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AN INTEGRATED APPROACH TO SELECTING THE OPTIMAL SET OF MACHINES FOR SORTING AND CRUSHING MUNICIPAL SOLID WASTE AND SUBSTANTIATION OF THEIR KEY PARAMETERS

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The article is devoted to solving a complex problem, including the issues of selecting the optimal set of machines and the technological scheme for implementing the sorting and crushing of municipal solid waste at transfer and recycling stations, and the justification of the key parameters of crushing and sorting machines, considering properties of waste. When examining the main parameters, the input and output characteristics of machines are considered in the developed technological scheme. When determining the properties of waste, 12 administrative districts of the territory of Tashkent were used as objects for cluster sampling. Through an in-depth study of the process of sorting and crushing municipal solid waste, based on the developed technological scheme, the type and design of the crushing machine were determined. Based on the methods of regression analysis and mathematical statistics, a series of multifactor experiments were conducted on the main parameters of a hammer crusher. In addition, considering the properties of waste, the main parameters of the drum screen were determined, in particular, the diameter of the grid opening. The developed optimal set of machines with substantiated rational parameters will make it possible to maximally prepare the components of municipal solid waste for use in the form of secondary raw materials.

Keywords: municipal solid waste, sorting, crushing, optimal set of machines, drive power, rotor shaft speed

1 INTRODUCTION

The composition, properties, and quantity of municipal solid waste (MSW) generated in the process of human activity depend on people’s standard of living, the method of collecting and transporting waste, climatic zones of the area, etc. An analysis of the waste structure shows that packaging materials have recently occupied a significant share in its structure. This is primarily due to the fact that if the packaging of goods was previously considered exclusively as a method of storage and delivery, now packaging is looked at as an additional source of profit [1].

Solid waste is a significant source of environmental pollution and can pose health risks by introducing microbes into the environment and human bodies. However, it also serves as a valuable source of secondary raw materials, which is particularly important as natural resources become scarce. Therefore, extracting valuable components from solid waste is important for several reasons: first, the extracted waste can be used as secondary raw materials for production; second, recycling waste will lead to a significant decrease in its volume, reducing the costs of processing, transportation, and disposal in landfills; and third, this will help to reduce environmental pollution on a large scale.

Numerous technological schemes were developed to extract valuable components from waste, to process and dispose of it. However, it should be noted that the developed and created technological scheme for processing solid waste in a particular country might not be effective when implemented in another country. This is seen in the example of the operation of an experimental solid waste processing plant built in Tashkent in 2006. The plant was closed down due to the high glass content in compost - the product of the waste processing plant [3]. Therefore, when creating and putting into operation a complex for sorting and crushing solid waste or waste processing plants, it is necessary to consider local conditions and properties of waste and the trends of change in the next 10 years.

1.1 Literature Review

There has been significant research dedicated to developing technological processes and selecting machinery for processing solid waste. For example, L.Ya. Shubov et al. [3, 4] have focused on the patterns of solid waste separation in complex processing technologies, resource saving, and waste enrichment. However, they have not addressed the scientific basis for creating impact crushing and screening machines in the complex processing of solid waste.

A.N. Mirny [5] has conducted studies that not only analyzed modern technologies for neutralizing and disposing of solid waste but also considered the selection of effective technologies based on local conditions.

Issues of choosing sorting technologies, calculating the main parameters of sorting devices, and their efficiency are considered in [6, 7, 8]. However, these publications do not address the influence of a complex of factors on technology and equipment for waste processing.

Studies conducted by N.F. Abramov [9] primarily focus on the selective collection of solid waste and the sanitary cleaning of cities and populated areas from solid waste.

A.M. Gonopolsky et al. [10] investigated issues related to the disposal of food waste at the point of generation. In the research, the design of the crusher was developed and the main design and technological parameters were justified. A comprehensive evaluation of the crusher design was conducted to meet the requirements.

Issues related to the selection and calculation of the key parameters of various designs of crushers for grinding solid waste were considered by B.V. Klushantsev, A.I. Kosarev, Yu.A. Muizemnek [11]. The results obtained for determining the force and energy parameters showed that the data from theoretical and practical calculations differ greatly. B.S. Kirin and A.N. Klokova in [12] considered issues related to the separation of plastic from waste.

A.M. Musaev and R.G. Saifulin in [13] considered the method of vibration-pulsation sorting of solid waste. The working process was studied and the criteria for the effectiveness of sorting devices based on the vibration-pulsation principle were substantiated. However, these publications did not consider the issues of determining the power and energy parameters of machines.

Publications by L.N. Reutovich, M.P. Arlievsky, N.A. Averyanova [14] and V.F. Reshitko, G.Yu. Zatsepin, A.A. Shashnin, V.S. Maslov, E.B. Krelman [15] are devoted to the issues of purification compost from ballast inclusions, as well as the complex of machines that implements this technology. Based on thoroughly conducted patent search, devices for sorting solid waste and a complex for its implementation were developed.

Research conducted by V.B. Yushchenko [16] is devoted to developing automated complexes for processing household waste and its further utilization. However, the article does not address issues of equipment efficiency when working with mixed waste.

The works of I.Hussein, Abdel-Shafy, S.M.Mona [17] and Lu Hongmei [18] discuss certain issues of collection, transportation, and processing of solid waste.

R. Chernolutsky in [19] presented the feasibility study of the construction of a waste recycling plant built in Tashkent with a capacity of 150 thousand tons/year for the production of secondary raw materials. A rational technological scheme for processing solid waste, considering local conditions, was substantiated.

Issues of substantiating the rational parameters of machines using methods of physical modeling of solid waste processing and the issues related to developing technological schemes for waste processing are considered in articles by T.K. Khankelov et al. [20-30].

Despite the considerable number of studies conducted on addressing the collection, transportation, and processing of solid waste, there are still questions on the development of an integrated approach to selecting the most suitable machinery and devising a technological scheme for sorting and crushing waste. Additionally, determining and justifying the key parameters of machinery at the final processing stage remains an ongoing concern.

2 METHODOLOGY

To develop a new technological scheme for waste sorting, select the optimal set of machines for their processing, and justify the basic parameters of a crushing and sorting machine, it is necessary to have data on the morphological and fractional composition of waste.

Experiments were conducted in Tashkent, in 2023; the city consists of 12 districts, and it was necessary to select the required number of districts. The requirement for the selection of objects was explained by the following reasons: the objects of the selected districts should include retail chains, organizations, and blocks of multi-storey and private buildings.

We used 2-stage cluster sampling.

1. The first stage is the presentation of the city territory in the form of a cluster.
2. The average value of organic components of solid waste by season was determined.
3. Variance was determined

$$\delta = \sum (X_i - X_{av})^2, \tag{1}$$

4. The standard deviation was determined by the following formula:

$$\sigma = \sqrt{\frac{\delta}{n-1}}, \tag{2}$$

5. The number of districts required for research (a sample size) when the chance of implementation is 0.954 of the preference error and does not exceed 0.2% for a root mean square change σ = 0.224 %, is determined as:

$$n = \frac{t^2\sigma^2 N}{N\Delta_x^2 + t^2\sigma^2}, \quad (3)$$

where t – is the confidence coefficient determined from the Laplace table, taken as $t = 2$; N – is the volume of the general population, N =11 (administrative districts); Δ_x – is the sampling error.

To determine the morphological and fractional composition of MSW at waste collection points, 10 samples weighing 30 kg each were selected. The morphological composition of the waste was determined by the quartering method, i.e. waste samples were evenly distributed on a tarpaulin measuring 2000 x 2000 mm, then three-quarters of the waste was discarded and one-fourth was taken for study.

The percentage of waste components by size (fractional composition) was estimated by waste components by name, i.e. morphological composition. In the content of small fractions, the size of which is less than 50 mm, organic waste makes up approximately 90-95%. Consequently, the high content of fine fractions causes a high percentage of food waste in the screenings. To determine the percentage of waste constituents by size, a sieve was created with mesh sizes of 250 x 250 mm, 150 x 150 mm, 100 x 100 mm, 50 x 50 mm, and 15 x 15 mm. The size composition of municipal solid waste was determined by gradually passing "average" waste samples onto sieves with mesh sizes of 250 x 250 mm, 150 x 150 mm, 100 x 100 mm, 50 x 50 mm, and 15 x 15 mm.

Regression analysis methods were used to determine and optimize the parameters of a hammer crusher. Experiments to determine the main parameters were conducted according to the Box-Behnken design. They consider the complex interaction of factors. Box-Behnken design is the best system and contains the least sensitivity of coefficient results. In addition, varying factors at three levels provide the necessary accuracy of results at the smallest points of the plan.

3 RESULTS AND DISCUSSION

A program and methodology for experimental research were developed to select the optimal set of machines, develop a technological scheme for the implementation of waste sorting and crushing processes, and substantiate the key parameters of machines that ensure their effective use, considering the properties of waste.

- The initial data calculated on the basis of a two-stage cluster sample had the following results:
- The administrative division of the territory of Tashkent is divided into 11 clusters (one district is taken as one cluster)
- The average value of organic components based on the results of experimental studies for 2023 became equal to, X_{av}=33.3%
- The value of the sum of standard deviations calculated using formula (1) became equal to

$$\delta = 0{,}446$$

- The value of the standard deviation calculated using formula (2) became equal to

$$\sigma = \sqrt{\frac{0{,}446}{10}} = 0{,}224\%,$$

- The number of districts necessary and sufficient to obtain representative data calculated using formula (3) was equal to

$$n = \frac{2^2 0{,}224^2 \cdot 12}{12 \cdot 0{,}2^2 + 2^2 \cdot 0{,}224^2} = \frac{2{,}4}{0{,}68} = 3{,}5$$

i.e., to conduct research, it is enough to select 4 districts.

To study the morphological and fractional composition of solid waste, 16 points were selected in four districts of the city:

- Mirabad district - (private houses located between G. Aliev Street and Sarakulskaya Street, buildings located near the central office of the Tashkent railway station ticket offices, residential buildings located near the Poytakht store, residential buildings near the Aybek metro station).
- Chilanzar district - (Farkhad market, 9th quarter, 5th quarter, Al-Khwarizmi massif).
- Mirzo-Ulugbek district - (Center -2, area of the former Children's World, residential buildings near the Uzyulmashservice NPO, Feruza massif).
- Yunusabad district - (7, 13 and 19 blocks, "Bobodekhkan" mahalla).

Figure 1 shows the average value of the morphological composition of solid waste generated in Tashkent in 2023.

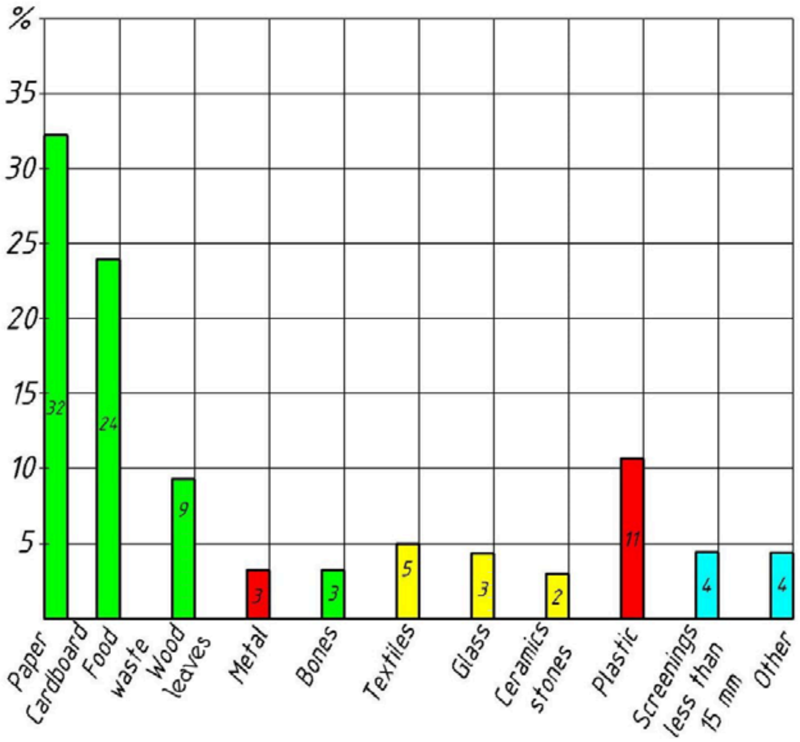
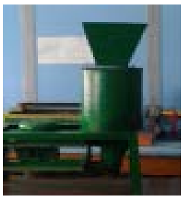


Fig. 1. Morphological composition of municipal solid waste generated in Tashkent

Analysis of data on the morphological composition of solid waste makes it possible to create a system of machines for sorting and crushing waste. In addition, it should be noted that solid waste is collected at waste collection points in plastic bags. Therefore, it is necessary to equip the waste processing line with bag breakers. A set of machines and a stage-by-stage change in the morphological composition of solid waste as a result of processing is shown in Table 1.

Table 1. Set of machines for crushing and sorting solid waste

№	Machines and mechanisms used in crushing and sorting solid waste	Morphological composition of solid waste after this operation [%]	Name of the machine, device
1		Paper, cardboard-32; food waste-24; trees, leaves-9; metal-3; bones-3; textiles-5; glass-3; ceramics, stones-2; plastic-11; screening less than 15 mm-4; other-4	Bag breaker
2		Food waste-24; trees, leaves-9; metal-3; bones-3; textiles-5; glass-3; ceramics, stones-2; plastic-4; screening less than 15 mm-4; other-4	Sorting table
3		Food waste-24; trees, leaves-9; bones-3; textiles-5; glass-3; ceramics, stones-2; plastic-4; screening less than 15 mm-4; other-4	Magnetic separator
4		Food waste-24; bones-3; glass-3; ceramics, stones-2; plastic-4	Drum screen

№	Machines and mechanisms used in crushing and sorting solid waste	Morphological composition of solid waste after this operation [%]	Name of the machine, device
5		Food waste-24; bones-3; glass-3; plastic-4	Sorting device
6		Food waste-24	Sorting machine equipped with artificial intelligence
7		Shredded food waste, raw materials meeting the requirement of compost production	Hammer Crusher

Based on the analysis of the data obtained, it is possible to develop a technological scheme for processing solid waste. The technological scheme for waste processing was developed considering the properties of waste, and in selecting machines and devices, the factors of cost and quality of work are also considered. The developed technological scheme is presented in Fig. 2.

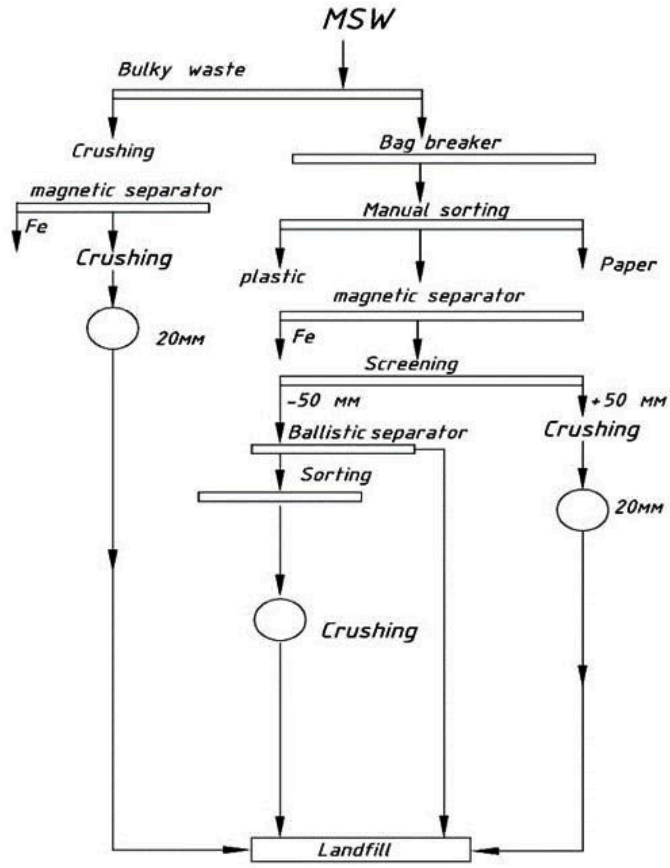


Fig. 2. New technological scheme proposed for sorting and crushing solid waste

The advantages of the proposed technological scheme for processing solid waste are as follows:

- the technological scheme is equipped with bag breakers since currently the bulk of waste is packaged in bags.

The maximum dimensions of plastic bags determine the main parameters of the bag breaker;

- for crushing large-sized waste, the technological scheme is equipped with disk crushers (shredders);

– for sorting food waste, the crushing and sorting complex presented in this technological scheme is equipped with a robotic sorting device, in the working process of which artificial intelligence elements are used.

Based on the morphological composition of solid waste generated in Tashkent, we have determined the set of machines for sorting and crushing waste; however, to justify the main parameters of the above machines we need data on the fractional composition of waste. To determine the fractional composition, ten "average" samples were created. Samples were taken from containers where they accumulated at different times of the day, weighing thirty kilograms each. The experimental results are shown in Table 2.

Table 2. Fractional composition of municipal solid waste generated in Tashkent

No.	Residue on mesh size sieve, mm [%]					
	250x250	150x150	100x100	50x50	15x15	Screening less than 15 mm
1		3.4	20.0	24.2	44.2	5.4
2		3.0	24.0	24.3	42.5	6.2
3		5.8	18.4	21.5	46.1	7.2
4		3.6	17.5	29.7	43.6	5.4
5		3.2	21.7	26.1	43.0	6.0
6		2.4	21.4	25.6	43.7	6.9
7		2.8	23.3	25.2	42.5	6.4
8		3.7	20.4	25.6	44.3	6.4
9		3.3	20.6	23.8	46.8	5.5
10		2.8	19.4	24.2	47.8	5.8
Average value		3.4	20.7	25.0	44.3	6.1

An assessment of the results obtained (Table 2) shows that slightly less than half of the waste has a size ranging from 15 to 50 mm. The results of a series of experiments to assess the percentage of waste by name depending on the size values are presented in Table 3 (in % of the weight of the residue on individual sieves).

Table 3. Morphological composition of solid waste depending on the size of the fraction

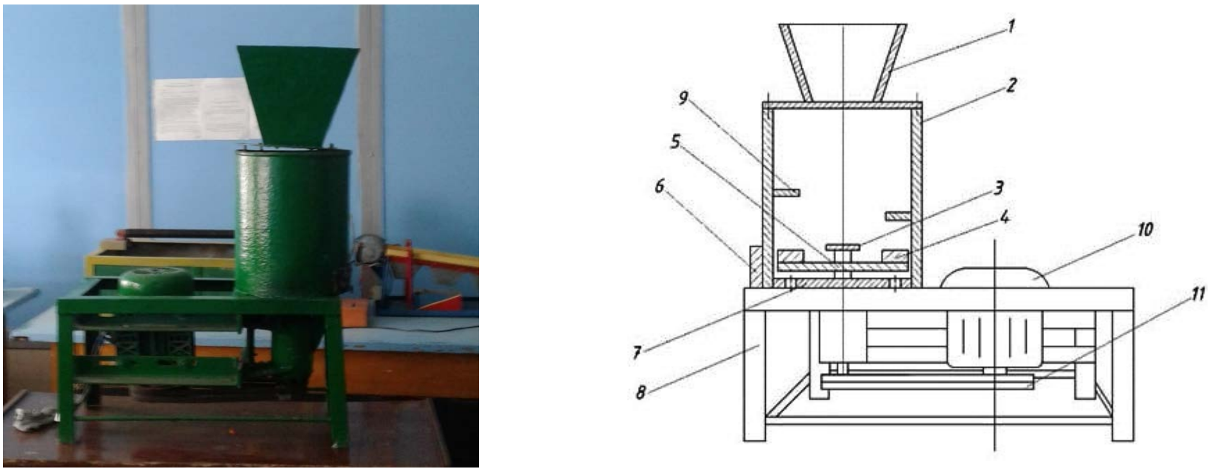
Components	>250 [mm]	150÷250 [mm]	100÷150 [mm]	50÷100 [mm]	15÷50 [mm]	<15 [mm]
Paper	-	28	37	22	13	-
Food waste	-	5	12	23	65	-
Textiles	-	12	17	4	2	-
Trees, leaves	-	20	-	6	4	-
Bones	-	-	12	6	4	-
Glass	-	-	-	4	3,5	-
Leather, rubber	-	12	11	7	2	-
Other	-	12	1	4	1	-
Metal	-	11	7	14	1.5	-
Stones	-	-	3	10	4	-
Screening (<15mm)	-	100	100	100	100	100

An assessment of the results of experiments to determine the percentage of waste components by name depending on the size of the components showed that the main part of the organic components has a size from 15 to 50 mm: paper - 13%; food waste - 60%; textiles - 2%; wood - 4%; bones - 4%; glass - 3.5%; stones - 9%.

A series of experiments conducted made it possible to determine the average values of the morphological composition of solid waste, which serves as raw material for experimental research. The probabilistic model of solid waste has the following values: paper, cardboard - 32%; food waste - 24%; trees, leaves - 9%; metal - 3%; bones - 3%; stones - 2%; textiles - 5%; glass - 3%; plastic - 11%; screening less than 15 mm - 4%; and other - 4%.

At the final stage of the process of crushing and sorting solid waste, waste components are crushed using a hammer crusher.

To substantiate the determining factors and intervals of their variation, and the rational values of the main parameters of the crushing machine, a physical model of the hammer crushing machine was developed and manufactured Fig. 3.



a) b)

Fig. 3. Hammer crusher: a) general view of the crusher; b) design scheme of the hammer crusher: 1-hopper; 2-working chamber; 3- rotating knife; 4-hammer; 5-rotor; 6- side grate; 7-lower grate; 8-frame crusher; 9-fixed knife; 10-electric motor; 11-V-belt

The stand for grinding organic components of solid waste works as follows. The waste arriving for grinding enters loading hopper 1. Next, the waste enters working chamber 2, where it is accelerated to a rotation speed equal to the rated rotation speed of electric motor 10, by creating air pressure with hammer 4. The waste accelerated to the rated rotation speed of electric motor 10 is crushed due to the collision of waste with knives 9 rigidly welded to the walls of working chamber 2. In addition, the waste is crushed by colliding with grate 5. The sharpened ends of rotating rotors 5 contribute to the effective grinding of waste. Fibrous and film waste is crushed due to abrasion between the lower part of rotor 5 and the bottom of working chamber 2. Due to abrasion, the waste passes through grate 7 located at the bottom of the working chamber.

To determine the impact of the type and location of the working bodies relative to the line passing through the dimensions of the crushing machine rotor on the grinding productivity, a cycle of preparatory experiments was organized.

a) b) c)

Fig. 4. Designs of rotors with various hammers: a) straight hammers located along the rotor axis; b) hammers located at an angle of 45 degrees to the rotor axis; c) paraboloid hammers

The process of crushing the components of solid waste is influenced by many factors, the degree of significance of which varies, especially in the production of mineral fertilizer (compost), since in the case of compost production, the crushing machine is equipped with grates. The ranking of factors influencing the crushing process made it possible to determine both primary and secondary factors. To unambiguously determine the crusher rotor, a series of one-factor experiments was conducted to substantiate the shape, weight, and angle of installation of the hammers relative to the rotor axis, and to study the effect of waste moisture content on the productivity of the crushing machine.

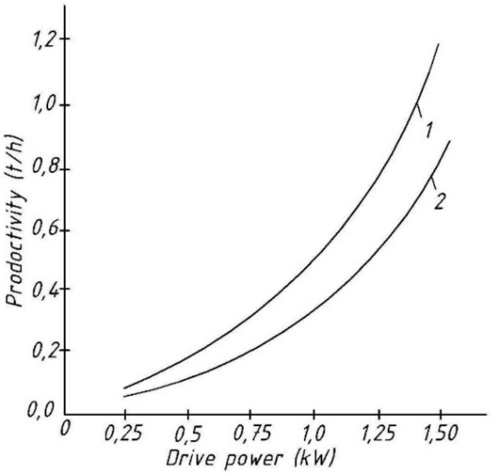


Fig. 5. Dependence of crusher productivity on the shape of the rotor hammers at different values of the drive power of the crushing machine: 1 - straight shape of the hammer; 2 - paraboloid shape of the hammer

Analysis of the graphs presented in Fig. 5 shows that with increasing power of the electric motor, the productivity of the crusher increases; however, with a straight shape of the hammer (line 1) the growth occurs more intensively than in the case of a paraboloid shape of the hammer (line 2). The reason for this discrepancy is the following: with a straight hammer, the impact on the components is direct, that is, all the impact energy is applied to the waste components, and, in addition, due to the shape of the blade, the waste components hit a large light surface. With the paraboloid shape of the hammer, first, a concentrated blow is obtained; second, due to the small distance, there is no noticeable dispersion of the flying components, thus the productivity of the crusher is relatively low. In the case of a paraboloid shape, electricity consumption will increase due to higher resistance. It was also established that when crusher drive values are less than 0.5 kW, there is a lack of drive power; this is explained by the fact that the existing moisture content of the waste prevents the rotation of the crusher rotor, and the crushing process does not occur.

To determine rational values for the diameter of the grate opening, which provides the required linear size of crushed waste components, regulated in the compost production, a series of one-factor experiments was conducted. The dependence of the productivity of the crushing machine on the diameter of the grate (the shape of the hammer is a plate of constant thickness) was determined.

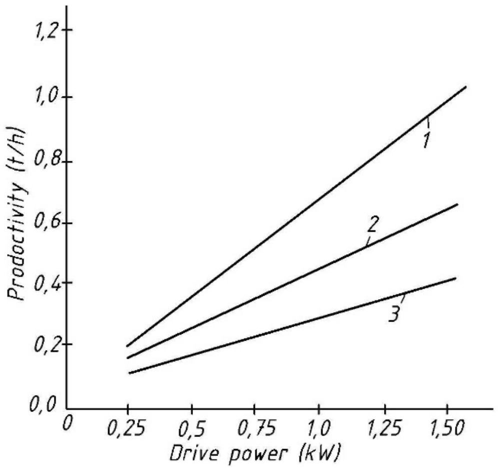


Fig. 6. Dependence of the productivity of a hammer crusher on the drive power (for different values of the grate diameter): 1- for the grate diameter of 25 mm; 2 - for the grate diameter of 20 mm; 3 –for the grate diameter of 15 mm

When the drive power of the hammer crushing machine is from 0.25 to 0.5 kW, partial jamming of the rotor occurs due to lack of power, and when the drive power of the crushing machine is 1.5 kW, the productivity of the crushing machine is approximately 1.0 t/h. The relatively low productivity value is due to the fact that the grating holes are partially clogged (line 1). When the drive power of the hammer crusher is from 0.25 to 0.5 kW, the grate holes are also clogged, but the relatively small difference lies in the sizes of the holes (lines 2 and 3), and when the drive power of the hammer crusher is 1.5 kW, the productivity of the crushing machine is approximately from 0.8 to 0.95 t/h. When the diameter of the grate hole is 25 mm, the maximum value is obtained. The disadvantage of this case is that the bulk of the crushed waste has a size of approximately 15-20 mm, which in turn does not meet the technical conditions for compost production.

Consequently, to obtain the size of crushed waste within 10-15 mm, a second stage of grinding is required, which leads to significant energy consumption. Therefore, the use of grates with a diameter of 15 mm completely covers such a minor difference in performance due to energy savings.

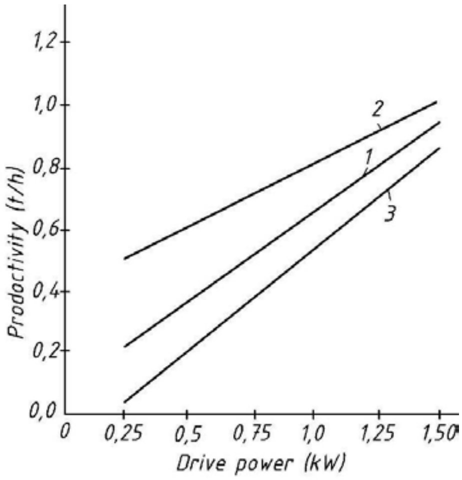


Fig. 7. Dependence of the productivity of a hammer crushing machine on the drive power of the hammer crusher (for different values of the rotor hammer installation angle): 1- for the hammer installation angle $\alpha_{м} = -45^{0}$; 2 - for the hammer installation angle $\alpha_{м} = 0^{0}$; 3 - for the hammer installation angle $\alpha_{м} = 45^{0}$.

When the drive power of the hammer crushing machine is from 0.25 to 0.5 kW, the rotor shaft jams due to the lack of drive power to overcome the resistance that arises from the waste components and static resistance forces. The best values are obtained at the hammer angle of $\alpha_{м} = 0^{0}$ (line 2). This is explained by two reasons: first, when the hammer installation angle is zero, a good pressure force is created in the working chamber, due to this, the waste components are accelerated to speeds equal to the nominal value of the rotor rotation speed. Obviously, the greater the speed of impact of the components on the wall of the crushing chamber of the machine, the greater the impact force; the data obtained confirms this. Second, when the hammer installation angle is zero, a direct impact occurs on the waste components. This circumstance is the reason for the collision of waste components against the walls of the working chamber with maximum force. In addition, when the hammer installation angle is zero, the “angle of fire” from the side of the hammer to the grate is the greatest. When the hammer installation angle is $\alpha_{м} = -45^{0}$ (line 1), an oblique impact occurs on the waste components, i.e. the impact force is dissipated, thereby the waste components collide with the walls of the working chamber of the hammer with little force. In addition, at an installation angle equal to $\alpha_{м} = -45^{0}$ the air pressure used to disperse the waste components is small.

When the hammer installation angle is $\alpha_{м} = 45^{0}$ (line 3), an oblique impact on the waste components also occurs, i.e. the impact force is dissipated, thereby the waste components collide with the walls of the working chamber of the hammer with little force. In addition, at an installation angle of $\alpha_{м} = 45^{0}$, the air pressure used to disperse the waste components is small. Another important circumstance is that with an installation angle of 45^{0}, the “angle of fire” on the grate from the hammer side is the smallest.

To investigate the impact of hammer weight on the crushing process and determine the ranges of their variation, a series of single-factor experiments was conducted.

Figure 8 illustrates the productivity graph of a hammer crushing machine based on the drive power (with hammer weights $m_{м}$ =1.0; 1.2; and 1.4 kg). The hammers are rectangular plates of consistent thickness. Only the width of the hammer was changed, while the height remained constant.

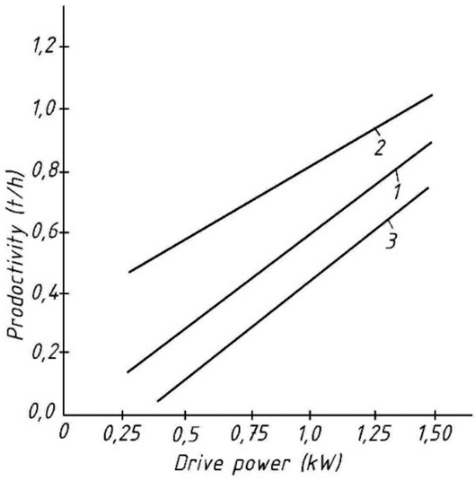


Fig. 8. Dependence of the productivity of a hammer crusher on the drive power of the hammer crusher at different values of hammer weight: 1- with a rotor hammer weight $m_{м}$ =1.0 kg; 2 - with a rotor hammer weight $m_{м}$ =1.2 kg; 3 - with a rotor hammer weight $m_{м}$ =1.4 kg.

Analysis of the graphs presented in Fig. 8 shows that when the drive power of the crushing machine is from 0.25 to 0.5 kW, the rotor shaft jams due to the lack of drive power to overcome the resistance forces that arise from the waste components and to overcome static resistance forces. The graphs show that productivity is greatest when the hammer weight is $m_{м}$=1.2 kg. This is explained by the fact that, first, an increase in the weight of the hammer helps to increase the pressure force created by hammers; this, in turn, helps to increase the impact force of the waste components on the walls of the working chamber of the crusher: second, an increase in the linear dimensions of the hammer, i.e., the area of contact with waste components increases the "angle of fire" of the grate from the side of the rotor hammer. The reason for the relatively low productivity of a hammer crusher with a hammer weight $m_{м}$=1.4 kg is the increase in resistance forces from the air medium and waste components.

An assessment of the dependencies shown in Figures 6-8 indicates that the highest percentage of grinding of organic waste components is achieved:

- at the size of the grate opening approximately equal to $D_{\text{р}}$ ≈15 mm;
- at the angle of installation of the rotor hammer approximately equal to $\alpha_{м} \approx 0$;
- at the rotor hammer weight approximately equal to $m_{м}$ ≈1.2 kg.

Data from a priori information and several installation experiments made it possible to clarify the factors that significantly affect the performance of the crushing machine at fixed values of the above parameters:

- rotor shaft rotation speed, $n_{\text{р}}$, rpm;
- light area of the grate, F_c, cm2;
- rotor diameter, $D_{\text{р}}$, cm.

To determine the level of variation of factors, and ranking factors by importance, a series of single-factor experiments was conducted.

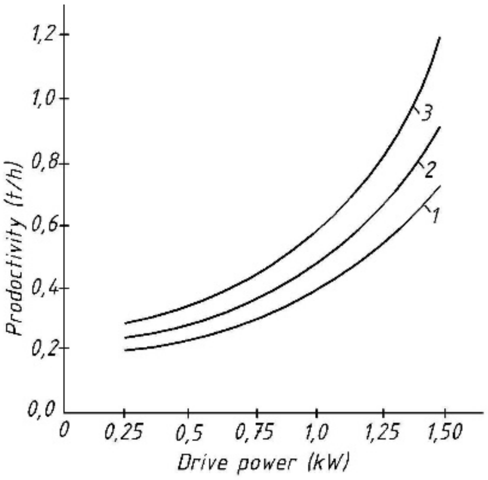


Fig. 9. Dependence of the productivity of a hammer crushing machine on the drive power at different values of the rotor shaft rotation speed: 1 - at the rotor shaft rotation speed of $n_{\text{р}}$=1250 rpm; 2- at the rotor shaft rotation speed of $n_{\text{р}}$=1750 rpm; 3 - at the rotor shaft rotation speed of $n_{\text{р}}$=1500 rpm.

Analysis of the graphs presented in Fig. 9 shows that when the drive power is from 0.25 to 0.5 kW, the rotor shaft jams due to the lack of power to overcome the resistance forces that arise from the waste components and to overcome static resistance forces.

As seen from the graphs, the highest performance value is achieved at a rotor shaft speed of $n_{\text{р}}$=1500 rpm, which corresponds to the nominal speed of the electric motor rotor shaft. In addition, when the rotor shaft rotation speed is $n_{\text{р}}$=1500 rpm, the specific energy intensity is minimal.

At the rotor shaft rotation speed equal to $n_{\text{р}}$=1750 rpm (line 3) and $n_{\text{р}}$=1250 rpm (line 1), the crushing machine has a higher specific energy intensity. In addition, an increase in rotation speed leads to a decrease in torque, resulting in a decrease in performance values. At $n_{\text{р}}$=1250 rpm (line 1), the waste components will not acquire the speed required for effective grinding.

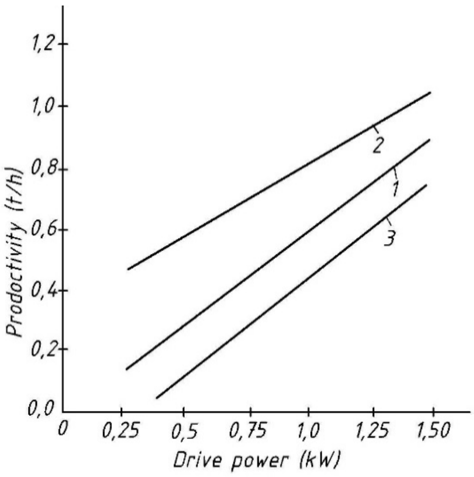


Fig. 10. Dependence of the productivity of a hammer crushing machine on the drive power at different values of the light area of the grate: 1 - at values of the light area of the grate F_c=250 cm^2; 2 - at values of the light area of the grate F_c=350 cm^2; 3 - at values of the light area of the grate F_c=300 cm^2

The highest performance values are observed when the light area value is F_c=300 cm^2 (line 3). The reason for the lower productivity of the hammer crushing machine when the area is F_c=350 cm^2 (line 2) is due to the waste scattering in different directions, causing environmental pollution. Additionally, the installation of the unloading device results in waste clogging the periphery of the internal part, leading to lower productivity.

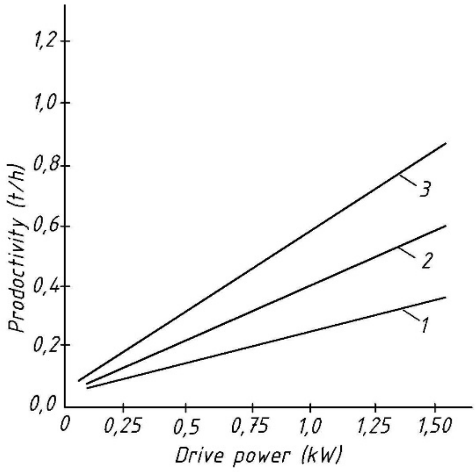


Fig. 11. Dependence of the productivity of a hammer crushing machine on the drive power for different values of the rotor diameter: 1 - for a rotor diameter equal to D_{p}= 24 cm; 2 - for a rotor diameter equal to D_{p}= 27 cm; 3 – for a rotor diameter equal to D_{p}= 30 cm

Analysis of the graphs presented in Fig. 11 shows that for D_{p}= 30 cm (line 3), the productivity of the crushing machine has the highest values; this is explained by the fact that at this value of the rotor diameter, there is no influence of boundary conditions, i.e., full coverage of the waste mass at the chamber wall is achieved. Full coverage of the waste mass allows the maximum value to be achieved. In the other two cases, there will be a effect of boundary conditions, when the waste mass pressed against the wall has zero speed resulting in a low productivity value.

Based on the methods of mathematical statistics theory, by preliminary distribution considering the review and results obtained in one-factor experiments, the main factors determining the grinding process were established. The dependence of crushing machine performance on the main process parameters in implicit form is:

$$Y = f(n_{\text{p}}, F_c, D_{\text{p}}) \tag{4}$$

where n_{p}- is the number of revolutions of the rotor shaft, rpm; F_c – is the light area of the grate, cm^2; D_{p} –is the diameter of the rotor shaft, cm; *Y* is the productivity of the crushing machine, kg/h.

The implicit relationship between factors and optimization parameters is as follows:

$$Y = a_0 + \sum a_i x_i + \sum a_{ij} x_{ij} + \sum a_i x_i^2, \tag{5}$$

where Y – is the value of the optimization indicator under consideration; x_i – is the encrypted value of factors ($i = 1,2,3$); a_i – is the value of the coefficient characterizing the contribution of the *i*-th factor; a_{ij} – is the value of the coefficient characterizing the interaction of factors.

The experiments were conducted according to the Box-Behnken design (B_3) [31,32]; they consider the complex interaction of factors. Box-Behnken design is the best system and it contains the least sensitivity of coefficient results. In addition, the variation of factors at three levels provides the necessary accuracy of results at the smallest points of the design. To control the feasibility of the experiments, the Cochran test was used to evaluate the hypothesis of the similarity of variance values with identical repetitions; the role of the empirical coefficients of the regression equation was assessed using the student t test with an accuracy level of 0.05. The ability to depict the rebound surface quite well, i.e., the conformity of the adopted model, was checked using standard methods.

$$F_{cal} < F_{tab}, \quad (6)$$

Table 4 shows the levels of factors and ranges of their variation.

Table 4. Levels of factors and ranges of their variation

№	Factors	Dim.	Codes	Factor levels			Range
				-1	0	+1	
1	Rotor shaft speed	rpm	X_1	1250.0	1500.0	1750.0	250.0
2	Light area of the grate	cm^2	X_2	250	300	350	50
3	Rotor shaft diameter	cm	X_3	24	27	30	3

Following the production of experimental data and verification of the importance of regression coefficients, a mathematical model of the performance of a prototype of a crushing machine was obtained.

$$Y = 89{,}2 + 7{,}4X_1 - 3{,}4X_2 + 2{,}7X_3 + 3{,}3X_1^2 - 2{,}4X_2^2 + 1{,}8X_3^2 \quad (7)$$

Assessment of model compliance using the Fisher criterion showed that the mathematical model is suitable with 95% confidence.

$$F_{cal} = 0{,}95, F_{tab} = 2{,}36 \quad (8)$$

To find the best values of the factors, equation (6) was examined to the maximum, the result of which is given in Table 5.

Table 5. Rational values of factors

Factor values	Factors		
	X_1(mm)	X_2(degree)	X_3(kg)
Coded	0	0	+1
Natural	1500,0	300	30
Rounded	1500,0	300	30

Therefore, the best values for the main parameters of the crushing machine are:

- rotor shaft rotation speed - n_p ≈1500 rpm;
- light area of the grate - F_c ≈300 cm^2;
- rotor diameter - D_p ≈30 cm.

4 CONCLUSION

When studying waste properties, we analyzed the morphological and fractional compositions to determine the composition and size of waste fractions. This analysis helped us define and justify the design and structure of machines, as well as determine their main parameters. We did this by analyzing the sizes of waste fractions, the diameter of the drum screen holes, and the angle of inclination of the drum relative to the horizontal axis. This made it possible to determine the initial values of the main parameters of the drum screen, such as: the diameter of the holes of the drum screen, the angle of inclination of the drum screen relative to the horizontal and the speed of rotation of the drum.

The use of regression analysis methods has enabled the optimization of the key parameters of a hammer crusher. This has allowed for the rationalization of the crusher parameters. However, it's important to note that research data obtained cannot be directly transferred without adjustment. This is due to the potential significant differences in the properties of waste in different districts, living conditions, and income levels of the population. In addition, the properties of solid municipal waste have significant dynamics of changes both in quantity and structure. In this regard, it is necessary to conduct research aimed at studying solid municipal waste on an ongoing basis.

4.1 Main conclusions

- An optimal set of machines for crushing and sorting solid waste was developed, allowing efficient waste sorting and crushing with minimal time and material costs.
- A new technological scheme for processing solid waste was developed, the implementation of which in waste sorting and crushing processes would allow for a rational arrangement of components and assemblies of processing machines during their installation.
- Determination of the fractional composition of the waste made it possible to justify the size of the holes in the drum grinding cells.
- The fractional composition of the waste obtained at the end of the technological chain made it possible to select the design of a hammer crusher with justified rational parameters.

The significant heterogeneity of the composition of municipal solid waste and the variability of its properties do not allow the development of clear mathematical models in the form of a system of differential equations that describe the process of their sorting and grinding. In this regard, we used an experimental method to determine the rational parameters of devices for crushing and sorting waste. The disadvantage of this method is that the resulting mathematical model of the process has limitations, i.e. it is reliable within the limits of changes in the selected parameters (factors). Changing the values of factors outside the accepted range may affect the efficiency of the crushing machine. Further research in this direction can be developed by using the achievements of fundamental sciences, i.e. combining theoretical and experimental research.

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