WORKING MECHANISM ANALYSIS AND EXPERIMENTAL STUDY OF GRASS CRUSHER
/
牧草粉碎机工作机理分析与试验研究

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ABSTRACT
In order to clarify the working mechanism of forage crusher, the combined cutting and crushing forage crusher was taken as the research object, the mechanical analysis was carried out on the cutting and crushing process of alfalfa stalk, the dynamic model was established, and the relationship between the shear force and the relevant parameters of the cutting mechanism was defined. It was found that the cutting Angle, the installation Angle and the wedge Angle had important effects on the cutting effect and power consumption. The force of alfalfa stem in the grinding chamber is mainly related to the speed of the grinding shaft, the gap between the hammer and the rolling plate. With the output speed of motor, feeding amount, screen diameter and water content as test factors, productivity, silking rate, power consumption and average crushing length as evaluation indicators, the single factor test was carried out to determine the influence of each test factor on the evaluation indicators. The research results can provide reference for the optimization design of grass crusher.

摘要
为明确牧草粉碎机工作机理，以切割粉碎组合式牧草粉碎机为研究对象，对苜蓿茎秆切割和粉碎过程进行了力学分析，建立了动力学模型，明确了剪切力与切割机构相关参数的关系，得到动刀遇角、安装后角和楔角对切割效果和功耗具有重要影响；苜蓿茎秆在粉碎室内受力主要与粉碎轴转速、锤片和揉搓板间隙有关。以电机输出转速、喂入量、筛孔直径、含水率为试验因素，生产率、丝化率、功耗、平均粉碎长度为评价指标，进行了单因素试验，确定了各试验因素对评价指标的影响规律，研究结果可为牧草粉碎机的优化设计提供参考。

INTRODUCTION
Animal husbandry is an important part of agriculture and plays an important role in the national economy of our country *(Zhang et al., 2021; Jiang et al., 2019)*. The production and supply of forage is the basis of the development of animal husbandry, which affects the scale and speed of animal husbandry development. China's grass planting area is close to 15 million mu, accounting for 8.2% of the arable land. The total annual output of forage is 90 billion kg, and the total output value is 12 billion US dollars *(Chen et al., 2023; Wu et al., 2022; Wu et al., 2018)*.

Grass processing can be divided into cutting processing, crushing processing and kneading processing according to the crushing form *(Wang et al., 2021; Zhao et al., 2019; Xu et al., 2020)*. The corresponding models are cutting mill, hammer mill and so on. The cutting mill breaks the grass by cutting, but the broken grass after processing is mostly round stem, and there are hard joints, which will lead to indigestion and palatability of livestock, which is not conducive to digestion and absorption of livestock *(Li, 2023; Wang et al., 2024; Liu et al., 2019)*.

The hammer mill first pulverizes the grass to a certain extent through the impact of the hammer, and then throws the grass at a faster speed to the kneading board and the sieve plate in the crushing room, and is further crushed by the collision of the kneading board and the rubbing of the sieve plate, which has high crushing efficiency and wide adaptability *(Ma et al., 2016; Wang et al., 2017; Liu et al., 2011)*.

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Because the forage with high water content has strong toughness, the force required when it is broken by blows and other effects is greater, and the whole forage is easy to wind the rotor when it is crushed, resulting in blockage *(Fan et al., 2021; Wang et al., 2021; Jia et al., 2014)*. Therefore, the existing grinder still has some problems, such as low efficiency, poor crushing quality, and not being suitable for forage with large water content.

To solve the above problems, our team designed a cutting and crushing combined grass crusher, which preprocessed the grass before crushing, and cut it into small segments of a certain length by cutting. However, its working mechanism is not clear. This study conducted a theoretical analysis of the cutting and crushing process, explored the crushing mechanism of the crusher on grass, identified the factors influencing crushing quality, and performed an experimental study using these factors to analyze their impact on the crushing effect.

MATERIALS AND METHODS

Structure and working principle

Cutting and crushing cooperative grass kneading machine is mainly composed of feeding conveyor belt, conveyor chain plate, feeding mechanism, screening mechanism, kneading mechanism, cutting mechanism and other parts. The structure is shown in Fig. 1.

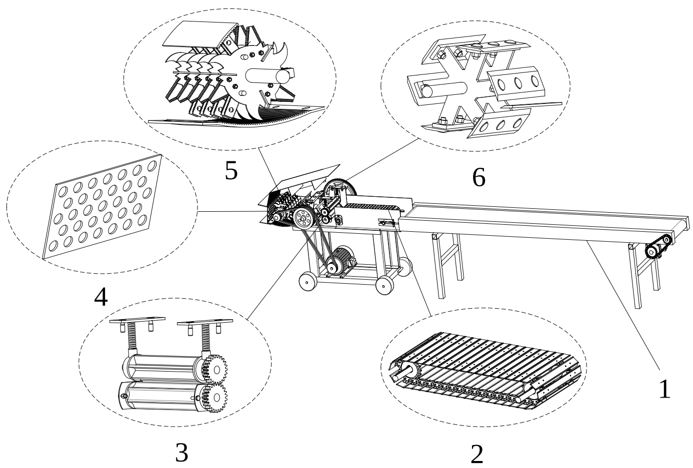


Fig.1 – Structural diagram of cutting and crushing cooperative forage kneader
1. Feeding conveyor belt; 2. Conveyor chain plate; 3. Feeding mechanism;
4. Screening mechanism; 5. Kneading mechanism; 6. Cutting mechanism

The kneading operation is mainly divided into the following stages: feeding stage, the whole grass is transported to the conveyor chain plate through the feeding conveyor belt, and the grass enters the cutting chamber by rotation of the feed roller. In the cutting stage, the grass is cut into a certain length under the shearing action of the rotating motion of the grass knife and the fixed knife, and the cut grass is pushed to the kneading chamber under the rotation of the grass knife. In the kneading stage, the grass section is broken into filaments under the synergistic action of the hammer and serrated knife, the kneading and tearing between the hammer and serrated knife and the kneading tooth plate, the impact and friction between the sieve plate, etc.

In the screening and sending stage, the broken grass that meets the kneading length is thrown to the outside of the kneading machine through the screen plate under the combined action of the air flow generated by the rotation of the kneading rotor and the centrifugal force. The broken grass that is larger than the kneading length needs is kneaded in the kneading chamber for the next time, and further broken through the same crushing method as the last kneading until the length meets the kneading demand.

Mechanical analysis of cutting process

The cutting process is realized by the combination of cutting knife and fixed knife, and the shear force generated on the stem and the thrust generated by the feed roller act on the stem together *(Wu et al., 2022; Jiang et al., 2019; Wu et al., 2018)*. In order to facilitate the force analysis of the whole system, the following assumptions are made: the shape of alfalfa stalk is cylinder, the whole organization is uniform and continuous; the shear of the stem is balanced at every moment; the force analysis is based on a single shear. Consider alfalfa layer as a whole; the compression and deformation of the feeding roller on alfalfa were ignored.

The stress of alfalfa stem and tool in the cutting process was analyzed, as shown in Fig. 2.

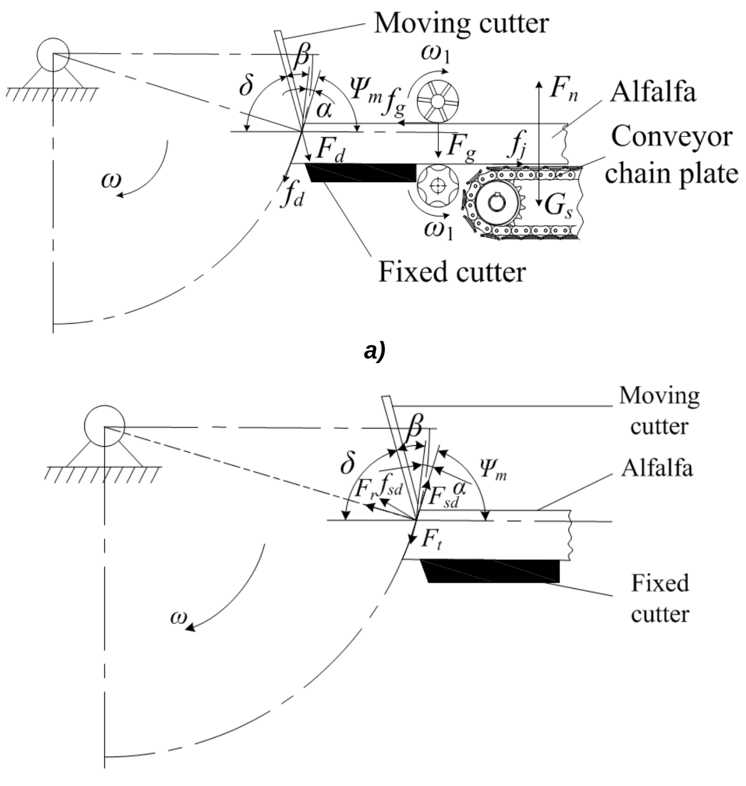


Fig. 2 – Force analysis of the chopping mechanism

a) Stress analysis of alfalfa stalk cutting process; b) Force analysis of the knife

In the process of cutting, the main forces on the stalk are: (1) the positive pressure F_d of the knife facing the stalk, the direction is perpendicular to the knife face down; (2) the friction force f_d of the knife facing the stalk, the direction is consistent with the direction of the knife movement; (3) the supporting force F_n of the feed tank and the fixed tool on the stalk, the direction is always perpendicular to the bottom surface of the feed tank and the fixed tool; (4) the direction of the pressure F_g and friction force f_g of the feeding roller on the stalk are vertically downward and consistent with the direction of the stalk feed, respectively; (5) the direction of gravity G_s on the stalk and friction f_j on the bottom of the feed tank facing the stalk are vertical downward and opposite to the direction of feed, respectively; (6) the tool is subjected to the force F_t and F_r provided by the cutting shaft, and the directions are respectively the tangential direction and the center direction of the tool moving path; (7) the tool is subjected to the friction F_{sd} of the stalk, and the direction is opposite to the direction of the knife movement; (8) the tool is subject to the supporting force f_{sd} provided by the stalk, and the direction is perpendicular to the tool face.

According to the horizontal force balance of alfalfa stalk, it can be obtained:

$$F_d \sin\delta = f_g + f_j + f_d \cos\delta \tag{1}$$

From the vertical force balance of the stem, it can be obtained:

$$F_d \cos\delta + G_s + F_g + f_d \sin\delta = F_n \tag{2}$$

With the cutting edge of the knife as the fulcrum, the moment of the stalk is balanced:

$$F_g L_1 + G_s L_3 + f_g (f - H_m) = F_n L_2 + f_j H_m \tag{3}$$

The horizontal component of F_d under the positive pressure of the blade facing the stalk is:

$$F_{d2} = f_g + f_j + f_d \cos\delta \tag{4}$$

The vertical component of F_d under the positive pressure of the blade facing the stalk is:

$$F_{d1} = F_n - G_s - f_d \sin\delta \tag{5}$$

The encounter angle of knife is:

$$\psi_m = 90^o - \sigma \tag{6}$$

The angle between the back cutter face and the horizontal direction is:

$$\delta = 180^o - \alpha - \beta - \psi_m \tag{7}$$

The shear force of cutting action on the stalk causing the stalk to break is:

$$\tau_s = \frac{F_n - G_s - F_g - f_d \sin(180^o - \alpha - \beta - \psi_m)}{S} \tag{8}$$

where: S is cross-sectional area of alfalfa stalk, m²; α is installation rear angle of the tool, (°); β is wedge angle of the knife, (°); ψ_m is knife angle, (°); H_m is vertical distance from any point on the knife path to the bottom of the feed tank, mm; L_1 is horizontal distance between the feed roll and the tool, mm; L_2 is the horizontal distance between the center of gravity of the alfalfa stem and the tool, mm.

Mechanical analysis of crushing process

Smashing process

The force analysis of alfalfa stem in the attack and breaking process is shown in Fig.3.

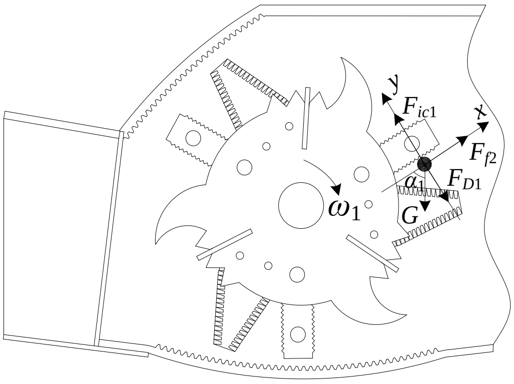


Fig. 3 – Force analysis of alfalfa stem during crushing

Alfalfa stems are mainly subjected to the combined action of four forces, namely gravity G, the striking force F_{D1} of the hammer on the alfalfa stalk, the friction force F_{f1} of the hammer on the alfalfa stalk and the Coriolis inertia force F_{ic1} of the alfalfa stalk. The center of the stalk is regarded as the center of mass, and all external forces act on the center of mass.

According to D 'Alembert's principle, the balance equation of the impact force on alfalfa stalk can be obtained as follows:

$$\begin{cases} \sum F_x = 0, \quad F_{f1} - G\cos\alpha_1 = 0 \\ \sum F_y = 0, \quad F_{D1} - G\sin\alpha_1 - F_{ic1} = 0 \end{cases} \tag{9}$$

where:

$$\begin{cases} F_{f1} = \mu m_1 g \sin\alpha_1 \\ F_{ic1} = -m_1 a_c = -2m\omega_e v_{r1} \end{cases} \tag{10}$$

By combining equations (9) and (10), the following is obtained:

$$F_{D1} = 2m_1\omega_e v_{r1} - m_1 g \sin\alpha_1 \tag{11}$$

where: F_{D1} is striking force of alfalfa stalk by hammer, N; G is alfalfa stem gravity, N; m_1 is alfalfa stalk mass, kg; F_{f2} is the friction force of alfalfa stem against the hammer, N; F_{ic1} is Coriolis inertia force, N; μ_1 is friction coefficient between alfalfa stem and sieve plate; ω_1 is angular velocity of the rotor, rad/s; v_{r1} is linear velocity at the end of the hammer, m/s; α_1 is the angle between alfalfa stem gravity and the X-axis, (°).

According to Formula (11), when the internal structure of the kneading machine remains unchanged, the impact force F_{D1} of the alfalfa stem under the hammer is mainly affected by the angular velocity ω of the kneading rotor and the linear velocity v_{r1} of the hammer end. The greater the angular velocity of the kneading rotor ω_1 and the linear velocity of the end of the hammer piece v_{r1}, the greater the impact force on the alfalfa stalk, and the change of the two sizes depends on the change of the speed of the crushing shaft.

Impact crushing

The force analysis of alfalfa stems during impact crushing is shown in Fig. 4.

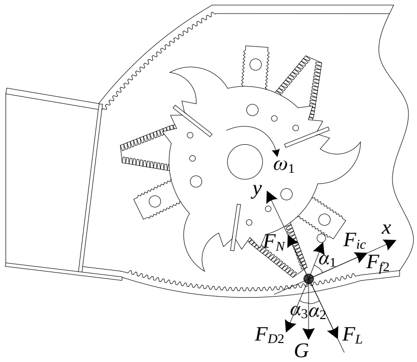


Fig.4 – Force analysis of alfalfa stem impact crushing process

According to D 'Alembert's principle, the equilibrium equation of the impact force on alfalfa stalk can be obtained:

$$\begin{cases} \sum F_x = 0, \quad F_{D2}\sin(\alpha_2+\alpha_3) - F_{ic2}\cos\alpha_4 - F_{f2} = 0 \\ \sum F_y = 0, \quad F_L + G\cos\alpha_2 + F_{D2}\cos(\alpha_2+\alpha_3) - F_N - F_{ic2}\sin\alpha_4 = 0 \end{cases} \tag{12}$$

where:

$$\begin{cases} F_{ic2} = -2m_2\omega_{e1}v_{r1} \\ F_{f2} = \mu_2 \dfrac{m_2 g}{\cos\alpha_2} \\ F_L = m_2 \dfrac{n^2}{r_1} \end{cases} \tag{13}$$

By combining equations (12) and (13) the following is obtained:

$$F_{D2} = \frac{(2\omega_{e1}v_{r1}\sin\alpha_4 - n^2)\cos\alpha_2 - r_1 g(1-\cos\alpha_2)}{\cos(\alpha_2+\alpha_3)} \tag{14}$$

where:

F_{D2} is impact force on alfalfa stem, N; F_{f1} is friction force on alfalfa stem kneading plate, N; F_{ic2} is Coriolis inertia force, N; F_L is centrifugal force on alfalfa stem, N; n is spindle speed, r/min; r_1 is distance between the center of mass of alfalfa stem and the center of rotor, m; μ_2 is friction coefficient between alfalfa stem and kneading plate; α_2 is the angle between alfalfa stem and impact force, (°); α_3 is the angle between the alfalfa stem and the impact force (°); α_4 is angle between Coriolis inertia force and X-axis, (°); g is acceleration of gravity, m/s^2.

Rubbing crushing

The force analysis of alfalfa stems during rubbing and crushing is shown in Fig. 5.

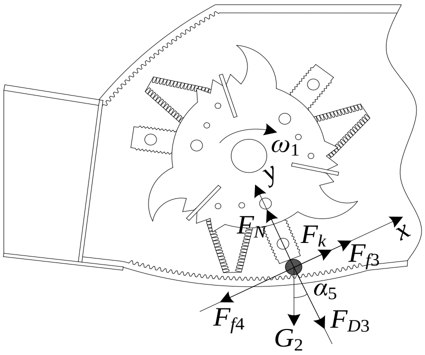


Fig. 5 – Stress analysis of alfalfa stem kneading and crushing process

According to the law of conservation of momentum:

$$Mv = Mv_1 + m_3 v_2 \tag{15}$$

$$\begin{cases} v = \dfrac{\pi n_1 D}{60} \\ v_1 = \dfrac{\pi n_2 D}{60} \end{cases} \tag{16}$$

By combining equations (15) and (16), it is obtained:

$$v_2 = \frac{\pi MD(n_1 - n_2)}{60 m_3} \tag{17}$$

where: M is weight of hammer, kg; v is linear velocity at the end of the hammer, m/s; v_1 is velocity after the hammer hits the alfalfa stalk, m/s; v_2 is alfalfa stalk speed after being hit, m/s; n_1 is rotational speed before the hammer hits the alfalfa stalk, r/min; n_2 is rotational speed after the hammer hits the alfalfa stalk, r/min.

According to D 'Alembert's principle, the balance equation of kneading-force on alfalfa stems can be obtained as follows:

$$\begin{cases} \sum F_x = 0, \quad G\sin\alpha_5 + F_{f4} - F_k - F_{f3} = 0 \\ \sum F_y = 0, \quad F_{D3} + G\cos\alpha_5 - F_{ic3=0} \end{cases} \tag{18}$$

where:

$$\begin{cases} F_{f3} = \mu F_{D3} \\ F_{f4} = \mu m \dfrac{v^2}{D+\delta} = \mu \dfrac{m^2 \pi^2 D^2 (n_1 - n_2)^2}{3600(D+\delta)} \\ F_{ic3} = 2m\omega v_r \\ F_k = \dfrac{1}{2} C\rho S v_{r2} \end{cases} \tag{19}$$

By combining equations (18) and (19), it is obtained:

$$F_{D3} = \mu_2 \frac{M^2 \pi^2 D^2 (n_1 - n_2)^2}{3600 m (D+\delta)} \tag{20}$$

where: F_{D3} is kneading force on alfalfa stem, N; F_{f3} is friction of the end of the hammer against alfalfa stalk, N; F_{f4} is friction of kneading board on alfalfa stalk, N; F_k is air resistance, N; F_{ic3} is Coriolis inertia force, N; δ is hammer plate clearance, m; C is air resistance coefficient; ρ is air density, kg/m^3; S is alfalfa stem windward area, m$_2$; v_{r2} is relative velocity of material to air, m/s

According to formula (20), the extrusion rubbing force on alfalfa stems is mainly affected by the rotational speed n_1 before the hammer hits the alfalfa stalk, the rotational speed n_2 after the hammer hits the alfalfa stalk, rotor diameter D, and the gap δ between the hammer and the kneading board.

It can be seen from the above analysis that the main factors affecting the kneading effect of alfalfa stem in the kneading room are the rotating speed of the kneading shaft and the gap between the hammer and the kneading board.

RESULTS AND DISCUSSIONS

The performance test of the designed crusher was carried out. Alfalfa was processed and collected in Duerbert County, Daqing City, Heilongjiang Province. The collected alfalfa was cut in full field at the bud stage, and there was no obvious mechanical damage. The average density of alfalfa was 996 kg/m^3 after many measurements and calculations. The experiment was conducted in the crop harvesting Laboratory of Heilongjiang Bayi Agricultural University, and the test site was shown in Fig. 6.

Fig. 6 –Test Site

1. Power consumption test device; 2. Crusher; 3. Feeding conveyor belt

According to the theoretical analysis results and in order to check the grinding effect of the machine on high water content alfalfa, productivity, silking rate, average crushing length and power consumption were selected as performance indexes, and a single factor test was carried out with motor rotation speed, screen diameter, feeding amount and water content as test factors. Alfalfa with required moisture content was obtained by natural drying. The evaluation indexes were calculated as follows:

Productivity

Feed the weighed alfalfa, record the feeding test time, weigh the output sample quality, and calculate the productivity:

$$y_1 = \frac{m}{t} \times 3600 \tag{21}$$

where: m is quality of alfalfa for testing; t is test time, s.

The test time t is short. In order to meet the test accuracy, the working time of this test is obtained from the data analysis of the torque-time curve of DYN-200 torque sensor.

Silk rates

Samples were collected at the outlet, at the same time interval for 3 times, each time no less than 200 g. All samples were mixed and weighed. Qualified alfalfa silk was screened and weighed, and its silk rate was calculated as:

$$y_2 = \frac{m_1}{m_0} \times 100\% \tag{22}$$

where: m_1 is quality of alfalfa silk in the sample, g; m_0 is alfalfa sample quality, g.

Average crushing length

By weighing 500 g samples of broken materials for measurement and classification: below 30 mm, 30~40 mm, 40~50 mm, 50~60 mm, 60~70 mm, 70~80 mm and above 80 mm, the average length of broken stems and the corresponding mass mi between each grade are measured, weighed and measured 3 times, and the average value is taken. The average crushing length is calculated as:

$$ln\,\overline{L} = \frac{\sum_{i=1}^{n} m_i \, ln\,\overline{L_i}}{\sum_{i=1}^{n} m_i} \tag{23}$$

Power consumption

The power consumption is determined by the DYN-200 torque power sensor installed on the motor spindle. After each group of tests, the instantaneous torque, power and required time measured by the sensor are derived through the torque measurement system, and the instantaneous power of the effective working period is calculated to obtain the kneading power consumption. The calculation formula is as follows:

$$W_z = \int P(t)dt_z \tag{24}$$

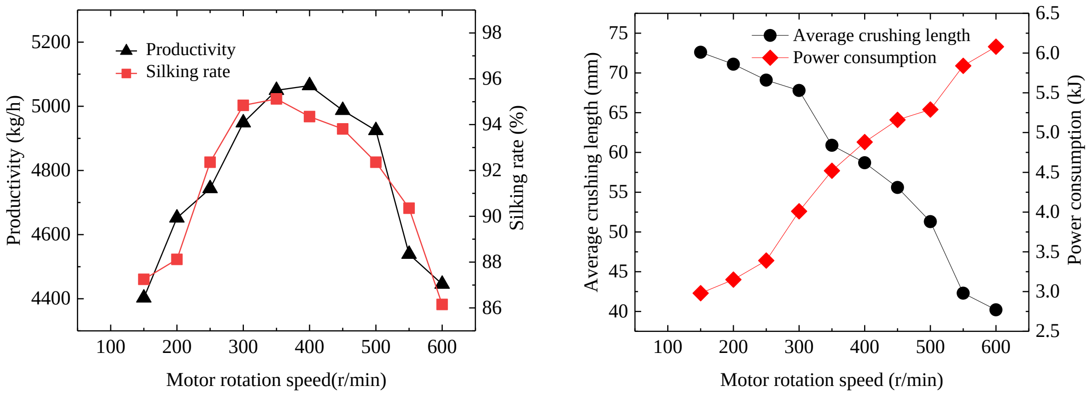
where: W_z is kneading power consumption, kJ; $P(t)$ is instantaneous power, kW; t_z is kneading time, s.

Test results and analysis

According to the pre-test and the adjustable range of the machine, the rotation speed of the motor ranges from 150 to 600 r/min, the sieve diameter from 12 to 22 mm, and the feeding amount from 0.5 to 2.5 kg/s. According to the different water content requirements of the post-harvest processing of alfalfa, the water content of the single factor test ranges from 10% to 80%.

(1) Effect of motor rotation speed on performance evaluation index

The influence of motor rotation speed on performance evaluation index is shown in Fig. 7 (Sieve diameter is 16 mm, feeding amount is 1.5 kg/s, moisture content is 80%).



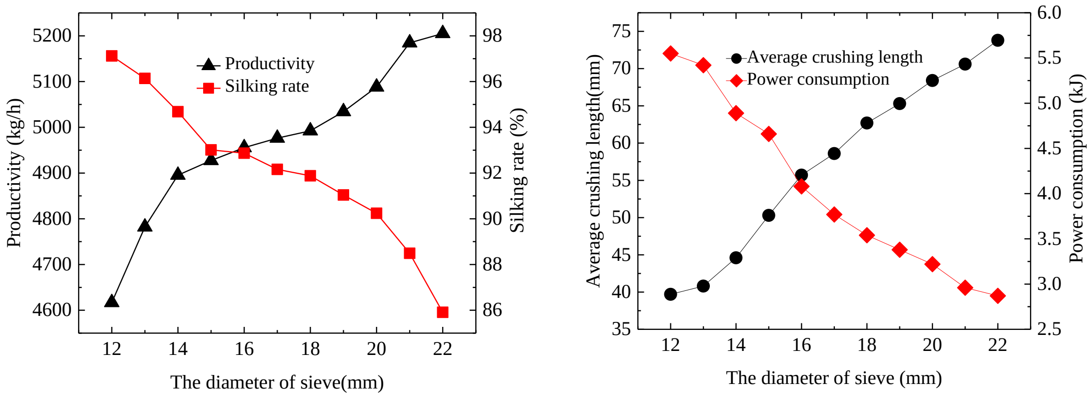
a) b)

Fig. 7 – Influence of motor rotation speed on performance evaluation index

It can be seen from the figure, that with the increase of the motor rotation speed, the productivity and silking rate both increase first and then decrease, the average crushing length decreases, and the power consumption increases. The reason is that with the increase of the motor rotation speed, the chopping and crushing rotor speed will be accelerated, and the interaction frequency between alfalfa and the crushing parts can be increased per unit time, so the productivity and silk rate increase. The increase of interaction frequency also reduces the length of the stalk crushing and increases the power consumption. When the motor rotation speed is too large, the broken grass will rotate along with the crushing rotor, forming a circulation, which cannot be thrown out of the body through the screen in time through the centrifugal force, and will cause excessive crushing, and the silked alfalfa is too fine, so the productivity and silking rate show a decreasing trend. The motor rotation speed is in the range of 250~500 r/min, the productivity and the silk rate are at a high level, when the motor rotation speed exceeds 500 r/min, the productivity and the silk rate drop sharply, the average crushing length decreases sharply, and the power consumption rises sharply, so the motor rotation speed should not exceed 500 r/min. Considering the performance evaluation index comprehensively, the grinding performance is better in the range of 250~500 r/min.

(2) Effect of sieve diameter on performance evaluation index

The influence of sieve diameter on performance evaluation index is shown in Fig. 8 (motor rotation speed is 350 r/min, feeding amount is 1.5 kg/s, water content is 80%).



a) *b)*

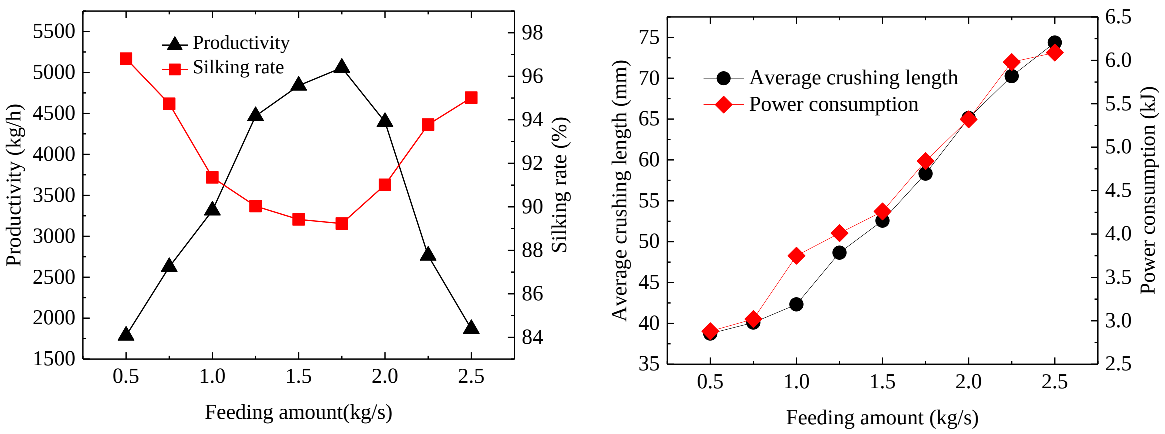
Fig. 8 – Influence of sieve diameter on performance evaluation index

It can be seen from the figure that with the increase of the screen diameter, the productivity and average crushing length show an increasing trend, while the silk rate and power consumption show a decreasing trend. The reason is that the larger the diameter of the sieve hole, the lower the limit of broken grass passing through the sieve hole, the longer the length of the stalk that can pass through the sieve, the more alfalfa can be fed in the same time, the higher the discharge efficiency, and the higher the number of crushing per unit time, so the productivity increases and the power consumption decreases.

However, some alfalfa whose length is longer than the requirement of crushing will pass through the sieve, resulting in a decrease in the silking rate and an increase in the average crushing length. When the sieve diameter is less than 14 mm, the broken grass through the sieve is more limited, so the productivity is low, the silk rate is high, the average crushing length is short, and the power consumption is large. When the screen diameter exceeds 20 mm, although the productivity is on the rise, the power consumption is low, but the silk rate drops sharply, and the average crushing length exceeds the crushing requirements. Therefore, the screen diameter should not exceed 20 mm. Considering the performance evaluation index comprehensively, the screen diameter ranges from 14 to 20 mm, the productivity and silk rate are relatively stable, and at a high level, the average crushing length is close to the crushing requirements, the power consumption is at a moderate level, and the crushing performance is better.

(3) Effect of feeding volume on performance evaluation indexes

The influence of feeding amount on performance evaluation index is shown in Fig. 9 (motor rotation speed is 350 r/min, screen diameter is 16 mm, water content is 80%).



a) *b)*

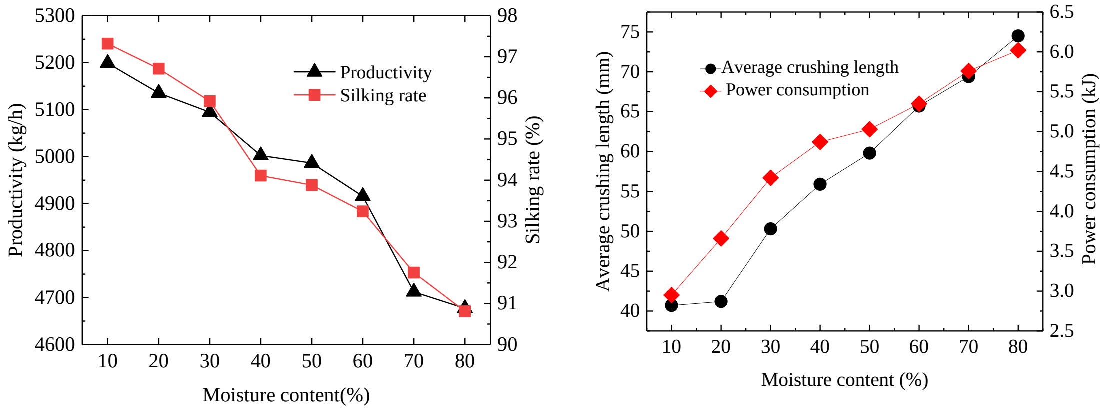
Fig. 9 – Influence of feeding amount on performance evaluation index

As can be seen from the figure, with the increase of feeding amount, the production first increased and then decreased, the silk first decreased and then increased, and the average crushing length and power consumption showed an increasing trend.

When the feeding amount is 0.5~1.75 kg/s, the feeding mechanism has self-adjustment ability, alfalfa can enter the machine smoothly, and the alfalfa in the cutting bin and crushing bin increases, so the productivity increases, the power consumption increases, the interaction frequency between a single alfalfa and the crushing parts decreases, so the silking rate decreases, and the average crushing length increases. When the feeding amount is greater than 1.75 kg/s, the self-adjustment ability of the feeding mechanism is weakened, part of alfalfa begins to accumulate at the feeding outlet, and the alfalfa in the cutting and crushing bin decreases, so the productivity decreases, and the interaction frequency between a single alfalfa and the crushing parts increases, so the silking rate increases. When the feeding amount exceeds 2 kg/s, the productivity begins to drop sharply. Considering the performance evaluation index comprehensively, the crushing performance is better in the range of 1~2 kg/s.

(4) Effect of moisture content on performance evaluation index

The influence of water content on performance evaluation index is shown in Fig. 10 (motor rotation speed is 350 r/min, screen diameter is 16 mm, feeding amount is 1.5 kg/s).



a) *b)*

Fig. 10 – Influence of moisture content on performance evaluation index

As can be seen from the figure, with the increase of water content, both productivity and silking rate showed a downward trend. The average pulverizing length and power consumption are on the rise. The reason is that when the moisture content of alfalfa stems is low, it is brittle and easy to break, so the productivity is high and the power consumption is low. With the increase of moisture content, the toughness of alfalfa is greater, the adhesion between the internal components of the stems is enhanced, and the crushing force required is greater, and it requires multiple strikes, rubbing and impact to meet the requirements of crushing length, so the productivity and silking rate are gradually reduced. The average crushing length is long and the power consumption is large. However, the silking rate is always greater than 90%, which reflects that the machine can crush alfalfa with different moisture content.

CONCLUSIONS

(1) Dynamic analysis was carried out on the cutting process of alfalfa stalk, a dynamic model was established, and the relationship between shear force and relevant parameters of the cutting mechanism was defined. It was found that the cutting Angle, installation Angle and wedge Angle had important effects on the cutting effect and power consumption. The dynamic analysis of the grinding process of alfalfa stalk in the grinding chamber shows that the force of alfalfa stalk in the grinding chamber is mainly related to the rotation speed of the grinding shaft, the gap between the hammer and the kneading board.

(2) Through the single factor test, the influence law of motor output speed, sieve diameter, feeding amount and moisture content on productivity, silking rate, average length of silk kneading and power consumption are respectively explored. The test results show that with the increase of the output speed of the motor, the productivity and the spinning rate increase first and then decrease, the average length of the spinning wire decreases gradually, and the power consumption increases gradually. With the increase of the screen diameter, the productivity and the average length of the yarn increase gradually, and the silk rate and power consumption decrease gradually. With the increase of feeding amount, the production increases first and then decreases, the silk decreases first and then increases, and the average kneading length and power consumption increase gradually. With the increase of water content, the productivity and silking rate gradually decrease, and the average length and power consumption of the kneading wire gradually increase.

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