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RESEARCH OF MECHANIZED PROCESS OF ORGANIC WASTE COMPOSTING

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ABSTRACT. The article is devoted to mechanising composting based on energy-saving technical systems. The goal of the research is to determine the patterns that describe the impact of different drum-blade working bodies' design and technological parameters on their work energy performance, the homogeneity of the mixture components distribution and their structure in the formed composting pad of a certain height. The physical-mathematical model of the mechanized composting process of organic raw materials from agroecosystems by technical equipment with drum-blade working bodies has been theoretically substantiated and experimentally investigated. There has been developed the mathematical model that correlates the value of the mixing quality variation coefficient with the load factor and the kinematic indicator of the operating mode. It has been established that, if provided the composting pad layer height is the same, the use of a double-drum working body is more rational in terms of power loss in comparison with a single-drum one.

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Introduction

Mechanized composting based on energy-intensive technical systems was economically feasible due to additional crop production (Center for Clean Air Policy, 2019; Modupe *et al.*, 2020; Kiyonori, 2021). In modern conditions of the financial, material and raw material resources shortage usage of these technologies and technical equipment leads to increased production costs and economic inexpediency of controlled composting in many cases as production costs are not covered by increased yields from their use. (Baba *et al.*, 2018; Pergolaa *et al.*, 2018a; Pergolaa *et al.*, 2018b; Singh *et al.*, 2020). As a result, there is a problematic situation: on the one hand, there is a need to increase the application of organic fertilizers to restore soil fertility, provided the actual significant reduction in manure. On the other hand, there is an inconsistency of existing technologies and technical equipment with social requirements and economic feasibility.

It's not the first time the topic of mechanized livestock waste composting being researched (Nelson, 2002; Golub, 2007; Golub *et al.*, 2017a; Golub *et al.*, 2017b; Nghi *et al.*, 2020; Aliiev *et al.*, 2021). Modern technological equipment for mechanized composting technologies today can be divided into three basic groups of machines: usage of modernized and adapted to economic conditions trailers-spreaders for organic fertilizers, loaders, road-building machines; usage of aerators-mixers – trailed, mounted, self-propelled, tunnel, aerator-mixer loaders with the intermittent operation; usage of aerator-mixer loaders with the continuous operation – self-propelled or trailed.

Monitoring of constructive solutions of the technological equipment models for mechanized compost production technologies has shown that manufacturers offer technical tools that provide different economic and technological conditions. Therefore, the variety of technical solutions is quite large. The following leading companies and corporations that develop and manufacture aerators-mixers and other composting equipment can be listed: Sittler MFG, Brown Bear (Australia), TAGR (China), BACKHUS, Menart, Compost systems GMBH, Gujer Landmaschinen (Germany), ALLU Group, Sandberger (Finland), Frontier, HCL Machine, Wildcat, SCARAB (USA), ABONO (Turkey), Caravaggi, PEZZOLATO (Italy), KOMPTECH, Morawetz (Austria), *etc*.

The only common thing between aerators-mixers is the performance of the working bodies (Fig. 1). The main structural elements that the drum-blade working bodies consist of are the drum, inclined blades, straight blades, or screws. Straight blades are located radially in the centre of the drum. Inclined blades are installed symmetrically from the drum centre (respectively symmetrical to the straight blades) and fixed along the helical winding lines. The inclined blades' attack angle differs from the angle of the helix. When running, the drum-blade working body performs both translational and rotational movements and, as a result, interacts with the compacted compost material. While cutting into the structure of the compost material, inclined blades or a screw, separate a certain part of the compost material and at the same time separate the portion (chips), mix, loosen, move and throw it behind the drum, forming a new composting pad as a result. Straight blades that work in the area of the greatest height of the composting pad, separate the material from the pad's mass, overturn it with a one-time formation of a new pad. The presence of a technologically free zone behind the working body, which limits the possibility of re-transfer of the compost mass, is an important parameter. During the operation of both straight and inclined blades (screw), the mixture in the separated particles flight zone becomes saturated with oxygen and weathering of carbon dioxide is formed because of microbiological processes. Reforming of the composting pads is also followed by a decrease in mass temperature, weathering of moisture and other gaseous substances.

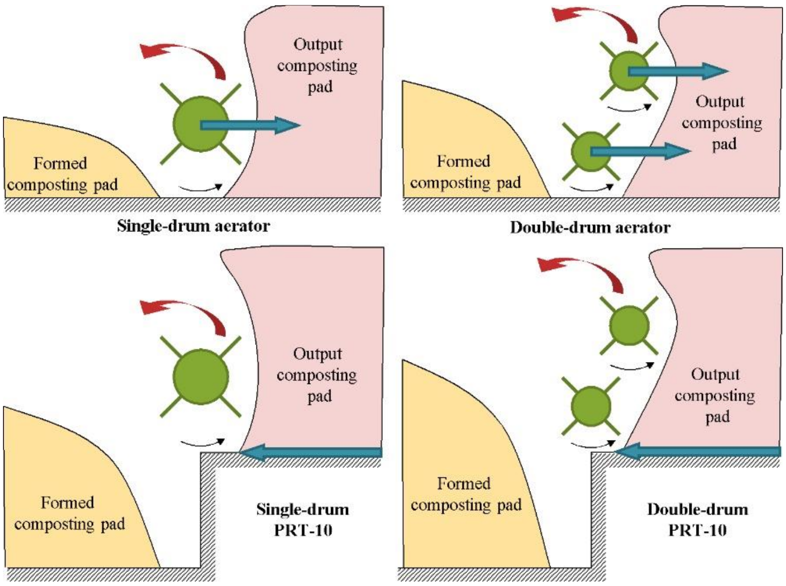
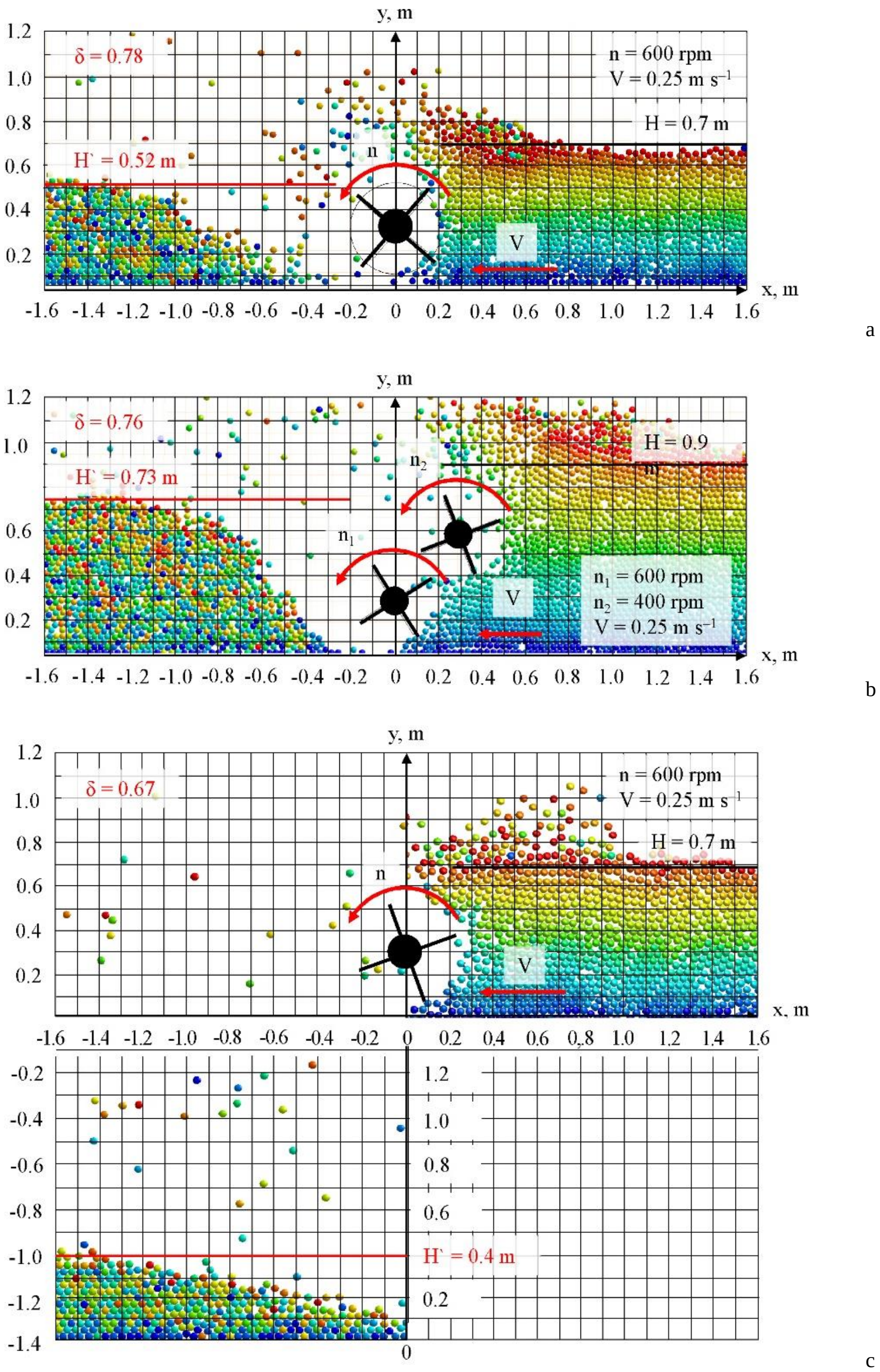


Figure 1. Rotary drum-blade grinding, mixing and formatting machines operation schemes

Many researchers (Mironov, 2006; Golub, 2007; Petunov, 2007; Kudrya, 2015; Golub *et al.*, 2017a; Shevchenko, Aliiev, 2021) are devoted to studying the process of interaction of certain types of working bodies with the manure-compost mixture, which is formed into composting pads. However, it is very difficult to compare the results of these studies due to different conditions. Therefore, the goal of the research is to determine the laws that describe the influence of design and technological parameters of different drum-blade working bodies on the energy performance of their work, the homogeneity of the mixture components and their structure in the formed composting pad with a certain height.

Numerical Simulation Results

To implement numerical simulation in the software package Simcenter Star CCM+ (Siemens Digital Industries Software, Germany) we have made the calculation scheme of the manure-compost mixture mixing process by a single-drum blade working body in two versions (Fig. 2a,b) and a double-drum blade working body in one embodiment (Fig. 2c). Simcenter Star-CCM + software uses numerical simulation methods based on models of k-ε turbulence of split flow, gravitational field, real Van der Waals gas, discrete elements, multiphase interaction to solve this issue (Shevchenko, Aliiev, 2021).



a– single-drum blade working body at the level of the original composting pad;
b – single-drum blade working body at the level higher than original composting pad;
c – double-drum blade working body at the level of the original composting pad

Figure 2. Calculated scheme of the manure-compost mixture mixing process

To model the manure-compost mixture mixing process with a single-drum blade working body, the following design and technological parameters have been adopted: outer radius R = 0.2 m; shaft radius r = 0.05 m; blade thickness $\delta = 0.004$ m; the height of the option "a" location (Fig. 2) h = 0.22 m; the height of the option "b" location (Fig. 2) h = 1.42 m. The following design and technological parameters have been used as modelling factors: speed n (200–600 rpm, step – 200 rpm), the linear speed of movement of the working body (or manure-compost mixture) V (0.05–0.25 m s^{-1}, step – 0.1 m s^{-1}) and the height of the output composting pad H (0.3–0.7 m, step – 0.2 m).

The following design and technological parameters have been used to model the manure-compost mixture mixing process with a double-drum blade working body: outer radii of the first and second drum $R_1 = R_2 = 0.2$ m; the radius of the first and second drums shaft $r_1 = r_2 = 0.05$ m; blade thickness $\delta = 0.004$ m; the height of the first drum location $h_1 = 0.22$ m; the height of the second drum location $h_2 = 0.41$ m. The following design and technological parameters have been used as modelling factors: speed of the first drum rotation n1 (200–600 rpm, step – 200 rpm), frequency of the second drum rotation n_2 (200–600 rpm, step – 200 rpm), the linear velocity of the working body (or manure-compost mixture) V (0.05–0.25 m s^{-1}, step – 0.1 m s^{-1}).

The simulation has been performed on a full factorial experiment with a total number of experiments – $3^3 = 27$. To summarize the data, we introduce the kinematic index of the operating mode λ and the load factor of the working body κ that are determined by the formulas:

$$\lambda = \frac{\omega R}{V}, \tag{1}$$

$$\kappa = \frac{H}{2R}. \tag{2}$$

The height of the obtained manure-compost mixture and the quality of its mixing, which has been determined by the coefficient of variation, have been determined as a modelling criterion

$$s_{\delta} = 1 - \frac{1}{\overline{C}} \sqrt{\frac{\sum_{i=1}^{n} (C_i - \overline{C})^2}{n-1}}, \tag{3}$$

where $\overline{C}$ – the average concentration of material in the composting pad; C_i – material concentration in the i-th zone of the composting pad; n is the number of zones in the composting pad.

As a result of the compost mixture mixing process simulation and approximating the obtained data using the Mathematica software package (Wolfram Research, USA), the dependencies between the formed composting pad height H` and the coefficient of variation of mixing quality δ on rotational speeds n (n_1, n_2), the linear velocity of the working body movement (or compost mixture) V and the height of the output pad H:

– single-drum blade working body at the level of the original composting pad:

$$H` = 0.268866 + 0.296528\,H + 0.319444\,H^2 - 0.00103403\,n - 0.000208333\,H\,n + 9.02778\cdot10^{-7}\,n^2 - 1.05417\,V + 2.54167\,H\,V + 0.000125\,n\,V + 0.944444\,V^2; \tag{4}$$

$$\delta = 1.0964 + 0.413927\,H - 0.569826\,H^2 - 0.00161823\,n - 0.00023426\,H\,n + 1.44573\cdot10^{-6}\,n^2 - 1.94199\,V + 2.33282\,H\,V + 0.00149216\,n\,V + 1.84121\,V^2; \tag{5}$$

$$\delta = 0.667428 + 0.298578\,\kappa - 0.0911722\,\kappa^2 - 0.00112821\,\lambda - 0.000888689\,\kappa\,\lambda + 4.88711\cdot10^{-6}\,\lambda^2; \tag{6}$$

– single-drum blade working body higher than original composting pad:

$$H` = 0.186875 + 1.34236\,H + 1.5\,H^2 - 0.0016798\,n - 0.00129167\,H\,n + 2.08333\cdot10^{-6}\,n^2 + 1.70972\,V - 6.20833\,H\,V + 0.00120833\,n\,V - 3.33333\,V^2; \tag{7}$$

$$\delta = 1.16933 - 0.199309\,H - 0.184407\,H^2 - 0.000914836\,n + 0.000523364\,H\,n + 6.78265\cdot10^{-7}\,n^2 - 1.11349\,V + 1.03217\,H\,V - 0.000416279\,n\,V + 0.017169\,V^2; \tag{8}$$

$$\delta = 0.684991 + 0.0632616\,\kappa - 0.0295052\,\kappa^2 + 0.000994089\,\lambda - 0.000140935\,\kappa\,\lambda - 1.35072\cdot10^{-6}\,\lambda^2; \tag{9}$$

– double-drum blade working body at the level of the original composting pad:

$$H` = 0.97787 + 0.977778\,V - 2.11111\,V^2 - 0.000499306\,n_1 + 0.000291667\,V\,n_1 + 4.3055\cdot10^{-7}\,n_1^2 - 0.001878\,n_2 + 0.002708\,V\,n_2 - 2.29167\cdot10^{-7}\,n_1\,n_2 + 1.4305\cdot10^{-6}\,n_2^2; \tag{10}$$

$$\delta = 0.630425 - 0.357841\,V + 0.926431\,V^2 - 0.000119875\,n_1 - 0.000149469\,V\,n_1 + 2.50835\cdot10^{-7}\,n_1^2 + 0.00094284\,n_2 + 0.000114028\,V\,n_2 - 1.10538\cdot10^{-7}\,n_1\,n_2 - 1.04456\cdot10^{-6}\,n_2^2; \tag{11}$$

$$\delta = 0.721983 - 0.000132435\,\lambda_1 - 8.24555\cdot10^{-7}\,\lambda_1^2 + 0.00110122\,\lambda_2 + 2.33733\cdot10^{-6}\,\lambda_1\lambda_2 - 4.359\cdot10^{-6}\,\lambda_2^2. \tag{12}$$

Material and Methods

The program of experimental research includes:

– research of the universal device for grinding and mixing of solid organic fertilizers;
– research of the trailed fertilizer spreader PRT-10 with the double-drum hinged device for the firm organic fertilizers grinding;
– research of the aerator of manure-compost mixes with a double-drum working body.

Experimental studies of the grinding and mixing process of solid organic fertilizers have been carried out with the creation of the universal experimental installation, which consists of a plant, double-drum working bodies and an electric drive. The created device for solid organic fertilizers grinding and mixing can be placed on the trailed fertilizer spreader like PRT-10 (Fig. 3a) or on tracks that are placed on the ground (Fig. 3b). In the first case, the flow of solid organic fertilizers on the drum working bodies is carried out by a conveyor, and in the second case, it is performed by the movement mechanism of the device (Fig. 3c). It is also possible to install single or double-drum working bodies of a different configuration on the device (Fig. 3d,e).

The following factors were selected as factors of experimental research: manure type (factor A) – litter cow manure (density γ = 680–750 kg m$^{3-1}$; humidity W = 42–66%), bedding litter (density γ = 360–460 kg m$^{3-1}$; humidity W = 32–44%); location (factor B) – on a trailed spreader (type PRT-10), on tracks (aerator type); type of drum working body (factor C) – auger-blade type D = 350 mm (W-shaped), blade type D = 540 mm (V-shaped); number of drum working bodies (factor D) – 1, 2; rotation frequency of the drum working body, n (factor E) – 180, 320, 460 rpm. The frequencies of the lower and upper working bodies' rotation have been set via the transmission mechanisms. Experimental studies have been conducted according to the plan with a total of 36 experiments. We have used the coordinate plane with a unit size of 100 mm as a background to determine the trajectories of the compost particles. This process has been recorded on a video camera. Based on the obtained photographs, we have determined values of the greatest particle velocity V_p, the greatest particle flight altitude h_p, the greatest particle flight range, l_p. We have chosen the following values as criteria of experimental research: homogeneity of components distribution of the output compost mix δ, consumed power P, composting pad's structural indicator θ.

The calculated homogeneity of the distribution of the manure-compost mixture components of the pre-formed composting pad has been determined by the discrete feature method – humidity. Homogeneity in humidity is determined by the coefficient of variation

$$\delta_i = 1 - \upsilon_i = 1 - \frac{\sigma_i}{W_i}, \tag{13}$$

where υ_i is the coefficient of variation of the manure-compost mixture humidity in the experiment; σ_i is the standard deviation of humidity in a series of manure-compost mixture portions in the experiment; w_i is the arithmetic mean value of the moisture content in a series of manure-compost mixture portions in the experiment. For raw materials, the homogeneity in terms of humidity was 0.33–0.47. We have adopted repetition ten times to determine the manure-compost mixture homogeneity in terms of humidity.

a – location on a trailed fertilizer spreader PRT-10;
b – the location on tracks;
c – device moving mechanism;
d – V-shaped double-drum working body;
e – W-shaped single-drum working body

Figure 3. The general look of a universal experimental plant for grinding and mixing solid organic fertilizers

The composting pad's structural indicator θ has been defined as the total percentage of the most valuable fractions up to 5 mm:

$$\theta = \frac{m_{<5}}{M} 100\,\%\,, \qquad (14)$$

where $m_{<5}$ is the mass of the most valuable fractions up to 5 mm, g; M is the mass of the original sample, g. The mass of the original sample M is selected in the range of 200 to 300 g. Each measurement has been repeated 10 times.

The average value of power consumption P has been used as the energy criterion for evaluating the process of grinding and mixing solid organic fertilizers. The dynamics of changes in power consumption P has been determined by the frequency converter VLT Micro Drive (Danfoss, Denmark).

We have created an experimental plant based on the trailed fertilizer spreader PRT-10 with a two-drum mounted device for grinding solid organic fertilizers to carry out experimental studies of the compost mixture mechanical aeration and mixing process (Fig. 3a). The following constructive-technological parameters have been set as experimental researches factors: rotation frequency of the lower working body n_1 (170–490 rpm, step – 160 rpm), the rotation frequency of the upper working body n_2 (170–490 rpm, step – 160 rpm), linear movement velocity of the compost mixture (PRT-10 spreader's velocity) V (0.05–0.25 m s^{-1}, step – 0.1 m s^{-1}), location of the upper working body with the lower one L (–0.4...+0.4 m, step – 0.4 m). The simulation has been performed according to the Box-Benkin plan with a total of 27 experiments. On the second stage of the experiment, we have performed the calculation of research results with the following factors: kinematic index of the lower working body λ_1, kinematic index of the upper working body of the drum λ_2, location of the upper working body with the lower one L. Fresh litter based on sunflower husk (unloaded from the premises) with an average volume weight of $\gamma = 480$ kg $m^{3\,-1}$ and average humidity of W = 32.2% has been used as raw material for experimental research. Technological criteria for assessing the formation of the composting pad is its height H, which should be 1.5 m. This value is achieved by periodically moving the unit MTZ-80+PRT-10.

We have created an experimental plant based on the compost mixtures aerator with a double-drum working body (Fig. 3b) to carry out experimental studies of the compost mixture mechanical aeration and mixing process. The following constructive-technological parameters have been established as factors of experimental research: rotation frequency of the lower drum n_1 (180–460 rpm), the rotation frequency of the upper drum n_2 (180–460 rpm, step – 140 rpm), linear movement velocity of the working body V (0.05–0.15 m s^{-1}, step – 0.05 m s^{-1}), output composting pad's height H (0.5–1.1 m, step – 0.3 m). Rotation frequencies of the lower and upper working bodies have been set by changing the sprockets and chains on the transition mechanisms. The linear speed of the compost mixture movement has been set by changing the sprockets on the movement mechanism of the device. The height of the original composting pad has been formed by a fertilizer spreader PRT-10 conveyor. The simulation has been performed according to the Box-Benkin plan with a total of 27 experiments. The second stage is to obtain the results of studies with the following factors: the kinematic index of the lower working body λ_1, the kinematic index of the upper drum λ_2, the height of the output-composting pad H. We have set homogeneity in humidity as qualitative criteria for evaluating the process of mechanical aeration and the compost mixture mixing. Quantitative criteria for performance evaluation is capacity Q (m^3 h^{-1}). Energy criterion is the average value of power consumption P (kW). The criterion for evaluating the research is the specific energy consumption of the process, which has been determined by the expression $E = P/Q_p$ (kWh $m^{3\,-1}$).

We have used the method of mathematical planning of multifactor experiment, which allows obtaining mathematical models of work processes in the form of regression equations (polynomial) of the second-order to study the influence of each factor on the criterion of process optimization and determination of technical equipment's rational parameters. Processing of the experimental research results have been conducted by the method of mathematical factor planning of experiments and performed using the Mathematica software package. The mathematical model is determined by one optimization criterion. The regression coefficients of the mathematical model are calculated by formulas for D-optimal experimental plans. The confidence limits of the random error of the measurement results are calculated according to the Student's test. The adequacy of the model is checked using a correlation coefficient. The adequacy of the model is checked using Fisher's test.

Results

We have obtained the rational design variant of the developed universal device for cow manure grinding and mixing (single blade W-shaped drum working body mounted on a trailed spreader PRT-10 type, rotating at 460 rpm) using analysis of variance, this provides the greatest observed distribution homogeneity of the obtained compost mixture components $\delta = 0.98 \pm 0.1$ and the greatest composting pad's structural indicator $\theta = 90.4 \pm 0.2$ at the smallest average value of the consumed power – $P = 8.7 \pm 0.2$ kW. Thereafter, the rational design version of the developed universal device for manure grinding and mixing is the following: single-drum W-shaped working body, which is installed on the tracks (aerator) and rotates at a frequency of 460 rpm. With these parameters, the greatest distribution homogeneity of the obtained compost mixture components $\delta = 0.95 \pm 0.1$ is observed and the composting pad's structural indicator equals $\theta = 90.1 \pm 0.2$ at the smallest average value of the consumed power $P = 8.4 \pm 0.2$ kW.

The trajectories of the mixture particles have been experimentally determined for each experiment. Visualization of one of the experiments is shown in Figure 4 on which the trajectory of the particles of the compost mixture is visible and it is possible to determine for the particles the largest values of velocity V_p, flight altitude h_p and flight range l_p. Analysis of the obtained data shows that the highest velocity of compost mixture particles V_p = 13.1–13.4 m s^{-1} is observed for the variant of the universal device with a single-drum working body, which is installed on a trailed spreader PRT-10 type at the highest speed. In this case, for particles, the largest values are their flight altitude h_p = 6.2–6.5 m and flight range l_p = 18.9–19.8 m. Comparison of real trajectories of particles with theoretical shows that the correlation coefficient is R = 0.82–0.93 which allow us to state that the theoretical physical and mechanical models are adequate.

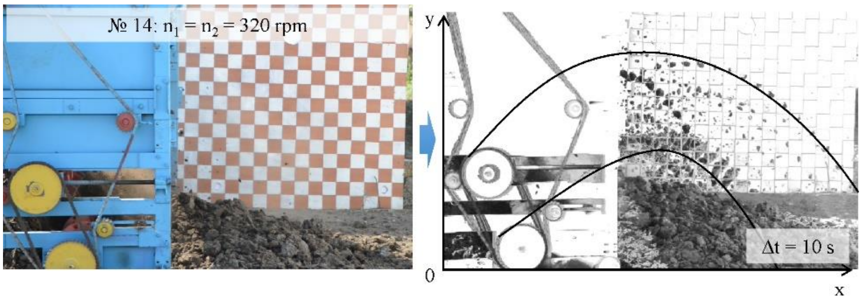


Figure 4. Visualization of the compost mixture particles movement process under the impact from the working bodies of the universal experimental installation

The following dependencies have been established because of experimental research of the trailed fertilizers spreader PRT-10 with the double-drum hinged device for the solid organic fertilizers grinding:

– average power consumption value P

$$P = 3.88672 + 0.764405\ L + 0.922574\ L^2 - 0.00828371\ n_1 + 0.000198171\ L\ n_1 + \\ + 0.0000146636\ n_1^2 - 0.0021879\ n_2 - 3.0726\cdot 10^{-7}\ n_1\ n_2 + 6.46516\cdot 10^{-6}\ n_2^2 - 1.4447\ V - \\ - 0.641768\ L\ V + 0.000320122\ n_1\ V - 0.000301067\ n_2\ V + 15.313\ V^2; \quad (15)$$

– compost mixture homogeneity δ_W

$$\delta = 0.542498 - 0.330861\ L + 0.0013886\ n_1 - 1.69596Ч10^{-6}\ n_1^2 - 0.000102664\ n_2 + \\ + 0.000398441\ L\ n_2 - 1.04511\ V + 0.3625\ L\ V + 0.00153125\ n_1\ V + 0.0025\ n_2\ V - 2.7604\ V^2. \quad (16)$$

We have established rational constructive-technological parameters of the developed hinged device for solid organic fertilizers grinding as a result of solving the compromise problem, in particular: ensuring the greatest homogeneity of the compost mixture with low energy losses: n_1 = 320 rpm, n_2 = 170 rpm, V = 0.05 m s^{-1}, L = –0.4 m. The homogeneity of the compost mixture is δ = 0.88, and power consumption is P = 3.34 kW.

Because of experimental research of the trailed fertilizers spreader PRT-10 with the double-drum hinged device for firm organic fertilizers grinding we have found dependencies for determination (Figs. 5–6):

– average compost mixture homogeneity value δ_W

$$\delta = 0.349092 - 0.116667\ L + 0.00555772\ \lambda_1 - 0.0000233032\ \lambda_1^2 + \\ + 0.00174708\ \lambda_2 - 0.0000104244\ \lambda_2^2; \quad (17)$$

– specific energy consumption E

$$E = 0.0025768 + 0.0125862\ L + 0.00748881\ L^2 + 0.000198874\ \lambda_1 + \\ + 0.00000239753\ \lambda_1^2 + 0.000306521\ \lambda_2 - 0.00000512468\ \lambda_1\ \lambda_2 + 0.00000201042\ \lambda_2^2. \quad (18)$$

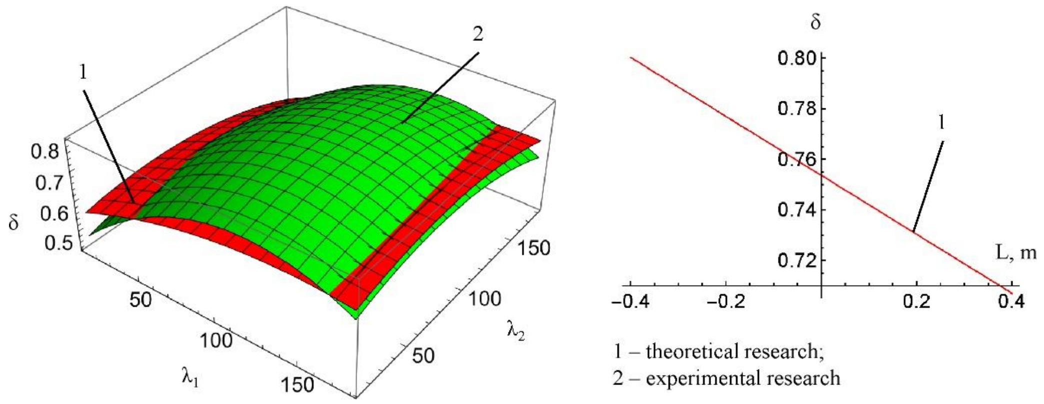


Figure 5. Dependence between the compost mixture homogeneity during its mechanical aeration mixing and research factors

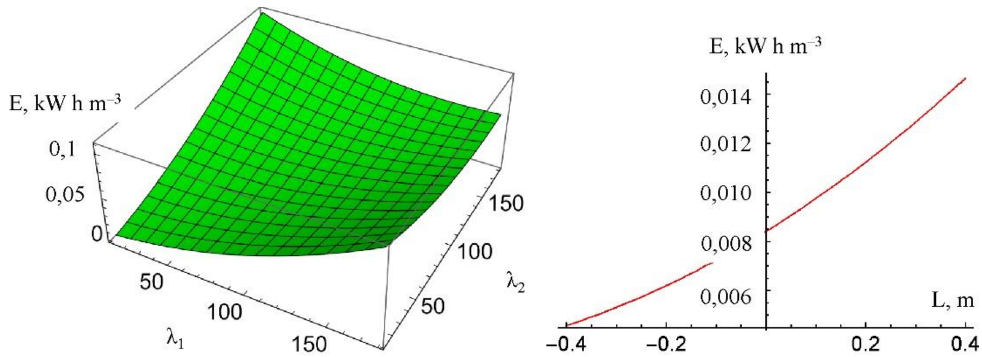


Figure 6. Dependence between the specific energy consumption of mechanical aeration mixing process and research factors

Comparison of theoretical and experimental (at $L = -0.4$ m) dependencies has been performed using a correlation coefficient of $R = 0.78$.

Analysis of the obtained data shows that for the kinematic coefficients $\lambda_1 = 119.2$ and $\lambda_2 = 83.8$ the maximum value of the compost mixture homogeneity is $\delta = 0.80$. Rational values of research factors are determined under the condition of ensuring the minimum specific energy intensity of the process: $E\,(\lambda_1 = 12.4,\ \lambda_2 = 12.4,\ L = -0.4\text{ m}) = 0.0046$ kWh $\text{m}^{3\,-1}$.

Because of experimental research of the aerator with the double-drum hinged device for solid organic fertilizers grinding we have obtained the dependencies for the definition of the following (Figs. 7–8):

– formed composting pad's height H`

$$H` = 0.61079 + 0.55894\,H - 0.001214\,n_1 + 1.1735\cdot10^{-6}\,n_1^2 - 0.001204\,n_2 - 0.0005868Hn_2 + 1.20822\cdot10^{-6}\,n_2^2 - 2.10133\,V + 2.01556\,H\,V + 0.00166191\,n_1\,V + 0.00323809\,n_2\,V; \quad (19)$$

– homogeneity δ_W

$$\delta = 0.465213 + 0.0833333\,H + 0.0000381031\,n_1 + 3.57128\cdot10^{-7}\,n_1^2 + 0.00137346\,n_2 - 8.33327\cdot10^{-7}\,n_1\,n_2 - 1.3847\cdot10^{-6}\,n_2^2 + 0.438326\,V - 0.833333\,H\,V; \quad (20)$$

– structural indicator θ of the compost mixture

$$\theta = 70.0153 - 55.0926\,H - 2.70062\,H^2 + 0.125581\,n_1 + 0.00992063\,H\,n_1 - 0.00014384\,n_1^2 + 0.0358717\,n_2 + 0.0248016\,H\,n_2 - 0.000106293\,n_1\,n_2 - 0.0000549178\,n_2^2 - 81.5785\,V - 125.\,H\,V + 0.35119\,n_1\,V + 0.505952\,n_2\,V - 850.689\,V^2; \quad (21)$$

– average power consumption value P

$$P = 7.10504 + 1.12952\,H - 0.0130359\,n_1 + 0.0000171157\,n_1^2 - 0.0102114\,n_2 - 0.00357143\,H\,n_2 + 0.000014824\,n_1\,n_2 + 0.000018041\,n_2^2 - 18.5434\,V + 18H\,V + 63.5024\,V^2. \quad (22)$$

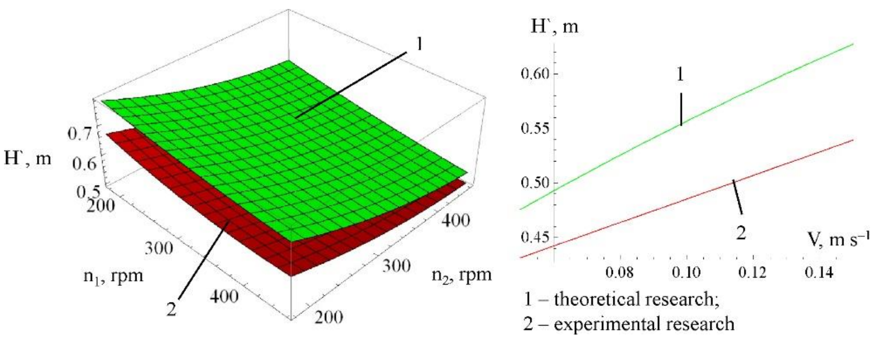


Figure 7. Dependence of the formed compost mixture height from the research factors

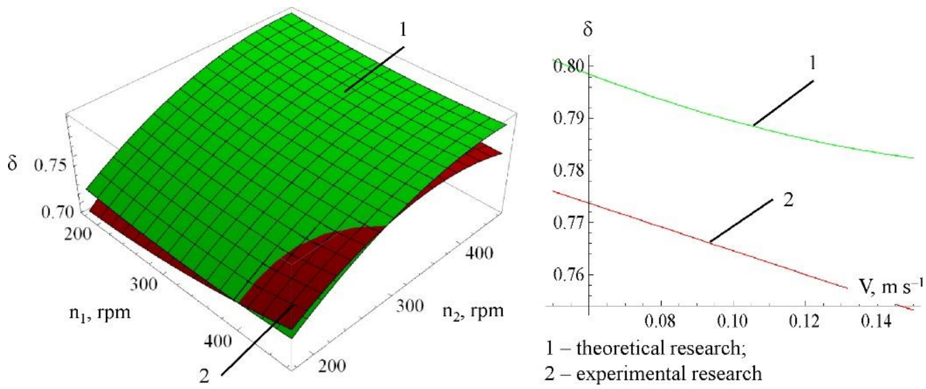


Figure 8. Dependence of the compost mixture homogeneity per humidity from research factors

The following rational design and technological parameters of the developed attachment device for solid organic fertilizers grinding have been developed as a result of solving the compromise problem, in particular, ensuring the greatest homogeneity, structure and height of the compost mixture with low energy losses: $n_1 = 293$ rpm, $n_2 = 180$ rpm, $V = 0.05$ m s^{-1}, $H = 0.62$ m. The homogeneity of the compost mixture is $\delta = 0.71$, the composting pad's structural indicator is $\theta = 62.4\%$, the height of the formed composting pad is $H` = 0.47$ m, and the power consumption is $P = 4.37$ kW.

Comparison of theoretical and experimental (at $H = 0.8$ m) dependence has been performed using a correlation coefficient of $R = 0.96$.

The following dependencies have been determined because of experimental studies of the aerator with a double-drum mounted device for solid organic fertilizers grinding:

– average homogeneity value δ_W

$$\delta = 0.717503 - 0.0000510901\,Q - 0.00152583\,\lambda_1 + 2.05241\cdot10^{-6}\,Q\,\lambda_1 + 4.70363\cdot10^{-6}\,\lambda_1^2 + \\ +0.00250197\,\lambda_2 - 9.8496\cdot10^{-7}\,Q\,\lambda_2 - 8.82403\text{Ч}10^{-6}\,\lambda_2^2; \tag{23}$$

– compost mixture composting pad's structural indicator θ

$$\theta = 98.1988 - 0.21856\,Q + 0.0001382\,Q^2 + 0.109371\,\lambda_1 + 0.0000199\,Q\,\lambda_1 - 0.00304718\,\lambda_1^2 - \\ - 0.116435\,\lambda_2 + 0.000494316\,Q\,\lambda_2 + 0.00436899\,\lambda_1\,\lambda_2 - 0.00246702\,\lambda_2^2; \tag{24}$$

– specific energy consumption E (Fig. 9)

$$E = 0.0564278 - 0.00008622\,Q + 1.32731\cdot10^{-7}\,Q^2 + 0.000223716\,\lambda_1 - 4.76335\cdot10^{-7}\,Q\,\lambda_1 - \\ - 8.873\cdot10^{-7}\,\lambda_1^2 + 0.000259487\,\lambda_2 - 5.367\cdot10^{-7}\,Q\,\lambda_2 + 6.64573\cdot10^{-7}\,\lambda_1\,\lambda_2 - 9.54008\cdot10^{-7}\,\lambda_2^2. \tag{25}$$

The following rational values of research factors on the condition of ensuring the minimum specific energy consumption of the process have been determined: $E\,(\lambda_1 = 168,\ \lambda_2 = 168,\ Q = 535$ m^3 h$^{-1}) = 0.0052$ kWh m$^{3\,-1}$.

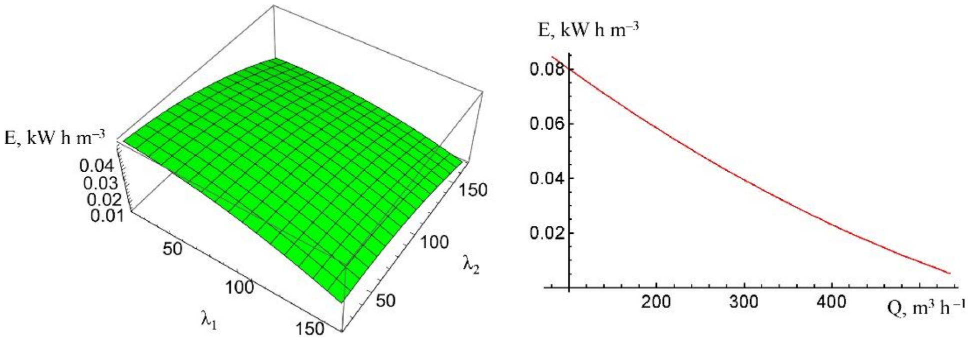


Figure 9. Dependence of the aerator's specific energy consumption from research factors

Comparisons of research results for single and double working bodies that are placed on PRT-10 for cow manure are presented in Figure 10. Comparisons of the research results for single and double working bodies that are placed on the aerator for the bedding and cow manure mixture are presented in Figure 11. The analysis has shown that the quality of mixing (homogeneity in humidity δ) and the quality of grinding (composting pad's structural indicator θ) is better in the double-drum working body. However, this causes greater consumption of energy.

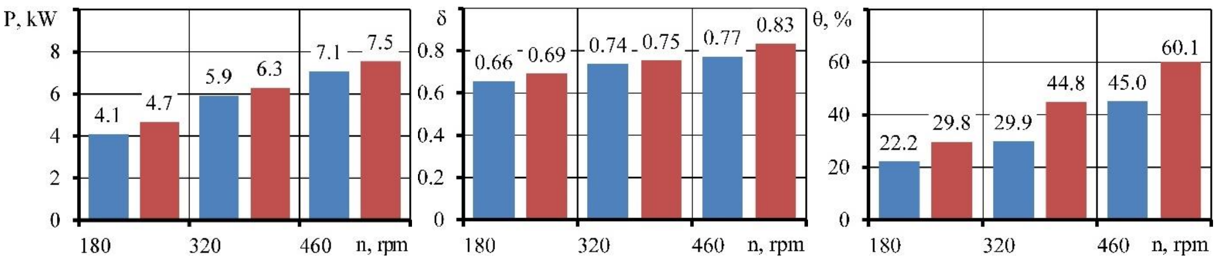


Figure 10. Comparisons of research results for single (blue) and double (red) working bodies that are placed on PRT-10 for cow manure

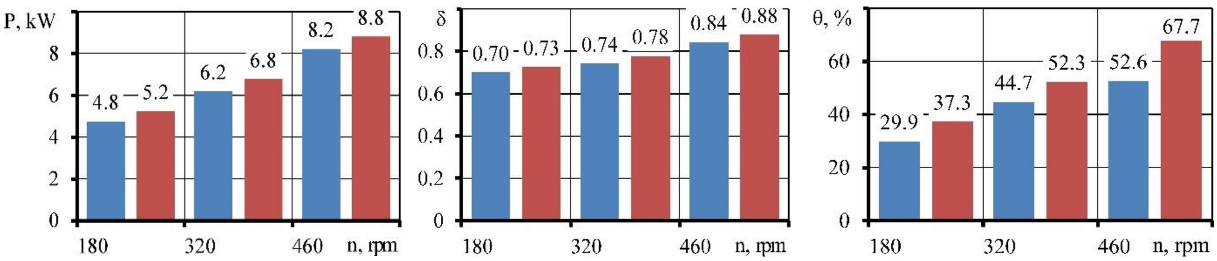


Figure 11. Comparisons of research results for single (blue) and double (red) working bodies that are placed on an aerator

Discussion

Unlike the research Mironov (2006), which examines the analytical process of a cascade drum machine interaction with a particle of manure-compost mixture in the form of a material point, our research is aimed at numerical modelling by discrete elements. Thus, we have determined the dependencies of the formed composting pad's height H` V and the original pad's height H as a result of the discrete element method modelling of the manure-compost mixture mixing process via single-drum and double-drum blade working body in two variants of placement on the formed pad.

Because of the obtained data analysis, we have acquired the mathematical expression, which connects coefficient of mixing quality variation δ with loading factor κ and operating mode kinematic index λ and specifies the obtained mathematical models of research (Golub, 2007; Golub *et al.*, 2017b). Similar methods as in our research have been considered in the article (Shevchenko, Aliiev, 2021), which presents the results of modelling the flow mixing process of bulk materials.

We have determined the rational design variant of the developed universal device for grinding and mixing of cow manure (single-blade W-shaped drum working body, which is mounted on a trailed spreader PRT-10 and rotates at a frequency of 460 rpm), as a result of experimental research, using analysis of variance, the greatest homogeneity of components distribution of the obtained manure-compost mix δ = 0.98 is observed at the specified parameters and the composting pad's structural indicator θ = 90.4 at the lowest average value of power consumption P = 8.7 kW. In turn, a rational design variant of the developed universal device for grinding and mixing manure is as follows: single-blade W-shaped drum working body installed on tracks (aerator type) and rotates with frequency 460 rpm, at which the greatest homogeneity of the received manure-compost mix components distribution is observed δ = 0.95 and composting pad's structural indicator

θ = 90.1 with the lowest average value of power consumption P = 8.4 kW.

We have determined the dependencies between the average value of power consumption P and homogeneity of manure-compost mixture δ_W on frequencies of lower and upper working bodies n_1, n_2, the speed of the manure-compost mixture movement (speed of the PRT-10 conveyor) V and the l upper working body location relative to the lower one L as a result of the trailed fertilizer spreader PRT-10 with a double-drum mounted device for solid organic fertilizers grinding experimental studies. We have established rational design and technological parameters of the developed attachment device for solid organic fertilizers grinding as a result of solving a compromise problem, namely ensuring the greatest homogeneity of manure-compost mixture with low energy losses: n_1 = 320 rpm, n_2 = 170 rpm, V = 0.05 m s^{-1}, L = –0.4 m. The homogeneity of the manure-compost mixture is δ = 0.88, and power consumption P = 3.34 kW.

We have determined the dependences between the average value of the manure-compost mixture homogeneity δ_W with specific energy E and the kinematic parameters for the lower and upper working bodies λ_1, λ_2 relative to the lower one L as a result of the trailed fertilizer spreader PRT-10 with a double-drum mounted device for solid organic fertilizers grinding experimental studies. Analysis of the obtained data shows that for the kinematic coefficients λ_1 = 119.2 and λ_2 = 83.8 the maximum value of the manure-compost mixture homogeneity δ = 0.80 is observed. We have determined rational values of research factors from the condition of ensuring the minimum specific energy consumption of the process: E (λ_1 = 12.4, λ_2 = 12.4, L = –0.4 m) = 4.57 J kg^{-1}.

We have determined dependencies between the height of the formed composting pad H`, homogeneity δ_W and structural indicator θ of manure-compost mix and the average value of the expended power P and rotation frequency of lower and upper working bodies n_1, n_2, the aerator's speed V and the height of the output pad H as a result of experimental researches of the aerator with the double-drum hinged device for firm organic fertilizers grinding. We have established rational design and technological parameters of the developed mounted device for solid organic fertilizers grinding as a result of solving the compromise problem, namely ensuring the greatest homogeneity, structure and height of the manure-compost mixture with low energy losses are determined: n_1 = 293 rpm, n_2 = 180 rpm, V = 0.05 m s^{-1}, H = 0.62 m. The homogeneity of the manure-compost mixture is δ = 0.71, the composting pad's structural indicator is θ = 62.4%, the height of the formed pad is H` = 0.47 m, and the power consumption is P = 4.37 kW.

We have determined dependencies between the average value of homogeneity δ_W and the composting pad's structural indicator θ of manure-compost mixture with specific energy E and the kinematic values for the lower and upper working bodies λ_1, λ_2 as a result of experimental studies of an aerator with a double-drum attachment for solid organic fertilizers grinding. Rational values of research factors with the condition of ensuring the minimum specific energy consumption of the process have been determined: E (λ_1 = 168, λ_2 = 168, Q = 535 m^3 h^{-1}) = 0.0052 kW·h m^{3-1}. The above results complement the study (Mironov, 2006; Petunov, 2007; Kudrya, 2015) with the dependences of the manure-compost mixture homogeneity δ_W and the composting pad's structural indicator θ.

Conclusion

The physical-mathematical model of the mechanized composting of organic raw materials process in agro-ecosystems by technical equipment with drum-blade working bodies has been theoretically substantiated and experimentally investigated.

Modelling of the compost mixture mixing process by single-drum and double-drum blade working body in two variants of the forming composting pad placement has determined patterns for determination of the dependency of pad's height H` from the frequency of rotation n, the linear speed of movement of a working body (or compost mix) V and height of an initial pad H.

It has been established that considering that the height of the composting pad layer is equal, the usage of a double-drum working body in comparison with a single-drum one is more rational in terms of power loss indicators $P_{s.d.}$ = 5.9–6.2 kW, $P_{d.d.}$ = 6.3–6.8 kW (at a speed of n = 320 rpm). Single-drum working body provides higher indicators of the side forming, the particles range, and the structure of $\theta_{s.d.}$ = 29.9–44.7%, $\theta_{d.d.}$ = 48.8–52.3%, homogeneity $\delta_{s.d.}$ = 0.74, $\delta_{d.d.}$ = 0.75–0.78 (at a rotation frequency of n = 320 rpm).

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;
GG – study conception and design;
OB – drafting of the manuscript.

References

Aliiev, E., Pavlenko, S., Aliieva, O., Morhun, O. 2021. Accelerated biothermal composting of manure-compost mixture. – Agraarteadus, 32(2):169–181. DOI: 10.15159/jas.21.30

Singh, A., Tiwari, R., Chandrahas, Dutt, T. 2020. Augmentation of farmers' income in India through sustainable waste management techniques. – The Journal for a Sustainable Circular Economy (WM&R), 39(6):849–859. DOI: 10.1177/0734242X20953892

Baba, I.A., Banday, M.T., Khan, H.M., Khan, A.A. Unto, M. 2018. Economics of composting of poultry farm waste. – Journal of Entomology and Zoology Studies, 6(2):2925–2928. DOI: 10.20546/ijcmas.2018.706.250

Golub, G.A. 2007. Ahropromyslove vyrobnytstvo yistivnykh hrybiv. Mekhaniko-tekhnolohichni osnovy [Agro-industrial production of edible mushrooms. Mechanical and technological bases]. – Monograph: Kyiv. Agricultural science: 332 p. [In Ukrainian]

Golub, G.I., Kukharets, S.M., Marus, O.A., Pavlenko, S.I., Lopatko, K.G., Skorobogatov, D.V. 2017a. Mekhaniko-tekhnolohichni osnovy protsesiv vyrobnytstva orhanichnoyi produktsiyi roslynnytstva [Mechanical and technological bases of processes of production of organic crop products]. – Monograph: NUBiP Ukrayina: 431 p. [In Ukrainian]

Golub, G., Pavlenko, S., Kukharets, S. 2017b. Analytical research into the motion of organic mixture components during formation of compost clamps. – Eastern-European Journal of Enterprise Technologies, 3/1(87):30–35. DOI: 10.15587/1729-4061.2017.101097

Center for Clean Air Policy. 2019. High-level pre-feasibility analysis for a composting project in Arequipa. Prepared for: Municipalidad Provincial de Arequipa. – Prepared by: Center for Clean Air Policy on behalf of the Climate and Clean Air Coalition Municipal Solid Waste Initiative. February 2019. 83 p. https://www.waste.ccacoalition.org/sites/default/files/files/arequipa_high-level_pre-feasibility_study_final.pdf Accessed on 01/03/2022.

Kudrya, V.O. 2015. Obgruntuvannya parametriv robochoho orhanu rotorno-lopatevoho typu navisnoho modulya do rozkyduvacha orhanichnykh dobryv. [Substantiation of parameters of the working body of the rotor-blade type of the hinged module to the spreader of organic fertilizers]: – PhD thesis. National Scientific Center, Institute of Mechanization and Electrification of Agriculture, National Academy of Agricultural Sciences of Ukraine, Glevaha, Ukraine, 12/02/2015, 149 p. [In Ukrainian]

Kiyonori, H. 2021. Sustainable Recycling of Livestock Wastes by Composting and Environmentally Friendly Control of Wastewater and Odors. – Journal of Environmental Science and Engineering B, 10: 163–178. DOI:10.17265/2162-5263/2021.05.001

Modupe, S.A., Oluwaseyi, S.O., Olubukola, O.B., Olu, O. 2020. Waste Management through Composting: Challenges and Potentials. – Sustainability, 12:4456. DOI: 10.3390/su1211445

Mironov, V.V. 2006. Issledovaniye protsessa prigotovleniya organicheskikh udobreniy v aeratsionnom bioreaktore [Investigation of the process of preparing organic fertilizers in an aeration bioreactor]. – Mekhanizatsiya i elektrifikatsiya sel'skogo khozyaystva [Mechanization and electrification of agriculture], 5:9–11. [In Russian]

Nelson, V. 2002. Technical assessment of physical compost aeration mechanisms and the system effect on the mechanical and biological efficiency of composting. – In AIC 2002 Meeting, CSAE/SCGR Program. Paper No. 02-216. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.606.5554&rep=rep1&type=pdf Accessed on 01/03/2022.

Nghi, N.T., Romasanta, R.R., Hie, N.V., Vinh, L.Q., Du, N.X., Ngan, N.V.C., Chivenge, P., Hung, N.V. 2020. Chapter 3. Rice Straw-Based Composting. – Sustainable Rice Straw Management, pp. 33–41. DOI: 10.1007/978-3-030-32373-8_3

Pergolaa, M., Piccolob, A., Palesea, A.M., Ingraoc, C., Di Meod, V. Celanoe, G. 2018a. A combined assessment of the energy, economic and environmental issues associated with on-farm manure composting processes: Two case studies in South of Italy. – Journal of Cleaner Production, 172:3969–3981. DOI: 10.1016/j.jclepro.2017.04.111

Pergolaa, M., Persiania, A., Palesea, A.M., Di Meoc, V., Pastorea, V., D’Adamoa, C., Celanob, G. 2018[b]. Composting: The way for a sustainable agriculture. – Applied Soil Ecology, 123:744–750. DOI: 10.1016/j.apsoil.2017.10.016

Petunov, S.V. 2007. Sovershenstvovaniye tekhnologi prigotovleniya komposta iz otkhodov zhivotnovodstva i derevoobrabotki. [Improving the technology of preparing compost from animal waste and woodworking waste] – PhD thesis. Federal State Educational Institution of Higher Professional Education, Buryat State Agricultural Academy named after V.I. V.R. Filippov, Ulan-Ude, Russian Federation, 28/12/2006, 161 p. [In Russian]

Shevchenko, I. Aliiev, E. 2021. Improving the efficiency of the process of continuous flow mixing of bulk components. – Eastern-European Journal of Enterprise Technologies, 6/1(108):6–13. DOI: 10.15587/1729-4061.2020.216409