0 m) and similar treatments as in the composting pad №3, thermal processes are 5–10 °C lower. During aeration, the temperature of the raw material decreases to 38–44 °C. The influence of external temperature fluctuations (10–25 °C) on the change of internal temperatures is statistically insignificant. Comparing the revealed experimental dependences of temperature dynamics with theoretical models (Golub, 2007; Golub *et al.*, 2017b) it is possible to assert their adequacy due to the similar nature of the regularities. However, the proposed theoretical models need to be clarified through the introduction of appropriate empirical coefficients.

As a result of experimental studies of biothermal processes of manure composting, it was found that during the observation period on the composting pads without treatment (36 days) the weight of the composting pad №1 (H = 1.5 m) decreased by 20% (moisture content decreased by 5%), and the composting pad № 2 on – 15% (humidity of raw materials on 5%). In liquids with the addition of liquid – water, the weight of the composting pad №3 and the composting pad №4 varied depending on the amount of introduced water, which led to an increase in the moisture content of the raw material. The change in the mass of the composting pad confirms the model proposed (Bari *et al.*, 2000; Robinson *et al.*, 2000; Straatsma *et al.*, 2000). From this we can conclude that the mass of the composting pad during the biothermal process, logarithmically changes with temperature.

Conclusion

Because of experimental research of conditions of biothermal processes of composting of manure-compost mix the mathematical laws describing dynamics of change of a temperature field in the composting pad of a different configuration for various mechanized conditions are received. It was established that mechanized composting of raw materials provides growth of internal temperatures to the maximum temperature of 65–71 °C (at height of the composting pad of 1.5 m) for 2–3 days after laying of the composting pad. In 15–17 days, the temperature is up to 50 °C, which does not correspond to the thermophilic mode of bacterial activity and the processes gradually pass into the mesophilic mode – up to 40 °C. As a result of experimental studies of biothermal processes of composting manure, it was found that during the fermentation of raw materials in the composting pad without treatment (36 days) the weight of the composting pad (at the composting pad height of 1.5 m) decreased by 20% (raw material moisture decreased by 5%). In the composting pad with mechanical treatment and addition of water, the weight of the composting pad varied from the amount of water introduced, which led to an increase in the moisture content of the raw material. There was a significant decrease in organic matter from 47–50 to 32–35% in the raw material against 50–52 to 40–41%. At the same time, the structure of the treated compost has changed significantly: small and dusty parts under the action of moisture, temperatures have turned into an aggregate medium of particles from 5 to 10 mm with a significant reduction in the number of lumps and layers.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Author contributions

EA –critical revision and approval of the final manuscript;
SP – analysis, interpretation and acquisition of data;
OA – study conception and design;
OM – drafting of the manuscript.

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