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THEORETICAL RESEARCH OF PROCESS REGULARITIES OF GRINDING STRUCTURAL-HETEROGENEOUS ORGANIC MATERIALS

For the efficient functioning and successful development of the animal production sector, the key condition is correct feeding of animals. This feeding is only possible if enough feed is produced, nutrient losses during harvesting are reduced, and feed is correctly prepared for feeding. The introduction of concentrated feed helps to achieve a balance between energy, protein and amino acid content in the animal ration. Technologists compose and select components of feed rations based on the species, age group, morphological and biological characteristics of animals, as well as other factors. Despite the chosen technology and feeding strategy, concentrated feeds such as processed cereals based on wheat, barley, corn and other crops continue to be the main source of nutrients for animals. The quality of grinding concentrated feed is important for animal productivity. This treatment results in the formation of numerous particles with a larger surface area, which promotes faster digestion and better absorption.

Grinding is one of the most high-energy processes used in animal feed technology. Since plant residues are structurally uneven, this makes it difficult to use conventional grinding methods efficiently, which reduces their energy efficiency and requires the use of several grinding stages with appropriate equipment.

In order to ensure efficient processing of agricultural plant residues, it is important to create an appropriate technical infrastructure, given the significant energy costs associated with traditional processes of preparing biomass for granulation. To do this, it is necessary to conduct research aimed at solving the problem of energy-efficient grinding of structurally heterogeneous materials, in particular materials that contain a large amount of moisture. This is what determines the relevance of this research topic.

Keywords: *plant waste, grinding, energy consumption, moisture content, grinding material, dispersion*.

Introduction. One of the strategically significant aspects of practical implementing the «Association Agreement between the European Union and Ukraine» is to solve the problem of accumulating wastes, including also wastes from agricultural production. Considering these commitments, the Ministry of Economic Development and Trade worked out the «National Waste Management Strategy in Ukraine by 2030», and one of the directions of its implementation is the development of the material and technical base for using plant-derived wastes from agriculture for processing into fuel briquettes.

Since plant-derived wastes belong to structural-heterogeneous materials, this reduces the energy efficiency of using one or another familiar method of destruction, which necessitates the use of several stages of grinding applying appropriate equipment. Taking into account the strategic importance of forming the material-technical base to ensure highly efficient processing plant-derived wastes from agriculture, as well as high energy costs, which mark the conventional preparation of biomass for briquetting, there is a need to conduct research aimed at solving the problem of energy-efficient grinding of structural-heterogeneous materials, including those with high moisture content, that determines the **relevance** of the topic.

Analysis of recent research and publications. In the grinding process, under the action of forces applied to the processed products that exceed the temporary resistance or its ultimate tensile strength, elastic and plastic deformations are formed, resulting in microcracks that divide the material into particles. When external forces act within elasticity, cracks due to molecular relationships can close, that is, the destruction of the body does not occur. When external forces exceed the elastic limit, the grinding process occurs, which is closely related to the energy expenditure to overcome the internal friction of particles during their deformation, interaction between themselves and the executive body of the machine. There are a number of hypotheses to determine the energy consumption for grinding [4, 7, 10].

According to Rittinger's surface hypothesis, the work spent on grinding is proportional to the size of the newly formed surface of the crushed material, which considers energy A_s, necessary for the separation of the crushed material on one plane and is expressed by the following dependence:

$$A_s = K_{pr} \cdot S, \quad (1)$$

where K_{pr} – the proportionality coefficient J/m^2, S – the size of the newly formed surface m^2.

Total energy *AΣ* (J) for grinding a certain size D_c depending on the size of the source material d is:

$$A\sum = 3A_s\left(\frac{D_c}{d} - 1\right) = 3A(i-1) \quad (2)$$

where $i = \frac{D}{d}$ – The degree of grinding the material.

From the above dependence it can be seen that the work spent on the specified process is proportional to the degree of grinding the material being processed or the size of the newly formed surface.

According to the theory of V.N. Kirpichov, and later – F. Kick, the energy expenditure for this process is proportional to the volume of the body and, as a result, the product of the work A_V, spent on grinding two bodies having volumes *V*:

$$A_V = K_V \cdot V = K_V \cdot D_c^3, \quad (3)$$

where K_V – the empirical proportionality coefficient, J/m^2; *V* – the volume of cubic body with edge D.

The disadvantage of the hypotheses of Rittinger and Kirpichov-Kick is the lack of numerical values of specific coefficients, that complicates their practical implementation.

There is F. Bond's law, according to which total energy must contain the work of deformation and the formation of new surfaces. Bond's law assumes that energy is initially distributed over its mass and is proportional in sum D^3, and from the moment of forming the crack on the surface is proportional D^2.

Then total energy:

$$A = K_e \cdot \sqrt{V \cdot S} = K_e \cdot D^{2,5}. \quad (4)$$

where D – a minimum size of the material; K_e – the experimental coefficient.

Thus, according to the volumetric theory, the work carried out during grinding is proportional to the volumes of bodies, and the acting forces are proportional to the surfaces of these objects.

The founder of physical and chemical mechanics P. O. Rebinder [11, 2] believed that the closest hypothesis to the truth is in the middle between the assumptions of Rittinger and Kirpichov-Kick, and the work spent on grinding, in general, is the sum of two terms:

$$A = \sigma\Delta F + k\Delta V, \quad (5)$$

where σ – specific energy attributed to a unit body surface; ΔF – body surface formed during destruction; k – work of elastic and plastic deformations, attributed to the unit volume of a solid bidy; ΔV – the volume of the body that has undergone deformation.

Thus, the researched work of this process is proportional to both the newly formed surface and the volume of the crushed material. Obviously, at the initial stage, with coarse crushing, the main work is spent on deforming the body, few new surfaces are formed and, as a result, the second term has a small numerical value.

The energy consumption while grinding increases with decreasing a particle size. In this regard, to avoid unproductive costs, it is imperative that during the organizational process the expected particle size of the feedstock is known in advance. To reduce energy consumption, it is advisable to remove sufficiently crushed particles periodically from the grinding zone.

The process of grinding the material is accompanied by forming electrostatic energy through discharges and radiation, which contributes to mechanoemission and mechanoactivation of the material structure. Newly formed surfaces and particles have an excessive amount of kinetic energy, due to which their movement and subsequent destruction occurs.

Thus, the grinding of the material, the formation of its new surfaces, internal defects, leads to the activation of many phenomena associated with the mechanical, thermal, electrical and chemical properties of substances. It is very difficult to take into account the complex change of all these properties during the course of this process.

The aim of the research is to determine process regularities of grinding structural-heterogeneous organic materials by developing a mathematical model describing the relationship between the dispersion of solids and the energy consumption for the grinding process.

Materials and methods. The scientific provisions of this article are based on grinding theories, mechanics of dispersed media, solid mechanics, III theory of strength.

For analytical researches and graphical interpretation of research evaluation results, MathCad 15 and Excel software were used.

Research results. The relationship between the dispersion of grinding solids and the energy consumption for the grinding process is known as the law of grinding. Currently, several such experimentally found laws are distinguished, each of them is valid only in a case of sufficiently coarse variance.

As Charles proved, many of them can be formally expressed by the following empirically ascertained relationship:

$$d\varepsilon = -C''dX/X^m = C'dS/S^{2-m}, \quad (6)$$

where ε – the energy transferred to a unit volume of a collapsing body, X – the size of average source material, m²;

S – the specific surface area, м⁻¹; C', C and m – empirically selected constants.

After integrating the relation (6) at m = 1, we shall obtain the equation:

$$\varepsilon = C' \ln(S/S_0), \quad (7)$$

where S_0 – the specific surface area of a solid before grinding it.

When reaching the extremely stressful state by compression, geometrically similar bodies, regardless of their size, split like each other. In this case, the newly formed surface and the average particle size are determined by the size of the body X_i levels, respectively $\alpha_1 X$ and $\alpha_2 X^2$, where α_1 and α_2 – permanent, independent of the size of the collapsing body. If energy is transferred to the body $U_0' > U_0$, then it causes an increase in these coefficients, which are at a constant energy density $e = U_0/V$ remain permanent [9,12,17].

According to the theory of elasticity, at $\sigma<\sigma_0$, the destruction of the body does not occur, and after unloading, all the energy received by it is dissipated. However, it is known that even a slight periodic mechanical action leads to the formation of fatigue cracks, as a result of which solids are destroyed at $\sigma<\sigma_0$. The energy expenditure on the tedious grinding process is greater than the greater magnitude of the difference $\sigma_0 - \sigma$, and is determined by the number of cycles preceding the destruction [14, 15]. Taking it into account, let us suppose that the amount of energy required for the destruction of a solid body of size X into parts whose total surface is $\alpha_2 X^2$ α_2 X^2 is always determined by the constant value of the energy density required for brittle fracture.

We consider the grinding of a particle whose volume V is bX_0^3 bX_0^3 on the basis of the foregoing. For the sake of simplicity, we assume that in every act of destruction, n^3 of identical, respectively, much smaller particles are formed from each particle. Each of these particles is crushed independently of the second also into n^3 parts. The linear size of particles after the first act is X_0/n, after the second X_0/n^2X, after the i-th X_0/n^i. Since the number of particles is n^{3i}, the surface of such particles after the i-th act, taking into account the surface shape factor α_2 is equal:

$$s = \alpha_2 (X_0/n^i)^2 n^{3i} = \alpha_2 X_0^2 n^i. \quad (9)$$

Since the volume of solid material in the grinding process does not change, during all i acts of destruction, the volume of performed work equal to the volume factor of the form:

$$U = beX_0^3 i; i = U/eV = \varepsilon/e. \quad (10)$$

Defining the number of cycles through the amount of energy expended and substituting in (9) from equation (10), we obtain:

$$s = \alpha_2 X_0^2 n^{U/eV} = s_0 n^{\varepsilon/e}. \quad (11)$$

Since in (11) $n^{\varepsilon/e}$ does not depend on the size of the particles, after averaging the dimensions of the initial particles over the entire spectrum and dividing both parts (12) by the volume of the grinding solid, we obtain:

$$S = S_0 \exp(\varepsilon/e \ln n), \quad (12)$$

where S – specific surface area of the material, m²/m³.

The work of friction forces, that is, the work of surface deformation and fracture, the energy of plastic deformations and the work on the formation and destruction of aggregates depend on the dispersion of the material. It can be assumed that at constant pressure created in the crusher, the work spent on friction is proportional to the newly formed surface. The energy spent on plastic deformations, in a first approximation, is also proportional to the surface.

On the bases of the above mentioned we derive an equation relating the energy consumption for grinding and dispersion of the material, taking into account the energy expenditure for plastic deformations in the surface layers and other losses that increase in proportion to the increase in the specific surface. The thickness of the layers in which surface deformations occur will be considered as a constant value $(l = const)$, independent of the particles' size. We also consider large-scale hardening during grinding, as such, which can be neglected.

In each individual act of destruction, the energy expenditure on plastic deformations is determined by the volume of the deformation region, which for particles of any shape is assumed to be equal:

$$n^3 b[X_1^3 - (X_1 - 2l)^3] = b\left[X^3 - \left(X - \frac{2l}{\alpha_1}\right)^3\right], \quad (13)$$

where $X_1 = \alpha_1 X$ – an average size of fracture fragments, m²; b – volume factor of the form, n^3 – average amount of debris equal to $1/\alpha_1^3$.

For the destruction of particles, it is necessary to transfer energy to them:

$$U = b\{eX^2 + \beta[X^3 - (X - l_1)^3]\} + (\chi + \alpha_2\sigma_\Pi)X^2, \qquad (14)$$

where β – energy density of plastic deformations preceding fracture, J/m³; $l_1 = 2l/\alpha_1$, mm; χ – surface density of friction forces and energy of formation and destruction of aggregates; σ_Π – free surface energy, J/m². For particle's sizes $X - \Delta X$ similar energy costs are:

$$U + \Delta U = b\{e(X + \Delta X)^2 + \beta[(X + \Delta X)^3 - (X + \Delta X - l_1)^3]\} + (\chi + \alpha_2\sigma_\Pi)(X + \Delta X)^2. \qquad (15)$$

Subtracting (14) from (15) and taking into consideration the increase in surface growth during fracture $ds = 2\alpha_2 X\Delta X$ we obtain the equation for the grinding energy expenditure:

$$d\varepsilon = \frac{9be}{\alpha_2}\frac{dS}{S} + \frac{3b\beta}{2\alpha_2}\left(2l_1 - \frac{l_1^2 S}{6}\right)dS + \left(\frac{\chi}{\alpha_2} + \sigma_\Pi\right)dS,$$

or

$$d\varepsilon = \frac{9be}{\alpha_2}\frac{dS}{S} + \left(\frac{3b\beta l_1 + \chi}{\alpha_2} + \sigma_\Pi\right)dS - \frac{b\beta l_1^2}{4\alpha_2}SdS. \qquad (16)$$

In equation (16), the first term represents the energy expenditure on the volumetric deformation of a solid in accordance with the the Kirpichev-Kick law, the second – on inelastic deformations, the work of friction forces and the creation of new surfaces, the third takes into account the change in the volume of the area of plastic deformations due to changes in the size of parts.

The maximum amount of mechanical energy received by a particle in each act is determined as equal to $\varepsilon_m V_m$. Part of this energy *W* is spent on plastic deformations and other losses. If during this process $\varepsilon_m V_m \le W + \sigma_0^2 V_m/2E$, then grinding material, whose volume is smaller V_m, It can only take place through «fatigue», which leads to a sharp increase in energy consumption for this process. Therefore, as a first assumption, we assume that particles by volume $V < V_m$ not crushed at all. Such particles, which receive energy, but practically do not grind, accumulate more and more with increasing dispersion, which leads to a slowdown in the whole process.

The amount of energy expended directly on grinding, as a result of which the surface increases by dS, is:

$$dW = \left[\sum_X V_i - \sum_{X<X_m} V_i\right]d\varepsilon = d\varepsilon V(1 - V_{0m}/V_0), \qquad (17)$$

where V_{0m} – total volume of particles with dimensions $X \le X_m$, equation V_{0m}/V_0 is equal to zero at the beginning of grinding, and close to 1 with prolonged grinding. Taking into consideration the ratio S/S_m, where S_m – specific surface area of extremely crushed material with particle sizes $X \le X_m$, have the same values in appropriate boundary cases and that in a wide range of dispersion between the values of the specific surface area and the mass content of the fraction with particle sizes less than a given one, proportionality is observed, and the ratio between the ratio S/S_m and the relative content of the fine fraction practically does not change during grinding, it can be presented as follows:

$$dW = V_0\left(1 - \frac{S}{S_m}\right)d\varepsilon. \qquad (18)$$

Substituting (18) in equation (15), we obtain a dependence taking into account the limiting value of the energy density transmitted by the material shredder in a single act of destruction, and taking into account the unproductive costs of deformation of small particles [38]:

$$\frac{d\varepsilon}{dS} = \frac{9be}{\alpha_2 S\left(1 - \frac{S}{S_m}\right)} + \frac{3b\beta l_1 + \chi + \alpha_2\sigma_\Pi}{\alpha_2\left(1 - \frac{S}{S_m}\right)} - \frac{b\beta l_1 S}{4\alpha_2\left(1 - \frac{S}{S_m}\right)}. \qquad (19)$$

Considering the energy expenditure on the formation of a new surface and the work of friction forces equal to $(\alpha_1\sigma_\Pi + \chi)X^2$ in case $l < X$, we receive:

$$X_m = \frac{\alpha_2(\beta l + \sigma_\Pi + \chi/\alpha_2)}{b(\varepsilon_m - e)}. \qquad (20)$$

Almost always real values $\beta > (\varepsilon_m - e)$, so $X_m > l_1$. The approximate value (20) is sufficiently accurate at $X_m > l_1$ or at $\beta > (\varepsilon_m - e)$. Taking into account the energy expenditure on the formation of a new surface and the operation of friction forces, the value will be slightly greater than the value in (21)

Taking into account the above mentioned, the grinding equation we get the following form:

$$d\varepsilon = \frac{9b(e+\beta)}{\alpha_2}\frac{dS}{S\left(1 - \frac{S}{S_m}\right)} + \left(\frac{\chi}{\alpha_2} + \sigma_\Pi\right)\frac{dS}{(1 + S/S_m)}. \qquad (21)$$

The integration of the grinding differential equation (22) ranging from S_0 to *Si* from $\varepsilon = 0$ shows the relationship between energy consumption and the grinding result over a wide range of dispersion:

$$\varepsilon = \frac{9be}{\alpha_2}\left(ln\frac{S}{S_0} + ln\frac{S_m - S_0}{S_m - S}\right) + \frac{S_m}{\alpha_2}(3b\beta l_1 + \chi)\,ln\frac{S_m - S_0}{S_m - S} + \frac{b\beta l_1^2 S_m^2}{4\alpha_2}\left(\frac{S - S_0}{S_m} - ln\frac{S_m - S_0}{S_m - S}\right). \qquad (22)$$

The energy spent on grinding can be divided into the work on overcoming elastic and the work on plastic deformations:

$$А_Т = А_{ПЛ} + А_{ПР}, \qquad (23)$$

As a result, fractures appear in the material, and consequently – destruction.

Then, considering (23):

$$A_{ПР} = e \cdot V; A_{ПЛ} = \beta \cdot V. \quad (24)$$

Based on the curves of theoretical work of destruction (Fig. 1) [the paper co-authored with Kravets R.A. №1] and relative deformation of grain (Fig. 2) [the paper co-authored with Kravets R.A. №2], the value of absolute plastic deformation, the value of energy expenditure to overcome elastic and plastic deformations and, accordingly, the energy density coefficients *e* and *β* in a single act of destruction (Table 1), with a grain volume V=250·10^{-9}·$м^3$ will be found.

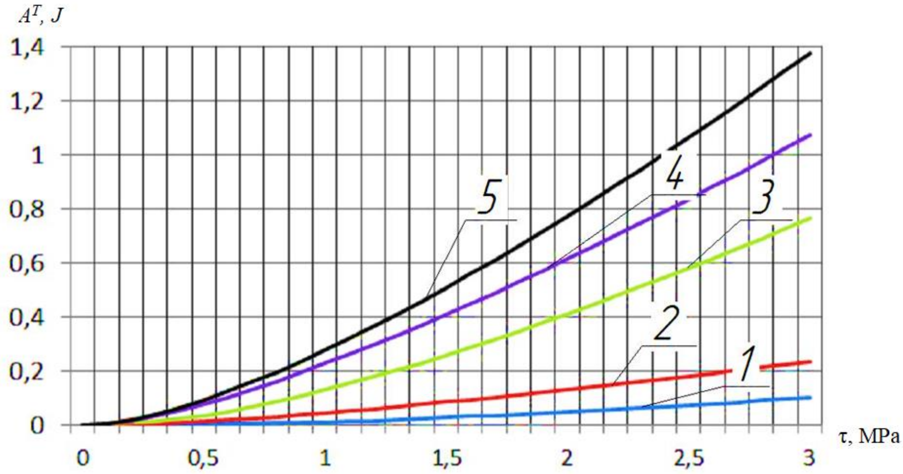

Fig. 1. Dependence of theoretical work of destruction of maize grain on normal stresses at moisture values [2]: 1. W=13-14%; 2. W=16-17%; 3. W=19-20%; 4. W=22-23%; 5. W=25-26%

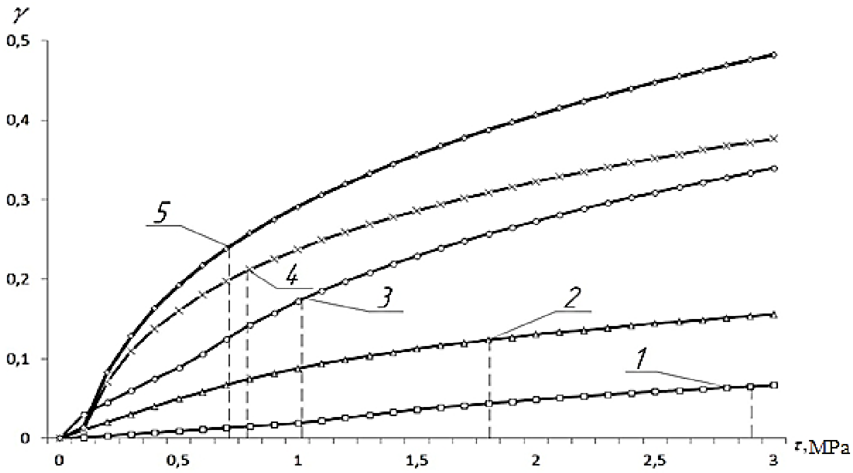

Fig. 2. Dependence of the relative deformation of maize grain on tangential stresses at moisture values [8]: 1. W=13-14%; 2. W=16-17%; 3. W=19-20%; 4. W=22-23%; 5. W=25-26% – the strength limit of the material.

To simplify the calculations, let us assume that in acts of destruction particles are destroyed so that their linear size is averagely halved ($\alpha_1 = 1/2$) (α_1 = 1/2), which makes it possible to count $\alpha_2 = 3$ α_2 = 3 and the value of the shape factor $b = 1$.

Table 1

Determination of process energy intensity parameters

Parameters	Relative humidity of the material, %				
	13-14	16-17	19-20	22-23	25-26
A^T, J	94·10^{-3}	121·10^{-3}	152,8·10^{-3}	174·10^{-3}	195,94·10^{-3}
$A^T_{ПР}$, J	12,19·10^{-3}	36·10^{-3}	47·10^{-3}	65·10^{-3}	82·10^{-3}
$A^T_{ПЛ}$, J	82,71·10^{-3}	85·10^{-3}	105,8·10^{-3}	109·10^{-3}	113·10^{-3}
e, J/m^3	48,76·10^3	144·10^3	188·10^3	260·10^3	340·10^3
β, J/m^3	330,84·10^3	340·10^3	423,2·10^3	436·10^3	452·10^3
$\gamma_{пл}$	0,035	0,045	0,077	0,085	0,092
$\Delta h_{пл}$, m	0,22·10^{-3}	0,283·10^{-3}	0,484·10^{-3}	0,535·10^{-3}	0,579·10^{-3}

The value of the surface density of the friction forces and the energy of formation and destruction of aggregates can be neglected, since its value is several orders of magnitude less than the coefficients of eta β [3, 16, 1].

The specific surface area of a material with diameter x can be calculated by equation:

$$S_x = \frac{6}{\rho_x d_x}; \quad (25)$$

where ρ_x, d_x– respectively, the the specific weight of the material fraction X (kg/m^3) and the average diameter of the particle of this fraction (m).

Keeping in mind that:

$$d = \frac{d_1P_1 + d_2P_2 + \dots + d_nP_n}{100}, \quad (26)$$

where d_n – average hole size of two adjacent sieves, m; P_n – mass production of particles of a particular class ($\sum P = 100\%$), and the data of previous researches [3, 12], we obtain:

$$S = \frac{600}{\rho(d_1P_1 + d_2P_2 + d_3P_3 + d_4P_4 + d_5P_5 + d_6P_6)}.$$

Taking into consideration that ρ =480…530 kg/m^3 [6] S=7200…11660 m^2/m^3.

The average specific surface area of a particle with initial dimensions S_0 according to [13,5] is 1,25... 1,40 m^2/kg, or 857... 923 m^2/m^3.

Since it can be assumed that in a rotary crusher the material is not crushed in a more degree than the size of starch grains, then, on this basis, the specific surface area of the minimum particle that is not subjected to grinding is S_m=46500…54000 m^2/m^3. Taking into account the specific density of the material ρ_3= 1150…1350 kg/m^3, we shall build the dependence of energy consumption for grinding 1 kg of material in a wide range of dispersion (Fig. 1).

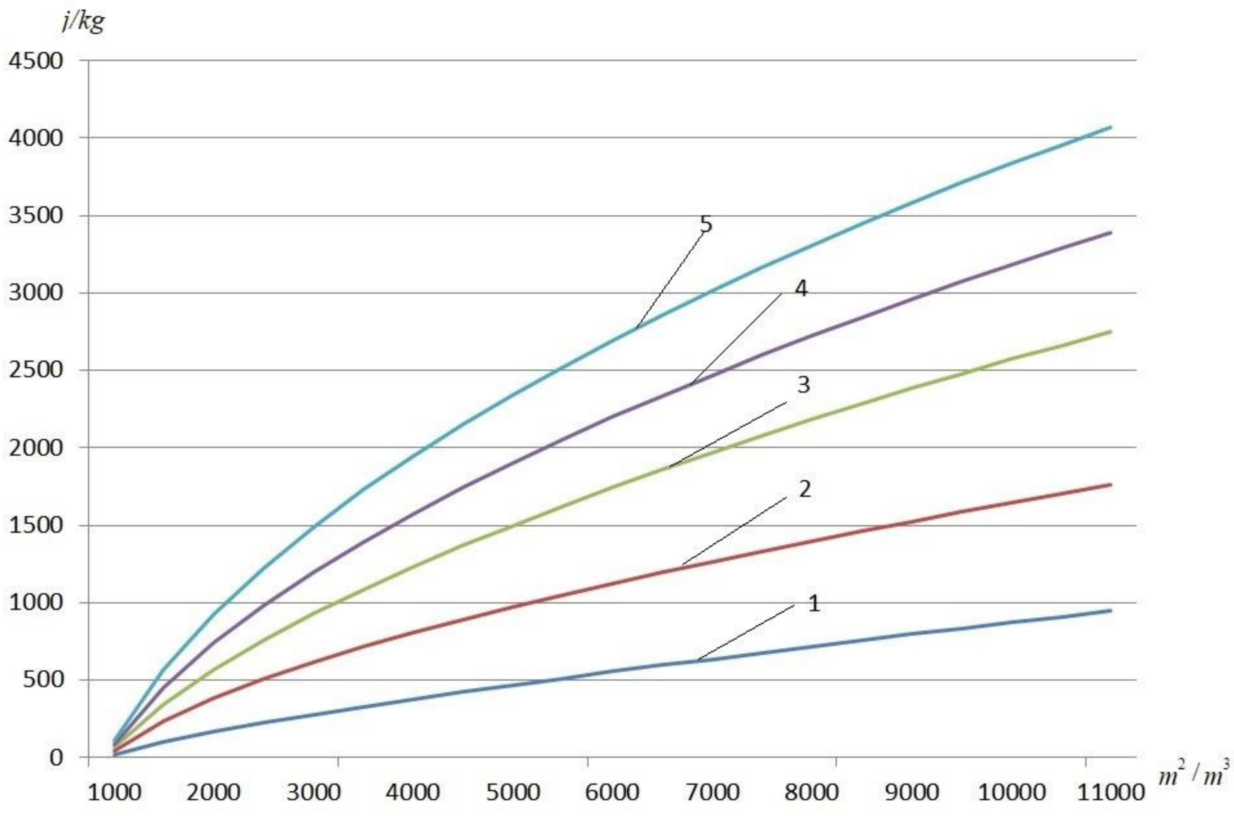

Fig. 3. The dependence of energy consumption for grinding material depending on the specific surface area of the end product: 1. W=13-14%; 2. W=16-17%; 3. W=19-20%; 4. W=22-23%; 5. W=25-26%.

Conclusions. From the graphical dependence (Fig. 3) it has been ascertained that with increasing moisture content of the material, specific energy consumption increases significantly to reach a surface area of 7500...10000 m^2/m^3, this meets the requirements of alcohol production. Thus, for grinding material with relative humidity W=13-14%, energy consumption is 650-800 J/kg, W=25-26%, respectively, 3200-3700 J/kg, caused by an increase in the plasticity of the material and grinding resistance.

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ТЕОРЕТИЧНІ ДОСЛІДЖЕННЯ ЗАКОНОМІРНОСТЕЙ ПРОЦЕСУ ПОДРІБНЕННЯ СТРУКТУРНО НЕОДНОРІДНИХ ОРГАНІЧНИХ МАТЕРІАЛІВ

Для ефективного функціонування та успішного розвитку сфери виробництва тваринницької продукції, ключовою умовою є належна годівля тварин. Дана годівля можлива лише за умови, коли виробляється достатня кількість кормів, зменшуються втрати поживних речовин під час заготівлі та коректно підготовлюються корми до подачі. Введення концентрованих кормів у раціон годівлі допомагає досягти балансу між вмістом енергії, протеїну та амінокислот у раціоні тварин. Технологи складають та відбирають компоненти кормових раціонів, керуючись видом, віковою групою, морфологічними та біологічними характеристиками тварин, а також іншими факторами. Незалежно від обраної технології та стратегії годівлі, концентровані корми, такі як оброблені зернові, на основі пшениці, ячменю, кукурудзи та інших сільськогосподарських культур, залишаються основним джерелом поживних речовин для тварин. Якість подрібнення концентрованих кормів важлива для продуктивності тварин. Ця обробка призводить до утворення

численних часток з більшою поверхнею, що сприяє швидшому травленню та кращій засвоюваності.

Подрібнення – це один з найбільш високоенергетичних процесів, що використовуються в технології приготування кормів для тваринництва. Оскільки рослинні відходи мають структурну нерівномірність, це утруднює ефективне використання звичайних методів подрібнення, що знижує їх енергоефективність та вимагає використання кількох етапів подрібнення з відповідним обладнанням.

З метою забезпечення ефективної обробки сільськогосподарських рослинних відходів важливо створити відповідну технічну інфраструктуру, враховуючи значні енергетичні затрати, пов'язані з традиційними процесами підготовки біомаси до гранулювання. Для цього належить провести дослідження, спрямовані на вирішення проблеми енергоефективного розмелювання структурно-неоднорідних матеріалів, зокрема тих, що містять велику кількість вологи. Саме це визначає актуальність даної теми.

Ключові слова: *рослинні залишки, подрібнення, енерговитрати, вміст вологи, подрібнювальний матеріал, розсіювання.*

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