# Effect of Roller Layout on Biomass Bales Quality and Baling Energy Consumption during Rotary Compression

Jie Zhang, Yong Zhang,* Yanhua Ma, Jian Wang, and Lide Su

Baling cellulosic biomass into round bales is an effective way to reduce the cost of storage and transportation. To improve the quality of bales and reduce the baling energy consumption, this paper introduces the steel roller layout parameters of the round baler into the biomass baling process. Alfalfa was used as an experimental material for five levels pitch value of roller circumferential layout baling experiments. The results showed that the introduction of chamber non-roundness (pitch value of roller circumferential layout) destroyed the formation of the entanglement high density ring cylindrical shell lamination of the outer layer of bales, which was beneficial to the compression of bales core material. When the pitch value was 30 mm, the maximum baling pressure, radial pressure transfer loss, and the baling energy consumption of baler were reduced by 30.4%, 33.4%, and 13.7%, respectively. When the pitch value was 60 mm, the relaxation ratio and radial density difference were reduced by 6.3% and 35.8%, respectively, and the radial density uniformity of alfalfa bale was increased by 32.0%. The experimental results provide a theoretical basis and technical support for the chamber structural optimization design of the round baler.

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*Keywords: Steel roller layout; Non-roundness; Round baler; Maximum baling pressure; Energy consumption; Density uniformity*

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## INTRODUCTION

China has abundant cellulosic biomass resources such as agricultural and forestry wastes and herbage; 700 million tons of crop straw and 1 billion tons of forest waste are produced annually (Liu and Zhou 2015; Chang 2021). These materials are burned or discarded, causing environmental pollution and increasing greenhouse gas emissions. Recycling these biomass resources is the most effective way to meet the needs of animal husbandry raw materials and respond to the national policy of energy conservation and emission reduction (Tumuluru *et al.* 2011). Because of their low bulk density and dispersed distribution, they are difficult to collect, handle, transport, and store in their natural form (Tumuluru 2014). The best solution is to densify the cellulosic biomass into round or square bales (Cui *et al.* 2014; Ma *et al*. 2016). The formed products with high quality and low processing cost solve the problems of high transportation costs and waste of biomass resources.

The round baler is the main machine for baling grass. The steel roller round baler belongs to the fixed baling chamber structure. It is used in the grass harvesting process because of its advantages such as cheap price, stable performance, good universality, simple structure, and convenient maintenance (Fang and Zhang 2018; Zhang *et al*. 2022). However, compared with the straw bales produced by the round baler in the variable baling chamber and the square baling machine, the straw baling density produced by the round baler in the fixed baling chamber is about 10% and 60% lower, respectively, which results in the decrease of the cost performance and product competitiveness of the steel roller round baler (Yang 2020; Wang *et al*. 2022). If the advantages of the round baler with fixed chamber can be maintained, and the disadvantages of low overall bales density relative to other types of baling machine can be improved, and the energy consumption of baling per unit mass biomass be reduced again, the economic benefits of round balers will be more prominent. This will contribute to the commercialization process of grass products and the promotion of round balers.

Therefore, in order to improve the density uniformity of bales and reduce the radial pressure transfer loss of bales and baling energy consumption, it is necessary to understand the formation mechanism of the density characteristic of the round bale with dense outer layer and a loose core. The non-roundness of the roller circumferential layout can reduce the pressure bearing capacity of the entangled high-density annular cylindrical laminated bale outer layer (Gao *et al.* 2015). This paper clarifies the influence law of round baler roller layout pitch parameters on the baling quality and baling energy consumption through the baling experiment. Within the scope of this experiment, with the increase of the pitch parameters of the roller layout, the four evaluation indexes of alfalfa bale quality, namely, the relaxation ratio, radial density difference, radial density uniformity, and baling energy consumption showed the same change rule of decreasing first and then increasing. The data provides a theoretical basis and implementation method for improving the alfalfa bale quality and provides a reference for upgrading and optimizing the steel roller round baler.

## EXPERIMENTAL

### Materials

The alfalfa used in the tests was obtained from local farmers in the suburb of Hohhot (Inner Mongolia, China), as shown in Fig. 1.

**Fig. 1.** Experimental materials are packaged separately

The alfalfa was air-dried to approximately 7% moisture content. The moisture content was adjusted to approximately 18% by adding water using a spray bottle and subsequent incubation it in a plastic bag at room temperature for 48 h. The moisture content of the materials was determined according to the technical specifications of DD CEN/TS 14774-2 (2004).

## Experimental System

The experimental system was constructed at the Agricultural Machinery Laboratory of West Campus of the Inner Mongolia Agricultural University, China, as shown in Fig. 2. The 9YQ-710 type steel roller outer coil round baler produced by Weifang Fulaiwo Machinery limited company was used in the experiment. The round baling machine was modified according to the requirements of the experiment. Five steel rollers on both sides of the baler feeding entrance could adjust their distance from the chamber center, to realize the purpose of redistributing the rollers layout in the chamber. The size of the alfalfa bale was φ450 mm × 680 mm; the overall size of the experimental platform is 1280 mm × 730 mm × 1520 mm, which is mainly composed of picker, chamber, rope binding mechanism, hydraulic system, transmission system, and data acquisition system. Ten steel rollers (diameter: 156 mm) are arranged in the circumferential direction along the chamber, and there are eight raised edges on the outer surface of the steel roller, which is conducive to improving the friction force of the steel roller on the alfalfa. When the round baler works, the sprocket drives each steel roller to rotate, and the baling process is completed under the action of friction force and extrusion pressure on the steel roller. Round alfalfa bales are rolled and formed under the friction force and extrusion pressure of each steel roller on alfalfa materials. The motor power of round baler is 18.5 kw, pick up width of baler is 710 mm, the production of biomass bale mass is less than 20 kg, and production efficiency is 30 to 70 bales /h.

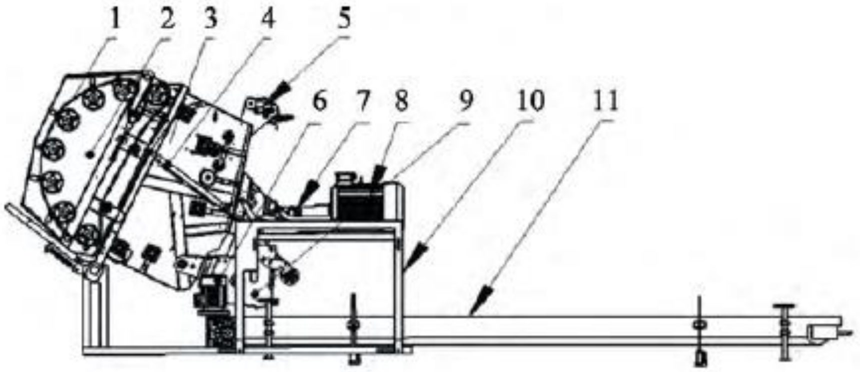


**Fig. 2.** Rotary compression experimental platform for round baler: 1: drive sprocket; 2: rear door; 3: chamber; 4: hydraulic system; 5: bale rope mechanism; 6: conveyer motor; 7: dynamic torque transducer; 8: round baler motor; 9: pickup; 10: round baler support frame; 11: belt conveyer

Figure 3 shows the data acquisition system of the bale internal radial pressure. An observation window was placed on the right side of the round baler to observe the alfalfa bale during the whole baling process and arrange pressure sensor inside the alfalfa bale through the observation window.

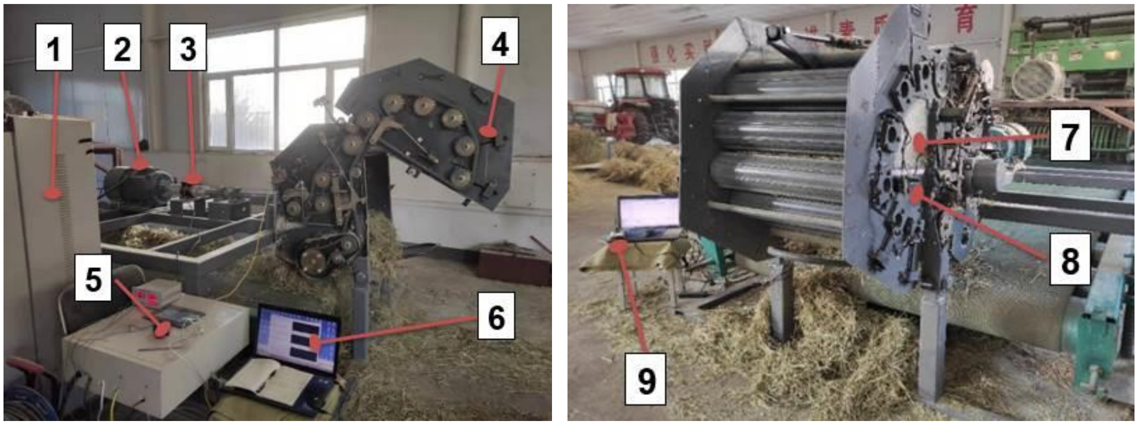


**Fig. 3.** Photo of radial pressure data acquisition process in alfalfa bale inside 1: frequency converter; 2: motor; 3: dynamic torque sensor; 4: roller position adjustment device; 5: control system; 6: computer; 7: observation port; 8: wireless strain node; 9: wireless data receiver

Figure 4 shows the layout diagram of pressure sensors. Six JHBM-H3 pressure sensors (ZhongWanJinNuo Company Ltd., Anhui, China) were placed inside the bale to measure the radial pressure data at 37.5 mm, 75 mm, 112.5 mm, 150 mm, 187.5 mm, and 225 mm of the bale radius. The data were obtained through SG404 wireless strain node (Beijing BeeTech Inc., Beijing, China), BS903 wireless gateway (Beijing BeeTech Inc., Beijing, China) and BeeData data acquisition software (V11.7; Beijing BeeTech Inc., Beijing, China). The data were plotted using OriginPro8 software (OriginLab, Pro8, Northampton, MA, USA). As the material is fed in the baling process, the pressure sensors move to the straw core following the compression process of the alfalfa. To ensure that the data collected by the pressure sensors were at a specific radius of the bale, it was necessary to suspend the baling process once every 20 seconds, and then readjust the positions of the six pressure sensors inside the bale until the end of the rolling.

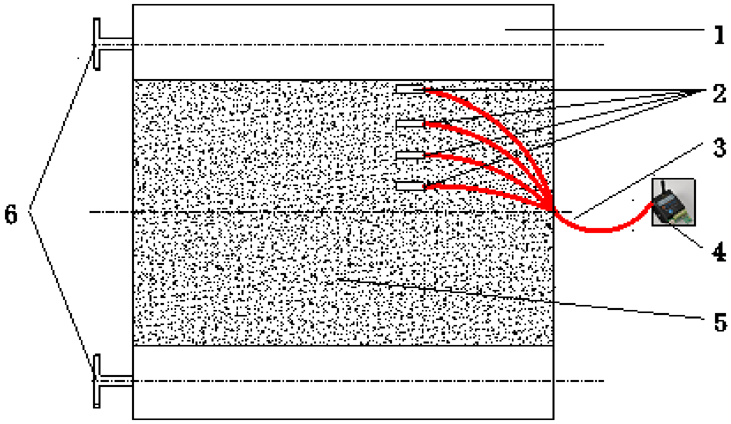


**Fig. 4.** Layout diagram of pressure sensors inside bales: 1: steel roller; 2: pressure sensor; 3: data transmission line; 4: wireless strain node; 5: alfalfa bale; 6: Steel roller power input gear

## Methods

To examine the effect of roller layout on baling energy consumption and forming quality of alfalfa bales, five levels of non-roundness conditions of roller circumferential layout were set in the experiment: 0%, 3.3%, 6.7%, 10%, 13.3%, and corresponding five levels of pitch values conditions of roller circumferential layout: 0 mm, 30 mm, 60 mm, 90 mm, and 120 mm. The other experimental conditions are shown in Table 1.

**Table 1.** Experimental Conditions

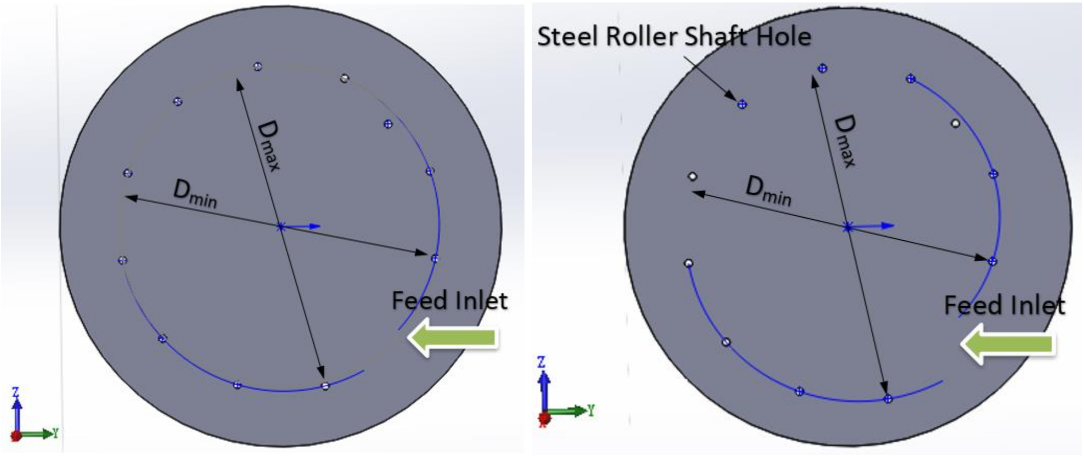
| Particle Moisture Content (%) | Feed Mass (kg) | Feed Rate (kg/s) | Steel Roll Speed (rpm) | Temperature (°C) |
|---|---|---|---|---|
| 18 | 21 | 0.16 | 350 | 14 to 18 |

Non-roundness, which is defined as the roundness deviation of a circular structure or a circular object, is an important factor affecting the strength of a cylinder structure in the crushing theory (Timoshenko and Gere 1961). The formula is shown in Eq. 1. In order to obtain a circular baling chamber with roundness defects, this paper chooses to fix the axle of each roller in a new position according to the shape of the Archimedean plane helix. The corresponding relationship between the non-roundness of the baling chamber and the pitch value of the roller layout has been mentioned above. Therefore, this work will completely adopt the standard pitch value of the Archimedean helix as experimental conditions to analyze its influence on various evaluation indexes.

$$\Delta_0 = \left(D_{\max} - D_{\min}\right) / D \times 100\% \tag{1}$$

where, $\Delta_0$ (%) is the non-roundness, $D_{\max}$ (mm) is the maximum diameter of circular section of baler chamber composed of steel rollers, $D_{\min}$ (mm) is the minimum diameter, and $D$ (mm) is the nominal diameter.

By adjusting the position of each roller, the five levels pitch value of steel roll circumferential arrangement were obtained for the experimental conditions. Taking the pitch values of 30 and 120 mm as an example, the distribution diagram of roller shaft holes on the side wall of the round baler is shown in Fig. 5.



**(a)** S=30 mm （$\Delta_0$ = 3.3%） **(b)** S=120 mm （$\Delta_0$ = 6.7%）

**Fig. 5.** Distribution diagram of roller shaft holes on the side wall of round baler

In a single test, 21 kg alfalfa was rolled and a bale was formed. The test was repeated three times under each working condition. The total mass of the bale was approximately 18.5 kg due to the undetected rate (about 15%) of the materials picked up by the pickup.

The radial density distribution of alfalfa bale was measured by the following methods: The alfalfa layer mass in the radius range of 0 to 37.5 mm, 37.5 to 75 mm, 75 to 112.5 mm, 112.5 to 150 mm, 150 to 187.5 mm, and 187.5 to 225 mm were measured by the stratified cutting method (Lei 2015). The average of the three measurements was the density of each alfalfa layer. The volume of each alfalfa layer can be calculated. Density $\rho_n$ (kg/m$^3$) of each alfalfa layer is defined by Eq. 2,

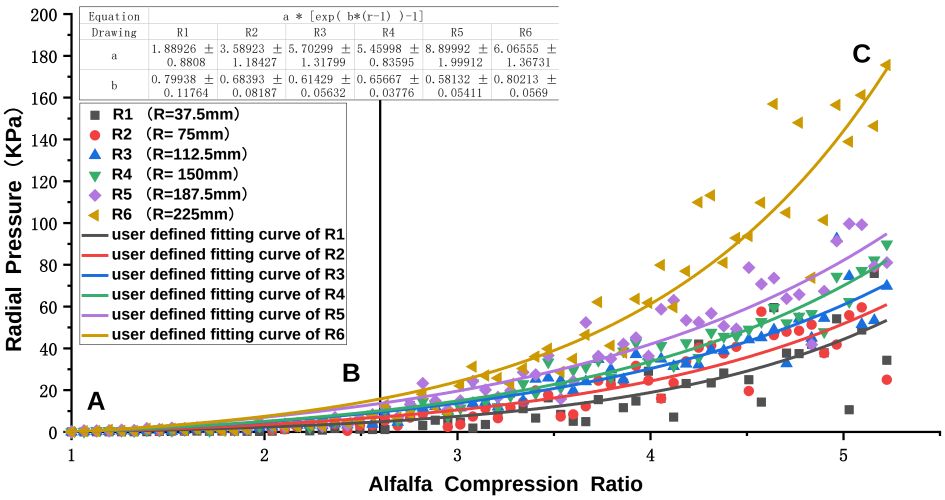
$$\rho_n = m_n / v_n \tag{2}$$

In the formula, n is the number of alfalfa layers. When the measured bale diameter range was set as 0 to 37.5 mm, its value was 1; when the measured bale diameter range was 37.5 to 75 mm, its value was 2, and so on. The value range of n was 1 to 6.

The method of measuring the baling energy consumption of straw bales is as follows: Install an electricity meter (model: DT862-4 three-phase four-wire active power meter, accuracy: 0.005kW·h; Shanghai People Electric Meter Company Ltd., Shanghai, China) at the input end of the driving motor of the round baler to measure the energy consumption of each alfalfa bale in the baling process. Record the mean value of three repeated tests.

## RESULTS AND DISCUSSION

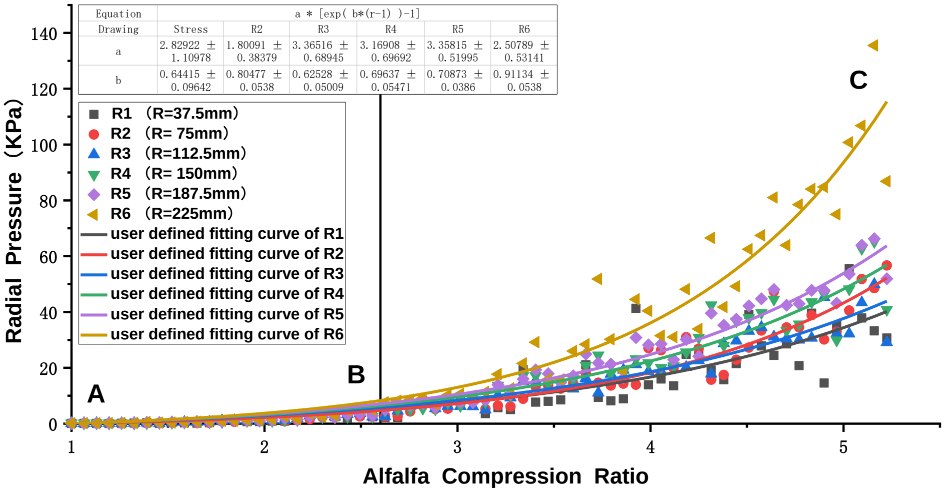
In order to clarify the influence of pitch parameters on the maximum pressure and the change rule of pressure transfer within the bale during the baling process, the data collected by pressure sensor during the experiment were analyzed. Figure 6 shows the radial compression pressure-compression ratio curves inside the alfalfa bale when the pitch values were 0, 30, 60, 90, and 120 mm. R1 to R6 were the radial compressive pressure data of specific radius inside the bale (R=37.5, 75, 112.5, 150, 187.5, and 225 mm, respectively).



| Equation | a * [exp( b*(r-1) )-1] | | | | | |
|---|---|---|---|---|---|---|
| Drawing | R1 | R2 | R3 | R4 | R5 | R6 |
| a | 1.88926 ± 0.8808 | 3.58923 ± 1.18427 | 5.70299 ± 1.31799 | 5.45998 ± 0.83595 | 8.89992 ± 1.99912 | 6.06555 ± 1.36731 |
| b | 0.79938 ± 0.11764 | 0.68393 ± 0.08187 | 0.61429 ± 0.05632 | 0.65667 ± 0.03776 | 0.58132 ± 0.05411 | 0.80213 ± 0.0569 |

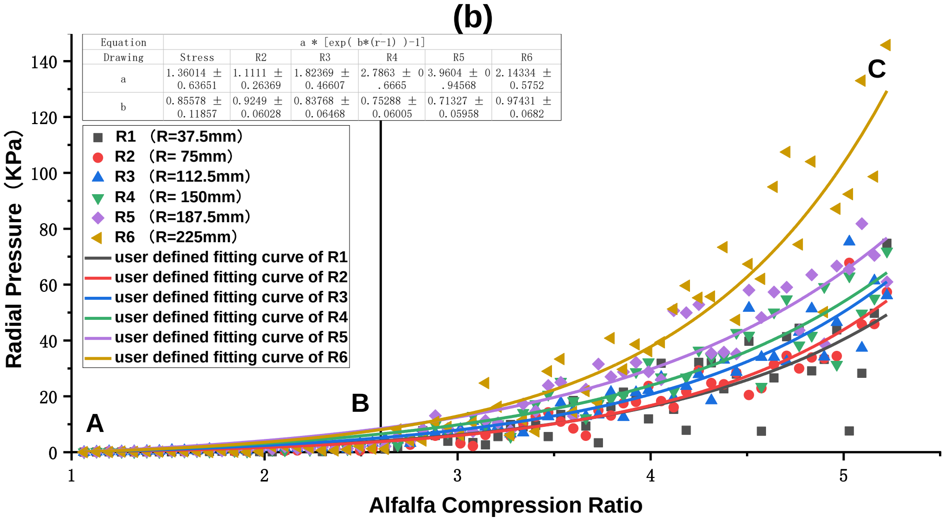
**(a)**

**Fig. 6(a).** Compression curves of alfalfa with pitch value at (a) 0 mm, (b) 30 mm, (c) 60 mm, (d) 90 mm, and (e) 120 mm



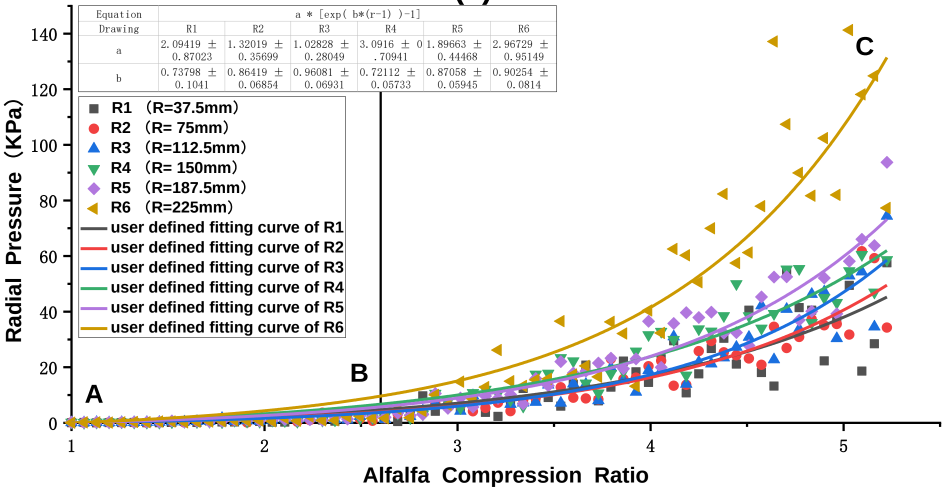
| Equation | a * [exp( b*(r-1) )-1] | | | | | |
|---|---|---|---|---|---|---|
| Drawing | Stress | R2 | R3 | R4 | R5 | R6 |
| a | 2.82922 ± 1.10978 | 1.80091 ± 0.38379 | 3.36516 ± 0.68945 | 3.16908 ± 0.69692 | 3.35815 ± 0.51995 | 2.50789 ± 0.53141 |
| b | 0.64415 ± 0.09642 | 0.80477 ± 0.0538 | 0.62528 ± 0.05009 | 0.69637 ± 0.05471 | 0.70873 ± 0.0386 | 0.91134 ± 0.0538 |

(b)



| Equation | a * [exp( b*(r-1) )-1] | | | | | |
|---|---|---|---|---|---|---|
| Drawing | Stress | R2 | R3 | R4 | R5 | R6 |
| a | 1.36014 ± 0.63651 | 1.1111 ± 0.26369 | 1.82369 ± 0.46607 | 2.7863 ± 0.6665 | 3.9604 ± 0.94568 | 2.14334 ± 0.5752 |
| b | 0.85578 ± 0.11857 | 0.9249 ± 0.06028 | 0.83768 ± 0.06468 | 0.75288 ± 0.06005 | 0.71327 ± 0.05958 | 0.97431 ± 0.0682 |

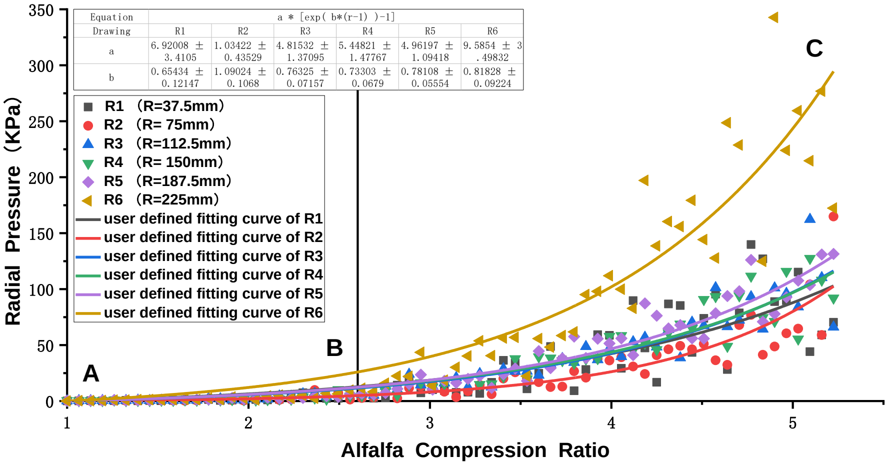
(c)



| Equation | a * [exp( b*(r-1) )-1] | | | | | |
|---|---|---|---|---|---|---|
| Drawing | R1 | R2 | R3 | R4 | R5 | R6 |
| a | 2.09419 ± 0.87023 | 1.32019 ± 0.35699 | 1.02828 ± 0.28049 | 3.0916 ± 0.70941 | 1.89663 ± 0.44468 | 2.96729 ± 0.95149 |
| b | 0.73798 ± 0.1041 | 0.86419 ± 0.06854 | 0.96081 ± 0.06931 | 0.72112 ± 0.05733 | 0.87058 ± 0.05945 | 0.90254 ± 0.0814 |

(d)

**Fig. 6 (b, c, d).** Compression curves of alfalfa with pitch value at (a) 0 mm, (b) 30 mm, (c) 60 mm, (d) 90 mm, and (e) 120 mm



| Equation | a * [exp( b*(r-1) )-1] | | | | | |
|---|---|---|---|---|---|---|
| Drawing | R1 | R2 | R3 | R4 | R5 | R6 |
| a | 6.92008 ± 3.4105 | 1.03422 ± 0.43529 | 4.81532 ± 1.37095 | 5.44821 ± 1.47767 | 4.96197 ± 1.09418 | 9.5854 ± 3.49832 |
| b | 0.65434 ± 0.12147 | 1.09024 ± 0.1068 | 0.76325 ± 0.07157 | 0.73303 ± 0.0679 | 0.78108 ± 0.05554 | 0.81828 ± 0.09224 |

**(e)**

**Fig. 6 (e).** Compression curves of alfalfa with pitch value at (a) 0 mm, (b) 30 mm, (c) 60 mm, (d) 90 mm, and (e) 120 mm

The alfalfa compression ratio in the abscissa of Fig. 6 is defined as the ratio between the current density of bales ( $\rho$ ) and the material Initial natural packing density ( $\rho_0$ ), as shown in Eq. 3.

$$r = \rho / \rho_0 \tag{3}$$

The baling process under the five working conditions was similar and could be divided into two stages. The first stage was AB (pre-compression stage). Because of the low bulk density of alfalfa, the required pressure was low, and the growth was slow. The second stage was the BC stage (compression stage), where the material was further compressed and began viscoelastic deformation. With increasing density, the material was squeezed into the narrow section of the round baler chamber, and the required pressure increased rapidly.

In the five horizontal test experiments of the pitch value parameters of roller layout, the compressive pressure at different radial positions inside the bale showed the characteristic of increasing with the diameter of the measured position. The compression force of the outermost material in the bale was the largest (defined as the maximum forming pressure) (Wang *et al.* 2021). The compression force decreased in the process of transmission to the straw core. The compression force of the material in each layer of the bale increased exponentially with the continuous feeding of alfalfa.

The maximum pressure required in the densification process was an important parameter to estimate energy consumption. The compression pressure was determined by the degree of compression (Faborode and O'Callaghan 1986). Based on the compression theory of Faborode, the relationship model between the compression degree of alfalfa and the radial compression stress of the bale during the round bale compression was deduced.

The curve in figure 6a-e was obtained by fitting the experimental data. The form of the function model was shown in Eq. 4,

$$P = a\left[e^{b\cdot(r\text{-}1)} - 1\right] = a\left[e^{b\cdot(\rho\text{-}\rho_0)/\rho_0} - 1\right] \tag{4}$$

where $\rho$ is the present compression density of bale, $\rho_0$ is the initial density of alfalfa, and $r$ is the compression ratio of alfalfa. The parameters $a$ and $b$ are the experimental coefficients, and their values are shown in Fig. 6.

Compression pressure loss between every alfalfa layer was caused by the resistance of the grass layer structural strength to the baling pressure $F_j$, and the friction between the material and the side wall of the round baler chamber $f_c$, as shown in Eq. 5.

$$\Delta P = P - P_0 = \sum 2 f_c + \sum F_j \tag{5}$$

The maximum compression pressure and the pressure transfer loss of alfalfa bales (compression pressure difference value between R6 and R1) also varied when the roller layout of the baler was varied, as shown in Table 2. Maximum pressure-alfalfa compression ratio curves had the same variation trend under 5 steel roll layout pitch parameters, as shown in Fig. 7.

**Table 2.** Maximum Pressure and Pressure Transfer Loss under Different Pitch Value

| Parameter | Working Condition | | | | |
|---|---|---|---|---|---|
| Pitch Value (mm) | 0 | 30 | 60 | 90 | 120 |
| Maximum Pressure (KPa) | 165.72 | 115.42 | 129.37 | 131.61 | 294.55 |
| Pressure Transfer Loss (KPa) | 112.91 | 75.19 | 86.1 | 87.06 | 191.64 |

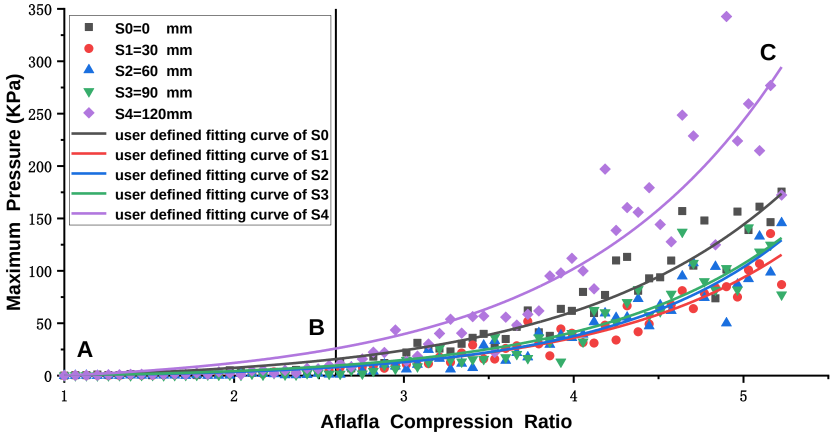


**Fig. 7.** Maximum pressure-compression ratio curves under the different pitch value

By comparing the alfalfa baling process of the round baling machine with the round baling chamber (pitch value S=0 mm), it was found that the maximum forming pressure and pressure transfer loss of alfalfa crimping were small when the round baling machine adopt the spiral steel roller layout and the pitch parameter was not more than 90 mm. When the pitch parameter was 30 mm, the forming pressure was the smallest, and the maximum forming pressure and pressure transmission loss were reduced by 30.4% and 33.4%, respectively, compared with the round chamber rolling test (S=0 mm).

In the circular chamber structure of the traditional round baler, the pressure environment of each roller during the baling process was very different. The compression pressure of the lower roller in the chamber was significantly higher than that of the upper roller (Fang and Zhang 2018). The round baler with optimized spiral shape chamber structure had adjusted the position of the rollers and redistributed the compression pressure of each steel roller on the bale, resulting in a more uniform pressure on the rollers in the bale chamber, and finally the total compression pressure of the 10 rollers on the bale had been reduced. Based on the collapse theory, the non-roundness of the annular cylindrical shell structure will have a great destructive effect on its own bearing capacity (Zhang 1997). Therefore, the spiral shaped roller layout could effectively destroy the pressure of the outer layer of the high-density annular columnar bale during baling, making it easier for the steel roller to transmit the compression force of the material to the straw core, which indicated that adjusting the roller layout of the round baler can reduce the compaction resistance of the bale and the transmission loss of the compression pressure of the roller on the bale in the radial direction of the bale.

To explore the main causes of pressure transmission loss, through the experimental method of measuring the internal pressure of the bale in Fig. 4, the pressure sensor was used to measure the axial compressive stress between the straw material at each diameter position of the bale and the side wall of the round baler, which was the value of fc in Eq. 5. Because the test results of different bale radial positions and different pitch parameter values were basically the same, the axial pressure test results between the alfalfa straw and the side wall of the round baler at the pitch value S of 60 mm and the bale radius R of 150 mm are shown in Fig. 8.

Figure 8 shows that the axial pressure between the bale and the side wall of bale chamber increased slowly with baling process, but the value was negligible compared with the radial pressure inside straw bales. According to Eq. 5, the radial baling pressure transfer loss in the rolling process of straw bales could be thought to be caused by the resistance of the straw layer structural strength to the baling pressure. Although the adjustment of roll layout could improve the pressure transfer to the inner core of straw, from the analysis of experimental results, it could be seen that roller layout pitch parameter of the bale chamber could not completely solve the loss problem in the process of pressure transfer.

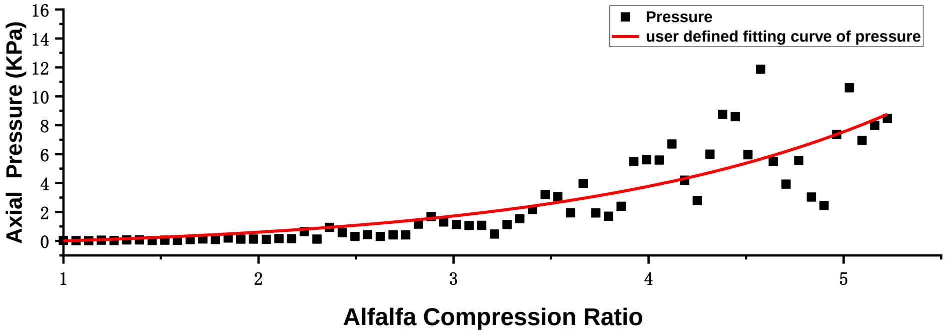


**Fig. 8.** Axial compressive pressure -compression ratio curve with pitch value at 60 mm

Energy consumption is an important index to evaluate the rationality of biomass densification process (Hu *et al.* 2013). The energy consumption, maximum rolling pressure, and pressure transfer loss of a single alfalfa bale were analyzed in this paper with the variation of pitch parameters. The influence law of pitch value on maximum pressure, pressure transfer loss, and energy consumption of round baler is shown in Fig. 9.

Within the range of pitch value in this experiment, with the increase of pitch value, the maximum baling pressure and pressure transfer loss of alfalfa bale decreased rapidly first and then increased slightly. The baling energy consumption of round baler also decreased first and then increased. When the pitch value was 30 mm, the maximum baling pressure, pressure transfer loss and baling energy consumption reached the minimum values, which were 115.42 KPa, 75.19 KPa, and 22W·h, respectively. Compared with the test group with pitch value of 0 mm, they decreased by 30.35%, 33.41% and 13.73%, respectively. This indicated that the roller circumferential layout pitch value of 30 mm was the best choice from the perspective of baling energy consumption, and the round baler could compress alfalfa into bales with the same density only with less pressure and energy consumption.

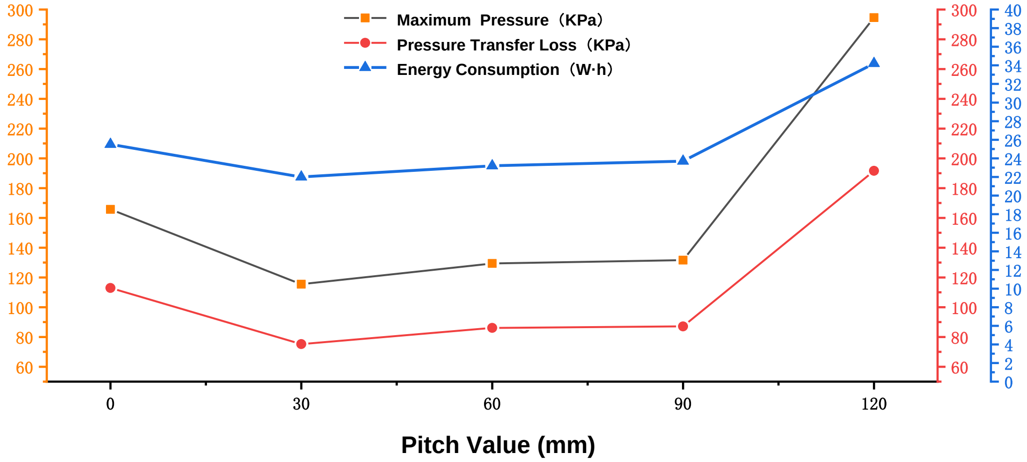


**Fig. 9.** The curves of pitch parameters versus the maximum pressure and pressure transfer loss and energy consumption of baling process

The difference was that the baling energy consumption increased rapidly when the pitch value was 90 to 120 mm. Further, the baling energy consumption was higher than all other four experimental groups when the pitch value was 120 mm, indicating that the roll layout at this pitch value condition had been unreasonable. Considering the angle of reducing the energy consumption during baling process, the pitch value of 120 mm had exceeded the reasonable level of the roller layout adjustment.

The relaxation ratio indicates the degree of relaxation of the bales (Adapa *et al.* 2002). The density of bales gradually decreased after round baler finished the baling operation and released bales (Viswanathan and Gothandapani 1999). After releasing the bales from the chamber of the round baler, the density of the bale was measured every 24 h, and the data of three replicated experiments of every level of pitch were averaged. The time-density curves of the bales produced under different pitch values are shown in Fig. 10. The density of the bale decreased rapidly at the beginning and then slowed down over time. The smaller the density difference between two adjacent measurements, the slower the stress relaxation. The average value of data measured through three experiments are shown in Table 3.

The relaxation ratio of alfalfa bales rolled by the spiral shape chamber was smaller than that of the bales rolled by the traditional bale chamber (pitch value S=0 mm), indicating that the roller layout of spiral shape reduced the deformation recovery of alfalfa bales. When the pitch value was 60 mm, the relaxation of bale was relatively small, and the relaxation rate increased by 6.34% compared with that of the bale rolled by the traditional compression chamber. The reason might be that the rollers arranged in the form of helix helped the alfalfa move to the core during the rolling process, which reduced the density difference between the outer material and the inner material of the bale, reduced the elastic deformation recovery force of alfalfa, homogenized the internal stress of each layer of alfalfa bale, so the alfalfa bale maintained a high density after long-term storage.

**Table 3.** Relaxation Density, Relaxation Ratio, and Other Measurement Data for the Alfalfa Bales

| Parameter | Working Condition | | | | |
|---|---|---|---|---|---|
| Pitch Value (mm) | 0 | 30 | 60 | 90 | 120 |
| Formation Mass (kg) | 18.1±0.13 | 18.5±0.16 | 18.6±0.19 | 18.8±0.14 | 18.3±0.16 |
| Formation Perimeter (m) | 1.414±0.007 | 1.483±0.015 | 1.489±0.006 | 1.552±0.021 | 1.527±0.009 |
| Formation Height (m) | 0.604±0.009 | 0.603±0.005 | 0.603±0.009 | 0.608±0.007 | 0.604±0.002 |
| Formation Volume ($m^3$) | 0.096±0.021 | 0.106±0.025 | 0.106±0.019 | 0.108±0.029 | 0.112±0.014 |
| Relaxation Perimeter (m) | 1.552±0.004 | 1.590±0.008 | 1.577±0.013 | 1.627±0.010 | 1.646±0.007 |
| Relaxation Height (m) | 0.613±0.002 | 0.609±0.005 | 0.609±0.004 | 0.612±0.005 | 0.611±0.004 |
| Relaxation Volume ($m^3$) | 0.117±0.013 | 0.122±0.017 | 0.121±0.020 | 0.129±0.019 | 0.132±0.018 |
| Formation Density ($kg/m^3$) | 188.541±1.275 | 174.528±2.981 | 175.472±0.977 | 174.074±1.676 | 163.393±2.155 |
| Relaxation Density ($kg/m^3$) | 154.701±1.824 | 151.639±1.668 | 153.719±1.126 | 145.736±2.217 | 138.636±1.775 |
| Relaxation Ratio (%) | 121.88% ±0.61% | 115.09%±1.02% | 114.15% ±0.45% | 119.44% ±0.79% | 117.86%±0.72% |

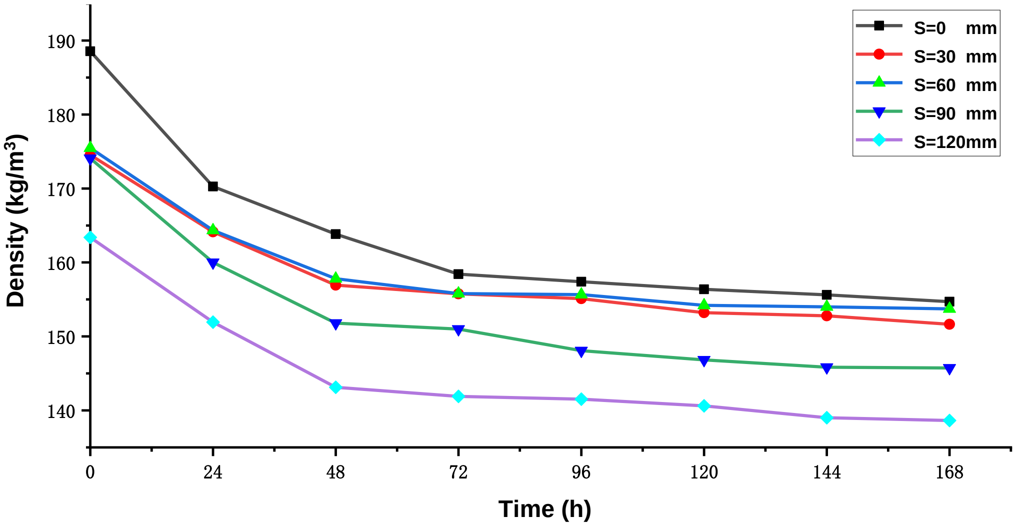


**Fig. 10.** The density-time curves of the bales after formation

To study the variation of the radial density distribution of bales under different pitch parameters, the method of cutting bales by layers was adopted in this paper. The local grass layer density of each alfalfa bale was measured within the radius range of 0 to 37.5 mm, 37.5 to 75 mm, 75 to 112.5 mm, 112.5 to 150 mm, 150 to 187.5 mm, and 187.5 to 225 mm. The results are shown in Fig. 11.

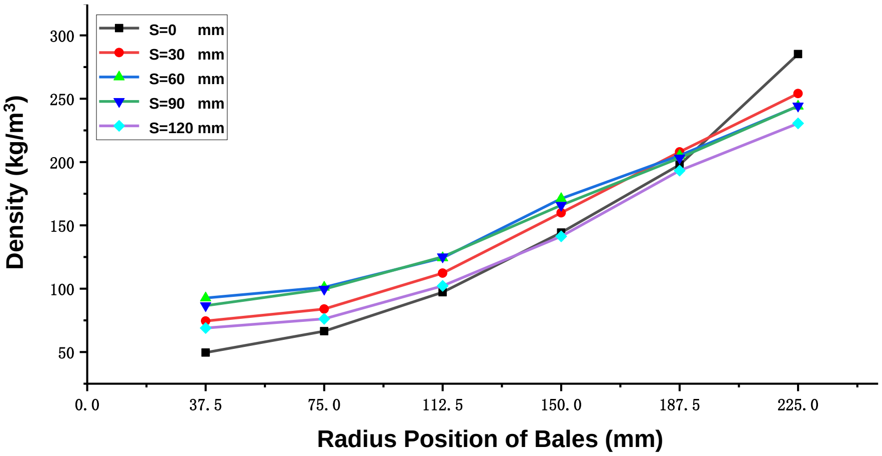


**Fig. 11.** Radial density distribution curves of alfalfa bales under different pitch parameters

The radial density distribution characteristics and relaxation ratio of bales under different pitch parameters are shown in Fig. 12. With increasing pitch values, the radial density difference between outer and of alfalfa bales, standard deviation of bales radius density, and relaxation ratio of alfalfa bales first decreased rapidly and then increased slightly. When the pitch value was 60 mm, the radial density difference, standard deviation, and relaxation ratio of bales reached the minimum values, which were 151.4 kg/m$^3$, 60.7 kg/m$^3$, and 114%, respectively. Considering the angle of improving the quality of alfalfa bales, roller circumferential layout of the optimal pitch value should be 60 mm.

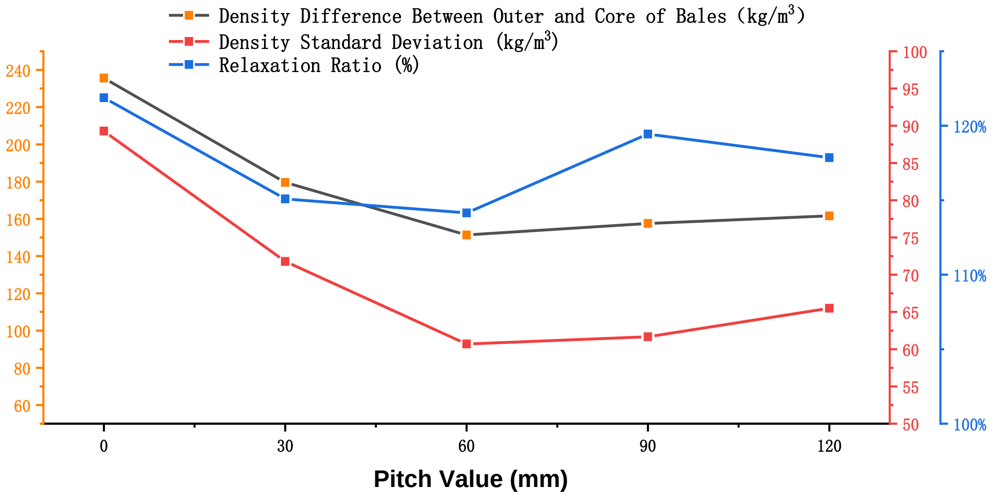
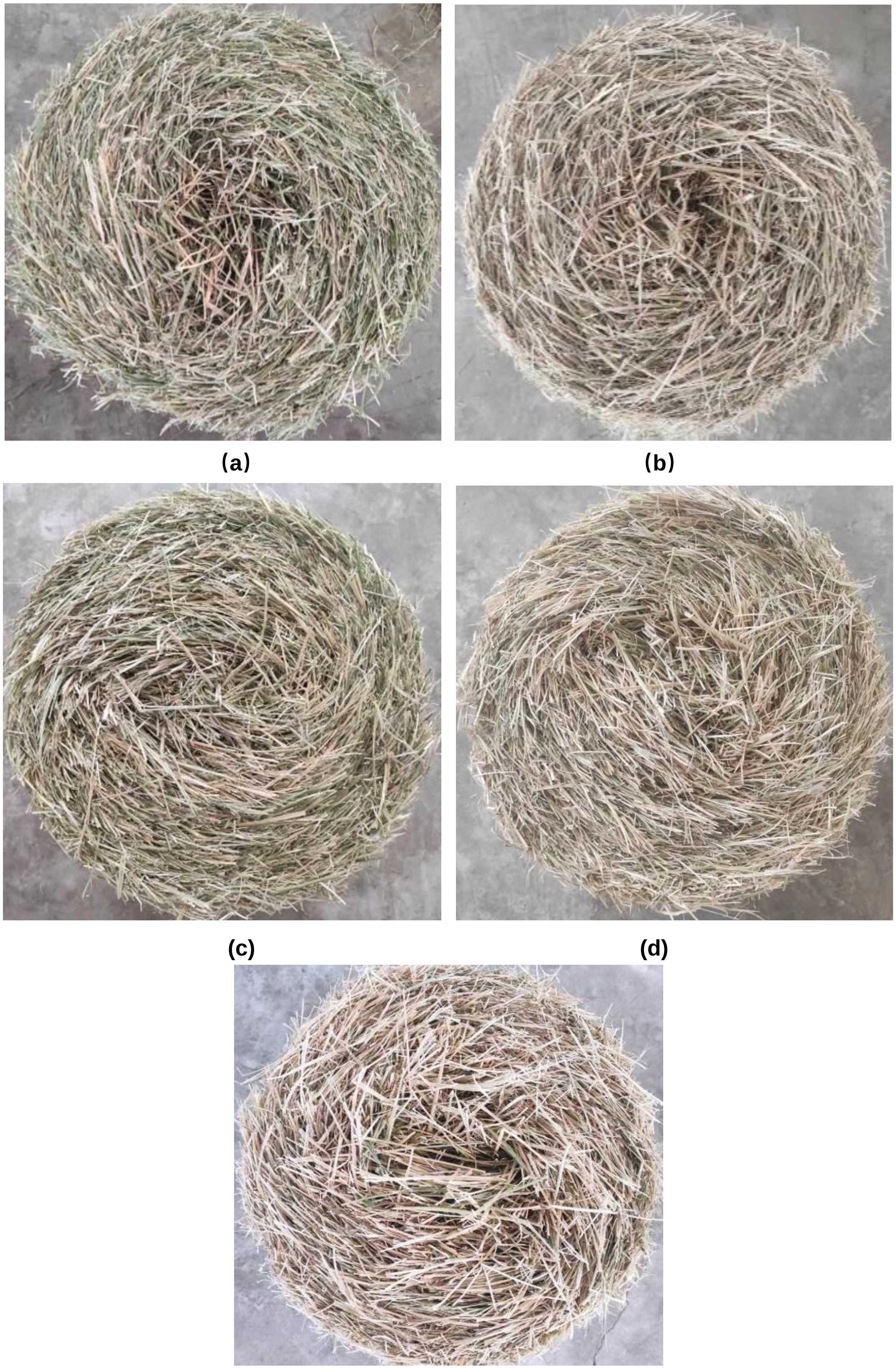


**Fig. 12.** The curves of pitch parameters versus the density difference and density standard deviation and relaxation ratio of bales

Figure 13 shows the surface picture of alfalfa bales when the pitch values of steel roller were 0, 30, 60, 90, and 120 mm. There was a relatively consistent evolution with the density distribution characteristics of bales above. When the circumferential layout of the roller was circular, the bale core was obviously loose; the alfalfa formed a superimposed annular column and gathered in the outer layer of the bale. The radial pressure transmission loss of the bale was large during the rolling process of the round bale chamber round baler, and the compression stress of the roller on the straw material was difficult to transfer to the straw core, resulting in the accumulation of materials in the outer layer of the bale.



(a) (b) (c) (d) (e)

**Fig. 13.** Surface picture of biomass bales side: a) S=0 mm; b) S=30 mm; c) S=60 mm; d) S=90 mm; e) S=120 mm

The resulting lamination intensified the resistance of the high-density annular cylinder shell structure to the compression force, making it more difficult to transfer the compression force to the straw core, finally resulting in the hollow core.

When the pitch value was 30 mm (Fig. 13b), there was a slight hollow core phenomenon in the alfalfa bale, but it could be seen that most of the hollow core space of the bale was squeezed inward by the alfalfa in a spiral shape. When the pitch value was 60 mm and 90 mm (Figs. 13c and 13d), alfalfa was evenly distributed in obvious spiral shape on the side of the bale. Until pitch value was 120 mm (Fig. 13e), tiny grass cores were found again. The reason for this phenomenon might be that the non-roundness parameter of the chamber composed by rollers was too large, the outward-spiraling steel roller not only couldn’t compress the material, but also provided a relaxed space for the bales, which hindered the normal baling process of the alfalfa bales.

The influence law of the pitch value of the roller layout on the pressure state of the alfalfa bale, the forming quality of the bale and the energy consumption during the baling process were comprehensively analyzed. The results showed that the optimal range of the pitch value parameter of the roller layout for 9YQ-710 type round baler should be 30 to 60 mm. When the pitch value was higher than 60 mm, the maximum compression pressure, radial pressure transfer loss, radial density distribution uniformity, relaxation ratio and other evaluation indexes of experiment showed a decline in the quality of bales. Especially when the pitch value was as high as 120 mm, the baling energy consumption increased rapidly, and the quality of the bales decreased, which indicated that the setting range of pitch parameters in this experiment included the upper limit of reasonable optimization of circumferential roller layout.

## CONCLUSIONS

1. Optimizing roller layout can effectively improve the quality of alfalfa bales and can reduce the energy consumption of the baling process. When the pitch value was 30 mm, the maximum baling pressure, radial pressure transfer loss, and the baling energy consumption of baler reached the minimum values of 115.4, 75.2, and 22 W·h, and were reduced by 30.4%, 33.4%, and 13.7%, respectively. When the pitch value was 60 mm, the relaxation ratio, radial density difference and density standard deviation reached the minimum values of 114%, 151 kg/m$^3$, and 60.7 kg/m$^3$, the relaxation ratio and radial density difference were reduced by 6.34% and 35.8%, respectively, and the radial density uniformity of alfalfa bale was increased by 32.0%.
2. With the increase of pitch value of roller layout, the maximum forming pressure, radial pressure transfer loss, density difference between outer and core of bales, energy consumption, and relaxation ratio were decreased first and then increased. When the pitch value was around 30 mm, the maximum forming pressure, radial pressure transfer loss and energy consumption were smaller in this experiment. When pitch value was around 60 mm, the density difference and relaxation ratio were relatively small, and the side density of alfalfa bale was more uniform and the surface morphology was better, so the optimum pitch value of roller layout might be in the range of 30 to 60 mm, corresponding to the chamber non-roundness parameter adjusting range of 3.3% to 6.7%.

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