Investigation of the roof-breaking device parameters for unloading composting installations of the bunker type

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Abstract. The article discusses the increasing efficiency of composting animal waste by substantiating the unloading processes, taking into account the formation of vaults in composting bunker-type installations. The technology of accelerated composting and the characteristic features of unloading the processed material is presented. The design and layout of the working bodies of the arch-breaking unloading device are theoretically and experimentally substantiated. Based on the research results, the unloading device's optimal design and operating parameters and the values of the consumed power have been determined.

1. Introduction
Currently, the rational use of natural resources, including agriculture, is an urgent task. The solution's effectiveness depends on the degree of reasonableness of approaches to the disposal of animal waste [1-3]. With the development of specialized high-tech industries for processing manure into organic fertilizers, emphasis is placed on obtaining high-quality fertilizers at a low cost. The main link in the technological chain of such industries is accelerated composting units [2], structurally vertical bunker-type units (Fig. 1).

The advantages of using these installations are mechanized loading and unloading of compostable material, automated bio-fermentation air supply devices while maintaining the flow rate, and continuity of the processing process [2, 4].

Plants of this design are widely used. However, during their operation, many problems arise associated with the unloading of the compostable material. Unloading devices made in the form of screws, scrapers, and paddle mechanisms do not provide uniform (dosed) unloading and the required structure of the processed product. This process reduces the efficiency of fixing nutrients and increases the processing time and costs in the production of compost [5].

It is necessary to consider the characteristic features of composting processes to achieve economic and environmental compliance of the applied technical means (bunker-type composting plants) and technologies. Composting processes can be considered processes of biological oxidation of organic matter with elevated temperature and humidity values. Composting processes should also be considered physical and mechanical processes with a change in the density and porosity of the processed material, which leads to the formation of stable material vaults in the bottom of the plants [6, 7].

The work aims to study the parameters affecting the formation of the vaults of the discharged material and increase the efficiency of the vertical composting installation by substantiating the process of its unloading.
Bridging is the phenomenon of the spontaneous emergence of arches of material particles above the discharge channel (hole) of the device from which particles are removed. The following properties of materials influence the formation of vaults: moisture, stickiness, caking, cohesion, and size; the stronger these properties are expressed, the greater the tendency to bridging. There are several methods for determining the parameters of the arch [5-7]. At the same time, the obtained data cannot be used in the case of considering the unloading of composting mixtures and considering the above characteristic features of the composting process.

![Diagram of the technological process of compost production](image)

**Figure 1.** Diagram of the technological process of compost production: I – delivery of components; II – stage of warming up the compostable mass; III – stage of active processing (disinfection and deworming); IV – stage of compost maturation; V – separation of compost and use of the finished product; 1,2 - platforms for cattle manure and moisture-absorbing material; 3 - machine for stacking collars; 4,7 - collars; 5 - vertical composting plant; 6 - collar ripper; 8 - point separation and packaging of the product; 9 - fertilization

2. **Materials and methods**

The formation of arches is observed in the bunkers when unloading from them materials that have a high degree of connectivity. This process requires additional theoretical and experimental studies, taking into account the relationship between the design parameters of the installations and the properties of the discharged materials. It also becomes necessary to use fundamentally new unloading devices, which make it possible to increase the efficiency of the unloading process by destroying the arches.

The research program included two stages: 1. theoretical and experimental determination of the spatial characteristics of the arches formed; 2. substantiation of the design parameters of the developed unloading device and its energy assessment. Standard methods determined the values of compostable materials' physicochemical and technological properties, and the research material was selected at a particular stage of processing.

Consider a scheme for determining the characteristics of the resulting vault (Fig. 2). It is known that vertical pressure arises from a column of material at the bottom of the hopper, which begins to drop when the outlet is opened. In the initial phase of unloading, the material's structure remains elastic due to the absence of mutual sliding of particles. In this case, the stress state of the environment remains unchanged. Further, the drop in vertical pressure contributes to the occurrence of plastic deformations, while the stress state of the medium begins to change. As a result of deformations of the medium, shear stresses arise in the area of the unloading hole. This process leads to the appearance of
a thrust reaction and provided that the vertical component of the thrust reaction and the mass of the load lying above the hole are in equilibrium, a vault is formed.

![Figure 2. Determining the height of the vault line](image)

The derivation of the equation for the arch line formed in a slotted bunker with a hole width $b$ is based on the assumption of its coincidence with the trajectory of principal stresses [12]. However, the value of the boom height $f$ is influenced not only by the width of the unloading opening $b$ but also by the angle of approach of the unloaded material to it (the angle of inclination of the sidewalls of the bunker installation $\alpha_{st}$).

There is a dependence showing that the force on the vault from the side of the sidewall located at an angle $\alpha_{st}$ to the horizontal coincides with the direction of the principal stress vector $P$ and should be directed tangentially at an angle $\psi$, i.e.:

$$\psi = \alpha_{st} - \phi_{\text{external}}$$  \hspace{1cm} (1)

where $\alpha_{st}$ is the angle of inclination of the sidewalls of the bunker to the horizontal, deg; $\phi_{\text{external}}$ is the angle of external friction of the discharged material against the walls.

Substituting the value of $\psi$ from (1) into the known stress equations, we obtain:

$$\sigma_s = P \cdot \cos(\alpha_{st} - \phi_{\text{external}}),$$  \hspace{1cm} (2)

$$\tau = P \cdot \sin(\alpha_{st} - \phi_{\text{external}}).$$  \hspace{1cm} (3)

Expressing $x$ through $\psi/2$, we get:

$$tg(\alpha_{st} - \phi_{\text{external}}) = \frac{y \cdot \tau_0 \cdot g(b/2)}{\tau_0 \cdot \cos \phi_{\text{internal}}},$$  \hspace{1cm} (4)

The formula for finding the height of the boom of the arch $f$ can be written in the following form:

$$f = \frac{1}{2} \cdot b \cdot \frac{y \cdot \tau_0 \cdot g(b/2)}{\tau_0 \cdot \cos \phi_{\text{internal}}},$$  \hspace{1cm} (5)

Further, we will have that the height of the boom of the arch, taking into account the angle of inclination of the sidewalls, is equal to:

$$f = \frac{1}{2} \cdot b \cdot tg(\alpha_{st} - \phi_{\text{external}}).$$  \hspace{1cm} (6)

Thus, from expression (6), it can be seen that the height of the boom of the arch is directly proportional to the width of the unloading opening and also functionally depends on the difference in
the angle of inclination of the sidewalls of the installation and the angle of external friction of the material being unloaded.

For the efficiency of material unloading, it is necessary to consider that the design and operating parameters of the working bodies destroying the arch must correspond to the geometric characteristics of this arch and the speed with which the unloaded material will be supplied.

After one day of finding the compostable mass in the body of the experimental installation, when the lower gate is opened, a roof is formed, which completely prevents the passage of the unloaded compostable mixture through the section of the unloading hole.

At the same time, it was found that the phenomenon of bridging, characterized by certain values of $f$ and $t_{br}$, is observed in the entire range of variation in the width of the discharge opening (Fig. 3, Fig. 4).

![Figure 3](image)

**Figure 3.** Dependence of the height of the boom of the arch on the width of the unloading opening, m.

For a compostable mixture of cattle manure with straw (H + C), the height of the boom of the arch varies from 0.115 m with a hole width of 0.40 m to 0.210 m with a hole width of 0.60 m, and for a mixture of cattle manure with sawdust (H + O) – from 0.135 m to 0.315 m, respectively. These values allow assuming that the value of the boom height does not change significantly. Also, these values show that the vault is characterized by the thickness of its structure and the vault commensurate with the width of the discharge opening and is in the lower part of the installation body.

At the same time, the assumption that the vault has a different structure, in which all internal force factors are balanced, was confirmed. The value of the vault thickness when changing the width of the unloading opening from 0.4 m to 0.6 m is respectively within:
- for the compostable mixture (H + C) – 0.460 ... 0.085 m;
- for a mixture (H + O) - 0.340 ... 0.065 m.

This characteristic makes it possible to constructively determine the number of parallel axes and the geometric dimensions of the working bodies located on these axes. From the presented dependences, it can be seen that the value of the width of the unloading hole, equal to 0.55 m, allows placing two shafts with a set of disc cutters, the diameter of which is determined by the thickness of the vaulted structure, and can be taken equal to $D_{fr} = 0.220$ m. Any other combination of the obtained values of $f$ and $t_{br}$ contributes either to an increase in the required overall dimensions of the working bodies, or to an increase in the number of shafts with a set of disc cutters.
for a mixture of cattle manure + straw (H + C)

for a mixture of cattle manure + sawdust (H + O)

Figure 4. Dependence of the thickness of the roof structure on the change in the width of the discharge opening, m.

Based on the data obtained for the values of $f$, it is possible to geometrically determine the location of the working bodies of the unloading device.

3. Results and Discussion

When creating a pilot production model of a vertical composting unit, the design of an unloading device was developed [8, 12] (Fig. 5), the working bodies of which consist of disc cutters located in the lower part of the unit body and fixed on horizontal shafts.

Studies of the process of bridging during the unloading of materials on an experimental installation showed the following results. With a value of the width of the unloading hole $b = 0.55$ m, it is necessary to use two shafts with a set of disc cutters with a radius of $R_f = 0.11$ m, the axes of rotation of which are located at the height of 0.17 m from the level of the unloading hole.

The distance between the cutters is ensured by installing spacer sleeves. The unloading process consists of the destruction of the most compacted lower layers of the compostable material at a particular stage of its processing due to the rotational movement of the working bodies. Unloading the material is accompanied by its additional loosening, which positively affects the further maturation of the compost [7].

For carryout a multifactorial experiment, the significance of the selected number of factors was checked by calculations using the MathCad program. According to the results of calculations, Table 1 shows the levels and intervals of variation of the design-mode parameters of the working bodies.

After implementing all series of experiments, many values of the consumed power were obtained. After processing the results and converting the factors to named values, we obtained regression equations for the power expended.
Figure 5. Placement of the working bodies of the roof-breaking unloading device

When unloading the manure-straw (H + C) compostable mixture:

\[ N = 5391,5 - 61,07 \cdot \omega + 13886,72 \cdot p_i - 11,82 \cdot \alpha + 295,1 \cdot \omega \cdot p_i - 0,074 \cdot \omega \cdot \alpha - 30,63 \cdot p_i \cdot \alpha + 1,78 \cdot \omega^2 - 52078 \cdot p_i^2 + 0,24 \cdot \alpha^2 \]  

When unloading the manure and sawdust (H + O) compostable mixture:

\[ N = 5225,98 - 62,21 \cdot \omega + 11473,5 \cdot p_i + 0,67 \cdot \alpha + 309,06 \cdot \omega \cdot p_i - 0,055 \cdot \omega \cdot \alpha - 5,58 \cdot p_i \cdot \alpha + 1,83 \cdot \omega^2 - 48117,5 \cdot p_i^2 - 0,0042 \cdot \alpha^2 \]  

Table 1. Levels and intervals of variation of factors

| Factor name                          | Factor designation | Variation levels | Variation intervals |
|--------------------------------------|--------------------|------------------|--------------------|
| Angle rotational speed of cutters \(\omega_{fr}\) \(s^{-1}\) | \(x_1\)            | 6                | 12                 | 18                 | 6                |
| Installation step of cutters \(p_t\) \(m\)                  | \(x_2\)            | 0,075            | 0,115              | 0,155              | 0,040            |
| The angle of attack of cutters knives \(\alpha\) \(^\circ\)    | \(x_3\)            | 15               | 30                 | 45                 | 15               |

Fisher's test checked the adequacy of the obtained models at a 5% significance level.

Based on the results of a multifactorial experiment, the optimal design and operating parameters of the unloading device were determined: the rotation frequency of the working bodies of the unloading device \(n = 120 \text{ min}^{-1}\); angle of attack of cutters knives \(\alpha = 30^\circ\); the pitch of disk cutters \(p_t = 0,115 \text{ m}\). These parameter values provide the lowest energy consumption in the process of unloading compostable materials. So, the consumed power, productivity, and specific energy consumption of the developed device, respectively, were:

- for the mixture (H + C): \(N = 5.96 \text{ kW}; Q = 17 \text{ kg / s}; N_{sp} = 0.098 \text{ kWh / t}\);
- for the mixture (H + O): \(N = 5.83 \text{ kW}; Q = 22 \text{ kg / s}; N_{sp} = 0.074 \text{ kWh / t}\).
4. Conclusion
Experimental studies carried out made it possible to start a pilot test of the developed unloading device and an economic assessment of its use.

Based on the experimental data obtained, the research results were adopted for implementation in many industries in order to increase the efficiency of composting and improve the operation of vertical composting units of the bunker type.

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