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Improving the quality of feed by optimizing the structural and kinematic parameters of a straw crushing machine

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Abstract. The article presents theoretical and experimental research results on the parameters of a semi-conical straw shredder. During operation, the straw is fed to the knife through a chute and guide. The incoming straw is cut by a counter-knife and then shredded within the body or shredding chamber with the help of the knife and counter-knives. The flat rotor knife captures the straw entering the shredding chamber, directs it toward the counter-knife, and it is cut between them. During shredding, the straw undergoes bending, tearing, and cutting. The shredded straw moves toward the outlet funnel under the influence of the airflow generated by the rotation of the flat rotor knife, exiting and forming a pile. The study examines the rotation frequency of the shredding drum, the diameters of the drum, the shape of the knives, the number of knives on the flat disk of the drum, the inclination angle of the cutting edge, the sharpness angle, and both theoretical and experimental results of the shredding drum. The results of the study contribute to increasing the nutritional value of straw, reducing losses, and ensuring energy efficiency in the feed preparation process.

INTRODUCTION

Straw is one of the most widespread agricultural by-products and plays a significant role as feed in livestock production. However, its rigid structure and low digestibility limit its nutritional value for animals, making mechanical processing-such as grinding or chopping-essential to improve its digestibility and uniformity. Mini-grinders are widely used in small and medium-sized farms because they are energy-efficient, effective, and adaptable to different types of straw. The operational efficiency of a mini-grinder is directly influenced by its structural and technological parameters, including drum diameter, rotational speed, number and length of blades, and blade inclination angle. Previous studies often focused on individual parameters, while a comprehensive approach considering all factors simultaneously is necessary. The aim of this study is to determine the optimal parameters for improving straw grinding efficiency and to develop a new mini-grinder design, which will enhance feed quality and promote resource-efficient practices in livestock farming.

EXPERIMENTAL RESEARCH

The quality of feed prepared from straw can be improved by optimizing the grinding process, i.e., cutting straw in feed preparation machines. This enhancement leads to better nutritional properties of the straw, reduces losses, and conserves material resources. To ensure improved quality of straw from cereal crops, we developed a shredder with a conical working element featuring a backward-inclined blade [1, 4, 6-40].

According to researchers, the material is primarily destroyed by the cutting edge of the blade, while the bevel surfaces of the edge perform a secondary, sometimes even detrimental, role by pushing apart the cut straw. At the same time, some studies have demonstrated the significant role of the bevel in the process of cutting straw with a knife, which makes this process similar to wood cutting using a chisel.

To date, drum-type and hammer-type impact-abrasive shredders have been studied. However, the blade inclination angle of the working element in a straw shredder performing an oblique cutting action has not yet been investigated.

As is known, the cutting speed of the knife is necessary, and consequently the power, to ensure sliding cutting at the moment of cutting cereal crop stems [2, 7, 8]. Since the sliding of straw along the blade at the moment of cutting is largely determined by the angle (β) of the knife blade relative to the radius of the working element, let us consider the dependence of the cutting process on the value of this angle (Fig. 1).

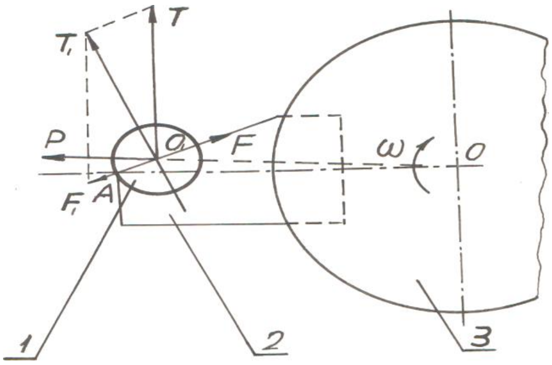


FIGURE 1. Diagram for determining the inclination angle of the knife blade of the working element. 1 – straw, 2 – knife, 3 – rotor.

The straw is subjected to centrifugal force:

$$P = \frac{m*V^2}{R} \tag{1}$$

where: m– mass of the cut part of the straw, reduced to the cutting plane, g; V –tangential (circumferential) speed of the straw in the cutting plane, m/s; R –distance from the straw axis to the axis of rotation of the working organ, m.

Using the cone theorem, from ΔOO_1A we find:

$$R = \sqrt{R_p + \frac{d_{cм}^2}{4} * cos^2 \propto_н - R_p * d_{cm} * cos \propto_н * cos\beta} \tag{2}$$

where: R_p – rotor radius, mm; $d_{cм}$- diameter of the straw, m; $\propto_н$– angle of straw feed, degrees.

After transformation, we obtain

$$P = \frac{m*V^2}{\sqrt{R_p + \frac{d_{cm}^2}{4} * cos^2 \propto_н - R_p * d_{cm} * cos \propto_н * cos\beta}}. \tag{3}$$

And so, the inertia force

$$T = ma, \tag{4}$$

where a is the tangential component of the straw's acceleration in the cutting plane, m/s².

According to the accepted assumption

$$a = \frac{V}{\Delta t} \tag{5}$$

At the same time, the sliding of the straw along the knife blade is resisted by the force of friction.

$$F = f * N, \tag{6}$$

where f-is the coefficient of friction of the straw on the blade, and N- is the normal pressure of the straw on the blades, in newtons (N).

Since at high peripheral speeds of the knife the bending of the straw is small, its elastic resistance is also negligible, and we will not take it into account [3, 9, 10].

Then, according to the above assumption, we determine the condition for the straw to slide along the knife. In this case, the sum of the projections of all forces responsible for cutting the straw must be greater than the friction force [11, 12, 13]. For a blade with a backward inclination, this condition is expressed by an inequality.

$$\frac{mV}{\Delta t} * sin\beta + \frac{2mV^2}{\sqrt{4R_p^2 + d_{cм}^2 * cos^2 \propto_н - 4R_p * d_{cм} * cos\propto_н * cos\beta}} > f(\frac{mV}{\Delta t} * cos\beta - \frac{2mV^2}{\sqrt{4R_p^2 + d_{cм}^2 * cos^2 \propto_н - 4R_p * d_{cm} * cos\propto_н * cos\beta}} \tag{7}$$

After the transformations, we obtain:

$$\frac{1}{4} * d_{\text{см}}^2 * cos^2 \propto_{\text{н}} - R_p * d_{cm} * cos\beta * cos \propto_{\text{н}} + R_p^2 - \Delta t^2 * V^2 * ctg(\beta - V) < 0 \quad (8)$$

We denote $x_1 = \Delta tV$ —the displacement of the straw during the cutting process, in mm.

Then, solving inequality (8) with respect to β, we obtain:

$$\beta < -arcctg \frac{\sqrt{d_{\text{СМ}}^2 * cos^2 \propto_{\text{н}} - 4R_p * d_{\text{СМ}} * co\beta * cos\propto_{\text{н}} + 4R_p^2}}{2X_1} \quad (9)$$

Expression (9) defines the dependence of the blade inclination angle (β) of the working organ knife of the straw chopper on other factors during the straw cutting process [4]. Calculations show that for R_p=0,13...0,19 m, X_1= 0,5...2 mm, φ =24...30^0, $\propto_{\text{н}} = 0 \dots 20^0$, $d_{\text{см}}$ =3...7 mm the inclination angle of the chopper knife blade lies within β =0...38^0.

Based on the theoretical research, a straw chopper with a semi-conical working organ was developed (Fig. 2).

FIGURE 2. Straw chopper with a semi-conical working organ

RESEARCH RESULTS

From this, the rotation frequency of the chopping drum, the drum diameter, and other parameters were studied. The results of the experimental research showed that increasing the rotation frequency of the chopping drum from 500 rad/min to 900 rad/min, with intervals of 100 rad/min, affects the quality of straw chopping (Table 1).

The following parameters were adopted: diameter of the chopping drum – 550 mm; number of knives on the disk – 3; knife length – 100 mm; knife blade tilt angle – 38°; and knife sharpness angle.

According to zootechnical requirements, the fractions of chopped straw should be as follows: straw length up to 30 mm – 10%, straw length 30–50 mm – 80%, and straw length over 50 mm – 10%.

When the rotation frequency of the chopping drum was increased to 800 rad/min, the fraction of straw up to 30 mm increased by 1.8%, then decreased to 0.7%. For straw of 30–50 mm, the chopping quality increased by 3.3% and later decreased to 0.6%. For straw longer than 50 mm, the chopping quality decreased by 4% and then increased to 0.4%.

TABLE 1. The effect of the quality of shredding straw on the frequency of rotation of the shredding drum

Chopped straw fraction	**Rotational speed of the grinding drum, rad/min**				
	500	600	700	800	900
Length of straw up to 30 mm (%)	6,3	6,7	7,1	8,1	7,4
Length of straw 30–50 mm (%)	82,4	83,2	84,5	85,7	85,1
Length of straw over 50 mm (%)	7,8	6,5	5,2	3,8	4,2

Thus, the optimal rotational speed of the grinding drum is 800 rad/min. It can be seen that with an increase in the drum diameter from 400 mm to 600 mm with an interval of 50 mm, the quality of straw grinding changes (Table 2).

At this, the adopted rotational speed of the grinding drum is 800 rad/min. For a drum diameter of 500 mm and straw length up to 30 mm, the grinding quality of straw decreased by 0.6%, then increased up to 1.2%. Also, for a drum diameter of 550 mm and straw length of 30–50 mm, the grinding quality increased up to 5.3%, then decreased by 1.2%. Additionally, for a drum diameter of 600 mm and straw length over 50 mm, the grinding quality decreased by 2.9%.

TABLE 2. The dependence of the quality of shredding straw on the diameter of the shredding drum

Chopped straw fraction	**Diameter of the grinding drum, mm**				
	400	450	500	550	600
Length of straw up to 30 mm (%)	7,5	7,2	6,9	7,3	8,1
Length of straw 30–50 mm (%)	78,5	80,3	82,3	83,8	81,3
Length of straw over 50 mm (%)	7,5	7,1	6,4	4,9	4,6

Thus, the optimal diameter of the grinding drum is 550 mm. It can be seen that as the diameter of the grinding drum increases from 400 mm to 600 mm in increments of 50 mm, the quality of straw grinding changes (Table 3). For these tests, the rotational speed of the grinding drum was set at 800 rad/min. With a drum diameter of 500 mm and straw length of 30 mm, the grinding quality initially decreased by 0.6% and then increased to 1.2%. With a drum diameter of 550 mm and straw length of 30–50 mm, the grinding quality increased up to 5.3% and then decreased by 1.2%. With a drum diameter of 600 mm and straw length greater than 50 mm, the grinding quality decreased by 2.9%.

TABLE 3. The dependence of the quality of shredding straw on the diameter of the shredding drum.

Chopped straw fraction	**Diameter of the grinding drum, mm**				
	400	450	500	550	600
Length of straw up to 30 mm (%)	7,5	7,2	6,9	7,3	8,1
Length of straw 30–50 mm (%)	78,5	80,3	82,3	83,8	81,3
Length of straw over 50 mm (%)	7,5	7,1	6,4	4,9	4,6

Thus, the optimal diameter of the grinding drum is 550 mm. It can be seen that with an increase in the number of blades on the disk from 2 to 6 with an interval of 1 blade, the quality of straw grinding changes (Table 4).

When the number of blades on the disk is 6 and the straw length is 30 mm, the quality of straw grinding decreased by 2.4%. Similarly, when the number of blades on the disk is 5 and the straw length is 30–50 mm, the quality of grinding increased by 3.0%, then decreased to 0.3%. When the number of blades on the disk is 6 and the straw length is greater than 50 mm, the grinding quality increased up to 2.6%.

TABLE 4. Dependence of straw grinding quality on the number of blades on the disks

Chopped straw fraction	**Number of knives on the discs, pcs**				
	2	3	4	5	6
Length of straw up to 30 mm (%)	4,1	3,6	3,1	1,9	1,7
Length of straw 30–50 mm (%)	79,2	80,4	81,2	82,2	81,9
Length of straw over 50 mm (%)	2,3	2,7	3,8	4,1	4,9

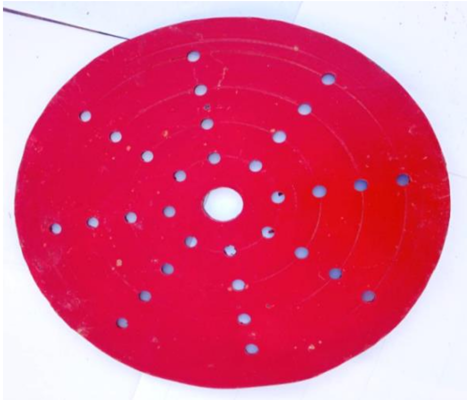
Thus, the optimal number of knives on the disks is 6. It can be seen that as the knife length increases from 70 mm to 110 mm in 10 mm increments, the quality of straw shredding changes (Table 5).

TABLE 5. Dependence of straw chopping quality on knife length

Chopped straw fraction	**Knife length, mm**				
	70	80	90	100	110
Length of straw up to 30 mm (%)	2,4	2,9	3,4	3,9	3,5
Length of straw 30–50 mm (%)	71,4	74,6	77,1	79,6	78,4
Length of straw over 50 mm (%)	2,7	3,4	4,1	4,8	5,3

In addition, experimental variants of knife length and a flat rotating rotor have been developed (Fig. 3).

a)



b)

FIGURE 3. The main parts of a straw chopper. a) knife lengths (1) 160 mm; 2) 170 mm; 3) 180 mm); b) flat rotating rotor

The knife length of 100 mm and straw length up to 30 mm increased the chopping quality of the straw by 1.5%, then decreased by 0.4%. For straw length of 30–50 mm, the chopping quality increased by 8.2% and then decreased to 1.2%. With a knife length of 110 mm and straw length over 50 mm, the chopping quality increased up to 2.6%.

Thus, the optimal knife length is 100 mm. Next, the following design parameters were adopted: knife blade angle – 35°, spacing between the flat rotating rotors – 45–55 mm, and diameter of the flat rotating rotor – 230 mm.

CONCLUSIONS

This study focused on improving the quality of feed from cereal straw by optimizing the chopping process. A new type of straw chopper with a conical working element and a backward-angled knife was developed. It was found that the optimal knife inclination angle (β) ranges from 0° to 38°, and that the drum diameter, rotational speed, number of knives, and knife length significantly affect the quality of straw chopping.

Experimental results showed that the optimal technological parameters are: drum diameter – 550 mm, rotational speed – 800 rad/min, number of knives – 6, and knife length – 100 mm. These parameters allow more than 80% of straw to be chopped into the 30–50 mm fraction, which meets zootechnical requirements for feed preparation.

The study demonstrated that the new chopper design reduces energy consumption, minimizes losses, and increases efficiency in feed preparation. Moreover, controlling the straw fraction and knife parameters helps maintain the nutritional value of the feed at a high level.

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