INTENSIFICATION OF STEM MATERIAL SHREDDING PROCESS

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Abstract. At the current stage of technology development, roughage shredding is carried out mainly by mechanical means, which ensures high reliability and is characterized by the simplicity of the design of working bodies. The main issues of our work are to improve the process of shredding roughage by changing the design of the chopper and optimizing its parameters, which will ensure shredding of roughage with minimal specific energy and metal consumption. To conduct the research, a two-stage chopper design was proposed, and a pilot plant was manufactured, which has the ability to chop long-fiber feed materials and separate them along the fibers with breakage of stem nodes. The operating range of the rotor speed was in the range of 500-700 rpm, and the gap between the movable and fixed pins 0.015-0.025 m. The nature of the interaction of a particle of roughage, after cutting the layer with a curved knife, with the wing and the pin during the splitting of the stem along the fibers was determined. It was found that with a decrease in the rotor speed, the material moving to the pins does not reach absolute speed, which ensures the creation of an impact that should be sufficient to destroy the stem. In addition, a rotor speed of less than 500 rpm does not allow for the creation of an air flow that ensures the removal of feed components from the splitting zone, thereby limiting the chopper throughput. Increasing the rotation speed above 900 rpm leads to an increase in energy performance and reduces the percentage of split stalks of roughage.

Keywords: splitting, stem, pins, combined shredder.

Introduction

Highly profitable and organic livestock production requires the use of machinery and equipment in production processes that can provide high economic and quality indicators, which in turn will make it possible to provide humanity with food and industry with raw materials, while reducing greenhouse gas emissions into the atmosphere and effectively utilizing long-fiber crop residues. It is known that organic livestock production around the world is based on four principles formulated by the international organization IFOAM, which is based on human health [1]. Organic production is an integrated system for agricultural work and food production, combining conditions for preservation of natural resources, minimum standards for keeping livestock and poultry, and high standards of production. Under such conditions, the priority is to take care of people, flora and fauna, and the environment [2]. All these aspects involve close interaction with organic farming, including to improve and preserve soil fertility [3]. The use of coarse long-fiber plants is carried out in two ways, in the form of fodder and bedding material. These uses involve reducing the length of the particles by shredding them.

Each shredding method has certain particle size limits and an acceptable ratio of the fractional composition of the resulting product and energy consumption [4]. At the current stage of technology development, roughage shredding is carried out mainly by mechanical means, which differs from others in its simplicity of design and high reliability. The main condition for substantiating the design scheme of a chopper that provides shredding of roughage is to determine its optimal parameters that would ensure high-quality performance of the technological process at minimal specific energy consumption. Studies of roughage choppers have been conducted since the 18th century [5; 6], but only in the 20th century were three main types of cutting investigated: normal, inclined, and sliding. The most efficient type of cutting in terms of energy consumption is sliding, because this type of cutting causes micro-sawing of the feed material. The analysis of literature sources [6-13] shows that the drum chopper has equal values of the angles of pinching and sliding, therefore, sliding cutting is practically impossible to realize in drum-type cutting machines, unlike in the disk chopper. However, a disk knife chopper has a low level of breakdown of feed components along the fibers. Splitting along the fibers makes it possible to use feed components efficiently and makes the bedding softer. The efficiency of use is explained by the fact that the area of contact of feed with gastric juice increases, as a result of which the nutrients of feed [14] are better digested and more fully absorbed by the animal. The development and design of combined working bodies will have a positive impact on issues related to the timely removal and sometimes burning of crop residues in the fields [15]. Combined machines have a wide versatility that allows them to be used in other industries [16-18]. Since the new machine should absorb the best quality indicators of existing machines, when justifying the rational structural and functional scheme of a stem feed chopper, it is necessary to carry out a step-by-step selection of design solutions for the machine units and components.

The aim of the proposed work is to improve the quality and economic indicators of the process of shredding stem materials by improving the structural and functional scheme of the combined shredder. The proposed shredder, in addition to low energy consumption, should ensure high uniformity of the particle size of long-fiber material and splitting of stems along the fibers.

Materials and methods

Despite the disadvantages associated with splitting the stems along the fibers, the knife chopper has positive features, such as low energy consumption, a wide range of particle size control, and an even cut of the stems. Improving the structural and functional scheme of the roughage chopper, we concluded that it should be two-stage. The first stage of shredding is a knife vertical-disk apparatus with sliding cutting. The second stage of shredding is a pin apparatus of impact action. The pin working bodies are located after the disk shredder. Structurally, the pin shredder requires the installation of movable and non-movable disks with pins in the working chamber and the supply of raw materials to this area. The shredding size in a pin chopper is regulated by the gap between the pins.

The analysis of literature sources confirms that hammer shredders also split the material along the fibers quite effectively, but the control over the shredding size is performed using sieves or a deflector, which leads to an increase in the energy intensity of the process. Therefore, the use of a pin shredder will be more acceptable in the developed machine.

To conduct the research, a pilot plant was made (Fig. 1), which has the ability to cut long-fiber feed materials and split them along the fibers with the breakage of stem nodes.

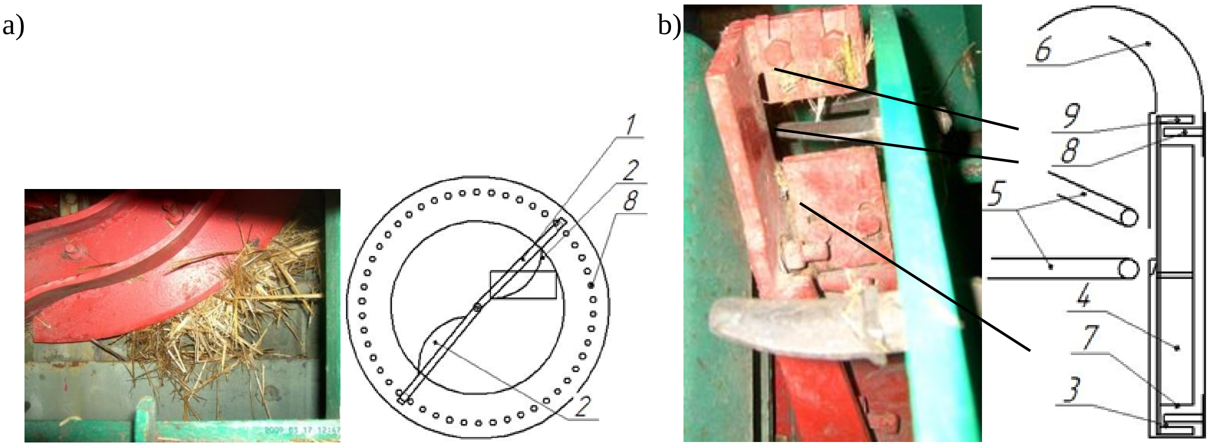

Fig. 1. **Schematic diagram of the shredder:**
a – front view of the disk–pin shredder; b – side view of the disk–pin shredder:
1 – impeller blade; 2 – disc knives; 3 – pin shredder; 4 – shredding chamber; 5 – loading device;
6 – discharge pipeline; 7 – movable pin; 8 – fixed pin; 9 – discharge blade

In the course of the research, digital laser DT-2234C + (error ±0.05%) and parallel mechanical TC10-R (error ±1%) tachometers were used to determine the rotational speed of the impeller, energy indicators were determined and recorded using wattmeters D8003 and H3095 (accuracy class of the device when measuring and recording the measured value is 1.5, accuracy class for recording time is 0.5), rulers, squares and tape measures were used to determine linear dimensions. The uniformity of shredding was determined using a Pennsylvania sieve (error ±1%).

The experimental pilot plant allows:

- change the rotational speed of the disk-pin chopper;
- change the size of the gap between the rows of moving and fixed pins;
- change the distance between the fixed pins in the rows;
- change the size of the first stage shredding products.

The working process of shredding stem components is as follows: the pre-compacted material is fed into the shredding chamber by means of the feeder 5, the disk knives 2 cut off a layer of material of a certain length, which is transported along the blade of the impeller 1 to the area of the pin shredder 3. Stem particles fall into the area of interaction between the impeller 1 and the fixed pin 8, due to the interaction (impact) of the working bodies with the material, the latter is split along the fibers. The material is discharged from the chopping chamber 4 through the discharge pipe 6, and it should be noted that the discharge blade 9 acts as a moving pin.

In the course of the experimental studies, the weighted average particle size l_s was determined by dividing into fractions and determining the sizes and masses of these fractions. The calculation was performed according to the formula:

$$l_s = \frac{\sum_{i=1}^{n} m_i \times l_i}{\sum_{i=1}^{n} m_i}, \tag{1}$$

where l_i – average length of particles of the *i*-th fraction, m;
m_i – mass of particles of the *i*-th fraction, kg;
n – number of fractions.

Samples of stem fodder were analyzed in the laboratory to determine the fractional composition. The percentage of split stems along the fibers and the percentage of particles of a given size were also determined.

The specific energy intensity q of the shredder is determined by the formula:

$$q = \frac{N}{Q}, \tag{2}$$

where N – power consumption, kW;
Q – productivity, kg·s^{-1}, defined as the ratio of the mass of the portion of feed components G (kg) loaded into the shredding chamber to the time t (s) of its processing:

$$Q = \frac{G}{t}, \tag{3}$$

The processing time of each portion of raw materials was recorded by a stopwatch and compared with the energy diagram recorded by a self-recording device.

Results and discussion

Our analytical studies related to the process of shredding stem materials allowed us to identify the rational limits of the parameters of the pin chopper. For example, the rational limits of the speed of moving pins, as evidenced by the technical characteristics of existing machines, are in the range of 60-80 m·s^{-1}, and the minimum speed of the pin working bodies is 38-47 m·s^{-1}. It should be noted that the speed of the active pins within these limits is recommended for the case of chopping coarse feed only due to the action of the pin apparatus. As for knife choppers, the cutting speed is in the range of 20-35 m·s^{-1}. At these speeds, the process of shredding stem material has the lowest energy costs. Taking into account the design features of the proposed chopper, it is possible to provide different chopping speeds for each chopper on the same rotation axis.

The dependence of the linear velocity on the angular velocity shows that the average shredding speed increases with the distance of the shredding point from the center of rotation:

$$\vartheta = 2\pi \cdot R \cdot n, \tag{4}$$

where υ – cutting speed, m·s^{-1};
R – distance of the cutting point of the raw material from axis of rotation of the disk, m;
n– knife rotation speed s^{-1}.

The shredder design uses a distance of 0.8 m from the rotation axis to the position of the fixed pins. Taking into account the conditions for ensuring material shredding in the pin apparatus and minimizing energy consumption, the minimum rotation speed of the shredder shaft is 7.5 s^{-1}, and the rational one is 9-11 s^{-1}.

Given the known speed characteristics, it is necessary to determine the density and number of pins. The feed rate of the raw material to the first stage of shredding is coordinated with the speed of the curved knife, which, when interacting with the countercutting plate, cuts off particles 45 mm long.

The calculation of the parameters of the second stage shredder should be based on the volume of material cut off by the knife in one revolution (Fig. 2). The cut material, after leaving the knife shredder, enters the interaction zone of the active blades and fixed pins. To ensure the shredder throughput capacity, all the cut material must pass through the pin apparatus during one revolution of the rotor t_{rev}.

The destruction of the outer shell and maximum splitting of the stems along the fibers without over-chopping depends on the pitch of the pins and the gaps between the moving and fixed elements. To substantiate the parameters of the pin chopper, we will provide a condition under which a cut particle 45 mm long will interact with only one of the moving or fixed elements (Fig. 3).

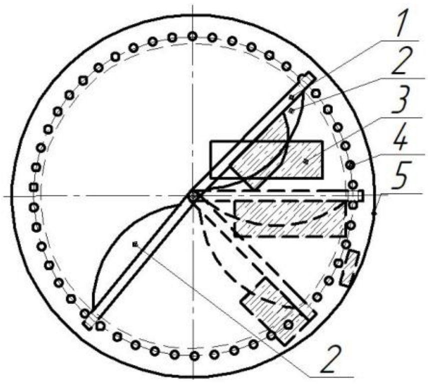

Fig. 2. **Scheme of material movement in the working chamber of the shredder:** 1 – impeller blade; 2 – knife; 3 – feeding mouth; 4 – fixed pins; 5 – side wall of the shredding chamber

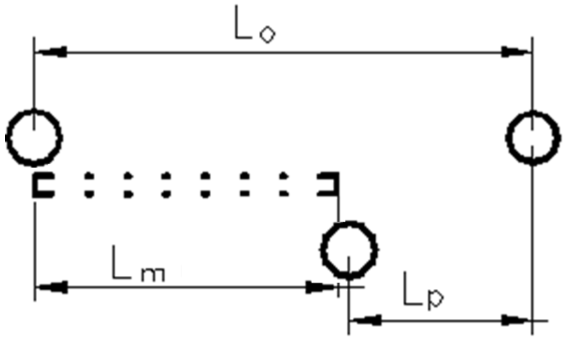

Fig. 3. **Scheme of interaction between the wing and the pin during feed chopping:** *Lo* – gap between the edges of the slot in the wing; *Lm* – length of particles after knife chopping; *Lp* – gap between the pin and the edge

The size of the space *Lp* that occurs between the pin and the blade rib must ensure that the stems that were not split during interaction with the moving and fixed pins are split. This will result in a particle impact with support from only one side, which causes twisting and tearing along the material fibers.

At the beginning of the experiment planning, the controllable factors affecting the performance of the stem chopper were identified with the help of expert evaluation. The main factors were the design of the knife chopper, the shape of the knife, the location of the loading mouth, the angle of sharpening of the knife, the speed of the working bodies, the size of the gap between the rows of movable and fixed pins, and the distance between the fixed pins in the rows. According to the preliminary expert assessment, these parameters affect the performance of the machine. The influence of the design of the knife chopper on performance has been sufficiently studied. Accordingly, these factors will be excluded from further analysis. The main levels and intervals of variation of the controlled factors were: the rotor speed n, 8.33-11.67 s^{-1} with an interval of 1.67 s^{-1}; the size of the gap between the movable and fixed pins δ, 0.015-0.025 m, with a variation interval of 0.005 m; the distance between the pins in a row (pin pitch f), 0.04-0.12 m, with a variation interval of 0.04 m.

Statistical processing of the results allowed us to obtain regression equations for:

- weighted average particle size (m)

$$s_a = 81.36497 - 0.066n - 753.309\delta - 522.197f + 1.255n\delta + 0.282nf + 2060.387f^2, \quad (5)$$

- specific energy consumption (kW)

$$q = 0.414 + 0.0139n + 175.82\delta - 28.215f - 0.33091n\delta + 198.2164f^2, \quad (6)$$

- level of material splitting (%)

$$R = -70.50 + 0.25n + 5114.8\delta + 757f - 0.375nf - 12083.3\delta f - 0.00019n2 - 103704\delta^2 - 2314.8f^2. \quad (7)$$

A graphical representation of the dependences of the average weighted particle size, specific energy consumption, and material splitting level is shown in Figures 4-6.

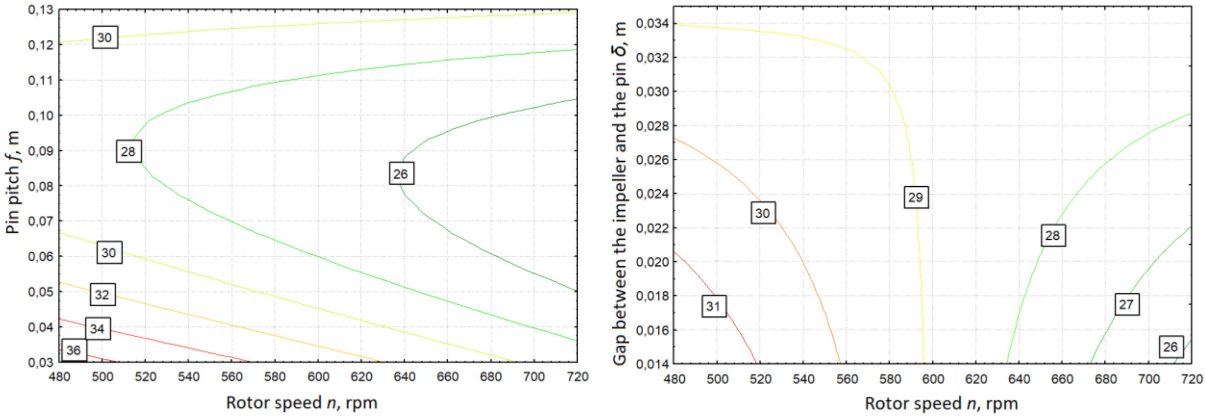

Fig. 4. **Dependence of the weighted average particle size s_a, mm, on the impeller rotation speed *n*, pin pitch *f*, and the gap between the impeller and pins δ**

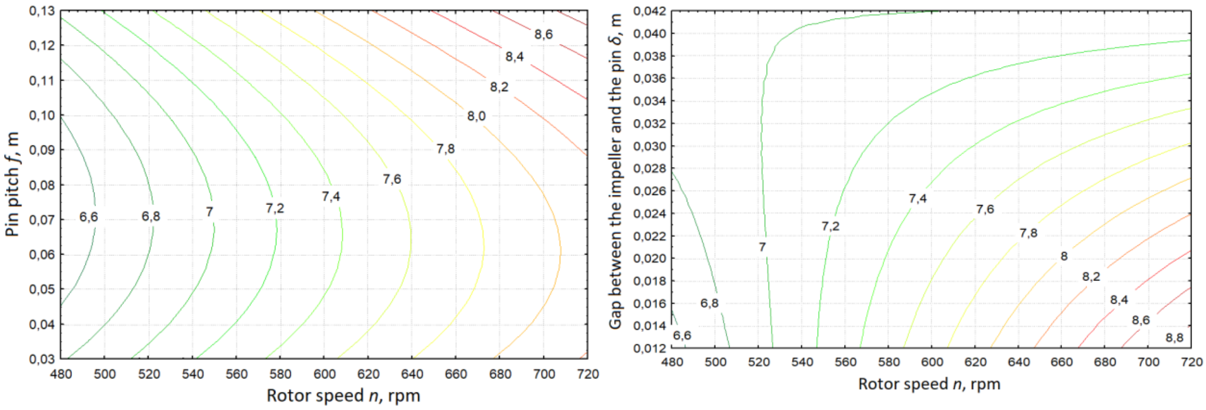

Fig. 5. **Dependence of the specific energy consumption *q*, kW on the impeller rotation speed *n*, pin pitch *f*, and the gap between the impeller and pins δ**

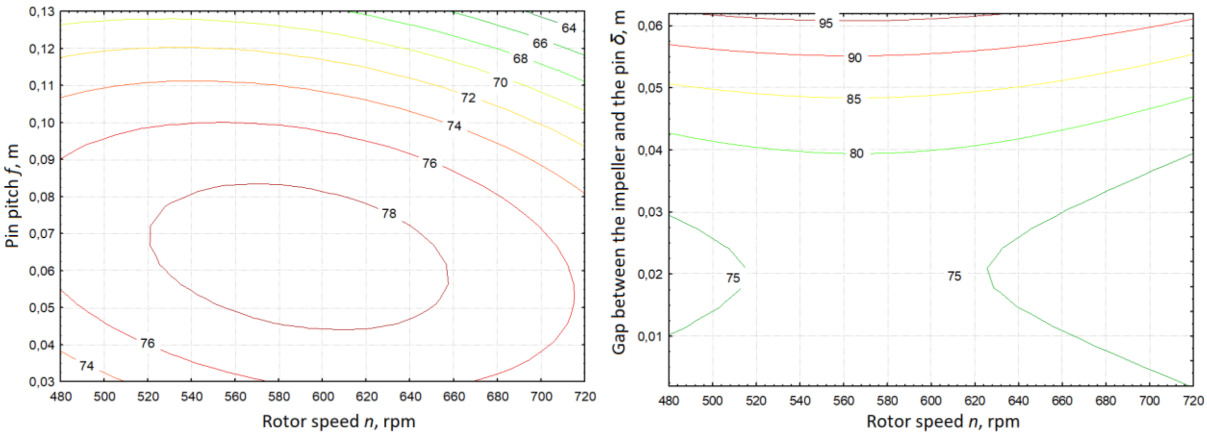

Fig. 6. **Dependence of the level of material splitting *R*, % on the blade rotation speed *n*, pin pitch *f*, and the gap between the blade and pins δ**

The analysis of the obtained characteristics of the shredding process shows that the quality and level of stem splitting depends on the rotation speed and tends to increase up to 10-11 s^{-1} (600-660 rpm), but with a further increase in the rotation speed of the impeller, the number of split particles decreases, which is due to an increase in the speed of particles passing through the shredder. As for the effect of the pin pitch, with an increase in the pin pitch, the splitting decreases, since the particles pass between the pins and do not interact with them. The gap between the pin and the edge of the impeller has the opposite effect, i.e. as the gap increases, the number of split particles decreases.

Regarding the effect of parameter changes on the level of energy consumption, it was found that an increase in the rotational speed and a decrease in the gap between the blade and the pins uniformly increases the specific energy consumption, but the pin spacing has an optimal range of 0.06-0.08 m.

Therefore, to ensure high quality of stem splitting with minimal energy consumption, the rational parameters of the combined chopper were determined: the rotor speed within 10 ± 0.5 s^{-1}, pin spacing 0.07 ± 0.01 m, and the gap between the blade and the pin 0.020 ± 0.005 m.

Conclusions

The developed machine has a disk-knife and pin chopper; their combination makes it possible to chop long-fiber raw materials into uniform particles and split them along the fibers, which leads to more efficient use of the fibers.

Experimental studies have confirmed the analytical choice of the rotor speed within 10 s^{-1}, the pin spacing of 0.07 m and the gap between the blade and the pin of 20 ± 5 mm. At the same time, the quality of stem splitting is 78%, and the total specific energy consumption is 7.35 kWh per ton of processed material.

Author contributions

Conceptualization, methodology, V.Kh. and V.R.; research, V.Kh., V.R., R.V. and S.P.; data curation, V.Kh. and S.P.; original writing, R.V.; reviewing and revising, R.V. and P.S. All authors have read and agreed with the published version of the manuscript.

References

[1] Velkommen til økologien. Kom godt fra start som ny økolog (Welcome to organic. Get off to a good start as a new organic farmer). Landbrug & Fødevarer F.m.b.A., SEGES. Danmark, 2019. (In Dutch) [online] [12.01.2024] Available at: https://www.landbrugsinfo.dk/-/media/landbrugsinfo/public/7/e/5/faktaark_okologi_kom_godt_fra_start.pdf
[2] Пирожок О. Хто в Україні виробляє справжню органічну продукцію. (Who produces real organic products in Ukraine.) Ekonomichna Pravda, 2019. (In Ukrainian) [online] [23.02.2024] Available at: https://www.epravda.com.ua/publications/2019/04/3/646613/
[3] Systèmes de production biologique Principes généraux et normes de gestion (Organic production systems General principles and management standards). CAN/CGSB32.310-2006. Remplace CAN/CGSB-32.310-99. Office des normes générales du Canada. Canadian General Standards Board. Norme nationale du Canada, 53. 2011 (In Franch) [online] [18.02.2024] Available at: https://ota.com·s^{-1}ites/default/files/indexed_files/COTA_FR_OrganicProductionSystemsPrinciplesMgmt.pdf
[4] Khmelovskyi V., Rogach S., Tonkha O., Rosamaha Y. Quality evaluation of mixing fodder by mobile combined units. Engineering for Rural Development, 2019. vol. 19. pp. 299-304. [online] [23.02.2024] Available at: https://www.tf.llu.lv/conference/proceedings2019/Papers/N468.pdf
[5] Small Pallmann Disc Chipper, Disc Chipper PHS [online] [23.02.2024] Available at: https://www.pallmann.eu/fileadmin/user_upload/Pallmann_Disc_Chipper.pdf
[6] Sridhar N., Surendrakumar A. Performance evaluation of rotary and flail shredders. International Journal of Agricultural Engineering Vol. 11 Issue 1, April, 2018 pp. 23-29. DOI:10.15740/HAS/IJAE/11.1/23-29
[7] Myhailovych Y., Potapova S., Achkevych O., Achkevych V. Increasing efficiency of grinding process in single-roller grain mill. Engineering for Rural Development, 2021, 20, pp. 712–717. [online] [23.02.2024] Available at: https://doi.org/10.22616/ERDev.2021.20.TF156.
[8] Revenko I., Revenko Yu. Quality of preparation and efficiency of utilization of concentrated and combined forages/Motrol. Commission of Motorization andnergetics in Agriculture. – 2013. - Vol. 15. No 3. 356-361
[9] Astanakulov K., Gapparov Sh., Karshiev F., Makhsumkhonova A., Khudaynazarov D. Study on preparation and distribution of forage by chopping coarse fodder. IOP Conference Series: Earth and

Environmental Science, Volume 614, 2020 [online] [23.02.2024] Available at: https://iopscience.iop.org/article/10.1088/1755-1315/614/1/012158

[10] Gapparov Sh., Karshiev F. Development chopper device that chops baled rough fodders. IOP Conference Series: Materials Science and Engineering, Volume 883, 2020. [online] [23.02.2024] Available at: https://iopscience.iop.org/article/10.1088/1757-899X/883/1/012158

[11] Cheng Q., Wang J., Liu K., Chao J., Liu D. Design of Rice Straw Fiber Crusher and Evaluation of Fiber Quality. 2022. Agriculture 12(5):729. [online] [23.02.2024] Available at: https://www.researchgate.net/publication/360776032_Design_of_Rice_Straw_Fiber_Crusher_and_Evaluation_of_Fiber_Quality

[12] Anjum A., Ghafoor A., Munir A., Iqbal M., Ahmad M. Design modification of conventional wheat straw chopper. Agricultural Engineering International: CIGR Journal, 2015, Vol. 17, No. 1, 50-58 [online] [23.02.2024] Available at: https://www.cabidigitallibrary.org/doi/full/10.5555/20153150121

[13] Bratishko V., Milko D., Kuzmenko V., Achkevych O. Results of experimental studies of stem raw material chopper. Engineering for Rural Development, 2021, 20, pp. 797–803. DOI: 10.22616/ERDev.2021.20.TF180

[14] Tavakoli H., Mohtasebi S., Jafari A., Mahdavinejad D. Power requirement for particle size reduction of wheat straw as a function of straw threshing unit parameters. Australian journal of crop science, 2009. [online] [23.02.2024] Available at: https://search.informit.org/doi/abs/10.3316/INFORMIT.037770014354392

[15] Maiviatov F., Karshiev F., Gapparov Sh. Movement of crushed stem particles when they interact with hammers IOP Conference Series: Earth and Environmental Science, 2021, Volume 868. [online] [23.02.2024] Available at: https://iopscience.iop.org/article/10.1088/1755-1315/868/1/012060

[16] Kruszelnicka, W., Tomporowski, A., Flizikowski J., and Kasner R. Control and monitoring of multi-disc comminution process. Journal of Physics: Conference Series, Vol. 1426, International Conference on Applied Sciences 9–11 May 2019, Hunedoara, Romania. DOI:10.1088/1742-6596/1426/1/012006

[17] Popa R., Popa V. Computer assisted simulation of forage chopping process. "Engineering for Rural Development". Volume 18, 2019, Jelgava, Latvia, pp. 1118-1122. [online] [23.02.2024] Available at: https://journals.indexcopernicus.com/api/file/viewByFileId/644696.pdf

[18] Novitskiy A., Banniy O., Novitskyi Yu. Logical-probabilistic model of the reliability of means for preparing and distributing fodder. Machinery & Energetics, 2023, 14(1). [online] [23.02.2024] Available at: https://technicalscience.com.ua/uk/journals/t-14-1-2023/logiko-imovirnisna-modyel-otsinki-nadiynosti-zasobiv-dlya-prigotuvannya-i-rozdavannya-kormiv