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Design and Experiment of Active Spiral Pushing Straw Row-Sorting Device

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Abstract: Aiming to solve the problems of excessive straw residue and large soil loss in the seeding belt of the straw row-sorting operation when the full volume of straw is crushed and returned to the field in the northeastern region of China, an active spiral pushing straw row-sorting device (ASPSRD) was designed in this paper. The straw on the surface of the land is collected and stirred by the high-speed rotating spiral-notched blades in the device and pushed to the non-seeding area for the purpose of cleaning the seeding belt. The parameters of key components were determined through theoretical analysis. The orthogonal combination test method of four factors and three levels was adopted. The EDEM discrete element simulation experiment was carried out by selecting the straw mulching quantity (SMQ), the rotating speed of the active rotating shaft (RSARS), the forward speed of the tractor (FST), and the notch width of the spiral notch blade (NWSNB) as the test factors, and the straw-cleaning rate (SCR) and soil loss rate (SLR) as the test indexes. Through range analysis, the parameters were optimized, and the optimal operation parameters of the straw row-sorting device were determined as follows: SMQ was 1.8 kg/m^2, RSARS was 120 rpm, FST was 4 m/s, and NWSNB was 9 mm. The operational performance of the device was verified by field experiments. The results of the test showed that after the device was operated with the optimal combination of parameters, the SCR of the 20 cm wide seeding belt was 95.32%, and the SLR was 7.12%, which met the agronomic and technical requirements of corn no-tillage sowing operation in Northeast China. This study can provide a reference for the design of a straw row-sorting device of a no-tillage machine.

Keywords: no-tillage sowing; row-sorting of the straw; active spiral; notches and picks; EDEM simulation

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1. Introduction

Conservation tillage is an advanced agricultural technique that covers the surface of the soil with crop residues and carries out no-tillage sowing. It has the effect of reducing wind and water erosion and improving soil fertility [1,2]. No-tillage sowing covers the harvested crop stalks on the ground. Before the next sowing, the straw row-sorting machine is used for land preparation. The crop stalks on the seeding belt are collected on the non-seeding belt after the operation. The quality of the straw cleaning of the machine will directly affect the operation of the subsequent sowing link [3]. The terrain in Northeast China is uneven, the growth cycle of corn is long, the length of the straw is shorter after it is fully crushed and returned to the field, and the total amount is large [4]. Direct seeding will lead to difficulties in the operation of machines and tools, which will seriously affect the seeding effect [5,6], and row-sorting of the straw before sowing is an effective way to improve the seeding quality [7,8]. However, problems such as high soil loss in the seeding belt, incomplete cleaning of short straw, straw blockage of row-sorting parts, and so on are prone to occur during the straw row-sorting operation [9]. Therefore, it is necessary to identify how to achieve the high-efficiency and high-quality row-sorting of corn straw under the premise of minimizing the soil loss in the seeding belt.

The straw row-sorting device can be divided into passive type and active type according to different driving modes. Among them, for the passive straw row-sorting device, Kristina Vaitauskienė et al. [10] studied the effects of the rake angle, interval, working speed, and other factors of the sawtooth disc-type straw-cleaning device on the straw-cleaning efficiency and determined the optimal parameters. V. Dadi et al. [11] studied the influence of different shapes of discs on the efficiency of straw cleaning, and through the comparison of different schemes, developed a straw row-sorting device that combines the rotating wheel with the conical wave wheel. Honglei Jia et al. [12] studied the straw-cleaning device that can intelligently control the operation depth, designed the structure of the straw-cleaning wheel according to the bionic principle, and determined the optimal parameter combination through the data processing software. The passive straw row-sorting device has a better straw-cleaning effect when the amount of straw is small, but when operating on the ground where the straw is completely crushed and returned to the field, it is easy to block the row-sorting parts of straw, which affects the efficiency of straw cleaning. For the active straw row-sorting device, Gu et al. [13] studied the influence of rod teeth on straw, using the tearing force during rotation to disperse the straw, which can effectively improve the uniformity of the straw after operation. Hou et al. [14] studied the movement trajectory of straw scattering and determined the optimal structural parameters of a stubble cleaning knife according to the trajectory in order to improve the stubble removal rate and reduce soil loss in the seeding belt. Chen et al. [15] studied the influence of different arrangements of the straw-cleaning device on the whole machine and optimized the design to reduce vibration and power consumption. The active straw row-sorting device needs to be powered by the tractor transmission shaft to make the shaft of the straw-cleaning device rotate to realize a straw row-sorting mechanism that does not easily jam and can be applied to areas with large amounts of straw; however, there are some problems, such as large soil loss in the seeding belt, a poor cleaning effect for short straw, uneven straw coverage after operation, etc.

For the problems such as poor straw-cleaning effect and high soil loss during straw row-sorting operations in the areas of no-tillage sowing where corn straw is fully crushed and returned to the field in Northeast China, this paper comprehensively considered the advantages and disadvantages of active and passive straw row-sorting devices and proposed an ASPSRD. Under the premise of ensuring that there will be no congestion, the ground crushed straw is efficiently and qualitatively row-sorted to the left and right sides of the seeding belt. The soil affected by the machine cannot easily leave the seeding belt because the SLR is small. Through theoretical analyses and mathematical calculations, the structural parameters of the key components of the ASPSRD were determined. Through the discrete element simulation experiment, the optimal working parameters were determined using the test method of four factors and three levels. The operational effectiveness of the optimal parameter combination was verified through field tests. This paper aims to provide a reference for the research related to straw row-sorting machines in the no-tillage sowing area, where corn straw is totally crushed and then returned, in Northeast China.

2. Materials and Methods

2.1. Overall Structure and Working Principle of the ASPSRD

2.1.1. Overall Structure

Figure 1 illustrates the general structure of the ASPSRD. It mainly consists of the active rotating shaft, the right spiral-notched blade group, and the left spiral-notched blade group. Among the interactions between units, the right spiral notch blade and the left spiral notch blade are fixed together and symmetrical to each other, and the spiral notch blade group is fixed to the active rotating shaft. This results in synchronized rotation of the rotation shaft and the blade group. Each notched blade group has three notched blades corresponding to the spiral direction, and they are evenly distributed on the vertical plane of the axis of the active rotating shaft. The soil penetration depth of the spiral-notched blades is about 5 mm so as to ensure that the straw on the ground can still be fully in contact with the uneven position of the ground.

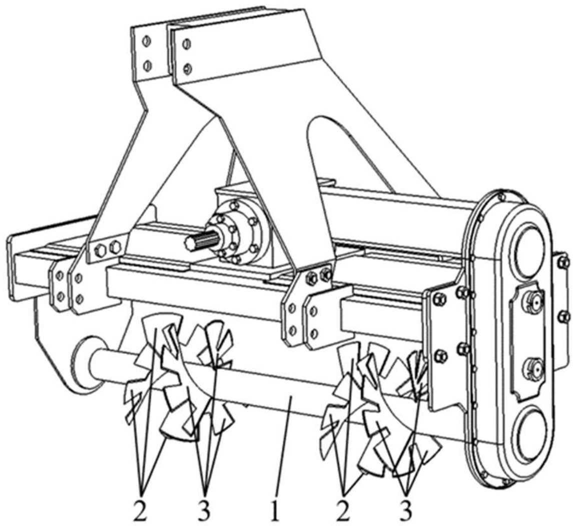


Figure 1. The structure diagram of ASPSRD. Note: 1, the active rotating shaft; 2, the left spiral-notched blade group; 3, the right spiral-notched blade group.

2.1.2. Working Principle

The ASPSRD is installed at the rear of the tractor. Its power is supplied by the tractor's rear output shaft, and it follows the tractor forward during operation. After operation, a seeding belt with almost no straw will be formed. Before operation, the penetration depth of the spiral-notched blades should be adjusted according to the straw coverage on the ground. During the operation, the rotation shaft on which the spiral notch blade is located is reversed, and the straw displacement caused by the reversal is large; after the operation, the straw can be evenly distributed on the surface, which is conducive to the absorption of soil fertility after decomposition. When the spiral-notched blade moving forward rotates, the soil and straw on the seeding belt will make contact with the spiral-notched blade in turn; that is, the contact between the right spiral-notched blade and the left spiral-notched blade will be taken as the center and pushed to either side of the seeding belt along the spiral direction, thus forming a straw removal seeding belt with a certain width. Soil has a greater mass than straw for the same volume, and some of the soil and straw will be thrown up when the machine is in operation. Under the action of gravity, the soil will fall back to the ground faster, and its landing place is closer to the seeding belt in front of the machine. However, the straw will fall back to the ground for a longer time, that is, it will be thrown further, and more straw will reach both sides of the seeding belt. The main function of the notch is to separate straw and soil. The main reason for the separation is that compared with straw, when the soil flows through the notch in the forward direction, due to its large mass, the backward flow force generated by inertia is larger, which makes it easier to pass through the notch and stay in the seeding belt. However, the quality of the straw is low, and the viscous effect between the straw is much greater than that of soil. Under the action of the forward movement of the device and the rotation of the spiral-notched blade, straw is more easily driven by the spiral-notched blade and is pushed to either side of the seeding belt in blocks, which do not easily flow out from the notch, to form a straw removal seeding belt on the premise of minimizing the soil loss.

2.2. Key Components and Parameter Design of ASPSRD

In order to produce a certain width of the straw-cleaning seeding belt after the operation of the machine, this study uses the property that the spiral mechanism can push the material in the axial direction when rotating. By installing the right spiral blade and the left spiral blade symmetrically, the straw on the seeding belt can be pushed to both sides of it, thus realizing the function of straw row sorting. Among them, the arrangement and structural parameters of the spiral blades are the key factors affecting the effectiveness of straw cleaning in the seeding belt, so it is necessary to analyze and study their arrangement and parameters.

2.2.1. Arrangement of Spiral Blades and Pitch of Spiral Blades *S*

Spiral blades are divided into two types: right spiral blades and left spiral blades, both fixed on the active rotating shaft, that is, the inner radius of the spiral blade is the same as the radius of the active rotating shaft. The specific structure is shown in Figure 2. The interaction between the right spiral blade and the left spiral blade is fixed together, and the right spiral blade and the left spiral blade on both sides of the fixed position are symmetrical with each other, that is, the width *W* of the right spiral blade and the left spiral blade remains the same, and their width *W* is half of the width of the seeding belt. The straw row-sorting device designed in this article is suitable for arable land with a seeding belt width of 200 mm, so the width *W* of both the right and left spiral blades is 100 mm. On a plane perpendicular to the axis of the active rotating shaft, three right or left spiral blades can be uniformly distributed. Three right spiral blades form a right spiral blade group, and three left spiral blades form a left spiral blade group. The pitch *S* of the spiral blade is three times the width *W* of the spiral blade installed on the active rotating shaft, that is, the pitch $S = 3W = 300$ mm, where the multiple is consistent with the number of right or left spiral blades. The view of the spiral blade group on the vertical plane of the axis of the active rotating shaft is a complete circle, as shown in Figure 2b so that the spiral blades can always come into contact with the ground during operation, which can improve the efficiency of straw row-sorting compared to devices that do not come into contact with the ground during operation.

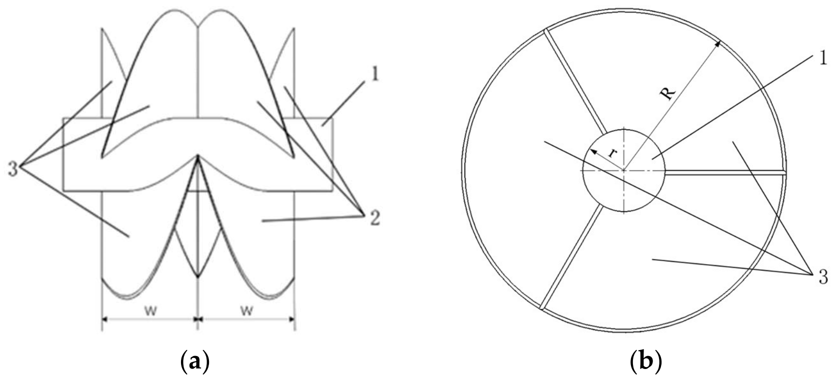


Figure 2. Active spiral push-type straw-cleaning wheel. (**a**) Main view; (**b**) left side view. Note: 1, active rotating shaft; 2, right spiral blade group; 3, left spiral blade group.

To ensure that the straw can move along the axial direction of the active rotating shaft, it is necessary to ensure that the axial velocity and axial force of the straw acted on by the spiral blade are greater than zero. The axial velocity and axial force can be simplified as the relationship between the pitch of the spiral blade and the inner radius of the spiral blade through formula deduction [16]:

$$S < \frac{2\pi r}{\mu}, \tag{1}$$

where *S* is the pitch of the spiral blade, mm; *r* is the inner radius of the spiral blade, mm; and μ is the coefficient of friction.

According to the machining requirements of the machine, the inner radius *r* of the spiral blade is taken as 40 mm. According to the "Agricultural Machinery Design Manual", the friction coefficient μ of straw is 0.3. By substituting the value of μ into Equation (1), the range of values for the spiral blade pitch can be calculated as $S < 837.758$ mm. As can be seen from the previous text, the pitch of the spiral blade is taken as $S = 300$ mm, which meets the design requirements.

2.2.2. Spiral Blade Straw-Pushing Quantity Q

The straw-pushing quantity Q of the spiral blade refers to the maximum total mass of the spiral blade in the straw-cleaning wheel pushing the straw to either side of the seeding belt in a unit time, which can also be understood as the maximum total mass of the disappeared straw in the seeding belt in a unit time. The main influencing factors of spiral blade straw-pushing quantity Q are straw mulching quantity, working width of the machine, tractor forward speed, and straw-cleaning rate. For the purpose of obtaining the calculation data of straw-pushing quantity Q of the spiral blades, a mathematical model of pushing quantity and influencing factors was established.

Because the actual situation is too complex to draw a definite conclusion, the mathematical model should be simplified. Hypothesis: the straw coverage on the ground before the operation of the machine is uniform; the tractor moves along a straight line and the speed is fixed; due to the effect of gravity and the different physical properties of soil and straw, the soil will flow out of the notch first, so the influence of soil on the pushing quantity is not considered in the process of mathematical modeling. This mathematical model can be simplified to an ideal operational process as described below: within a certain operation time t of this straw row-sorting machine, the total straw-pushing quantity Q_z of the spiral blade is equal to the quality difference of the straw in the seeding belt before and after the operation ($Q_1 - Q_2$). Among them, the poor quality in a certain period of time can be determined by straw mulching quantity C_s, tractor forward speed v, number of seeding belts z, total width L_s of straw-cleaning belt (i.e., seeding belt), and straw-cleaning rate λ jointly expressed. The mathematical model of the straw-pushing quantity Q of the spiral blade of the straw row-sorting machine is established by mathematical induction and quotient method as [17]

$$Q = \frac{Q_z}{t} = \frac{Q_1 - Q_2}{t} = \frac{1}{60} C_s v z L_s \lambda \quad (2)$$

where Q is the straw-pushing quantity of the spiral blade, kg/min; Q_z is the total straw-pushing quantity of the spiral blade in a certain operation time, kg; t is the operation time of the straw row-sorting machine, min; Q_1 is the quality of straw in the seeding belt before operation, kg; Q_2 is the quality of straw in the seeding belt after operation, kg; C_s is the straw mulching quantity, kg/m^2; v is the forward speed of the tractor, km/h; z is the number of seeding belts; L_s is the total width of straw-cleaning belt (i.e., seeding belt), mm; and λ is the straw-cleaning rate, %.

Due to the different quantities of straw mulching in different plots in Northeast China, according to previous research, the quantity of straw mulching in Northeast China is generally 0.6~1.8 kg/m^2; we used the maximum quantity of straw mulching C_s, which is 1.8 kg/m^2. The working speed of a straw row-sorting machine in Northeast China is generally 3~7 km/h [18], and we used the maximum speed v of the machine, which is 7 km/h. Each active spiral push straw-cleaning wheel corresponds to one seeding belt, so z is taken as 1. The total width of the seeding belt L_s is 200 mm. The straw-cleaning rate λ takes the maximum value of 1. From Equation (2), it can be calculated that the straw-pushing quantity Q of the spiral blade is 42 kg/min.

2.2.3. Depth of Spiral Blade into Soil h

The spiral blade should be at a suitable depth in the soil. If the depth into the soil is too deep, it will increase the contact area of the spiral blades with the soil, thus increasing the soil loss. If the depth into the soil is too shallow, the spiral blade cannot fully make contact with the straw, which means that some of the straw will pass through the bottom of the spiral blade during the row-sorting operation, and the amount of straw left on the seeding belt will increase. The ideal land condition is flat land, and the spiral blade should just touch the soil surface, that is, the depth into the soil is 0 mm. However, the actual land condition is more complex, and the spiral blade cannot be guaranteed to touch the soil surface at all times, so it is necessary to increase the depth into the soil as far as possible to ensure a low SLR. Considering the fluctuation of soil in the area of no-tillage sowing and returning all corn straw to the field in Northeast China, the depth h of the spiral blade into the soil is set as 5 mm.

2.2.4. Outer Radius of Spiral Blade R

The outer radius R of the spiral blade is an important parameter in the design of the ASPSRD, which is directly related to the structural size and straw-cleaning ability of the device. Referring to the solid conveying theory [19], the calculation formula of the outer radius R of the spiral blade [20] is

$$R \geq \frac{1}{2}K \cdot \sqrt[2.5]{\frac{60Q}{\psi \rho C}}, \tag{3}$$

where R is the outer radius of the spiral blade, m; K is the material characteristic coefficient; Q is the straw-pushing quantity of the spiral blade, kg/min; ψ is the filling coefficient; ρ is the material density, kg/m^3; and C is the inclination coefficient.

By consulting the relevant literature [19,21], the material characteristic coefficient K is taken as 0.05, the filling coefficient ψ is taken as 0.3, and the straw density ρ is taken as 243 kg/m^3. Because the ASPSRD is in a horizontal state during operation, the inclination coefficient C is taken as 1. According to Formula (3), the minimum value of the outer radius R of the spiral blade is about 0.1 m, that is, $R \geq 0.1$ m.

For the purpose of ensuring the feeding amount of straw and improving the straw-cleaning efficiency of the machine, the outer radius of the spiral blade should be as large as possible. However, according to the moment formula $M = FL$, when the inner radius of the spiral blade remains unchanged and the arm of force L, that is, the outer radius R of the spiral blade, increases, the moment M will also increase. When the arm of force L is too large, the working stability of the spiral blade will be seriously reduced, and even the spiral blade will break due to insufficient strength. Refer to the calculation formula of the spiral mandrel [22]:

$$R \leq \frac{r}{200}, \tag{4}$$

where R is the outer radius of the spiral blade, m, and r is the radius of the active rotating shaft or the inner radius of the spiral blade, mm.

It can be seen from the above that r is 40 mm, so $R \leq 0.2$ m.

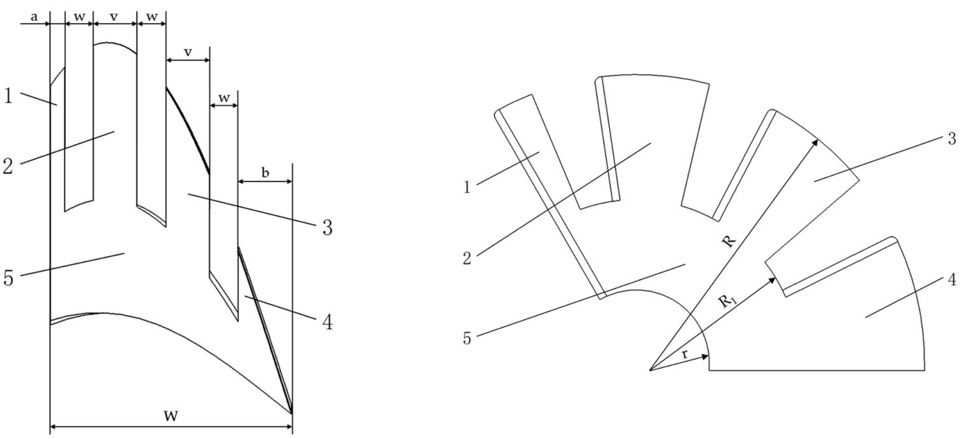
Considering the above factors, the outer radius R of the spiral blade is finally determined to be 0.15 m.

2.2.5. Design of Spiral Picks and Notches

The spiral blade described above can realize the function of a row-sorting straw, but it will cause great loss to the soil in the seeding belt after its operation, that is, the soil affected by the spiral blade will be row-sorted to either side of the seeding belt together with the straw, which does not meet the requirement of low SLR. Therefore, it is necessary to design notches on the spiral blade so that the acted soil flows out of the notch instead of being pushed to both sides. The spiral blade that produces the notched part becomes a pick. Compared with the complete spiral blade, the pick has the function of stirring the straw, which can make the affected straw row-sorting more efficient. But if the notch is too large and the pick is too small, the straw will flow back to the seeding belt from the notch, reducing the SCR after operation. Therefore, a design study of the notch and pick parameters is necessary.

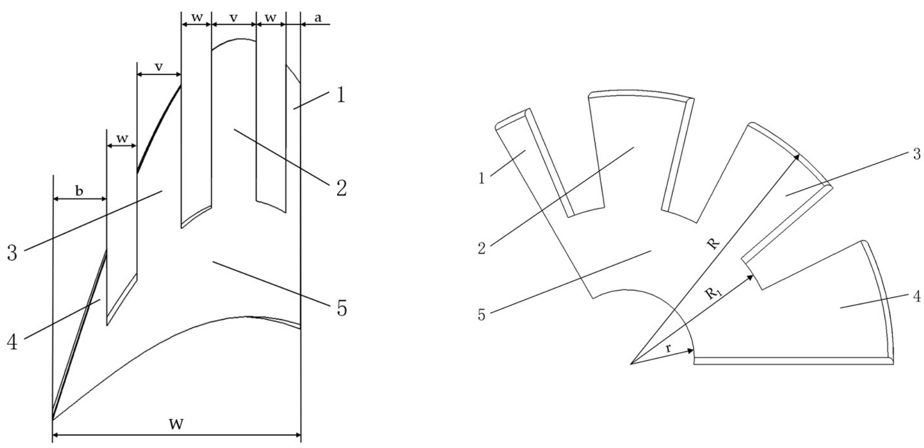
Design of Spiral Pick

All spiral blades need to be machined with notches by grinding. After grinding, the integrity of the spiral blade is destroyed, so that spiral picks are formed between adjacent notches and between the notch and the outside of the spiral blade. The length of the spiral pick is consistent with the notch depth, and its thickness is consistent with that of the spiral blade, as shown in Figures 3a,b and 4a,b. The shape and structure of the spiral pick achieve the purpose of spiral pushing the straw and playing the role of stirring the straw in the meantime, making the effect of the whole spiral blade row-sorting to the straw better. That is, the process changes from collecting and pushing straw to stirring, collecting, and pushing straw. This has led to a significant improvement in the effectiveness of straw clearing.



(**a**) (**b**)

Figure 3. Right spiral-notched blade. (**a**) Main view; (**b**) left side view. Note: 1, first-stage right spiral pick; 2, second-stage right spiral pick; 3, third-stage right spiral pick; 4, fourth-stage right spiral pick; 5, ungrounded right spiral blade.



(**a**) (**b**)

Figure 4. Left spiral-notched blade. (**a**) Main view; (**b**) left side view. Note: 1, first-stage left spiral pick; 2, second-stage left spiral pick; 3, third-stage left spiral pick; 4, fourth-stage left spiral pick; 5, ungrounded left spiral blade.

The number of notches on the spiral blade is positively correlated with the number of spiral picks, that is, when the number of notches is k, the number of spiral picks is $k + 1$. Here, take $k = 3$ as an example to explain in detail the structure and function of notch and pick. After grinding, the right spiral blade becomes a right spiral-notched blade, and its radius R remains unchanged. The structure is composed of the first-stage right spiral pick, second-stage right spiral pick, third-stage right spiral pick, fourth-stage right spiral pick, and ungrounded right spiral blade, as shown in Figure 3a,b. After grinding, the left spiral blade becomes a left spiral-notched blade, and its radius R remains unchanged. The structure is composed of the first-stage left spiral pick, second-stage left spiral pick, third-stage left spiral pick, fourth-stage left spiral pick, and the ungrounded left spiral blade, as shown in Figure 4a,b.

When machining the notch, grind it vertically in the direction of the main view, as shown in Figure 3a or Figure 4a, and ensure that the depth of the notch is the same, that is, both are $R - R_1$. At the same time, the length of the spiral pick is also $R - R_1$, as shown in Figures 3b and 4b. The length of the spiral pick is positively correlated with the straw mulching quantity, that is, when the straw mulching quantity is large, the spiral pick length should be increased, and when the straw mulching quantity is small, the spiral pick length can be taken as smaller. The value of the outer radius R of the spiral-notched blade must be 3/2 times greater than the notch radius R_1 of the spiral-notched blade, that is, $R > 3/2R_1$. If the difference between the values of R_1 and R is too small, the role of the spiral pick in stirring the straw is weakened, and it cannot significantly improve the quality of straw cleaning in the seeding belt. For the purpose of ensuring the role of the spiral pick in stirring the straw, under the condition that the outer radius R of the spiral-notched blade is fixed, the notch radius R_1 of the spiral-notched blade should be as small as possible. However, if the value difference between R_1 and R is too large, the working stability of the spiral pick will be reduced, and the spiral pick will be broken. Therefore, the value of the outer radius R of the spiral-notched blade shall not exceed twice the notch radius R_1 of the spiral-notched blade, that is, $R \leq 2R_1$. Considering the above factors, the value range of the outer radius R of the spiral-notched blade and notch radius R_1 of the spiral-notched blade is $3/2R_1 < R \leq 2R_1$. As can be seen from the above, the outer radius R of the spiral-notched blade is taken as 0.15 m. Therefore, the notch radius R_1 of the spiral-notched blade in this study is taken as 0.085 m, so the notch depth of the spiral-notched blade is $R - R_1$ = 0.065 mm.

When machining the notch, ensure that the width of the notch is consistent. As shown in Figures 3a and 4a, the width of the notch is w, and the width of the spiral pick between the notches is v. The notch width w is different with different straw mulching quantities. The width of the spiral pick on both sides of the right spiral-notched blade and the left spiral-notched blade needs to be adjusted according to the operation width and the number of notches. In addition, the width a of the spiral pick near the junction of the right spiral-notched blade and the left spiral-notched blade, that is, the first-stage right spiral pick and the first-stage left spiral pick, must be greater than or equal to half of the notch width w. The width b of the spiral pick that is farthest from the intersection, that is, the fourth-stage right spiral pick and the fourth-stage left spiral pick, must be greater than or equal to half of the notch width w; if it is less than half of the notch width w, the notch that is farthest from the center of the straw-cleaning wheel should be canceled to make it become a spiral pick.

Design of Spiral Blade Notch

For the purpose of preventing the straw from flowing out of the notch of the blade and ensuring that the soil driven by the spiral pick passes through the notch, the notch positions of different blades on the active rotating shaft are different. As shown in Figure 5, the thin solid line in the figure is the auxiliary line, highlighted so as to better observe the position relationship of different spiral picks and notches. The thick solid line is the arrangement line of the spiral picks, w is the notch width, v is the width of the spiral picks between notches, and W is the width of the spiral blades.

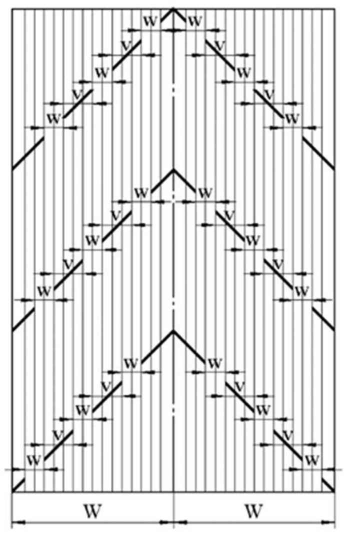


Figure 5. Layout of spiral picks and notches.

The spiral pick and notch are symmetrically distributed with the junction of the right spiral notch blade and the left spiral notch blade as the centerline. In the right spiral-notched blade group or the left spiral-notched blade group, the notches of each blade are arranged to one side along the axis of the active rotating shaft, and the spacing of close notches of adjacent blades is half of the notch width w, as shown in the auxiliary line of Figure 5. For the purpose of ensuring the collection and pushing effect of the spiral pick, the width v of the spiral pick between the notches of each blade should be greater than the width w of the notch. For the purpose of ensuring the stirring effect of the spiral pick, the width v of the spiral pick between the notches of each blade should be less than twice the width w of the notch, that is, $w < v < 2w$. In this study, the spiral pick width v between notches is 3/2 times the notch width w, that is, $v = 3/2w$.

2.3. Experiment of EDEM Discrete Element Simulation

The discrete element method is often used to study the relationship between soil, crops, and other multiparticle media and operating components [23]. It can observe and analyze the displacement and stress of particles after being acted upon by operating components and then provide the basis for the structure and parameter optimization of the operating components. In this paper, the discrete element simulation software EDEM 2020 is used to establish the interaction model between the soil, straw, and working parts and simulate and analyze the actual operation process of the straw row-sorting device. In the simulation process, the SCR and SLR in the seeding belt were selected as the evaluation indexes, and the SMQ, the RSARS, the FST, and the NWSNB were selected as the main test factors. Discrete element simulation was used to analyze the influence rule of various experimental factors on the SCR and SLR in the seeding belt in order to obtain the optimal structure of the working parts and the combination of operation parameters and lay the groundwork for subsequent processing machines and field validation tests.

2.3.1. Establishment of EDEM Simulation Model

The EDEM simulation model of the ASPSRD is shown in Figure 6, which mainly includes the soil trough model and the active spiral push notch straw-cleaning wheel model, in which the soil trough model is composed of the soil model and straw model. The straw in the soil trough is evenly laid on the soil to simulate actual farmland covered with a certain amount of straw. During the simulation, the active spiral push-notch straw-cleaning wheel moves along a plane in a straight line at a certain rotation speed and forward speed to simulate the process of straw cleaning in the field.

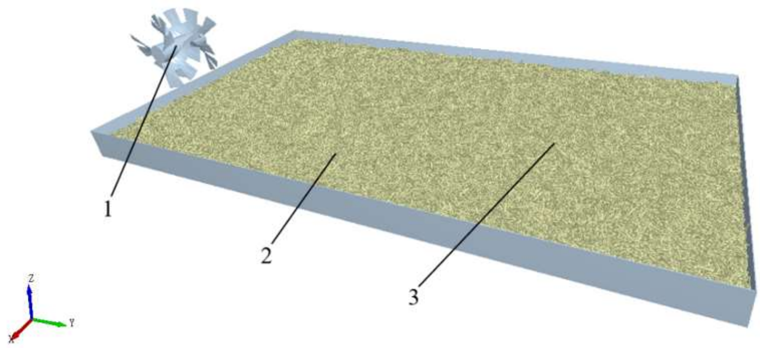


Figure 6. Simulation model of ASPSRD. Note: 1, simulation model of active spiral push notch straw-cleaning wheel; 2, simulation model of soil; 3, simulation model of straw.

Considering the computing power and simulation efficiency of the computer, it is necessary to simplify the model of the ASPSRD, that is, remove the parts that do not affect the operation effect and only keep one active spiral push notch straw-cleaning wheel. The three-dimensional modeling software SOLIDWORKS 2018 was used to establish the model of the active spiral push-notch straw-cleaning wheel, which was saved as a STEP file and imported into EDEM software. Then, the straight-line motion along the Y-axis direction and the rotation motion with the center axis of the active rotating shaft as the centerline are added to the active spiral push notch straw-cleaning wheel to simulate the forward motion of the tractor and the rotation motion of the active spiral push notch straw-cleaning wheel, respectively. The material of the active spiral push notch straw-cleaning wheel is 45 steel. The physical parameters of the simulated steel model are shown in Table 1.

Table 1. Physical parameters and contact parameters of simulation model.

Parameters	Soil	Straw	Steel
Density/(kg/m^3)	1850	243	7800
Poisson's ratio	0.38	0.4	0.31
Shear modulus/Pa	1.0×10^6	1.0×10^6	7.0×10^{10}
Restitution coefficient (Interaction with soil)	0.20	0.50	0.28
Static friction coefficient (Interaction with soil)	0.40	0.30	0.50
Rolling friction coefficient (Interaction with soil)	0.25	0.05	0.04
Restitution coefficient (Interaction with straw)	0.50	0.30	0.30
Static friction coefficient (Interaction with straw)	0.30	0.65	0.30
Rolling friction coefficient (Interaction with straw)	0.05	0.06	0.01
Restitution coefficient (Interaction with steel)	0.28	0.30	-
Static friction coefficient (Interaction with steel)	0.50	0.30	-
Rolling friction coefficient (Interaction with steel)	0.04	0.01	-

In order to truly reflect the speed and displacement of field straw and topsoil under the action of the straw-cleaning wheel, a soil model needed to be established and covered with a straw model in EDEM. In order to simulate the adhesion between soil particles, Hertz–Mindlin with a no-slip model was selected to model the contact between the soil particles [24]. The soil particles are represented by spheres with a radius of 5 mm [25]. The soil trough size (length × wide × height) is 2000 mm × 1000 mm × 100 mm, and the depth of soil in the soil trough is 50 mm. The physical parameters of the simulated soil model are shown in Table 1.

The soil trough model shown in Figure 6 shows the initial state of straw mulching on the ground before the simulation operation. For a more accurate simulation of the mulching state of crushed straw in the field, referring to the actual size, three long linear models with a total length of 39 mm arranged along the X-axis were generated, which were composed of 25 balls with a radius of 1.5 mm and a center-to-center spacing of 1.5 mm. The central axes of the three long linear models are parallel to each other, and the central axes are arranged in sequence with a spacing of 1.5 mm along the Y-axis direction, that is, the final dimension of the straw particle model (X-axis × Y-axis × Z-axis) is 39 mm × 6 mm × 3 mm, as shown in Figure 7. The physical parameters of the simulated straw model are shown in Table 1. When the straw particle model is generated in the soil trough, it falls freely and evenly in the whole soil trough by gravity. The simulation time should be as long as possible to ensure that a stable bond is formed between the particles and that the particles are completely static.

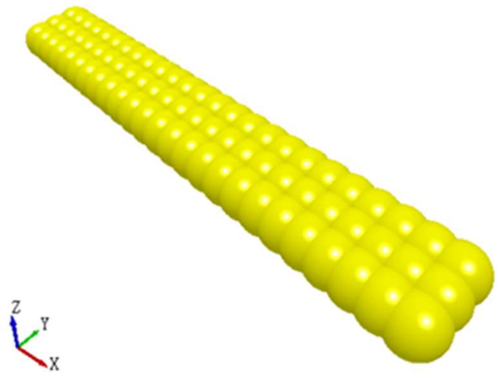


Figure 7. Straw particle model.

For the purpose of ensuring the accurate and smooth operation of the simulation, the contact parameters between soil and soil, soil and straw, soil and steel, straw and straw, and straw and steel should be set. The contact parameters of the simulation model obtained according to the literature [16,18,23,26] are shown in Table 1.

2.3.2. Experimental Scheme

Considering the purpose for which the device was designed and testing the effectiveness of the operation, this simulation experiment takes the SCR and SLR in the seeding belt as the evaluation index and selects the SMQ, the RSARS, the FST, and the NWSNB as the test factors. Each test factor has three test levels: the maximum value, the minimum value, and the intermediate value. But even if only these four test factors are considered and each factor only considers three test levels, 81 simulation tests are needed to simulate all cases, which is too heavy and unnecessary. Here, the orthogonal combination test method of four factors and three levels in mathematical statistics [27] is used to reduce the workload and obtain a more accurate conclusion.

The basic principle of the four-factor, three-level orthogonal combination test method is to select 9 groups of representative factor-level combinations from all the tests. They have the characteristics of "uniform dispersion, [and are] neat and comparable". This method has been proven to be a scientific and efficient test design method, which is widely used in the process of test analysis to reduce the number of tests and improve work efficiency [28]. Therefore, the orthogonal combination simulation test of four factors and three levels is carried out in EDEM. Through the structural parameter analysis and theoretical calculation of the device, and several groups of pre-tests, the value range of each factor is finally determined. For the purpose of researching the operation effect of the machine in areas with different straw quantities, the value range of SMQ was selected as 0.6~1.8 kg/m^2.

In order to minimize tractor energy consumption and reduce the throwing speed of the affected straw, the value range of the RSARS is set to 60~120 rpm. In order to significantly increase the operation speed under the premise of ensuring high SCR, the FST is set to be 3~4 m/s. For the purpose of studying the influence of different widths of the notch on straw cleaning, under the premise of complying with the design principle of notch width, the value range of NWSNB was determined to be 9~15 mm. The specific test factors and codes are shown in Table 2.

Table 2. Test factors and codes.

Code	The SMQ/(kg/m^2)	The RSARS/rpm	The FST/(m/s)	The NWSNB/mm
1	0.6	60	3	9
2	1.2	90	3.5	12
3	1.8	120	4	15

2.3.3. Experimental Index

It can be seen from the above that the cleaning width of the seeding belt of the active spiral push notch straw-cleaning wheel is 200 mm. For a more accurate observation of the straw-cleaning effect of the seeding belt, the "Setup Selections" function in the post-processing of EDEM software was used, and a 200 mm width seeding belt was selected. Considering the data fluctuation caused by the straw-cleaning wheel entering and leaving the soil trough, a total length of 1000 mm in front and behind the center of the soil trough was selected for the seeding belt. Finally, the detection plane range (length × wide) is determined as a 1000 mm × 200 mm rectangular seeding belt area, as shown in the red box in Figure 8. When measuring the straw quality in the rectangular area, it is necessary to ensure that the cuboid area formed by its height can contain all the straw in the seeding belt. When measuring the soil quality, considering that the sowing depth of corn seeds is generally 30~50 mm, the lowest plane of the cuboid height is 30 mm below the contact plane of straw and soil, and the highest plane of the cuboid should ensure that it covers all the soil in the seeding belt. By recording the changes in straw quality and soil quality in the cuboid area before and after the operation, and through formula calculation, the corresponding SCR and SLR are finally obtained.

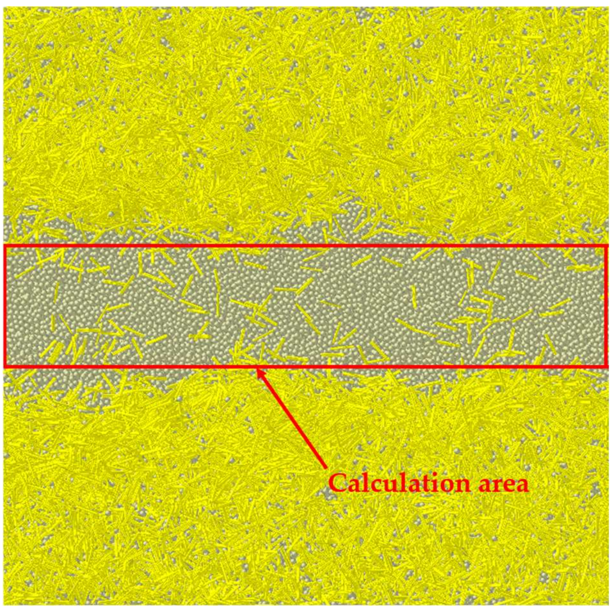


Figure 8. Calculation area of SCR and SLR in seeding belt.

The formula for calculating the SCR of the seeding belt is

$$\lambda = \frac{m - m_1}{m} \times 100\%, \tag{5}$$

where λ is the SCR, %; m is the straw quality before simulation operation, kg; and m_1 is the straw quality after simulation operation, kg.

The formula for calculating the SLR of the seeding belt is

$$\theta = \frac{q - q_1}{q} \times 100\% \tag{6}$$

where θ is the SLR, %; q is the soil quality before the simulation operation, kg; and q_1 is the soil quality after the simulation operation, kg.

2.3.4. Process of Simulation

The starting position of the active spiral push-notch straw-cleaning wheel is set on the outside of the soil trough, and its lowest position is equal to the highest position of soil particle accumulation in the soil trough. For the purpose of ensuring the accuracy and continuity of soil particles and straw particles in the process of simulation operation, through pre-experiment, the fixed time-step of the simulation operation is determined to be 7.5×10^{-6} s, the total simulation time is 1 s, and the grid size is set to 3 times the minimum particle size. The simulation operation process of the straw-cleaning wheel is shown in Figure 9.

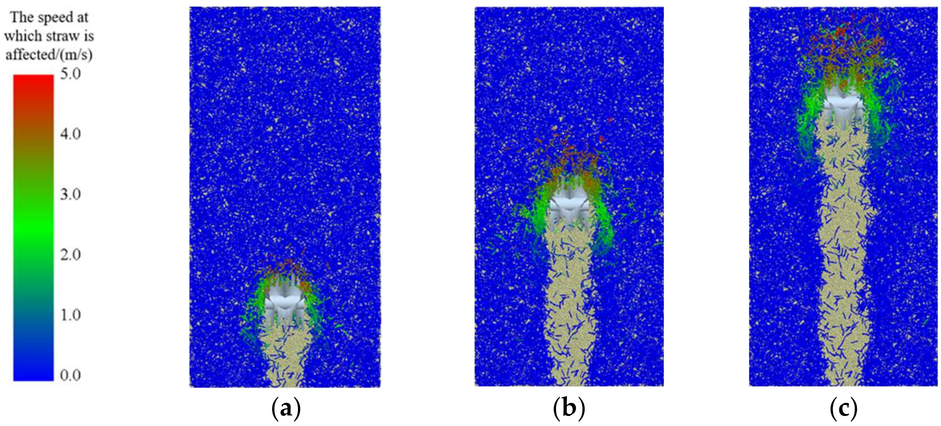


Figure 9. Simulation operation process of active spiral push notch straw-cleaning wheel. (**a**) Early stage of simulation operation; (**b**) middle stage of simulation operation; (**c**) later stage of simulation operation.

3. Results and Discussion

3.1. Results and Analysis of Simulation Experiment

The specific scheme of the four-factor, three-level orthogonal combination test and the final results of the EDEM simulation are shown in Table 3. In the table, the codes 1, 2, and 3 of each factor column indicate the level of the factor. See Table 2 for their specific values. X_1, X_2, X_3, and X_4 are the coded values of each factor. The simulation results of this experiment are the SCR and SLR in the seeding belt.

For further research on the impact of these four factors on the SCR and SLR, the data in Table 3 were analyzed by range analysis [29], and the results are shown in Tables 4 and 5. In these two tables, G_{mn} is the sum of SCR or SLR of the nth factor at the mth level. H_{mn} is the average value of the sum of SCR or SLR of the nth factor at the mth level. For the SCR in the seeding belt, the maximum value of H_{mn} is the optimal level of this factor, but for the SLR in the seeding belt, the minimum value of H_{mn} is the optimal level of this factor. The range is the difference between the maximum and minimum values in G_{mn}. The greater the range, the greater the impact of the level of change in this factor on the SCR or SLR, that is, the greater the importance of this factor in this experiment; on the contrary, the smaller the range, the smaller the importance of this factor.

Table 3. Test scheme and simulation results.

Test No.	The SMQ X_1	The RSARS X_2	The FST X_3	The NWSNB X_4	SCR in Seeding Belt/%	SLR in Seeding Belt/%
1	1	1	1	1	82.76	4.08
2	1	2	2	2	83.89	4.11
3	1	3	3	3	85.54	4.57
4	2	1	2	3	86.73	3.97
5	2	2	3	1	93.62	3.63
6	2	3	1	2	91.69	3.01
7	3	1	3	2	91.65	3.97
8	3	2	1	3	90.87	3.42
9	3	3	2	1	94.91	3.11

Table 4. Range analysis of SCR in seeding belt.

Index	The SMQ X_1	The RSARS X_2	The FST X_3	The NWSNB X_4
G_{1n}	252.19	261.14	265.32	271.29
G_{2n}	272.04	268.38	265.53	267.23
G_{3n}	277.43	272.14	270.81	263.14
H_{1n}	84.06	87.05	88.44	90.43
H_{2n}	90.68	89.46	88.51	89.08
H_{3n}	92.48	90.71	90.27	87.71
Range	8.41	3.67	1.83	2.72

Table 5. Range analysis of SLR in seeding belt.

Index	The SMQ X_1	The RSARS X_2	The FST X_3	The NWSNB X_4
G_{1n}	12.76	12.02	10.51	10.82
G_{2n}	10.61	11.61	11.19	11.09
G_{3n}	10.50	10.69	12.17	11.96
H_{1n}	4.25	4.01	3.50	3.61
H_{2n}	3.54	3.72	3.73	3.70
H_{3n}	3.50	3.56	4.06	3.99
Range	0.75	0.44	0.55	0.38

3.2. Discussion

As for the SCR in the seeding belt, it can be seen from Table 4 that the SCR is positively correlated with the SMQ, the RSARS, and the FST and negatively correlated with the NWSNB. With the increase in SMQ, the residual straw quality after the straw-cleaning wheel operation also increased, but the former increased the quality higher than the latter. According to Formula (5), the SCR will be improved. Because the rotating spiral pick will produce an axial force on the straw through the spiral pick, when the RSARS increases, the axial force will also increase, which makes the straw acted on by the spiral pick be pushed to both sides of the seeding belt more easily, so as to improve the SCR. The faster the FST, the faster the movement speed of the straw under the action of the spiral pick. Under the rotating action of the spiral pick, the straw will be thrown farther away, making more straw leave the seeding belt, thus improving the SCR. The smaller the NWSNB, the more difficult it is for the straw to flow out of the notch, so the higher the SCR.

As for the SLR in the seeding belt, it can be seen from Table 5 that the greater the SMQ and the faster the RSARS, the lower the SLR, while the faster the FST and the greater the NWSNB, the higher the SLR. When the SMQ increases, the soil that leaves the land due to the action of the spiral pick is more likely to be pressed back into the land by a large amount of straw, thus reducing the SLR. When the RSARS is accelerated, the change in the amount of time that the spiral pick is in contact with the soil is also accelerated, making it easier for the soil particles to pass through the notch and spiral pick and remain in the seeding belt, resulting in lower SLR. The faster the FST, the faster the movement speed of the soil pushed by the spiral pick, and the less time the soil particles have to return to the seeding belt, leading to an increase in the SLR. According to the above-mentioned spiral pick design principle, "the width of the spiral pick furthest from the center of the straw-cleaning wheel must be greater than or equal to half of the notch width. If it is less than half of the notch width, the notch furthest from the center of the straw-cleaning wheel should be canceled to become a spiral pick." Therefore, when the NWSNB increases to a certain extent, the number of notches will decrease, and the width of the spiral pick farthest from the center of the straw-cleaning wheel will increase. The spiral pick will push more soil to both sides of the seeding belt, leading to an increase in the SLR.

4. Optimization and Verification

4.1. Parameter Optimization

The order of magnitude of the effect of each test factor on the SCR is X_1, X_2, X_4, X_3. The optimal factor level combination of the straw-cleaning wheel when the SCR is the highest is X_1 = 1.8 kg/m^2, X_2 = 120 rpm, X_3 = 4 m/s, and X_4 = 9 mm. The order of magnitude of the effect of each test factor on the SLR is X_1, X_3, X_2, X_4. The optimal factor level combination of the straw-cleaning wheel when the SLR is the lowest is X_1 = 1.8 kg/m^2, X_2 = 120 rpm, X_3 = 3 m/s, and X_4 = 9 mm. Because the first consideration of the straw-cleaning wheel designed in this paper is the SCR and the fluctuation of SLR caused by X_3 change is within a reasonable range, the value of X_3 should be 4 m/s. Therefore, the optimal factor level combination of the straw-cleaning wheel operation is an SMQ of 1.8 kg/m^2, RSARS of 120 rpm, FST of 4 m/s, and NWSNB of 9 mm. Since the optimal factor combination does not exist in the orthogonal combination test in Table 3, under the same test conditions, this factor combination scheme was selected, and repeated simulation tests were carried out again. Finally, the average SCR in the seeding belt is 96.28%, and the average SLR in the seeding belt is 3.94%.

Compared with the test results in Table 3, the SCR of the optimal factor combination has been greatly improved. Although the SLR cannot reach the minimum value in Table 3, it is still within a reasonable range. And because the FST is significantly accelerated, the overall operation efficiency of the machine is improved.

4.2. Field Test

4.2.1. Field Test Conditions

To verify the authenticity of the above mathematical analyses and simulation tests and to determine the field operation performance of the ASPSRD, a field test was conducted in Qingshiling (longitude: 124.09046, latitude: 41.33486), Xiaoshi Town, Benxi Manchu Autonomous County, Benxi City, Liaoning Province, on 5 November 2023. The test field is a crop field covered with corn straw that has been completely chopped and returned to the field. The previous crop is the corn planted in May of the same year. The soil texture of the test field is brown soil. During the machine test, the daily average temperature during the test period was 9~13 °C. Affected by the continuous rainfall in this area, the moisture content of soil and straw in the field was high. The main parameters of the ground conditions in the test area are shown in Table 6, and the ground conditions before device operation are shown in Figure 10.

Table 6. Main parameters of field test.

Items	Parameters	Values
The straw of the field	Average length, mm	228
	Average diameter, mm	23
	Covering thickness, mm	52
	Mulching quantity, (kg/m^2)	1.8
	Moisture content, %	31.09
0–50 mm soil layer	Firmness, kPa	506
	Moisture content, %	20.64
	Bulk density, (g/cm^3)	1.31

Figure 10. Ground straw before operation.

4.2.2. Test Method and Result Analysis

Before the operation, five rectangular areas, 1000 mm in width and 1000 mm in length, were randomly selected from the field to be operated. The ground straw and soil more than 30 mm below the ground were collected and weighed. After the operation was completed, five rectangular areas with a width of 200 mm centered on the seeding belt and a length of 1000 mm along the direction of the seeding belt were randomly selected in the seeding belt with cleared straw. The residual straw mass and the soil mass more than 30 mm below the horizontal surface of the ground without operation were weighed.

The field test site of machine operation is shown in Figure 11. For the purpose of carrying out the comparative test, the machine for processing trial production was equipped with two straw-cleaning wheels. In Figure 11, the NWSNB of the straw-cleaning wheel on the left is 9 mm, and the NWSNB of the straw-cleaning wheel on the right is 15 mm. When the machine is operating, the RSARS is set to 120 rpm and the FST to 4 m/s. The effect of straw cleaning of the seeding belt after the operation of the machine is shown in Figure 12.

From Figure 12, it can be seen that the SCR of the straw-cleaning wheel with a notch width of 15 mm under this operating condition is significantly lower than that of the straw-cleaning wheel with a notch width of 9 mm. Therefore, only the straw and soil quality in the left seeding belt of Figure 12 are weighed. The SCR and SLR were calculated using Formulas (5) and (6). The final calculation results of the field test are shown in Table 7.

Table 7. Results of field test.

Parameters	SCR in Seeding Belt, %	SLR in Seeding Belt, %
Average	95.32	7.12
Variation	1.23	11.03

Figure 11. Field test site.

Figure 12. Effect of straw cleaning on the seeding belt after operation.

According to Table 7, the average SCR in the seeding belt is 95.32%, which is reduced by 0.96% compared with the simulation test. The reason for the decrease is that there are more fine straw and leaves on the field surface, which will pass through the notch and then fall back to the seeding belt, so they cannot be effectively row-sorted. In addition, in the process of machine operation, due to the long length of some straw, they will be thrown back into the seeding belt by the spiral notch blade, which will cause a decrease in SCR. According to Table 7, the average SLR in the seeding belt is 7.12%, which is increased by 3.18% compared with the simulation test. The reason for the increase is that the surface of the field is not flat and there are many raised parts. During the operation of the straw-cleaning wheel, the raised parts will be collected and pushed to both sides of the seeding belt, resulting in increased SLR. In general, the ASPSRD can basically meet the operation requirements of no-tillage sowing.

5. Conclusions

(1) This paper designs an ASPSRD which combines the advantages of passive and active straw row-sorting machines. The device is powered by the tractor to rotate the straw-cleaning wheel during operation. The picks in the straw-cleaning wheel stir, collect, and push the ground straw to the non-seeding belt. The notches in the straw-cleaning

wheel allow the affected soil to pass through and flow back to the seeding belt. It effectively solves the problems of low SCR and high SLR in the previous straw row-sorting device.

(2) The pitch range of the spiral-notched blade is determined by force analysis. The mathematical model of straw-pushing quantity was established using the mathematical induction and quotient method. Through theoretical analysis and formula calculation, the structural parameters of the straw-cleaning wheel, such as the outer radius of the spiral-notched blade, the number of spiral picks, and the notch width, were determined, and on this basis, the value range of the working parameters of the straw-cleaning wheel was established.

(3) The four-factor and three-level orthogonal combination test method was used to carry out the EDEM discrete element simulation test. The SMQ, the RSARS, the FST, and the NWSNB were selected as the test factors, and the SCR and SLR were taken as the test indexes. Range analysis and parameter optimization of the test results were carried out. The results showed that the optimal parameter combination of the operation of the straw row-sorting device was an SMQ of 1.8 kg/m^2, RSARS of 120 rpm, FST of 4 m/s, and NWSNB of 9 mm.

(4) The results of field experiments using the optimal parameters showed that the straw-cleaning effect of the ASPSRD was significant. The SCR was 95.32% and the SLR was 7.12% under the 20 cm wide seeding belt. This result is basically consistent with the simulation test results and can meet the agronomic and technical requirements of corn no-tillage sowing in Northeast China.

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Nomenclature

ASPSRD	Active spiral pushing straw row-sorting device
SMQ/C_s	Straw mulching quantity
RSARS	Rotating speed of the active rotating shaft
FST/v	Forward speed of the tractor
NWSNB	Notch width of spiral notch blade
SCR/λ	Straw-cleaning rate
SLR	Soil loss rate

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