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DETERMINING THE THERMAL MODE OF BIO-BASED RAW MATERIALS COMPOSTING PROCESS IN A ROTARY-TYPE CHAMBER

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One of the promising methods to dispose of agricultural bio-based raw materials is to produce compost by aerobic fermentation in rotary chambers. High efficiency of the composting process is achieved when a proper temperature mode is maintained at each phase of the process. Changes in temperature are directly related to the effective transformation of organic substrates by microorganisms and are the reason for the low quality of produced compost in terms of its agrochemical and microbiological parameters.

It was established that a high-temperature regime is achieved on the condition that the amount of heat released during the biodegradation of raw materials by microorganisms is greater than the heat loss associated with the substrate aeration and surface cooling. Therefore, the time during which the fermented mass remains warm depends entirely on the substrate's physical-chemical characteristics, the parameters of the equipment, and the modes of its operation.

To describe the established conditions, based on the equation of thermal balance, a mathematical model has been built. The model relates the thermal costs necessary to maintain the optimal temperature regime of the process to the substrate's moisture content and specific active heat generation, as well as to such an important thermal physical parameter of the chamber as the coefficient of heat transfer of the wall material.

A rotary chamber was manufactured to investigate the thermal mode of the bio-based raw materials composting process. It has been experimentally established that the chamber walls' heat transfer coefficient of 1.6 W/(m²·°C), a value of the substrate's specific active heat generation of 9.2 W/kg, and a moisture content of 58 % provide for the thermal needs for the process with the release of 140 MJ of excess heat.

The reported study could be the basis for the modernized methodology of thermal calculations of the bio-based raw materials composting process in closed fermentation chambers

Keywords: heat transfer coefficient, specific active heat generation, substrate, composting, fermentation, rotary chamber

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1. Introduction

Modern organic agricultural production is a holistic system that contributes to the development of biodiversity in agroecosystems and ensures an increase in the biological activity of soils. Organic production is based on the utilization of natural resources, that is mineral products and products of plant origin (organic substances), and the rejection of synthetic fertilizers and pesticides [1]. An effective method of processing organic substances and producing organic fertilizers is the composting process.

Composting is an aerobic process of biological decomposition of organic matter with the formation of compost, carbon dioxide, water, and heat [2].

The composting process efficiency largely depends on ensuring the proper temperature mode at each of its phases. In the lag phase, the temperature should rise from the ambient temperature to 20 °C; in the mesophilic phase, from 20 °C to 42 °C; in the thermophilic phase, from 42 °C to 65...70 °C; in the maturing phase, it should fall from 65...70 °C to ambient temperature [3].

Increasing the efficiency of the bio-based raw materials composting process is achieved by optimizing the structural and technological parameters of the process [2, 4] in accordance with the physicochemical properties of the starting substrate [5, 6] in compliance with the microbiotic parameters of the compost produced [7, 8].

The optimization of structural and technological parameters of the process involves the design or improvement of basic units and working bodies of equipment (rotary-type chambers or drums, mixers, modules for compost loading/unloading), the effective use of air aeration. In addition, to ensure the optimal temperature mode in the bioreactor during composting, the heat obtained from additional energy sources [9, 10] is used. That takes into consideration the physical-chemical properties of the starting substrate: its moisture content, carbon and nitrogen content, acidity, porosity, particle size, etc. Depending on the ratio of C:N, the corresponding ecological and trophic group of microorganisms dominates the compost.

An effective method of rational organization of the proper temperature regime of the composting process is to compile the thermal balance of the process, followed by determining the components of the intake and loss of heat. That makes it possible to determine the amount of heat that needs to be supplied or taken away from the reactor to achieve the optimal temperature at each of the composting phases [11].

Solving this issue requires the development of appropriate technical means and justification of technical and technological parameters of the process.

2. Literature review and problem statement

Our analysis of current studies [2, 4, 8] into the operation of closed fermentation chambers for the implementation of the technological process of composting of bio-based raw materials reveals a large enough number of publications addressing the regimes and microbiological parameters of this process. However, the issues related to the thermal processes that occur during the composting of bio-based raw materials remained unresolved. Taking into consideration that the cost of heating and cooling has a significant impact on the economic component of compost production, this issue is relevant for small-volume installations and requires additional research.

The substrate temperature is one of the key parameters of aerobic solid-phase fermentation [11, 12]. Temperature changes are directly related to the effectiveness of transformation of organic substrates by microorganisms, which are the basis of the fermented mixture. Analyzing temperature data, we can argue not only about the efficiency and speed of the process but also predict the quality of compost produced. For the implementation of temperature monitoring, it should be taken into consideration that the mass composted is characterized by an uneven distribution of heat throughout its volume. Thermal processes in closed chambers depend on their geometric and structural parameters, properties of materials used, aeration mode, the substrate's physicochemical parameters, and their fluctuations. Therefore, establishing the extent of influence of these parameters on the composting process would not only improve its efficiency but also reduce energy consumption for the process and ensure the high quality of the finished product.

In study [13], the mode of aeration of the substrate is considered to be a controlled parameter that affects the value of the quality indicator of the composting process (the time of the substrate stay in the reactor, which is associated with thermal and energy costs for the process). The aeration mode depends on the temperature and speed of the airflow, the aeration time, and the rotation interval of the drum. Physicochemical characteristics of raw materials, such as carbon to nitrogen ratio, moisture content, acidity, porosity, and particle size of components in the substrate are accepted as constant parameters. A key indicator that characterized the process of bio-fermentation was the fermentation temperature, which reached 67 °C in the thermophilic phase. A mathematical model presented in [13] aims to reduce energy consumption in the process of bio-fermentation of organic waste in the installation with constant structural parameters, without considering the closed installation in general. In addition, if the physicochemical properties of raw materials are fitted to the mathematical model as a constant parameter, such a model would demonstrate a significant discrepancy with experimental data. It is known that a change in the moisture content and value of the specific active heat generation of the substrate (which depends on its chemical composition) would cause changes in temperature at all phases of the fermentation process, hence for the duration of the substrate stay in the reactor and energy consumption for the process.

The authors of work [14, 15] report a model of the fermentation process, which relates the simultaneous transfer of air, heat, and moisture, which is inevitable in the exothermic processes of processing organic materials, to heat loss to the environment. They proposed, as an optimization criterion, a reduction in the loss of heat, which is released by the installation during the fermentation process. This model of bio-fermenter operation considers its objective function to be the amount of heat released during the self-heating of the recycled substrate. However, it is not possible to determine the proposed function in an explicit analytical way. The reported model could tackle only certain specific practical tasks under a stationary mode, which characterize the dynamic balance of the system.

In work [16], the thermal mode of the fermentation process was investigated under conditions of constantly variable influences that predetermine the quality of the finished product. Under actual operational conditions, the thermal mode of the fermentation process can be described by a set of variables, which are a vector function, and determine the qualitative implementation of the process over time. External factors act on the bio-fermentation plant, which form a vector function of perturbations and try to disrupt the desired course of the process. These perturbations include the mode of aeration, changes in the physical-chemical parameters of the substrate over time (moisture content, pH, C:N ratio), etc. As the initial variable, any of the random parameters is considered, characterizing a qualitative indicator of the course of the fermentation process in the bioreactor, or their totality. Such indicators are the changes in the temperature and speed of self-heating of the mixture over time, changing the thermal regime of the process, changing the quality indicators of the composting substrate, etc. However, the reported model disregards an important factor influencing the installation – the possibility of bio-based raw material rotation during the fermentation process to ensure uniformity of the structure and additional air aeration.

Our analysis of [11–16] reveals that understanding and studying the phenomena of energy generation and transmission during composting is an important parameter in monitoring, managing, and optimizing composting processes.

The available literature includes a limited number of works addressing the energy regime of the composting process. Their authors typically consider the installations of stationary type or only report data on the specific active heat generation by the substrate based on various types of bio-based raw materials.

Studies [17, 18] report values of specific active heat generation for different substrates. In particular, the high values of specific active heat generation are inherent in straw-based substrates (17.06 MJ/kg of the organic part of the substrate), bird droppings (12.8 MJ/kg of the organic part of the substrate). Slightly lower values of this indicator are characteristic of substrates based on industrial silt, green waste, wastewater, and liquid waste (7...10 MJ/kg of degraded organic matter). The lowest values of specific active heat generation are demonstrated by municipal waste – 1,136 MJ/kg of degraded substance. The authors note that knowing the value of the specific active heat generation by a substance, one can program this parameter, form multicomponent substrates. For example, the value of specific active heat generation by the substrate based on a mixture of bedding manure of cattle, bird droppings, and wood chips can equal 17 to 20 MJ/kg of the volatile solid part.

Thus, knowing the value of the specific active heat generation by the substrate, it is possible, based on the structural parameters of the installation, to provide an appropriate mode of aeration, under which the temperature of the process would reach maximum values in 3 4 days only. This would help reduce the period of composting and save energy costs on the process. Although papers [17, 18] highlighted the issue of heat release in the composting process in stationary installations, however, the issue of heat loss in the composting process was not considered.

These issues were studied in works [19, 20]. According to study [20] regarding laboratory installations, the highest heat loss was observed through the outer walls of the equipment, while for commercial-type installations the highest heat loss was associated with water evaporation from the substrate. According to [19], heat loss from the side walls of fermentation chambers is the highest and, depending on the efficiency of thermal insulation materials, can equal 30...90 % of the total heat of the process.

Paper [21] reported an energy analysis of the process of composting plant residues of tomatoes in the drum-type reactor. The authors noted that the total heat productivity of the composting process was 1.9 MJ/kg of the organic part of the substrate; only 4 % of the specified heat was used to meet the thermal needs of the process. About 96 % of the produced amount of heat were heat losses: 1 % – losses with thermal radiation; 2 % – with aeration; 69 % and 28 %, respectively, losses due to the cylindrical side and end walls of the reactor.

The authors of [19–21] investigated only the thermal losses in the composting process and provided general recommendations for their minimization. The information received is relevant in the design, management, and control of the compost production process in order to improve the efficiency of the bioreactor and the productivity of the process in general. However, the authors did not determine how much "balance heat" should be supplied to the reactor to ensure optimal temperature during the composting process, depending on the physical-chemical composition of the substrate, aeration mode, and ambient temperature.

According to [22, 23], the speed of the aerobic solid-phase fermentation process and the achievement of its thermophilic stage to a large extent depend on the starting moisture content in the substrate. Water is necessary for the transportation of microbial cells and determines their ability to form colonies.

It is believed that the highest activity of aerobic microorganisms is achieved at such a maximum moisture content of the substrate, which does not prevent the diffusion of oxygen through a layer of water to the particles of the substrate. The cited works investigated the effect of changes in moisture content on the vital activity of the compost microbiota and the rate of biodegradation of the organic component of the substrate. However, the influence of moisture content on the indicator of specific active heat generation of the substrate and the amount of heat that must be supplied to the reactor in order to ensure the optimal temperature regime of the process has not been investigated.

Most studies of thermal processes during aerobic solid-phase fermentation of substrates relate to stationary fermentation plants or those with periodic rotation. Research into the thermal processes of closed-type fermentation plants with a constant rotation of reactors is still lacking. Such studies are important both for ensuring optimal temperature mode and for tackling moisture evaporation processes in the composting process, especially in relation to substrates with an initial low moisture content of 40...45 %. In addition, quantitative assessment of the energy parameters of the composting process in rotary drum-type reactors is necessary to reduce heat losses and increase the rate of compost production in a short time.

Given this, there is a need to study the thermal processes that occur in fermentation chambers with a constant cycle of rotation depending on the physical-chemical properties of the substrate and the structural and technological parameters of the process.

3. The aim and objectives of the study

The purpose of this work is to establish the dependence of the amount of heat required to ensure the optimal temperature regime of the composting process on the moisture content and specific active heat generation of the substrate and the heat transfer coefficient of the rotary chamber wall. That could improve the efficiency of the compost production process.

To achieve the set aim, the following tasks have been solved:

– to compile a thermal balance in the system;

– to investigate experimentally the effect of moisture content and specific active heat generation of the substrate and the heat transfer coefficient of the chamber wall on the amount of heat required to ensure the optimal temperature regime of the composting process.

4. The study materials and methods

An experimental rotary-type chamber (Fig. 1) was designed and manufactured for our experimental study aimed to thermally support a compost production process.

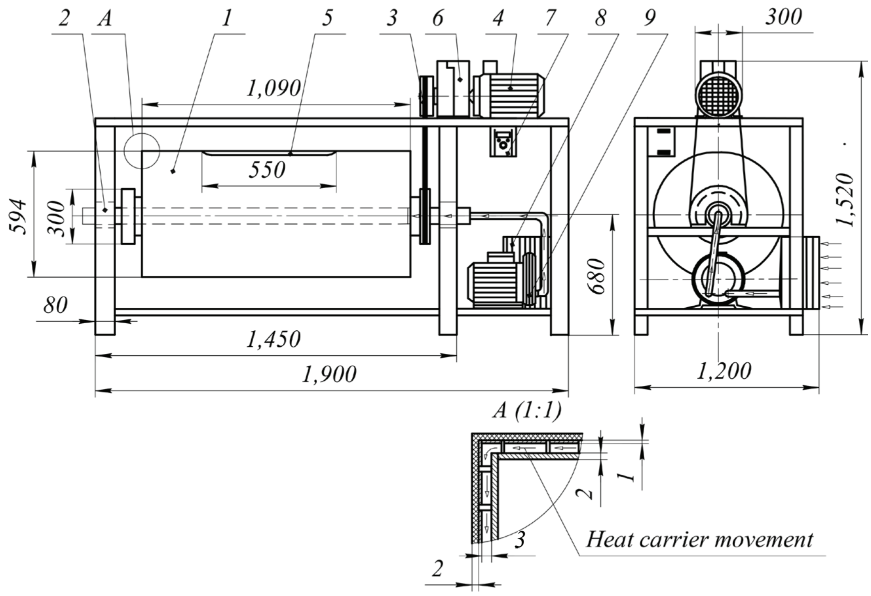


Fig. 1. Schematic representation of experimental rotary-type chamber

The rotary chamber (300 l) includes drum 1, belt transmission 3, electric motor 4 with frequency regulator 7, air compressor 9, heat exchanger 8, gearbox 6, hatch 5 to load the substrate and unload the finished compost. All installation units are mounted on frame 2. For uniform heating, the wall of the chamber around the perimeter was made double. Between the two metal layers of the wall is a casing through which the heat carrier moves, prepared in the heat exchanger. Air serves as a heat carrier. Depending on the time of year, heated (cooled) air is used to maintain the optimal temperature mode in the reaction zone of the substrate. This technical procedure makes it possible to avoid unwanted cooling (overheating) of the substrate due to external factors (frost, direct sunlight, etc.).

Loading of the substrate and unloading of compost is performed periodically. The drum chamber's substrate filling coefficient is 0.4...0.6. The drum is a steel barrel with an inside diameter of 590 mm, a length of 1,090 mm, and a wall thickness of 2 mm. The inside of hatch 5 is equipped with a rubber seal to ensure the tightness of the structure. In addition, hatch 5 is equipped with an automatic pressure control valve, which opens at a pressure increase exceeding 2 atm. The drum constantly rotates around a stationary horizontal axis (a 60 mm steel pipe) with a frequency of 5 rpm using a 0.25 kW electric motor (AIR71V8 model, Ukraine) with frequency regulator 7. The steel pipe, which serves as an axis, contains a plug on the side of the right flange of the drum. This structural technique makes it possible to execute the air supply for the aeration of the substrate, as well as to supply the heat carrier through the holes in the space between the layers of the drum wall to ensure thermal adjustment of the process.

To perform the aeration of the substrate, part of the steel pipe, which is in the rotary drum of the chamber, contains through holes with installed nozzles evenly distributed around the perimeter of the pipe.

Air for substrate aeration is continuously supplied at a flow rate of $5\cdot10^{-3}$ m^3/min from the air receiver (pressure, 1 MPa; volume, 0.22 m^3), connected to the air compressor 9 (model FORTE ZA 65-100; energy intensity, 1.5 kW; China). From the tank to the nozzles, air comes through a flow regulator with the ability to adjust the airflow rate in the range from $\cdot10^{-3}$ to $25\cdot10^{-3}$ m^3/min. The performance of the air supply system is configured in such a way that, subject to non-operation of the check valve in loading hatch 5 of drum 1, the ratio of the amount of air to the substrate is 4:1.

Heat exchanger 8 serves to generate heat, which must be supplied to the substrate to maintain the thermal mode of the composting process, or to dispose of excess heat released during composting.

Our study was conducted for three different types of the substrate with different specific active heat generation. Peat, bedding manure of cattle, chicken manure, wheat straw, and wood chips with an average particle size of 0.9 cm were used for the preparation of substrates. Straw was pre-dried to a moisture content of 45 % and crushed with a mechanical chopper (model Shredder FYS-76, China). The length of the component particles in the mixture for the substrate did not exceed 1 cm. Grinding of the raw materials contributed to better aeration of the substrate; reducing the particle size to 0.9 cm ensured an increase in the microbial degradation process. Next, the crushed components of the mixture were re-dried to a moisture content of 20 %.

The next step was to prepare substrates.

Substrate No. 1 consisted of 45 % peat, 40 % litter manure, 15 % chicken manure (nitrogen N_{total}=2.22 %; P_2O_5=1.99 %; K_2O=1.58 %; ph=6.1; ash content, 12,87 %; fiber, 20.85 %; fat, 2.88 %; and tryptophan, 0.26 %).

Substrate No. 2 consisted of 40 % peat, 35 % litter manure, 15 % chicken manure, and 10 % wood chips (nitrogen N_{total}=1.51 %; P_2O_5=1.3 %; K_2O=1.17 %; ph=5.6; ash content, 11.04 %; fiber, 25.13 %; fat, 2.16 %; and tryptophan, 0.17 %).

Substrate No. 3 consisted of 35 % peat, 35 % litter manure, 15 % chicken manure, and 15 % straw (nitrogen N_{total}=2.07 %; P_2O_5=1.49 %; K_2O=0.86 %; ph=6.3; ash content, 11.44 %; fiber, 20.38 %; fat, 2.5 %; and tryptophan, 0.26 %). For substrates No. 1–3, all values are given in % per absolutely dry matter.

The active phase of the composting process, which is mesophilic and thermophilic phases, was considered in our study.

We examined the heat consumption Q_{ad} required to maintain the temperature regime of the composting process by performing a multifactor experiment. The variable factors in the experiment were the moisture content of the substrate *W*, the specific active heat generation by the substrate *q*, and the coefficient of heat resistance of the chamber drum wall *k*.

In our research, the moisture content range of substrates from 45 to 75 % was chosen. At moisture content values other than the specified range, the activity of microorganisms is significantly reduced [3, 23].

The specific active thermal output of the substrate depends on its physical-chemical characteristics – pH, carbon to nitrogen ratio, the content of cellulose-lignin components, acidity, the particle size of components. The values of specific active heat output for substrates No. 1–3 were determined experimentally. Our study was carried out inside the premises of a small volume with an ambient temperature of 18 °C, moisture content of 60 %, and an air speed of up to 0.1 m/s.

Initially, the moisture content in substrates No. 1–3 was brought to 45 %. Substrate No. 1 was loaded into the drum of the chamber with no thermal insulation of the outer walls to study thermal costs for maintaining the composting process. A similar study was carried out for substrates No. 2 and No. 3. In the next step, the moisture content in the substrates was brought to 60 %; the studies were repeated. Further study was carried out for substrates with a moisture content of 75 %.

In order to determine the effect of heat loss in the environment on the heat consumption Q_{ad} during biomass fermentation, the outer surface of the drum was additionally thermally insulated (foam-based composite material was used). The thickness of the thermal insulation layer was changed from 0 to 20 cm so that the range of change in the parameter *k* varied from 10 W/(m^2·°C) to 1.6 W/(m^2·°C). The study was carried out for the values of the heat transfer coefficient *k* equal to 1.6; 5.8; and 10 W/(m^2·°C).

The temperature of the substrate was measured by a temperature sensor (model TSP 1-8, Ukraine). The reactor drum speed was measured by a portable optical tachometer (model testo 465, Germany). Ambient temperature and relative moisture content were measured using a thermohygrometer (model Walcom HT-350, China). Samples of stirred components of the substrate were selected by a tubular sampler at different points of the drum at the removed lid at each of the composting stages. The moisture content of the substrate was measured by a device (model SUPERTECH AGROLINE, Denmark). The mass of the sample was determined by means of laboratory scales (model FEH-320, Ukraine). The thickness of the insulation layer was measured by a mechanical caliper of 300 mm (SIGMA 3922291, Ukraine). The results from the experimental study were treated using the Microsoft Excel 2003 and Statistica 11.0 software packages (StatThusft, USA).

Variation intervals of factors: the substrate's moisture content *W* (%) – 45, 60, and 75; the heat transfer coefficient *k* (W/[m^2·°C]) – 1.6; 5.8; and 10; the substrate's specific active heat output *q* (W/kg) – 5.2; 7.2; and 9.2. Coded factors: $X_1=W$, $X_2=k$; $X_3=q$. Variation levels of the above factors are given in Table 1.

To obtain process models in the form of second-power polynomials, a second-order non-compositional plan was chosen on a Box-Benkin-type cube.

The planning stage included the coding of factors, the randomization of experiments, the implementation of the experiment, the verification of experiment reproducibility, the calculation of regression coefficients, the assessment of the regression coefficients significance, and the adequacy of the test model [24].

Table 1

Variable factors and the levels in their variation to determine heat consumption

Factor variation level	Substrate moisture content *W*, %	Chamber wall heat transfer coefficient *k*, W/(m^2·°C)	Substrate specific heat output *q*, W/kg
Upper level (+)	75	10.0	9.2
Medium level (0)	60	5.8	7.2
Bottom level (–)	45	1.6	5.2

For the reliability of the research data, it is accepted that the number of parallel experiments conducted under the same conditions is equal to 3. A series of 8 original experiments were carried out in accordance with the planning matrix; the coefficients of the linear part of the polynomial were calculated according to the methodology given in [24]. The experiments were repeated three times. The homogeneity of variance in experiments was determined according to the Cochrane criterion. If the reproducibility condition failed to meet the Cochrane criterion, the conditions of the experiment were checked that produced the maximum variance value, as well as the accuracy of the measurement, was checked. Then we increased the number of repeated experiments. When the reproducibility condition met the Cochrane criterion, we constructed a regression equation. Experimental coefficients of the equation were calculated, which reflected the extent of influence exerted by the variable factors of our experiment on the dependent parameter. The adequacy of the obtained polynomial was checked according to the Fisher criterion. The significance of each coefficient in the regression equation was established according to the Student criterion. Data from the experiments were statistically treated in advance in order to eliminate gross errors.

According to the plan of the multifactor experiment, the value of the relative error of the model was obtained, which is less than 2.67 %. This applies to all experiments. The average relative deviation was 2.2 %. Thus, the relative error was less than 10 %. The resulting relative error value is considered acceptable in modeling [25].

5. Results of studying the thermal mode of the bio-based raw materials composting process in a rotary-type chamber

5. 1. Thermal balance in the system

A study reported in [20] states that in order to maintain an optimal temperature regime during composting (especially in the cold season), an additional amount of heat should be supplied to the chamber drum.

In a general form, the equation of thermal balance to determine the specified required additional amount of heat is as follows:

$$Q_{ad.} + Q_{sub.} - Q_{h.ex.} - Q_{air} - Q_{heat} = 0, \quad (1)$$

where Q_{ad} is the additional amount of heat transmitted by a hot heat carrier to the composted substrate to maintain the optimal temperature regime of the composting process, W;

$Q_{sub.}$ is the amount of heat released by the substrate during the process, W;

Q_{heat} is the amount of heat required to heat the mixture to the optimum operating temperature of the composting process, W;

Q_{air} is the amount of heat lost with the air during aeration, W;

$Q_{h.ex.}$ is the amount of heat transmitted from the drum surface of the chamber to the environment by heat exchange, W.

The functional relationship between the temperature and the amount of heat flows over time is determined from the differential equation, which, for a stationary heat exchange process, can be recorded in the following form:

$$Q_{heat}=\left(m_{sub.}\cdot c_{sub.}+m_{drum}\cdot c_{drum}\right)\cdot\left(T_{opt.}-T_{in.t.}\right)/d\tau_{c.ph.}= \\ =\left(m_{sub.}\cdot c_{sub.}+m_{drum}\cdot c_{drum}\right)\cdot\frac{dT}{d\tau_{c.ph.}}, \qquad (2)$$

where $m_{sub.}$, m_{drum}, respectively, is the mass of the substrate and the drum of the chamber, kg;

$c_{sub.}$, c_{drum}, respectively, is the specific heat capacity of the substrate and drum material, J/(kg·°C);

$T_{opt.}$ is the optimal temperature of the corresponding phase of the process, °C;

$T_{in.t.}$ is the initial temperature of the compost and installation, °C;

$\tau_{c.ph.}$ is the duration of the phase in a composting process under investigation, s.

With an increase in the moisture content in the substrate, the specific heat capacity of the substrate increases as well. Thus, the higher the moisture content in the substrate, the greater the amount of heat one needs to supply to the chamber's reactor to maintain the optimal process temperature. The equation that sets the specified dependence is as follows:

$$c_{sub.}=\left(\left(m_{sub.}-m_{\mathrm{H_2O}}\right)\cdot c_{s.s.ph.}+m_{\mathrm{H_2O}}\cdot c_{\mathrm{H_2O}}\right)\Big/m_{sub.}, \qquad (3)$$

where $m_{\mathrm{H_2O}}$ is the water mass in the substrate, kg;

$c_{\mathrm{H_2O}}$ is the water specific heat capacity, J/(m^2·°C) ;

$c_{s.s.ph.}$ is the substrate's solid phase specific heat capacity, J/(m^2·°C).

$$m_{\mathrm{H_2O}}=W\cdot\left(m_{\mathrm{H_2O}}+m_{s.s.ph.}\right)\Big/100\,\%=W\cdot m_{sub.}/100\,\%, \qquad (4)$$

where W is the moisture content in the substrate, %.

Then equation (3), taking into consideration dependence (4), takes the following form:

$$c_{sub.}=\begin{pmatrix}\left(m_{sub.}-W\cdot m_{sub.}/100\,\%\right)\cdot c_{s.s.ph.}+\\+c_{\mathrm{H_2O}}\cdot W\cdot m_{sub.}/100\,\%\end{pmatrix}\Big/m_{sub.}= \\ =c_{s.s.ph.}+W\cdot\left(c_{\mathrm{H_2O}}-c_{s.s.ph.}\right)\Big/100\,\%. \qquad (5)$$

The additional amount of heat transmitted by a hot heat carrier to the substrate to maintain the optimum temperature at the appropriate phase of the process:

$$Q_{ad.}=V_{h.c.}\cdot c_{h.c.}\cdot\rho_{h.c.}\left(T_{inlet.h.c.}-T_{outlet.h.c.}\right)/d\tau_{c.ph.}, \qquad (6)$$

$c_{h.c.}$ is the specific heat capacity of a heat carrier, J/(kg·°C);

$\rho_{h.c.}$ is the heat carrier density, kg/m^3;

$V_{h.c.}$ is the volume of a heat carrier circulating in the inter-wall space of the drum during the composting cycle, m^3;

$T_{inlet.h.c.}$ is the heat carrier's temperature at the inlet to the chamber drum, °C;

$T_{outlet.h.c.}$ is the heat carrier's temperature at the outlet of the chamber drum, °C.

The loss of heat flux to the environment:

$$Q_{h.ex.}=F\cdot\left(T_{opt.}-T_{ambient}\right)\cdot k, \qquad (7)$$

where F is the heat exchange surface area, m^2;

$T_{ambient}$ – ambient temperature, °C.

$$F=\pi\left(D+2\sum_{i=1}^{n}h_i\right)\cdot\left(\frac{1}{2}D+\sum_{i=1}^{n}h_i+L\right), \qquad (8)$$

D is the inner diameter of the chamber drum, m;

$\sum h_i$ is the thickness of the walls of the chamber drum, taking into consideration insulation, m;

L is the length of the chamber drum, m;

k is the heat transfer coefficient of the chamber drum walls, W/m^2.

The amount of heat released by the substrate during the composting cycle:

$$Q_{sub.}=m_{sub.}\cdot k_1\cdot q/d\tau_{c.ph.}, \qquad (9)$$

q is the specific substrate heat output per composting cycle, J/kg;

k_1 is the coefficient that takes into consideration the proportion of heat released over an active phase.

The substrate's heat output during a composting cycle is uneven, which is associated with the activities of bacteria and the optimal conditions for their existence. The phenomenon of self-warming of the substrate continues as long as the rate of heat release exceeds the rate of its scattering. Upon reaching a certain temperature maximum, the activities of bacteria slow down, followed by a decrease, which reduces the intensity of the process.

The amount of heat lost with air aeration is:

$$Q_{air}=c_{air}\cdot\rho\cdot V_{air}\left(T_{air.outlet}-T_{air.inlet}\right)/d\tau_{c.ph.}, \qquad (10)$$

c_{air} is the specific heat capacity of air, J/(kg·°C);

ρ is the air density, kg/m^3;

V_{air} is the air volume of aeration supplied during a composting cycle, m^3;

$T_{air.inlet}$ is the air temperature of aeration at the inlet to the drum, °C;

$T_{air.outlet}$ is the air temperature of aeration at the outlet of the drum, °C;

The value of specific heat intensity of air differs at different values of moisture content. However, due to the insignificant amount of air, the effect of the specific heat capacity of the air on the accuracy of the model is insignificant; it can be neglected.

Upon fitting equations (2), (6), (7), (9), and (10) to dependence (1), we obtain:

$$V_{h.c.}\cdot c_{h.c.}\cdot\rho_{h.c.}\left(T_{inlet.h.c.}-T_{outlet.h.c.}\right)/d\tau_{c.ph.}+ \\ +m_{sub.}\cdot k_1\cdot q/d\tau_{c.ph.}-F\cdot\left(T_{opt.}-T_{ambient}\right)\cdot k- \\ -c_{air}\cdot\rho V_{air}\left(T_{air.outlet}-T_{air.inlet}\right)/d\tau_{c.ph.}- \\ -\left(m_{sub.}c_{sub.}+m_{drum}c_{drum}\right)\cdot\frac{dT}{d\tau_{c.ph.}}=0. \qquad (11)$$

Hence

$$\left(m_{sub.} \left(\begin{array}{l} c_{s.s.ph.} + \\ +W \cdot \left(c_{H_2O} - c_{s.s.ph.} \right) / 100\,\% \end{array} \right) + \atop + m_{drum} c_{drum} \right) \cdot \frac{dT}{d\tau_{c.ph.}} =$$

$$= V_{h.c.} \cdot c_{h.c.} \cdot \rho_{h.c.} \left(T_{inlet.h.c.} - T_{outlet.h.c.} \right) / d\tau_{c.ph.} +$$

$$+ m_{sub.} \cdot k_1 \cdot q / d\tau_{c.ph.} - F \cdot \left(T_{opt.} - T_{ambient} \right) \cdot k -$$

$$- c_{air} \cdot \rho \cdot V_{air} \left(T_{air.outlet} - T_{air.inlet} \right) / d\tau_{c.ph.}. \quad (12)$$

Transform the expression relative to the parameter under study:

$$\frac{dQ_{ad}}{d\tau_{c.ph.}} = m_{sub} \cdot k_1 \cdot \frac{dq}{d\tau_{c.ph.}} -$$

$$- \left(m_{sub} \left(\begin{array}{l} c_{s.s.ph.} + \\ +W \cdot \left(c_{H_2O} - c_{s.s.ph.} \right) / 100\% \end{array} \right) + \atop + m_{drum} c_{drum} + c_{air} \cdot \rho \cdot V_{air} \right) \cdot \frac{dT}{d\tau_{c.ph.}} - F \cdot k. \quad (13)$$

After integrating differential equation (13) for time, we obtain:

$$Q_{ad} = m_{sub} \cdot k_1 \cdot q -$$

$$- \left(m_{sub} \left(c_{s.s.ph.} + W \cdot \left(c_{H_2O} - c_{s.s.ph.} \right) / 100\,\% \right) + \atop + m_{drum} c_{drum} + c_{air} \cdot \rho \cdot V_{air} \right) \times$$

$$\times \left(T_{opt.} - T_{ambient} \right) - F \cdot k \cdot \tau_{c.ph.}. \quad (14)$$

The resulting equation relates the examined parameter, an additional amount of heat required to maintain the composting process, to such adjustable parameters as the substrate's moisture content, the heat transfer and heat output coefficients.

5. 2. Results of an experimental study into the thermal regime of bio-based raw materials composting process

The results of our experimental research and statistical treatment form an array of heat flow values required to maintain the optimal temperature regime of the composting process; they are given in Table 2.

Treating the experimental results using the software Statistica 11.0 (StatThusft, USA) produced the regression equation in an encoded form (15) and determined the corresponding regression coefficients: b_0=72.09; b_1=51.43; b_2=97.16; b_3=–60.73; b_{12}=–3.98; b_{13}=32.25; b_{23}=4.1; b_{11}=25.38; b_{22}=–0.8; b_{33}=12.9.

Regression equation:

$$Q_{ad} = 72.09 + 51.43 \cdot X_1 + 97.16 \cdot X_2 -$$

$$- 60.73 \cdot X_3 - 3.98 \cdot X_1 \cdot X_2 + 32.25 \cdot X_1 \cdot X_3 +$$

$$+ 4.1 \cdot X_2 \cdot X_3 + 25.38 \cdot X_1^2 - 0.8 \cdot X_2^2 + 12.9 \cdot X_3^2, \quad (15)$$

where Q_{ad} is the heat consumption required to maintain the optimal temperature regime of the composting process, MJ;

X_1 (W) is the substrate's moisture content, %;

X_2 (k) is the heat transfer coefficient of the chamber wall, W/(m^2·°C);

X_3 (q) is the specific active heat output of the substrate, W/kg.

The tabular value of Cochrane criterion at a 5 % significance level, the number of degrees of freedom equal to f_2=2, and with the number of experiments f_1=15, is G^{tab}= =0.3346 [24]. We have established that G=0.276. Since $G<G^{tab.}$, the process is fully reproduced.

The estimated value of the Fisher criterion at inadequacy variance S^2=8.41 was F=9.5. The tabular value of this parameter is $F^{tab.}$(0.05; 15; 2)=19.38. Since $F<F^{tab.}$, the hypothesis on the adequacy of the regression equation has been confirmed [24]. The determination coefficient was R^2=0.98.

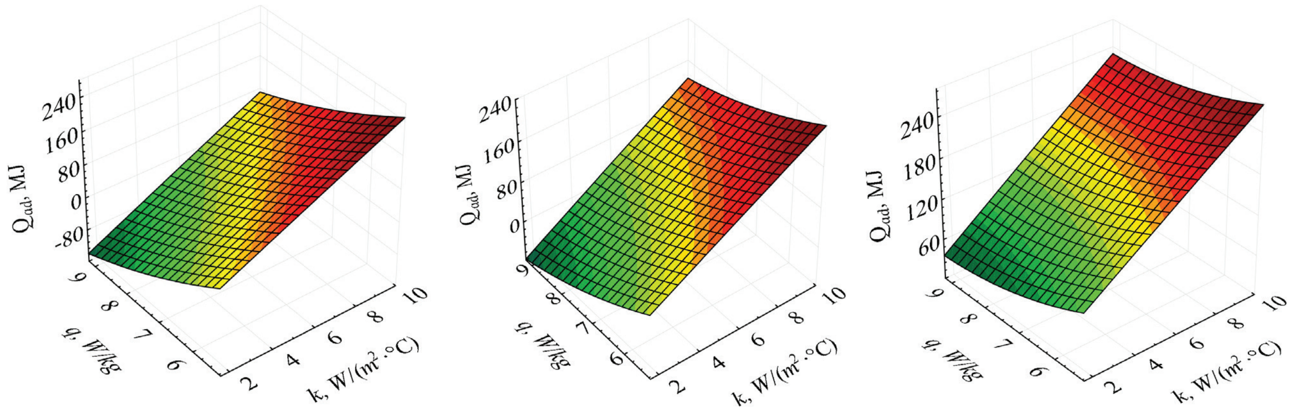
Based on the analysis of the regression equation coefficients (1), we can conclude that the heat transfer coefficient of the chamber wall X_2 (k) has the greatest influence on the response function. The substrate's specific active heat output X_3 (q) affects it to a lesser extent. The substrate's moisture content X_1 (W) has the least impact. The numerical increase in X_1 and X_2 increases the response function; the decrease in them leads to its descend.

A graphic representation of the above equation (15) is shown in Fig. 2–4.

Table 2

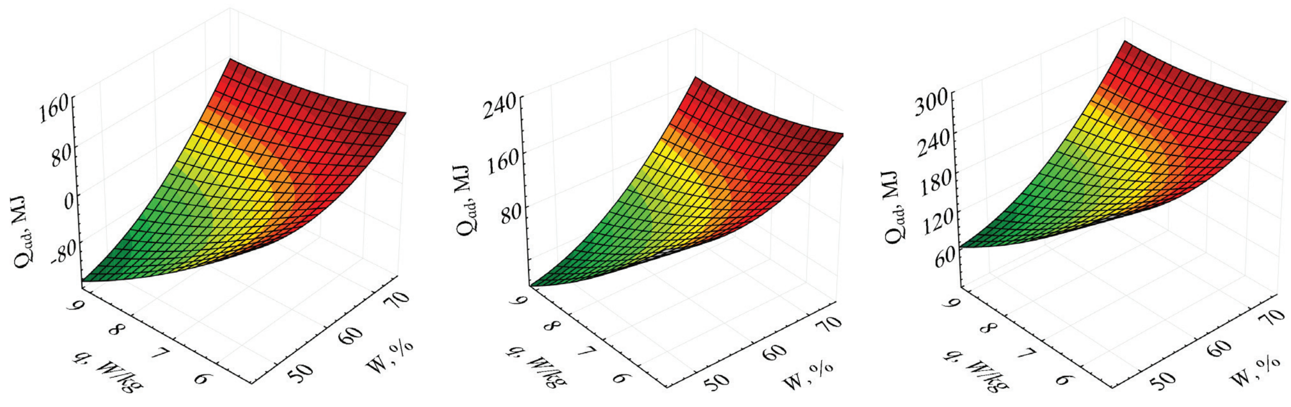
Multifactorial experiment planning matrix

Experiment No.	Factors			Experimental results				Model adequacy check		
	X_1	X_2	X_3	Q_{ad1}	Q_{ad2}	Q_{ad3}	$Q_{ad.m.}$	$Q_{ad.m.c.}$	$(Q_{ad.m.}-Q_{ad.m.c.})$	$(Q_{ad.m.}-Q_{ad.m.c.})^2$
7	+	+	0	239.5	244.5	240.5	241.5	241.3	0.2	239.5
8	+	–	0	50.7	51.1	50.8	50.9	54.9	–4.0	50.7
12	–	+	0	150.2	149.3	151.8	150.4	146.4	4.0	150.2
10	–	–	0	–56.6	–56.6	–55.2	–56.1	–55.9	–0.2	–56.6
2	0	0	0	73.2	72.8	72.5	72.8	72.1	0.7	73.2
11	+	0	+	135.7	133.6	133.5	134.3	133.3	1.0	135.7
15	+	0	–	192.5	195.3	193.6	193.8	190.3	3.5	192.5
6	–	0	+	–37.6	–37.7	–37.4	–37.6	–34.0	–3.5	–37.6
9	–	0	–	151.0	151.3	150.6	151.0	151.9	–1.0	151.0
3	0	0	0	71.9	72.6	72.7	72.4	72.1	0.3	71.9
5	0	+	+	121.4	123.9	121.9	122.4	124.7	–2.3	121.4
4	0	+	–	232.5	235.7	231.1	233.1	238.0	–4.9	232.5
13	0	–	+	–73.2	–72.9	–72.7	–72.9	–77.8	4.9	–73.2
1	0	–	–	54.0	54.5	54.0	54.2	51.9	2.3	54.0
14	0	0	0	70.8	71.6	70.7	71.0	72.1	–1.1	70.8



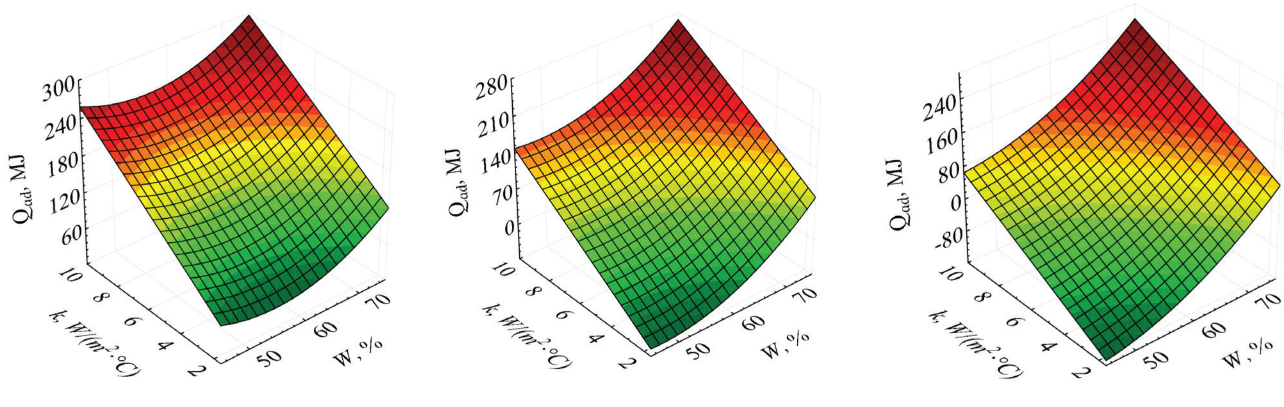
a *b* *c*

Fig. 2. Dependence of heat consumption Q_{ad} on the heat transfer coefficient of the chamber wall k and the specific active heat output of the substrate q: a – W=45 %; b – W=60 %; c – W=75 %



a *b* *c*

Fig. 3. Dependence of heat consumption Q_{ad} on the substrate's moisture content W and the substrate's specific active heat output q: a – k=1.6 W/(m^2·°C); b – k=5.8 W/(m^2·°C); c – k=10 W/(m^2·°C)



a *b* *c*

Fig. 4. Dependence of heat consumption Q_{ad} on the substrate's moisture content W and the chamber wall's heat transfer coefficient k: a – q=5.2 W/kg; b – q=7.2 W/kg; c – q=9.2 W/kg

Our analysis of graphical dependences in Fig. 2–4 indicates the similarity of the tendencies of the dependence of heat consumption on maintaining the optimal temperature regime of the substrate fermentation process on the variable factors of the experiment.

Fig. 2 shows that at the fixed values of substrate and external temperatures and the specified design parameters of the installation, an increase in the substrate's moisture content W leads to an increase in heat consumption Q_{ad} to maintain a composting process. At the values of the chamber wall's heat transfer coefficient k=1.6 W/(m^2·°C) and the substrate's specific active heat output q=5.2 W/kg, maintaining the substrate's composting process with a moisture content of 45 % requires about 54 MJ of heat (Fig. 2, *a*). Whereas the composting of the substrate with a moisture content of 75 %, subject to ensuring the temperature regime in the thermophilic phase within 65 °C...70 °C, requires 100.4 MJ of heat (Fig. 2, *c*). The increase in the moisture content in the substrate causes a significant absorption of an additional amount of heat Q_{ad}, which is associated with a high value, compared to other components of the substrate, of the specific heat capacity of water – 4,200 J/(kg·°C).

However, this trend is different for the substrate's moisture content range of W=58...62 %. In this range, there is a slight reduction in heat consumption Q_{ad}. This is because the moisture content within 58...62 % is optimal for the development of microorganisms; the microbiological processes have an advantage over the heat-generating ones.

The worst composting conditions with the highest amount of heat absorbed, Q_{ad}=278.6 MJ, are observed at the substrate's moisture content of W=75 %, the heat transfer coefficient of the chamber wall k=10 W/(m^2·°C), and a value of the substrate's specific active heat output q=5.2 W/kg (Fig. 2, *c*, 3, *c*, 4, *a*).

In our study (Fig. 4), an increase in the indicator of the substrate's specific active heat output q leads to a decrease in heat consumption Q_{ad} to maintain the optimum temperature during composting. Thus, increasing the parameter q from 5.2 W/kg (substrate 1) to 9.2 W/kg (substrate 3) led to a reduction in heat consumption by almost 113 MJ at W=60 %, k=10 W/(m^2·°C). Lower is the reduction of heat consumption at moisture content W=75 %, k=10 W/(m^2·°C); it is only 50 MJ. This fact is explained by a decrease in the activities of microorganisms with an increase in moisture content W above 62...65 %.

The greatest impact on heat consumption to maintain the composting process is exerted by the heat transfer coefficient of the chamber wall k (Fig. 3). At the highest values of this parameter k=10 W/(m^2·°C), there are the highest heat losses – Q_{ad}=248 MJ at W=45 %, and q=5.2 W/kg; Q_{ad}=237 MJ at W=60 %, and q=5.2 W/kg; and Q_{ad}≈279 MJ at W=75 %, and q=5.2 W/kg (Fig. 3, *c*). For comparison (Fig. 3, *a*), the lowest values of the parameter k=1.6 W/(m^2·°C) at W=45 % and q=5.2 W/kg required Q_{ad}≈54 MJ for composting process; Q_{ad}≈52 MJ at W=60 %, and q=5.2 W/kg; and Q_{ad}=100.4 MJ at W=75 %, and q=5.2 W/kg. In order to optimize the composting process, it is recommended to structurally ensure the thermal insulation of the chamber drum walls in such a way that the value of the heat transfer coefficient k is higher than 4.6 W/(m^2·°C).

6. Discussion of results of studying the thermal mode of the bio-based raw materials composting process in a rotary-type chamber

The use of rotary fermentation chambers makes it possible to produce high-quality compost in terms of its agrochemical indicators. However, to obtain high-quality compost, it is necessary to ensure the proper temperature regime at each of the composting phases, especially in the thermophilic phase, when the temperature should be within 65...70 °C.

Compiling the thermal balance has allowed us to determine the amount of heat Q_{ad} (14) necessary to maintain the proper temperature regime of the composting process, as well as its dependence on three important parameters – the substrate's moisture content W, the substrate's specific active heat output q, and the heat transfer coefficient of the chamber wall k.

The current techniques of the aerobic solid-phase fermentation process are based on the principal role of microbiocenosis in its implementation. Forming optimal conditions for the growth and development of microorganisms that carry out biotransformation is associated with the need to adjust the set of fermentation parameters [7, 8] and the application of various process stimulants.

Numerical experiments indicate that the rate and depth of fermentation depend on the physicochemical characteristics of the substrate, its biochemistry and microbiology. Physicochemical characteristics include pH, moisture content, the particle size of the composted matrix, etc. Biochemistry and microbiology imply the ratio of carbon to nitrogen, seeding with microorganisms, the content of macro and microelements, as well as toxic compounds [26].

Our study has shown that a significant factor that depends on the physical-chemical characteristics of the substrate and affects the thermal conditions of the composting process is the specific active heat output (Fig. 4). Increasing this indicator reduces the thermal costs of the composting process. The parameter q can be one of the regulating characteristics of the composting process. Adding wood chips and straw to the substrate increased the value of the substrate's specific active heat output from 5.2 W/kg (No. 1) to 7.2 W/kg (No. 2) and up to 9.2 W/kg (No. 3), respectively.

The maximum temperature increase was registered in experiments involving substrate No. 3, which contained chopped straw (there is the lowest heat consumption per process, Fig. 4, *c*). In addition, the substrate with straw content is characterized by a minimum speed of its cooling. This is due to the fact that, in this case, the microbial activity remained at a fairly high level until the end of the process. For experiments involving substrate No. 3, the maximum duration of the thermophilic phase was 5 days at a temperature of 68 °C, which testified to the positive effect of straw on the metabolism of thermophilic group microorganisms. For comparison, in the experiments involving substrate No. 1, the duration of the thermophilic phase was 6 days at a maximum temperature of this phase of 61 °C.

The content of wood chips in substrate No. 2 contributed to the rapid heating of the mixture and a reduction in the duration of the thermophilic phase compared to substrates No. 1 and No. 3. Thermal costs of the process (Fig. 4, *b*) significantly decreased compared to substrate No. 1 (Fig. 4, *a*). The thermophilic phase lasted 4 days at a maximum temperature of this phase of 65 °C. The reduction in the duration of the thermophilic phase indicates an inhibitory effect of an excess of lignin-cellulose components in relation to thermophilic microflora. The addition of wood chips to the substrate increased its acidity.

Based on our study (Fig. 4), in order to ensure the optimal temperature regime in the thermophilic phase (65...70 °C), the value of the substrate's specific active heat output should be higher than q=7.2 W/kg.

The results reported in [17–19, 21] indicate the possibility of increasing the indicator of the substrate's specific active heat output by forming multicomponent mixtures based on ingredients that increase heat output during composting. However, this issue requires additional research to determine the percentage of individual components in the substrate. Some additives have an inhibitory effect on the activity of microflora, as is the case with substrate No. 2, which contained wood chips.

In order to determine the influence of the thermal regime on the qualitative indicators of the compost produced from substrates No. 1–3, their chemical composition was studied.

Compost No. 1 contained the following components in its composition: N_{total}=2.01 %; P_2O_5=1.77 %; K_2O=1.73 %; C_{total}=18.3; ash content, 16.92 %; moisture content, 54 %.

Compost No. 2 consisted of nitrogen N_{total}=1.71 %; P_2O_5=1.73 %; K_2O=1.19 %; C_{total}=21.07; ash content, 15.4 %; moisture content, 56 %.

Compost No. 3: nitrogen N_{total}=2.03 %; P_2O_5=1.92 %; K_2O=1.71 %; C_{total}=22.46; ash content, 15.99 %; moisture content, 58 %. For composts No. 1–3, all values are given in % per absolutely dry matter. The moisture content of the starting substrates No. 1–3 was 62 %.

The highest fertilizing properties were demonstrated by compost No. 3 with straw content, which was characterized by high temperature throughout the composting cycle (Fig. 4, *c*). The lowest fertilizing properties were demonstrated by compost No. 2, although the active composting phase of substrate No. 2 was also characterized by a relatively high-temperature regime (Fig. 4, *b*). The reason, as noted above, is the reduction of the thermophilic phase to 4 days, which was not enough to complete the microbiological processes of this phase. Since the addition of wood chips to the substrate increases the values of its specific active heat output in general, therefore, the reason is the correct calculation of the percentage of this component in the mixture.

It is believed that the peak of activities of aerobic microorganisms is achieved at such a maximum moisture content of the fermented substrate, which does not prevent the diffusion of oxygen through a layer of water to the particles of the substrate components. According to [3, 23], for the effective progress of the fermentation process, not limited by aeration, the moisture content in the substrate should be within 45–70 %. Our study showed that the best thermal conditions for composting process were observed at the substrate's moisture content in the range from 58 to 62 % (Fig. 2). Over this range of moisture content values at the constant values of the heat transfer coefficient of the chamber wall, the heat consumption for the composting process for the examined substrates No. 1–3 were significantly lower than at a moisture content of 75 % (Fig. 2, *c*). And slightly exceeded the heat consumption for the process at a moisture content of 45 %. At moisture content exceeding 75 %, the leaching of nutrients was observed, with the volumetric oxygen content decreasing while the anaerobic processes began and the rate of biodegradation decreased. In addition, moisture, as a chemical, has a rather high value of specific heat capacity, which further worsens the temperature conditions of the process. With a decrease in moisture content to 45 % (with other parameters constant), the temperature of the substrate began to grow (heat cost of the process is the smallest, Fig. 2, *a*). However, in the thermophilic phase, the temperature was only 58 °C, not reaching its maximum value. The maximum temperature of the thermophilic phase was 68 °C; it was reached by composting the substrate with a moisture content of 58 %. This indicates that the decrease in the moisture content of the substrate slows down the activity of the microflora, and, at moisture content values of 20 % or less, the activity stops completely, which is confirmed by a study reported in [26].

Accordingly, with an increase in the heat transfer coefficient of the chamber wall from 1.6 W/(m^2·°C) to 10 W/(m^2·°C), the heat consumption in the composting process increased (Fig. 3). At the highest values of this parameter, k=10 W/(m^2·°C), the highest heat loss was observed, Q_{ad}≈279 MJ, for the active phase of the composting process at the moisture content of the substrate W=70 % (Fig. 3, *c*).

When the drum was thermally insulated (reaching k=1.6 W/(m^2·°C)) and we composted substrate No. 1 (q=9.2 W/kg) with a moisture content of 58 %, there was an excess heat release within 140 MJ (Fig. 3, *a*). This heat can be used for other technological processes (heating the air of aeration).

In order to optimize the composting process, it is necessary to structurally ensure the thermal insulation of the chamber drum walls so that the value of the heat transfer coefficient k is lower than 4.6 W/(m^2·°C) (Fig. 3) or use an additional external energy source. Subject to these conditions, one can achieve minimum values of additional heat consumption necessary to maintain the temperature regime of the composting process, and, in some cases, even have an excess of heat.

However, given the instability of heat output during the cycle, as well as due to fluctuations in the temperature of the external environment, it is impractical to completely abandon the system of adjusting additional heat. The optimization parameter, first of all, should be the duration of the substrate stay in the reactor and the associated energy costs for the composting process, as well as the quality indicators of the finished product, rather than the heat cost of the process.

The range of numeric values for input variables (Table 1) was chosen as the most used in composting technology, based on studies reported in [10, 21, 26]. Other parameters of our study were determined on the basis of the design features of the installation and the properties of the substrate, so their impact on the model was not investigated. Think of it, and the parameters k, q, and W have a more complex effect on the response function Q_{ad} (heat consumption per process). In particular, k is the parameter that takes into consideration the type of material of the walls, their design, the thickness of the layers of thermal insulation, the density of their fit, as well as the heat transfer from the substrate to the walls of the chamber and to the environment. However, the stability of the k parameter depends on the list of unaccounted factors, such as the existence of significant convection, corrosion wear of the drum walls, which increases the amount of heat loss in the environment. Neglecting the specified factors may affect the reproducibility of the experiment.

A rotary-type chamber (Fig. 1), when compared to its analogs [2, 4, 26], has a simple design and high operational reliability. Ensuring uniform heating of the chamber walls with heat, brought from external energy sources, made it possible to maintain the proper temperature at each of the phases of the composting process. The structure allows for adjusting the chamber speed (ensures uniform mixing of components in the substrate) and air volume for substrate aeration, which improves the accuracy of control over the process. The application of a given design makes it possible to reduce, depending on the substrate composition, the duration of composting by 20 %, which provides for a significant increase in the installation performance in terms of the compost produced, as well as ensures energy cost optimization.

These advantages make it possible to use the chamber extensively: at agricultural enterprises where there is a waste of crop production, livestock, woodworking; in garden and park complexes and in housing and communal services for the disposal of solid household bio-related waste.

Promising ways of further development of this study are determining the optimal geometrical parameters for the installation, their impact on its performance, and the energy intensiveness of the finished products.

7. Conclusions

1. A mathematical model was constructed on the basis of a thermal balance equation for the process of composting bio-based raw materials. The model makes it possible to establish the dependence of the amount of heat required to maintain the optimal thermal mode of the composting process on the heat transfer coefficient of the chamber wall, the substrate's moisture content, and its specific active heat output. The mathematical model agrees well with the experimental data. The determination coefficient is 0.98.

2. We have experimentally investigated the effect of the heat transfer coefficient of the chamber wall, the substrate's moisture content, and its specific active heat output on the thermal mode of the composting process. It has been established that:

– increasing the moisture content of the substrate leads to an increase in heat consumption to maintain the thermal mode of the composting process. The highest heat consumption for the composting process, 279 MJ, is observed at a substrate moisture content of 70 %, the heat transfer coefficient of the chamber wall of 10 W/(m^2·°C), and the indicator of the substrate's specific active heat output of 5.2 W/kg. The optimal moisture content, both to maintain the temperature regime of the process and to ensure the activity of microorganisms, is 58...62 %;

– with an increase in the specific active heat output of the substrate, heat consumption to maintain the thermal regime of the composting process is reduced. An increase in the specific active heat output of the substrate from 5.2 W/kg to 9.2 W/kg led to a reduction in the heat consumption for the composting process by almost 113 MJ. The data were acquired at a substrate moisture content of 60 % and the value of the heat transfer coefficient of the chamber wall of 10 W/(m^2·°C);

– with an increase in the heat transfer coefficient of the chamber wall from 1.6 W/(m^2·°C) to 10 W/(m^2·°C), heat consumption in the composting process increases. Reducing the heat transfer coefficient to 1.6 W/[m^2·°C] (by thermal insulation) leads to the release of 140 MJ of excess heat during composting of the substrate with a moisture content of 58 % with a value of specific active heat output of 9.2 W/kg.

Our results testify to the possibility of applying dependence (14) to perform theoretical modeling of thermal processes in fermentation chambers during the production of bio-based raw materials compost.

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