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Working Performance of Bidirectional Profiling Press Device in Hilly Areas of Northeast China

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Abstract: According to the conditions of seeding operations in hilly areas of Northeast China, a bidirectional profiling press device (BPPD) was designed. The BPPD mainly consists of a press roller and strength adjusting mechanism which could grant the BPPD horizontal and vertical profile ability. The orthogonal tests L_9 (3^4) in the field were conducted to investigate the press roller types and operating parameters effects of the BPPD working performance. In the field tests, three kinds of press rollers—rubber press roller (RPR), planar press roller (PPR) and squirrel cage-type press roller (SPR)—were tested under the condition of three spring deformations (10 mm, 20 mm, and 30 mm) and three forward speeds (3 km/h, 5 km/h and 7 km/h). The soil moisture content, average emergence time, emergence ratio, and plant height uniformity were tested as test indexes. Using statistical analysis software, the results of the orthogonal test are press roller type, spring deformation and forward speed have significant influence on the test indexes of soil moisture content, average emergence time, emergence ratio, and plant height uniformity which press roller type have highly significant influence on the average emergence time and emergence ratio index. Using a comprehensive weighted algorithm, the sequence of factors affecting the BPPD performance was determined: spring deformation, forward speed, and press roller type; optimal combination: press roller type PPR, a spring deformation of 20 mm, and a forward speed of 5 km/h.

Keywords: profiling press device; roller; forward speed; seedbed properties; corn emergence; hilly area

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1. Introduction

Cultivated land can be divided into two types: flat cultivated land and sloping cultivated land. The sloping cultivated land is mainly focused on hilly areas [1,2]. In Northeast China, hilly areas total approximately 788,000 hm^2, accounting for 37.2% of the total area, and they are mainly distributed in southwestern Heilongjiang Province [3], eastern Jilin Province [4] and western Liaoning Province [5]. These areas are located in the core region of the northeastern black soil region (one of the three major black soil belts in the world) [6–9], and the region is an important crop-producing area [10–12]. However, the hilly areas are characterized by undulating terrain, low altitude, gentle slope [13,14] and the uneven distribution of soil [15]. In addition, the hilly areas are usually in the transition zone between mountains or plateaus and plains [9]. Therefore, this terrain restricts the development of agricultural mechanization, and agricultural mechanization technology in hilly areas is weak [16]. In recent years, researchers have focused on flat cultivated land machinery technology but less on that for hilly areas, especially research on the related technology of seeders in hilly areas. Compaction after sowing is the key link in the mechanization of main crop operations in hilly areas [17]. The technology of compaction is also one of the related technologies of hilly sowing machines and directly affects the quality and performance of sowing. It is necessary to study the compaction technology of seeders in hilly areas to improve the soil environment of the seedbed, increase the emergence rate, and enhance the operational efficiency [18].

To meet the requirements of hilly sowing operations and improve sowing efficiency in hilly areas, researchers introduced the small-scale seeders used in flat cultivated land into hilly areas [19,20]. When sowing in hilly areas, the ditching, sowing and covering abilities of small-sized seeders are well known. When planting crops in hilly areas, farmers often choose to plant crops on the cross slope, along the slope, or on both the cross slope and along the slope [21,22]. Because the small seeders in flat cultivated land do not have the ability of horizontal profiles, the phenomenon of horizontally inhomogeneous compaction appears after operating. Aiming at the above problems, under the condition that the existing seeders can realize longitudinal profiling, it is necessary to design a compaction device with horizontal profile ability.

Soil compaction after sowing has significant effects on soil physical properties [23], such as soil moisture content, soil hardness, and soil temperature [24]. Soil compaction can increase the soil hardness, thereby increasing the soil moisture and maintaining soil temperature [25]. Appropriate soil moisture content and soil temperature are essential for seed germination [26,27]. Therefore, appropriate soil compaction can influence seed germination and seedling growth, such as shortening the emergence time, increasing the emergence ratio and accelerating the growth of seedlings [28,29].

In this study, to solve the problem of inhomogeneous compaction after corn seeding operations in hilly areas, the BPPD was designed. Furthermore, the working effects of three kinds of press rollers (RPR, PPR, and SPR) at three spring deformations (10 mm, 20 mm, and 30 mm) and three operating speeds (3 km/h, 5 km/h, and 7 km/h) were further explored. The purpose of this study was to determine the effects of the BPPD on seedbed properties and corn emergence in hilly areas of Northeast China.

2. Materials and Methods

2.1. Operating Principle of the BPPD

In the process of working in hilly areas, the BPPD can achieve a longitudinal profile through the connection between the upper bracket and front beam (the front beam of the seeder has a longitudinal profile device [30]), and the BPPD achieves a horizontal profile through the connection between the lower bracket and upper bracket. Figure 1 shows the structure of the BPPD. In the longitudinal profile, as the profiling device is between the front beam and the frame, the BPPD will fluctuate with the height of the terrain when the BPPD encounters a bulge on the ground [31].

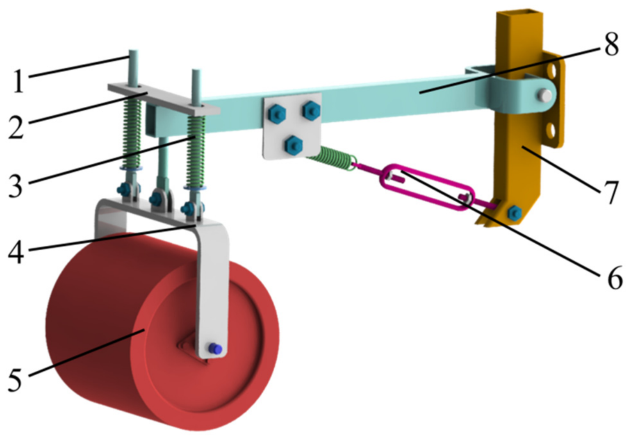

Figure 1. A structural diagram of the BPPD: (1) hanger rod, (2) limiting plate, (3) balance spring, (4) lower bracket, (5) press roller, (6) compression strength regulator, (7) front beam and (8) upper bracket.

When the seeder works in hilly areas, there is often an angle between the ground and the horizontal line (φ), and the frame is parallel to the inclined plane. The traditional press device is rigidly connected with the upper bracket and cannot rotate horizontally relative to the upper bracket, so there is an angle between the traditional press device and the soil surface after the overlying soil. In this way, the inconsistent penetration depth of the transverse press roller results in uneven transverse compaction, as shown in Figure 2a. The BPPD can rotate around the joint relative frame and can be parallel to the surface of the overlying soil under the action of gravity and a balance spring, so the depth of the press roller is the same and the lateral compaction is uniform, as shown in Figure 2b. When the seeder is not in operation, the press roller can automatically retract so that the impact force on the BPPD can be reduced, and the BPPD can be protected. The function of the compression strength regulator is to change the compaction intensity by changing the spring pre-tightening force and finally to achieve the purpose of enhancing the compaction effect [31]. The main structural parameters of the BPPD are shown in Table 1.

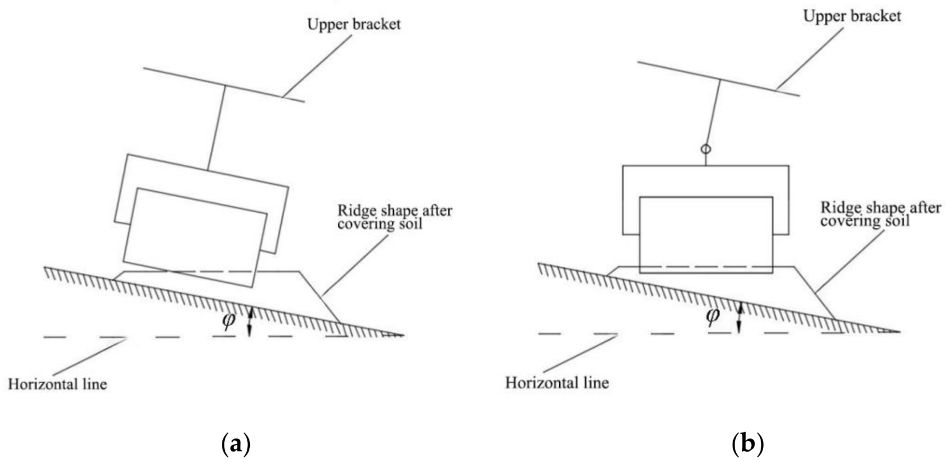

Figure 2. A motion sketch of the press device: (**a**) traditional press device; (**b**) the BPPD.

According to the schematic diagram in Figure 3, the horizontal profiling adjustment mechanism is designed. In Northeast China, the hills with slopes of 5° to 25° is mainly corn growing area. Thus, the maximum rotation angle of the press roller is designed to be 25° relative to the limit plate (Figure 3). Figure 3 shows that the vertical and lateral displacement change of the hanger rod is 38 mm and 7.5 mm, which determine the size of the hanger rod and the limiting plate. The function of the compression strength regulator is to change the compaction intensity by changing the spring pre-tightening force and finally to achieve the purpose of enhancing the compaction effect [31]. The main structural parameters of the BPPD are shown in Table 1.

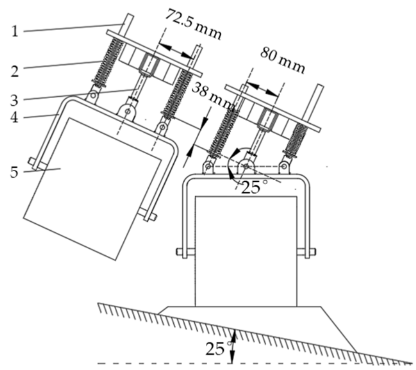

Figure 3. A motion sketch of the lateral balance state and lateral profiling state of the BPPD: (1) hanger rod, (2) balance spring, (3) upper bracket, (4) lower bracket and (5) press roller.

Table 1. Structural parameters of the BPPD.

Parameter	Value	Parameter	Value
Diameter of balance spring	16 mm	Diameter of extension spring	29 mm
Number of balance spring coils	20	Number of extension spring coils	14
Width of press roller	210 mm	Stiffness coefficient of tension spring	37.5 N/mm
Diameter of press roller	300 mm	Length of hanger rod	200 mm

BBPD has 2 degrees of freedom in space: longitudinal rotation and lateral rotation. In order to ensure the rationality of the mathematical model, the following assumptions are made: (1) ignoring the low-frequency vibration of the planter which is caused by the ground; (2) regarding the soil as a viscoelastic body; (3) ignoring the degree of freedom in the forward direction. The mathematical model of the BBPD is shown in Figure 4. D_4 is the center point of the press roller in the mathematical model of longitudinal motion, F is the center point of the press roller in the mathematical model of lateral motion, the moment of inertia around point B_3 is J_1, and the moment of inertia around point E is J_2, the initial deformation of the spring quantity δ, the spring stiffness is k, and the angle between the spring and the B_3C_3 line in equilibrium is φ. Take the rotation angles of the system around the hinge points B_3 and E as generalized coordinates (θ_3, θ_4).

According to the analysis of dynamic knowledge, the establishment of the system movement differential equation is as follows:

$$J_1 \cdot \ddot{\theta}_3 - (c_{xz} + c_{xy})(l_1 + l_2)\dot{\theta}_3\theta_3 - (k_{xz} + k_{xy})(l_1 + l_2)^2\theta_3 - k\delta l_1 \sin\varphi = 0 \quad (1)$$

$$J_2 \cdot \ddot{\theta}_4 - (c_{xz} + c_{yz})l_3\dot{\theta}_4\theta_4 - (k_{xz} + k_{yz}){l_3}^2\theta_4 = 0 \quad (2)$$

where c_{xy}, c_{xz}, c_{yz} is the soil damping coefficient, k_{xy}, k_{xz}, k_{yz} is the soil stiffness coefficient.

Using the vibration theory, the Equations (1) and (2) are 2 degrees of freedom system general differential equation of forced vibration, verifying the feasibility of the bidirectional copying motion. The working process of the motion mathematical model is related to soil parameter, structure size and spring stiffness. Soil parameters are not controllable factors; therefore, it is necessary for the related structure size design and selection of the spring stiffness and spring deformation. When other conditions are determined, spring deformation is the main factor for the BPPD.

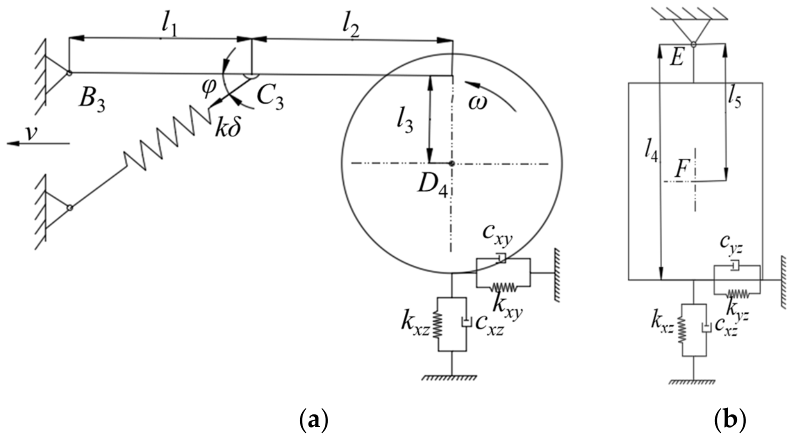

Figure 4. A 2-DOF mathematical model: (**a**) longitudinal rotation; (**b**) lateral rotation.

2.2. Experimental Conditions and Equipment

A field test was conducted on the Xiangyang farm of Northeast Agricultural University in Harbin, Heilongjiang, China. The Xiangyang farm is located at Xiangyang Village (45.45° N; 126.53° E; average elevation of 180 m), Xiangfang District, which is in the middle part of the Songneng Plain. The site has a continental climate of the cool temperate zone, which is characterized by strong winds and dry weather in spring, warm and rainy weather in summer and cold and dry weather in winter. The test was conducted on sloping land. The maximum slope angle was smaller than 15°, and the minimum slope angle was larger than 5°. Before this test, stubble cleaning was performed [14] (Figure 5). Ridge planting is a sowing method. Eighteen rows were reserved, and every row was 150 m. In the test, the tractor (John Deere (Ningbo) Agricultural Machinery Co., Ltd., Ningbo, China) and the no-tillage seeder (2BM-2) were used (Figure 5). For the no-tillage seeder, two kinds of press rollers were installed on each side. One side was the BPPD, and the other side was the traditional press roller.

Figure 5. The field test.

2.3. Experimental Design

An orthogonal design of three-factor and three-level ($L_9(3^4)$) was used for the experiment. The experimental factors were the kind of press roller and the operating parameters of the BPPD. There were three types of press rollers: rubber (RPR), planar (PPR) and squirrel-cage (SPR) (Figure 6). The operating parameters consisted of the combination of three spring deformations (10 mm, 20 mm, and 30 mm) and three forward speeds (3 km/h, 5 km/h and 7 km/h), as shown in Table 2. Each treatment test was repeated three times test was replicated 3 times; thus, 27 tests were performed in the field.

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

Figure 6. The types of press rollers: (**a**) the RPR and SPR; (**b**) the PPR and SPR.

Table 2. Factor coding and experimental levels.

Level	Factor		
	Press Roller Type *A*	**Spring Deformation *B*/mm**	**Forward Speed *C*/(km·h^{-1})**
1	RPR	10	3
2	PPR	20	5
3	SPR	30	7

2.4. Experimental Indexes

2.4.1. Measurement of Soil Moisture Content

The soil moisture content was measured manually with TZS-1k (the accuracy error of the precision is less than or equal to 2%). The measurement time was from the beginning of the seeding stage (the height of the sprout was approximately 20 mm) to the elongation stage (when the ear differentiated to elongation, the stem near the soil was approximately 20 mm). Measurements were made at 8:00 a.m. on the 14th day after seeding. Each zone was measured separately 3 times randomly. Figure 7 shows how the soil moisture content was measured in the field.

Figure 7. Measurements of soil moisture content at the seeding stage.

2.4.2. Measurement of the Emergence Ratio and Average Emergence Time Eight

A 5-m count zone was randomly chosen, and the number of emergences was counted in every experimental zone from the first day of emergence. To reduce the manual counting error, 3 testers were arranged to count the number of emergences in every experimental zone at 5 p.m. The test was finished when the emergence ratio in the experimental zone stopped changing. The calculation formula for the emergence ratio is Formula (3). The calculation formula for the average emergence time is Formula (4) [25].

$$PE = \frac{S}{M} \times 100\% \tag{3}$$

$$MET = \frac{N_1T_1 + N_2T_2 + \ldots + N_nT_n}{N_1 + N_2 + \ldots + N_n} \tag{4}$$

where S is the total number of emergences in the experimental zone, M is the total seeding number in the experimental zone, PE is the emergence ratio, MET is the average emergence time, $N_{1, \ldots, n}$ is the number of emergences since the time of the previous count and $T_{1, \ldots, n}$ is the number of days after seeding.

2.4.3. Measurement of the Uniformity of the Plant Height

The uniformity of the plant height is one of the most important indexes to evaluate the growth status of corn [32]. It directly influences the ultimate yield. The uniformity of the plant height needs to be measured in the trefoil stage of the corn seedling. Five seedlings were selected for height measurement in each experimental zone. The method of measurement was to measure the height of the seedlings with a dividing ruler on the 21st day after seeding. Then, the measurement data were processed, and the formula for uniformity of the plant height is as follows.

$$k = \frac{\overline{X}(N-1)}{\sqrt{\sum X^2 - \frac{(\sum X)^2}{N}}} \tag{5}$$

where k is the uniformity of the plant height, $\overline{X}$ is the average height of the seedling, X is the height of the seedling and N is the number of measured seedlings.

2.5. Data Analysis

(1) Analysis of variance

Analysis of variance (ANOVA), which was conducted by statistical software (IBM SPSS Statistic), was used to examine the effects of the experimental factors (speeds, press rollers) on the soil moisture content, emergence time, emergence ratio, and plant height uniformity. The means between treatments were compared with Duncan's multiple range tests at the significance level of 0.05.

(2) Standardized treatment

The measurement units of the four test indicators are different, the test index values need to be standardized before the comprehensive weighted analysis, and the standardized formula is

$$R_{in} = \frac{T_{in} - T_{id}}{T_{iM} - T_{iN}} \tag{6}$$

where R_{in} is the n test standard value of the i indicator, T_{in} is the n test value of the i indicator, T_{iM} and T_{iN} are the maximum and minimum values of the i indicator.

Using Equation (6), we can obtain the corresponding standard values of each indicator, which is composed of a relationship matrix

$$R = \begin{pmatrix} R_{11} & \cdots & R_{1n} \\ \vdots & \ddots & \vdots \\ R_{n1} & \cdots & R_{nn} \end{pmatrix} \tag{7}$$

(3) Indicator Weights

In the process of suppression operations, traction is not the main consideration, but the amount of soil adhesion will have a significant impact on the quality of the operation, according to expert experience, the sovereign weights of the four indicators are determined to be U = [0.2,0.3,0.3,0.2]. Using the formula $Y = UR$. Finally, the composite score for an indicator was obtained, where the smaller the score, the better.

3. Field Test Results

3.1. Effect of Test Factors on Working Performance

Results of the orthography experiment were shown in Table 3. According to the analysis results, the weight of the factors affecting the soil moisture content is $A > C > B$, and the optimal levels of the factors is A_1, B_2 and C_2, and the optimal combination is $A_1B_2C_2$; the weight of the factors affecting the average emergence time is $A > C > B$, and the optimal levels of the factors is A_3, B_3 and C_1, and the optimal combination is $A_3B_3C_1$; the weight of the factors affecting the emergence ratio is $A > B > C$, and the optimal levels of the factors is A_2, B_2 and C_2, and the optimal combination is $A_2B_2C_2$; the weight of the factors affecting the uniformity of the plant is $B > C > A$, and the optimal levels of the factors is A_2, B_1 and C_2, and the optimal combination is $A_2B_1C_2$.

Table 3. Results of the orthography experiment and range analysis.

No.		Factors			Soil Moisture Content (%)	Average Emergence Time (d)	Emergence Ratio (%)	Uniformity of the Plant Height (mm)
		A	*B*	*C*				
1		1	1	1	17.1	10.32	91.3	5.74
2		1	2	2	18.2	10.12	97.6	6.33
3		1	3	3	12.8	10.46	92.6	5.11
4		2	1	2	15.8	9.48	95.3	7.31
5		2	2	3	14.1	9.73	96.7	6.98
6		2	3	1	13.2	11.34	91.9	5.45
7		3	1	3	10.2	10.21	87.8	6.12
8		3	2	1	14.1	12.59	90.1	5.52
9		3	3	2	12.2	12.01	88.4	5.75
Soil moisture content	k_1	16.03	14.37	14.80				
	k_2	14.37	15.47	15.40				
	k_3	12.17	12.73	12.37				
	R	3.86	2.74	3.03				
Average emergence time	k_1	10.30	10.00	11.42				
	k_2	10.18	10.81	10.54				
	k_3	11.60	11.27	10.13				
	R	1.42	1.27	1.29				
Emergence ratio	k_1	93.83	91.47	91.10				
	k_2	94.63	94.80	93.77				
	k_3	88.77	90.97	92.37				
	R	5.87	3.83	2.67				
Plant height uniformity	k_1	5.73	6.39	5.57				
	k_2	6.58	6.28	6.46				
	k_3	5.80	5.44	6.07				
	R	0.85	0.95	0.89				

The variance of the test results, shown in Table 3, was analyzed by the statistics software Design-expert10.0.4 to study the influence of the test factors on the evaluation indicators.

It can be seen from Table 4 that in the indicators of soil moisture content, factors *A*, *B* and *C* are significant; in the average emergence time index, factors *B* and *C* are relatively significant, and factor *A* is highly significant; in the emergence ratio index, factors *B* and *C* are significant, and factor *A* is highly significant; in the plant height uniformity index, factors *A* and *B* are relatively significant, and factor *B* is significant. The test factors have a significant impact on the evaluation index, which shows that the selection of test factors is reasonable, and the test arrangement is appropriate.

Table 4. The variance analysis.

Index	Source	Sum of Squares	DF	Mean Square	F Value	*p* Value
Soil moisture content	*A*	22.57	2	11.28	41.12	0.02 **
	B	11.35	2	5.67	20.68	0.04 **
	C	15.48	2	7.74	28.21	0.03 **
	Pure Error	0.55	2	0.27		
Average emergence time	*A*	3.73	2	1.86	30.16	0.03 **
	B	2.47	2	1.23	19.97	0.05 *
	C	2.58	2	1.29	20.90	0.05 *
	Pure Error	0.12	2	0.06		
Emergence ratio	*A*	60.73	2	30.36	141.6	0.007 ***
	B	26.06	2	13.03	60.75	0.016 **
	C	10.68	2	5.34	24.89	0.037 **
	Pure Error	0.43	2	0.21		
Plant height uniformity	*A*	1.35	2	0.67	19.95	0.05 *
	B	1.63	2	0.81	24.11	0.04 **
	C	1.20	2	0.60	17.82	0.05 *
	Pure Error	0.07	2	0.03		

Note: * means relatively significant ($0.05 < p < 0.1$); ** means significant ($0.01 < p < 0.05$); *** means highly significant ($p < 0.01$).

3.2. Comprehensive Optimization of Experimental Factors

The index data in Table 3 are standardized, and the data is comprehensively weighted according to the results shown in Table 5. The comprehensive score values, shown in Table 6, are obtained according to Equation (6). The smaller the overall score, the better.

Table 5. The value of comprehensive evaluation.

NO.	R_{1n}	R_{2n}	R_{3n}	R_{4n}	Y
1	0.364	−0.121	−0.113	−0.134	−0.024
2	0.501	−0.185	0.530	0.135	0.231
3	−0.174	−0.076	0.019	−0.420	−0.136
4	0.201	−0.391	0.295	0.580	0.127
5	−0.011	−0.310	0.438	0.430	0.122
6	−0.124	0.207	−0.052	−0.265	−0.031
7	−0.499	−0.156	−0.470	0.039	−0.280
8	−0.011	0.609	−0.236	−0.234	0.063
9	−0.249	0.423	−0.409	−0.129	−0.071

Table 6. The range analysis of comprehensive scores.

Comprehensive Weighted Value	A	B	C
k_1	0.024	−0.059	0.002
k_2	0.073	0.139	0.095
k_3	−0.096	−0.080	−0.098
R	0.169	0.218	0.193
Main and Secondary Factor		$B > C > A$	
Optimal level	A_2	B_2	C_2

The comprehensive score value of $A_2B_2C_2$ is the smallest, while the optimal parameter combination are selected as: press roller type PPR, spring deformation 20 mm, and forward speed 5 km/h, as shown in Table 6.

4. Discussion

All of the experimental indexes were significantly different among the three press roller under different working conditions in Table 4, which showed that it is necessary to select the appropriate press roller for the BPPD. Table 3 shows that the SPR was different from the former two types and resulted in the lowest soil moisture content. The possible reason for this result is that when the SPR was operating, there was intermittent compaction of the soil, so parts of the soil were not completely compacted which led to an increase in the water evaporation [33]. Under the same loads and forward speed, the PPR made the soil-contact area larger than that of the RPR. The main reason is that the deeper the soil is compacted, the tighter the topsoil will be. This can effectively control water evaporation.

It can be seen from Table 3 that when the operating speed increases, it is difficult to cover the disturbed soil, which could lead to different depths of the seeds. In addition, the higher the working speed, the higher the working efficiency, which is better for agricultural production. However, this is not suitable for agricultural machinery equipment in hilly areas, because the higher the operating speed, the higher the probability of the tractor rolling over, which is not good for the operation. Thus, selecting low forward speed is appropriate for hilly areas. When the BPPD operated at 3 km/h and 5 km/h, the working performance indexes were almost the same, so to guarantee the operating efficiency and effectiveness, operating under 5 km/h is a better choice, which is consistent with the optimization results.

When the press roller type is certain, the compaction performance is determined by the forward speed and press load [25], and there is a positive correlation between velocity and press load. When the spring deformation was 20 mm, the corresponding grounding pressures were within the range 30–50 kPa, which met the grounding pressure requirements of corn growth in strong spring wind conditions in the hilly areas of Northeast China. In conclusion, press roller type PPR, spring deformation 20 mm, and forward speed 5 km/h is the ideal combination for the BPPD. A possible reason is that the soil can maintain the highest moisture content and highest temperature under these conditions. The adequate water and proper temperature shortened the time (from dormancy to germination) that the corn seed needed, accelerating the germination of the seed [28,34].

Compared with the traditional press device, the bidirectional profiling press device, a suitable press device for hilly areas of Northeast China, can be adjusted to meet the pressing strength requirements of different crops, and the spring parts can be replaced quickly. During the experiment, it was found that a certain profiling lag phenomenon occurs, which has little impact on the operation quality, but it is still necessary to improve the overall structure of the device, especially the longitudinal dimension. Besides, the real-time adaptive system of strength and profiling adjustment are the development direction of the press device. In follow-up studies, an intelligent control system will be added to improve the working performance of the bidirectional profiling press device.

5. Conclusions

Aiming at the ridge cultivation mode of corn in the hilly area of Northeast China, this study designed the BPPD, which had good effects on the seedbed properties and corn emergence. In this study, field tests were conducted to measure the soil moisture content, average emergence time, emergence ratio, and the uniformity of the plant height of three kinds of press rollers (RPR, PPR, and SPR) with three spring deformations (10 mm, 20 mm, and 30 mm) and three forward speeds (3 km/h, 5 km/h, and 7 km/h). Using statistical analysis software, the result of the orthogonal test are: factors press roller type, spring deformation and forward speed have significant influence on the test indexes of soil moisture content, average emergence time, emergence ratio, and plant height uniformity which factor press roller type have highly significant influence on the average emergence time and emergence ratio index. Using a comprehensive weighted algorithm, the sequence of factors affecting the BPPD performance was determined: spring deformation, forward speed, and press roller type; optimal combination: press roller type PPR, a spring deformation of 20 mm, and a forward speed of 5 km/h.

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