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Performance Optimization and Experimental Study of Small-Scale Potato-Grading Device

Haohao Zhao, Weigang Deng *, Shengshi Xie and Zexin Zhao

College of Mechanical and Electrical Engineering, Inner Mongolia Agricultural University, Hohhot 010018, China; 13772562813@163.com (H.Z.); xieshengshi@imau.edu.cn (S.X.); m15124756760@163.com (Z.Z.)
* Correspondence: dengwg@imau.edu.cn

Abstract: Traditional potato grading in China relies mostly on manual sorting, which is labor-intensive, time-consuming, costly, and inefficient. To enhance the operational performance of potato-grading devices, this paper focuses on optimizing the slide rail structure, which is the key component of a self-developed first-generation potato-grading device. A five-factor, three-level orthogonal experiment was designed, with the experimental factors being the height of the horizontal slide rail, angle of the first-stage inclined slide, angle of the second-stage inclined rail, chain horizontal movement speed, and conveyor belt speed. The indoor experiments were conducted using grading accuracy and grading efficiency as the experimental indicators. On the basis of the analysis of the orthogonal experiment results, two relatively optimal solutions were obtained, and validation experiments were conducted. The validation results show that when the height of the horizontal slide rail was 185 mm, the angle of the first-stage inclined rail was 4°, the angle of the second-stage inclined rail was 2.5°, the horizontal movement speed of the chain was 700 mm/s, and the movement speed of the conveyor belt was 275.60 mm/s, the performance of the movable rotating plate (MRP)-type grading device for potatoes reached its optimum. At this point, the grading accuracy was 94.88%, and the grading efficiency was 13.9477 t/h. Compared with the first-generation grading device, the optimized grading device achieved an improvement of 3.84% in grading accuracy and 12.94% in grading efficiency. The research methodology provided in this paper serves as a reference for the performance optimization of potato-grading devices.

Keywords: potato; grading device; performance optimization; orthogonal experiment

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1. Introduction

Potato is a crucial staple crop worldwide, cultivated in over 150 countries and regions [1–3]. Potato grading is an essential process in the potato harvesting phase. In some developed countries, there are two main research directions concerning grading equipment. One is mechanical grading [4–6], predominantly employing mesh and drum mechanisms, capable of efficiently grading and processing large quantities of potatoes in a short amount of time and featuring a simple operation [7–10]. The other direction is machine vision grading [11–13], offering higher grading accuracy without requiring direct contact with potatoes, reduced the damage to potatoes [14–17]. Mechanical grading equipment for potatoes is relatively inexpensive compared to machine vision technology. Mechanical devices typically employ simple physical principles and mechanical structures to achieve potato grading. These devices may include traditional vibrating screens or simple conveyor belt systems, which are relatively low in design and manufacturing costs. In contrast, machine vision technology often involves high-cost cameras, image processing software, and complex algorithms, resulting in higher expenses for purchasing and maintenance. Because of its high cost, machine vision technology is not suitable for small to medium-sized potato industries [18].

Potato ranks as China's fourth-largest staple crop following wheat, rice, and corn [19,20], with China leading the world in potato cultivation area and production in recent years [21]. In most potato cultivation areas in Inner Mongolia, China, the level of mechanized harvesting is relatively low, with limited application of potato combine harvesters. Typically, potato digging machines first perform the tasks of digging and separating potatoes from soil, followed by manual picking of potatoes and rough grading before bagging. This manual operation requires a large labor force, significantly impacting the scale production of potatoes. Therefore, the urgent need to mechanize potato-grading production cannot be overstated. In China, various agricultural research institutions, agricultural technology companies, and university research teams have been dedicated to studying potato-grading devices. Among these, research on mechanical classification includes drum-type, roller-type, shifting roller, and roller shaft-type. The drum-type potato-grading device is simple to operate and causes minimal damage, but it is prone to potato jamming on the mesh, potentially leading to lower efficiency. Roller-type grading device is suitable for large-scale production, offering high precision, but it requires complex maintenance and may cause slightly more damage. The disc roller device can reduce damage but requires more maintenance and has a narrower range of applications. The roller shaft device is easy to operate with minimal damage, but its cost is relatively higher compared to the previous types of devices [22–24]. Some researchers are also exploring the use of artificial intelligence and machine learning technologies for intelligent potato grading. They have developed grading algorithms based on computer vision and deep learning, enabling automatic recognition and classification of potatoes [25–27]. Domestic researchers have also studied other sorting equipment similar to potato crops. Du [28] combined mechanical devices with computer vision technology to develop an automatic grading machine for carrots. Wan [29] designed a new drum-type apple sorting machine. Yin [30] and Bao [31] utilized the principle of vibration screening and conveying to develop a new type of onion sorting device.

Given the current status of the potato industry in China, research has identified several issues with existing potato-grading equipment in China, including low efficiency, significant potato damage, and high costs. Drawing inspiration from similar sorting equipment used with potato crops, efforts have been made to address these challenges. The project team designed an MRP-type grading device for potatoes capable of sorting them into three grades based on the small, medium, and large sizes. However, the grading performance needs improvement. Therefore, this study conducted experimental research to analyze and optimize the grading performance of the device, exploring the optimal operating parameters. The findings of this study hold considerable reference value for enhancing the performance of potato-sorting equipment.

2. Materials and Methods

2.1. Structure and Working Principle of the MRP-Type Grading Device for Potatoes

A model diagram of the MRP-type potato-grading device is illustrated in Figure 1. It primarily comprises the body frame, MRP unit, slide mechanism, driving sprockets, sprocket shafts, sprockets, chains, and potato output mechanism. The body frame is segmented into the following two sections: chain fixation segment and base.

A schematic diagram illustrating the grading principle is depicted in Figure 2. During the potato-grading process, the primary grading function is performed by the uppermost layer of the MRP. The upper ends of the MRP are pivotally attached to the chain, enabling rotational movement relative to the chain. Meanwhile, the lower side is secured to the slide rail due to the influence of gravity and is supported by it. As the chain propels the MRP horizontally, the plate deflects under the combined effects of its own weight and the pressure exerted by the potatoes. The deflection angle can be regulated by adjusting the inclination angle of the inclined slide rail supporting the lower end. Simultaneously, as the MRP moves horizontally, it also oscillates around its fixed shafts located at the upper ends, gradually widening the gaps between adjacent plates. Driven by gravitational forces, potatoes of varying sizes descend into the potato collection apparatus through different gaps.

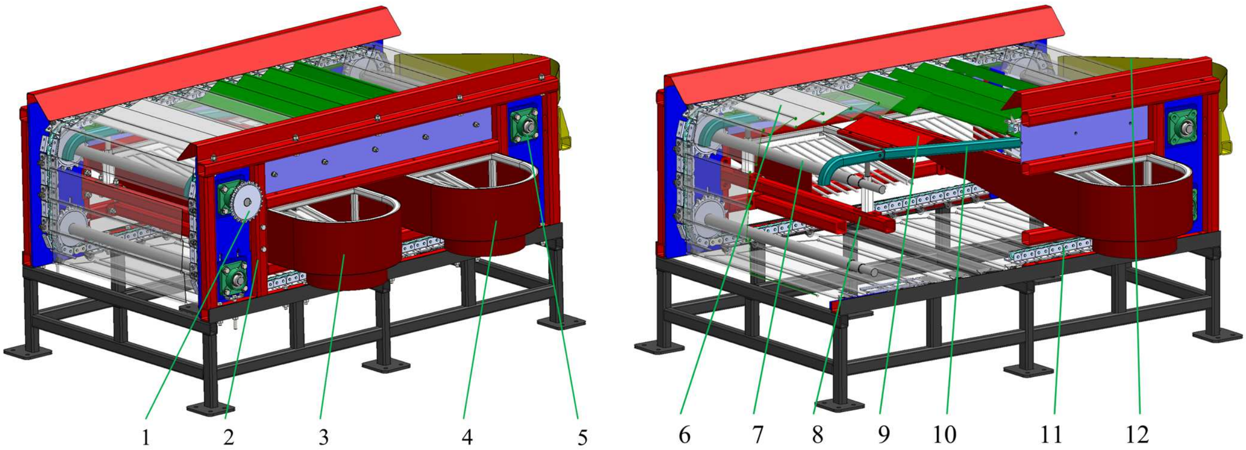

Figure 1. Structural diagram of the MRP-type grading device for potatoes. MRP, movable rotating plate. 1: Drive sprocket; 2: body frame; 3: the first level potato output device; 4: the second level potato output device; 5: bearing seat; 6: MRP; 7: sprocket shaft; 8: intermediate crossbeam; 9: herringbone baffle; 10: slide rail; 11: chain; 12: The third level potato output device.

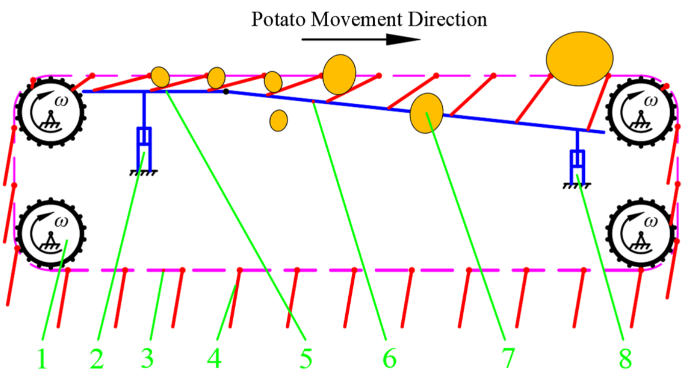

Figure 2. Potato-grading principles schematic diagram: 1: Sprocket; 2: horizontal slide rail height adjustment device; 3: chain; 4: MRP; 5: horizontal slide rail; 6: inclined slide rail; 7: potato; 8: inclined slide rail angle adjustment device.

The horizontal slide rail facilitates the smooth insertion of the MRP into the grading mechanism, whereas the inclined slide rail is tasked with the first- and second-level grading of potatoes. Altering its inclination angle can modify the spacing between adjacent MRP units, thus regulating the grading outcome of first- and second-level potatoes. Third-level potatoes are directed into the collection device at the terminus of the grading mechanism.

2.2. First-Generation Grading Device

In the initial phase, discrete element simulation analyses and laboratory tests were performed for the first-generation MRP-type grading device for potato [32,33]. The test factors encompassed the height of the horizontal slide rail, inclination angle of the inclined rail, and speed of the horizontal motion of the chain, with classification accuracy and efficiency serving as the experimental indicators. The laboratory testing process is depicted in Figure 3.

Figure 3. First-generation grading device test process.

Through experiments, the optimal parameter combination for the first-generation prototype was determined as follows: when the height of the horizontal slide rail was 185 mm, the inclination angle of the inclined slide rail was 3.5°, and the horizontal movement speed of the chain was 0.5 m/s; the corresponding grading accuracy was 91.04%, and the grading efficiency was 12.35 t/h. The simulation analysis and indoor experiments indicate that the first-generation MRP-type grading device can achieve potato grading according to specified grade standards [34]. However, improvements are still needed in grading accuracy and efficiency.

The sliding rail of the grading device is a critical component that affects its performance. Adjusting the inclination angle of the inclined slide rail in the first-generation grading device will simultaneously impact the grading results of both first- and second-grade potatoes, making it challenging to independently adjust the grading process for these grades. Therefore, optimizing the sliding rail structure of the first-generation grading device can enhance both its grading accuracy and efficiency.

2.3. Optimized Design of Sliding Rail Structure for Grading Device

The sliding rail structure of the first-generation grading device is illustrated in Figure 4, comprised primarily of a horizontal slide rail, inclined slide rail, smooth height adjustment device, and inclined angle adjustment device. To ensure the stability of the MRP's motion during the grading process, a set of sliding rails was installed on each side of the grading device. During grading, the horizontal slide rail primarily ensured the smooth entry of potatoes into the grading mechanism, while the inclined slide rail controlled the variation in gaps between the MRPs, thereby facilitating potato grading.

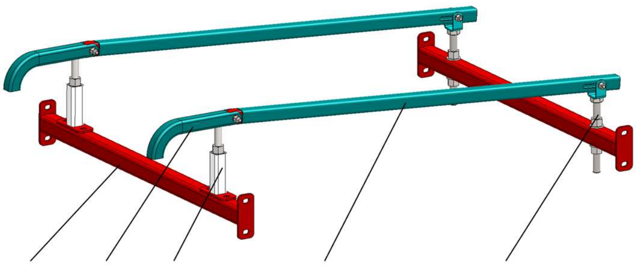

Figure 4. Grading unit slide mechanism: 1: fixed crossbeam; 2: horizontal slide rail; 3: horizontal slide rail height adjustment device; 4: inclined slide rail; 5: inclined slide rail angle adjustment device.

To balance the grading accuracy of first- and second-grade potatoes, the inclined slide rail in the first-generation grading device was initially designed as a single straight square steel tube. However, to facilitate the independent adjustment of the grading results for first- and second-grade potatoes, the inclined slide rail was optimized into two segments. The optimized sliding rail structure, depicted in Figure 5, was divided into the following three segments: horizontal slide rail, first-grade inclined slide rail, and second-grade inclined slide rail. To prevent interference between the MRP at the end of the grading device and the shaft, a slide rail tail rod was designed at the end of the second-grade inclined slide rail.

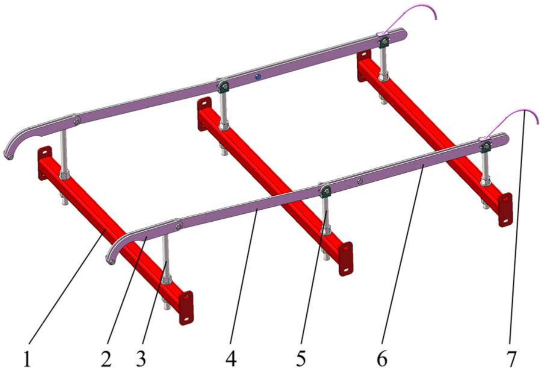

Figure 5. Optimized slide mechanism: 1: fixed crossbeam; 2: horizontal slide rail; 3: horizontal slide rail height adjustment device; 4: first-grade inclined slide rail; 5: inclined slide rail angle adjustment device; 6: second-grade inclined slide rail; 7: slide rail tail rod.

In the actual grading process, to prevent mechanical damage to potatoes in the collection device, the bottom of the collection device was designed with steel wire mesh. It can not only further separate the soil from the potatoes but also significantly reduce the weight to minimize the impact when potatoes are dropped. The collection device is depicted in Figure 6.

Figure 6. Bagging device.

2.4. Experimental Research

2.4.1. Experimental Conditions and Methods

To assess the operational performance of the optimized grading device, a prototype was developed and subjected to performance testing. The experiment utilized potatoes of the common variety "WoTu" from Hohhot, Inner Mongolia Autonomous Region, China. To minimize experimental errors, potatoes of the same variety were selected for the grading test. Before the experiment, manual sorting was performed based on the potato grade specifications [34], outlined in Table 1, to separate potatoes of different qualities. The process involved individually weighing purchased potatoes and labeling them according to size and quality, as depicted in Figure 7.

Table 1. Grades and specifications of potatoes.

Potato Specification	Small	Medium	Large
Single potato's quality (g)	<100	100~300	>300

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

Figure 7. Individual potato weighing: (**a**) small potato; (**b**) medium potato; (**c**) large potato.

The weighed potatoes were categorized into the following three groups: large, medium, and small. To reduce errors resulting from repeated experiments, each category of potatoes was further divided into three groups, with each group weighing 10 kg, totaling 90 kg. Specifically, large potatoes were labeled as A_1, A_2, and A_3; medium potatoes as B_1, B_2, and B_3; and small potatoes as C_1, C_2, and C_3, as illustrated in Figure 8.

Figure 8. Potatoes after grouping.

During the experiment, each group was replicated three times. In each replication, one group was selected from the large, medium, and small potatoes, respectively, thereby reducing errors resulting from material influence on the test results during repeated experiments.

2.4.2. Experimental Design

Through performance testing of the first-generation grading device [32,33] and discrete element simulation analysis of the optimized grading device, it can be concluded that factors affecting the grading performance included the height of the horizontal slide rail, the angle of the first-stage inclined slide, the angle of the second-stage inclined rail, and the speed of the chain horizontal movement. Additionally, there was a strong interaction between the height of the horizontal slide rail and the angle of the first-stage inclined slide, as well as between the angle of the first-stage inclined slide and the angle of the second-stage inclined rail. To improve the grading efficiency of the potato-grading device, the potato feeding rate was considered as an experimental factor. Considering the challenge of uniformly controlling the potato feeding rate, potatoes were transported into the grading device via a conveyor belt, and the conveyor belt's speed was adjusted to regulate the potato feeding rate. Through preliminary experiments, the conveyor belt speed was determined to be 256.55~294.64 mm/s.

Utilizing indoor orthogonal experiments to explore the optimal combination of operating parameters for the grading device required consideration of the interactions among factors. The experimental factors included the height of the horizontal slide rail (A), the angle of the first-stage inclined slide (B), the angle of the second-stage inclined rail (C), the speed of the chain horizontal movement (D), and the speed of the conveyor belt (E), while the experimental indicators were grading accuracy (X) and grading efficiency (η). The levels of the indoor orthogonal experimental factors were determined as shown in Table 2.

Table 2. Table of factor levels for indoor orthogonal tests.

Levels	Factors				
	Horizontal Slide Rail Height A (mm)	Angle of the First-Stage Inclined Slide B (°)	Angle of the Second-Stage Inclined Rail C (°)	Chain Horizontal Movement Speed D (mm/s)	Conveyor Belt Speed E (mm/s)
1	180	3	2	600	256.55
2	185	3.5	2.5	700	275.60
3	190	4	3	800	294.64

On the basis of the research information [35], a standard orthogonal array with interactive factors $L_{27}(3^{13})$ was selected. Three repeated experiments were conducted, and the average value of each test was recorded as the result. The indoor orthogonal experimental plan and results are presented in Table 3, while the indoor potato-grading process is illustrated in Figure 9.

Table 3. Indoor orthogonal test design program and test results.

Test Number	Factors													Evaluation Index	
	A	B	$(A \times B)_1$	$(A \times B)_2$	C	Null	Null	$(B \times C)_1$	D	Null	$(B{\times}C)_2$	Null	E	X	η
1	180	3	1	1	2	1	1	1	600	1	1	1	256.55	93.98	10.70
2	180	3	1	1	2.5	2	2	2	700	2	2	2	275.60	92.86	12.38
3	180	3	1	1	3	3	3	3	800	3	3	3	294.64	94.19	14.94
4	180	3.5	2	2	2	1	1	2	700	2	3	3	294.64	94.36	13.65
5	180	3.5	2	2	2.5	2	2	3	800	3	1	1	256.55	92.33	13.31
6	180	3.5	2	2	3	3	3	1	600	1	2	2	275.60	90.73	11.33
7	180	4	3	3	2	1	1	3	800	3	2	2	275.60	80.92	14.67
8	180	4	3	3	2.5	2	2	1	600	1	3	3	294.64	81.12	12.77
9	180	4	3	3	3	3	3	2	700	2	1	1	256.55	85.14	11.34
10	185	3	2	3	2	2	3	1	700	3	3	2	256.55	89.06	11.31
11	185	3	2	3	2.5	3	1	2	800	1	1	3	275.60	87.12	14.25
12	185	3	2	3	3	1	2	3	600	2	2	1	294.64	91.73	12.58
13	185	3.5	3	1	2	2	3	2	800	1	2	1	294.64	88.96	15.63
14	185	3.5	3	1	2.5	3	1	3	600	2	3	2	256.55	92.97	10.89
15	185	3.5	3	1	3	1	2	1	700	3	1	3	275.60	93.93	12.59
16	185	4	1	2	2	2	3	3	600	2	1	3	275.60	95.95	11.24
17	185	4	1	2	2.5	3	1	1	700	3	2	1	294.64	94.94	13.95
18	185	4	1	2	3	1	2	2	800	1	3	2	256.55	91.04	13.25
19	190	3	3	2	2	3	2	1	800	2	2	3	256.55	76.43	13.00
20	190	3	3	2	2.5	1	3	2	600	3	3	1	275.60	78.57	11.33
21	190	3	3	2	3	2	1	3	700	1	1	2	294.64	87.97	14.05
22	190	3.5	1	3	2	3	2	2	600	3	1	2	294.64	88.42	12.50
23	190	3.5	1	3	2.5	1	3	3	700	1	2	3	256.55	90.40	11.62
24	190	3.5	1	3	3	2	1	1	800	2	3	1	275.60	87.35	14.02
25	190	4	2	1	2	3	2	3	700	1	3	1	275.60	89.13	12.53
26	190	4	2	1	2.5	1	3	1	800	2	1	2	294.64	89.31	15.62
27	190	4	2	1	3	2	1	2	600	3	2	3	256.55	91.90	10.69

Figure 9. Potato-grading process: 1: conveyor belt; 2: drive chain; 3: sprocket; 4: first-level potato output device; 5: MRP; 6: second-level potato output device; 7: grading device.

3. Results and Discussion

3.1. Orthogonal Experiment Results Range Analysis

On the basis of the orthogonal experimental results, presented in Table 3, a range analysis was conducted for both grading accuracy and grading efficiency. The analysis results are summarized in Table 4, where $\boldsymbol{K_i}$ represents the sum of the experimental results corresponding to level $\boldsymbol{i}$ in any given column, while $\boldsymbol{k_i}$ represents the arithmetic mean of the experimental results obtained when the factor is set to level $\boldsymbol{i}$ in any given column; $\boldsymbol{R}$ denotes the range, which is the difference between the maximum and minimum values of $\boldsymbol{K}$ or $\boldsymbol{k}$ in any given column. In this study, the evaluation criteria for grading performance were grading accuracy and grading efficiency, both of which improve with larger values. Therefore, the optimal level corresponds to the level with the maximum range on any given column. Ultimately, the optimal solution is determined by selecting the solution with the maximum range value for each column.

Table 4. Table for range analysis of orthogonal test results.

Analytic Target	Range Source	A	B	(A × B)$_1$	(A×B)$_2$	C	Null	Null	(B × C)$_1$	D	Null	(B × C)$_2$	Null	E
Grading accuracy	K_1	805.6	791.9	829.1	827.2	797.2	804.2	811.5	796.9	805.4	800.5	814.1	802.1	803.2
	K_2	825.7	819.5	815.7	802.3	799.6	807.5	797.0	798.4	817.8	806.1	798.9	803.3	796.6
	K_3	779.5	799.4	766.0	781.3	814.0	799.1	802.3	815.6	787.7	804.2	797.8	805.4	811.0
	k_1	89.51	87.99	92.13	91.91	88.58	89.36	90.17	88.54	89.48	88.94	90.46	89.13	89.25
	k_2	91.74	91.05	90.63	89.15	88.85	89.72	88.55	88.71	90.87	89.57	88.76	89.25	88.51
	k_3	86.61	88.83	85.11	86.81	90.44	88.79	89.14	90.62	87.52	89.36	88.64	89.49	90.11
	R	5.14	3.06	7.01	5.11	1.86	0.94	1.62	2.08	3.35	0.63	1.82	0.36	1.60
	Factors order	(A × B)$_1$ > A > (A × B)$_2$ > D > B > (B × C)$_1$ > C > (B × C)$_2$ > E												
Grading efficiency	K_1	115.1	114.5	114.6	116.0	115.2	116.0	116.9	115.3	104	116.1	115.6	115.4	106.1
	K_2	115.7	115.5	115.3	115.1	116.1	115.4	114.9	115.0	113.4	114.7	115.9	116.0	114.3
	K_3	115.4	116.0	116.3	115.0	114.8	114.7	114.3	115.8	128.7	115.3	114.7	114.7	125.7
	k_1	12.79	12.73	12.73	12.88	12.80	12.89	12.98	12.81	11.56	12.90	12.84	12.82	11.79
	k_2	12.85	12.84	12.81	12.79	12.90	12.82	12.77	12.78	12.60	12.75	12.87	12.89	12.70
	k_3	12.82	12.89	12.92	12.78	12.75	12.75	12.71	12.87	14.30	12.81	12.74	12.75	13.96
	R	0.07	0.17	0.19	0.10	0.15	0.14	0.28	0.09	2.74	0.16	0.13	0.14	2.17
	Factors order	D > E > (A × B)$_1$ > B > C > (B × C)$_2$ > (A × B)$_2$ > (B × C)$_1$ > A												

3.1.1. Range Analysis of Grading Accuracy

On the basis of the range analysis of the grading accuracy, presented in Table 4, it is evident that within the experimental range, the interaction between factors A and B exerted a more significant influence on the experimental indicators compared to the individual effects of factors A and B alone. Therefore, determining the optimal levels of factors A and B necessitated evaluating the synergy or discordance between their respective levels. Similarly, the interaction between factors B and C demonstrated a more pronounced impact on the experimental indicators than the effect of factor C in isolation. Consequently, determining the optimal levels for factors B and C required assessing how well their respective levels complemented or detracted from each other. The pairing of factors A and B is detailed in Table 5, while the combination of factors B and C is depicted in Table 6.

Table 5. Grading accuracy factors: matching A and B levels.

Factors	A_1	A_2	A_3
B_1	93.68	89.30	80.99
B_2	92.47	91.96	88.72
B_3	82.39	93.97	90.11

Table 6. Grading accuracy factors: matching B and C levels.

Factors	B_1	B_2	B_3
C_1	86.49	90.58	88.66
C_2	86.18	91.90	88.46
C_3	91.30	90.67	89.36

According to the experimental results presented in Table 3, the formula for calculating the combination of each factor's levels in grading accuracy is provided by Equation (1).

$$\overline{X} = \frac{\sum_{i=1}^{n} X_i}{n} \tag{1}$$

where $\overline{X}$ is the average value of the sum of grading accuracy corresponding to the combination of two factors, $\boldsymbol{X_i}$ is the grading accuracy corresponding to the combination of two factors, and $\boldsymbol{n}$ is the number of combinations of two factors.

In the potato industry, grading accuracy refers to the ability to accurately classify potatoes into different grades. This entails ensuring that high-quality potatoes are correctly allocated to appropriate markets to meet the needs of various markets and consumers. Improving the grading accuracy helps maintain industry reputation and competitiveness, prevents mismatches of products entering the market, enhances the consumer experience, and ensures the potato industry can meet market demands. A higher accuracy in grading is preferred for a hierarchical performance. By plotting the corresponding bar graphs based on the data in Tables 5 and 6, as depicted in Figures 10 and 11, respectively, it can be inferred that the optimal parameter combination for factors A and B is A_2B_3 and for factors B and C it is B_2C_2. Comparing the range analysis results in Table 4, the mean values of factor D, denoted as $\boldsymbol{k}$, follow the sequence $\boldsymbol{k}_2 > \boldsymbol{k}_1 > \boldsymbol{k}_3$, indicating the optimal value for factor D to be D_2. Similarly, the mean values of factor E, also denoted as $\boldsymbol{k}$, follow the sequence $\boldsymbol{k}_3 > \boldsymbol{k}_1 > \boldsymbol{k}_2$, suggesting the optimal value for factor E to be E_3. Based on the aforementioned analysis, the two schemes exhibiting superior grading accuracy are $A_2B_3C_2D_2E_3$ and $A_2B_2C_2D_2E_3$.

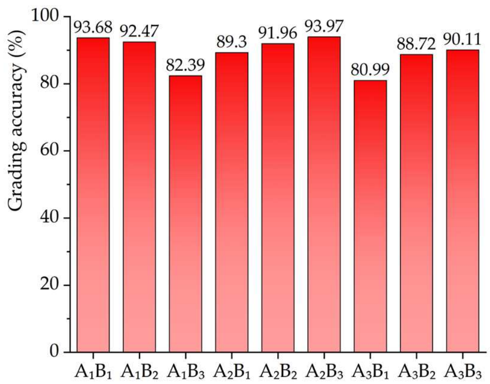

Figure 10. Bar chart matching A and B levels in grading accuracy.

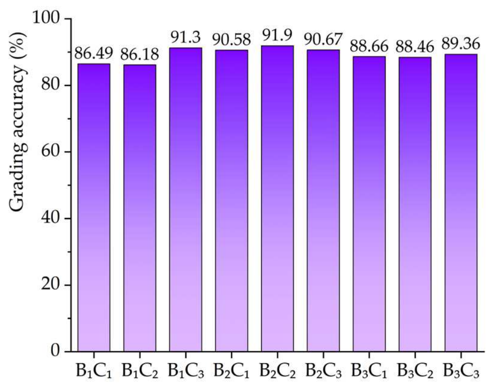

Figure 11. Bar chart matching B and C levels in grading accuracy.

3.1.2. Range Analysis of Grading Efficiency

Based on the range analysis of the grading efficiency, presented in Table 4, within the experimental range, the interaction between factors A and B exerted a greater influence on the experimental outcome compared to the individual effects of factors A and B. Thus, to ascertain the optimal levels of factors A and B, their efficacy should be assessed through the synergy of different levels of A and B. The pairing of factors A and B is outlined in Table 7, while the combination of factors B and C is illustrated in Table 8.

Table 7. Graded efficiency factors: matching A and B levels.

Factors	A_1	A_2	A_3
B_1	12.67	12.71	12.79
B_2	12.76	13.03	12.71
B_3	12.92	12.81	12.95

Table 8. Graded efficiency factors: matching B and C levels.

Factors	B_1	B_2	B_3
C_1	11.67	13.92	12.81
C_2	12.65	11.94	14.11
C_3	13.86	12.65	11.76

According to the experimental results presented in Table 3, the formula for calculating the combination of each factor's levels in grading efficiency is provided by Equation (2).

$$\overline{\eta} = \frac{\sum_{i=1}^{n} \eta_i}{n} \tag{2}$$

where $\overline{\eta}$ is the average value of the sum of the grading efficiency corresponding to the combination of two factors, η_i is the grading efficiency corresponding to the combination of two factors, and n is the number of combinations of two factors.

In the potato industry, grading efficiency refers to the quality of the potatoes that can be graded per unit of time during the grading process. Enhancing grading efficiency can reduce production costs, boost the competitiveness of potato processors, and better meet market demands. Therefore, improving the grading efficiency is crucial for the potato industry. In terms of graded performance, a higher grading efficiency is preferable. By plotting the corresponding line graphs based on the data from Tables 7 and 8, as depicted in Figures 12 and 13, respectively. It is evident that the optimal parameter combination for factors A and B is A_2B_2, while for factors B and C it is B_3C_2. Comparing the analysis of the variance results in Table 4, the mean values of factor D, denoted as k, followed the sequence $k_2 > k_3 > k_1$, indicating that the optimal value for factor D is D_2. Similarly, the mean values of factor E follow the sequence $k_3 > k_2 > k_1$, suggesting that the optimal value for factor E is E_3. Based on the aforementioned analysis, the two schemes exhibiting superior efficiency in grading are $A_2B_2C_2D_2E_3$ and $A_2B_3C_2D_2E_3$.

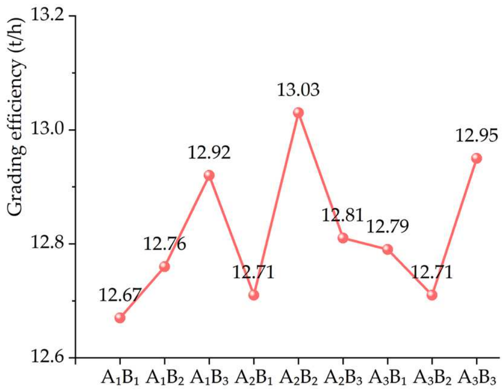

Figure 12. Line graph matching A and B levels in grading efficiency.

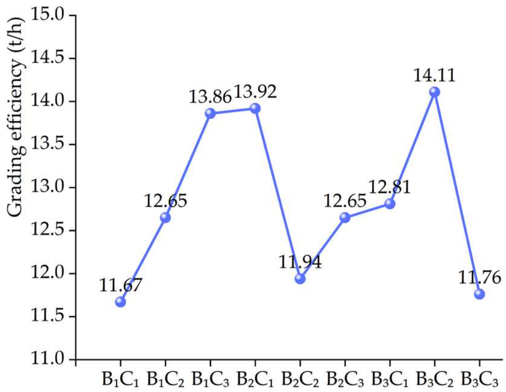

Figure 13. Line graph matching B and C levels in grading efficiency.

During the experimental process, the impact of each influencing factor on grading performance was as follows: as the horizontal slide rail height increased, the angle between the MRP and the slide rail decreased during the grading process, resulting in a reduction in the gap between adjacent MRP. Consequently, the number of potatoes falling into the collection box decreased, leading to a decrease in grading efficiency. When the horizontal slide rail height remained constant, an increase in the angle of the first-stage inclined slide allowed more potatoes to enter the grading device, falling from the first-stage grading area into the collection box, thereby increasing the grading efficiency. With both the horizontal slide rail height and the angle of the first-stage inclined slide unchanged, an increase in the angle of the second-stage inclined rail also increased grading efficiency. Grading efficiency increased with the increase in the horizontal movement speed of the chain. The faster the chain moved, the faster the MRP moved, resulting in a greater weight of potatoes transported per unit of time and, thus, an increase in grading efficiency. When the operating speed of the grading device increased, potatoes might move backward with the MRP due to inertia. Consequently, smaller potatoes might enter the second-stage collection device due to inertia, leading to a decrease in grading accuracy. Therefore, it was necessary to balance the values of various parameter factors in order to optimize the performance of the grading device.

In summary, two comparatively superior solutions have been identified for both the accuracy and efficiency of grading indicators. Notably, these optimal solutions coincide for both metrics as follows: $A_2B_2C_2D_2E_3$ (Solution One) and $A_2B_3C_2D_2E_3$ (Solution Two). Specifically, the optimal grading performance was achieved with a horizontal slide rail height of 185 mm, an angle of the first-stage inclined slide of either 3.5° or 4°, an angle of the second-stage inclined rail of 2.5°, a chain horizontal movement speed of 700 mm/s, and a conveyor belt speed of 275.60 mm/s. Thus, validation experiments were warranted to ascertain the optimal combination of operational parameters for the grading apparatus.

3.2. Verification Experiment

The verification test method was consistent with the aforementioned orthogonal test method. Each optimal solution underwent three repeated trials, and the test results were averaged. Ultimately, Scheme One achieved a classification accuracy of 93.12% and a classification efficiency of 13.9897 t/h, while Scheme Two achieved a classification accuracy of 94.88% and a classification efficiency of 13.9477 t/h. Drawing bar charts and line graphs to compare the results of the two approaches, as shown in Figure 14. By comparing the experimental results of the two optimal schemes, Scheme Two showed an increase of 1.76% in classification accuracy compared to Scheme One, while the classification efficiency decreased by 0.3%. Regarding the classification efficiency, the difference between the two was negligible. Therefore, considering all factors, Scheme Two was selected as the optimal solution.

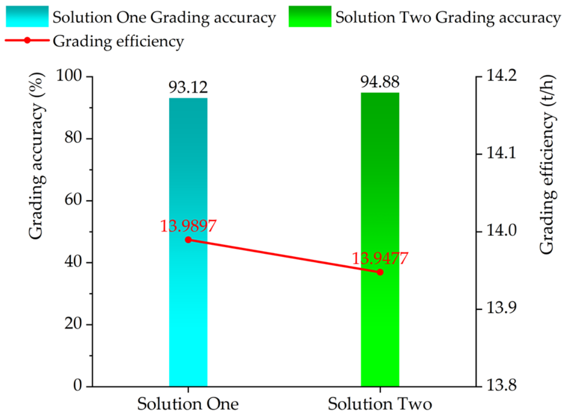

Figure 14. Comparison of the verification scheme results.

In conclusion, with the aforementioned parameters, including a horizontal slide rail height of 185 mm, a first-stage inclined slide angle of 4°, a second-stage inclined rail angle of 2.5°, a chain horizontal movement speed of 700 mm/s, and a conveyor belt speed of 275.60 mm/s, the grading performance of the MRP-type potato-grading device reached its optimum. In these settings, the grading accuracy achieved 94.88%, with a grading efficiency of 13.9477 t/h.

3.3. Comparative Analysis of Graded Performance

The initial classification device achieved an accuracy of 91.04% and an efficiency of 12.35 t/h [32,33]. Following optimization of its grading performance, the second-generation grading device achieved an accuracy of 94.88% and an efficiency of 13.9477 t/h. The comparison of the grading performance between the first and second generations is illustrated in Figure 15. Post optimization, the classification accuracy increased by 3.84%, and the efficiency improved by 12.94%. Therefore, when processing an equal amount of potatoes, the optimized grading device demonstrates greater practicality and higher production efficiency.

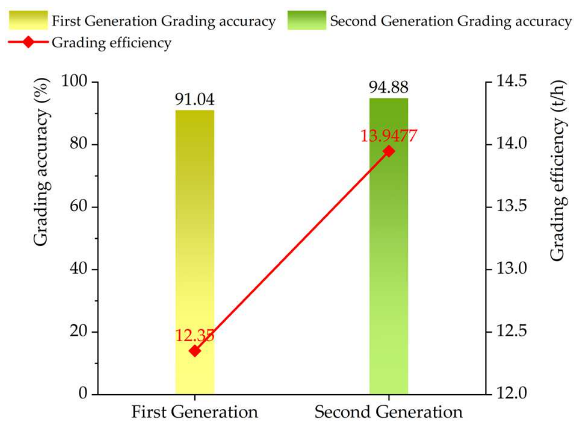

Figure 15. Grading performance comparison of the first and second generations.

Compared with similar small-scale potato-grading devices, a rod-type potato-conveying and -grading device achieved a grading accuracy of 88.07% in indoor trials at a potato feed rate of 12.67 t/h [10]. A nylon mesh drum-type potato-grading machine attained a grading accuracy of 70% in trials at a potato feed rate of 2.5 t/h [36]. A variable spacing potato-conveying and -grading device achieved a grading accuracy of 91.4% in field trials [37]. A mechanical roller-type potato-grading device achieved a grading accuracy of 92.5% in field trials [38]. A comparative analysis reveals that the MRP-type potato-grading device designed and optimized in this paper possesses higher grading accuracy and efficiency. The grading accuracy comparison of the MRP-type grading device for potatoes with similar small-scale potato-grading devices is depicted in Figure 16.

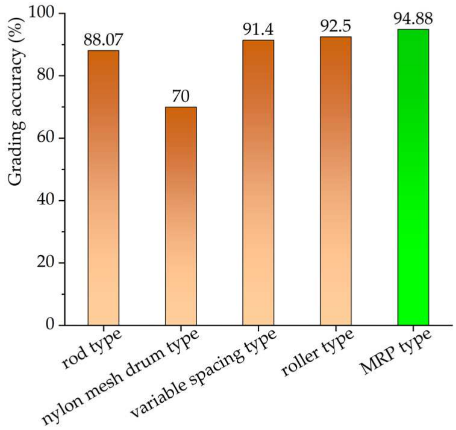

Figure 16. Comparison of the grading performances of similar small- and medium-sized potato-grading devices.

3.4. Positive Impacts of Improved Grading Devices

Improved grading devices can have several positive impacts on agricultural operations and potato processing.

(1) Improved grading devices can accurately classify potatoes based on size, shape, and quality parameters. This ensures that only high-quality potatoes meeting market standards are selected, thereby reducing waste and enhancing overall product quality.
(2) Compared to manual sorting methods, advanced grading devices can process potatoes at a faster rate. This efficiency improvement saves time and labor costs for farmers and processors, enabling them to handle a greater volume of potatoes within shorter timeframes.
(3) Consistently graded potatoes are more appealing to buyers and can fetch higher prices in the market. This can boost profitability for farmers, contributing to the economic sustainability of the potato industry.

Overall, the adoption of improved grading devices in the potato industry not only streamlines operations but also enhances product quality, market competitiveness, and sustainability across the entire supply chain.

4. Conclusions

The optimization design of the potato-grading device in this study significantly enhances its operational performance, offering promising prospects for the small- to medium-sized potato industry. The primary research conclusions derived from the optimized grading device are as follows:

(1) The sliding track of the first-generation activity transfer plate potato-grading device has been redesigned to achieve separate adjustments of the grading effects of first- and second-level potatoes.
(2) A five-factor three-level orthogonal experiment was conducted, with the experimental factors being the height of the horizontal slide rail, angle of the first-stage inclined slide, angle of the second-stage inclined rail, chain horizontal movement speed, and conveyor belt speed. Indoor experiments were carried out using grading accuracy and grading efficiency as the experimental indicators. The results indicate that when the height of the horizontal slide rail is 185 mm, the angle of the first-stage inclined rail is 4°, the angle of the second-stage inclined rail is 2.5°, the horizontal movement speed of the chain is 700 mm/s, and the movement speed of the conveyor belt is 275.60 mm/s, the operational performance of the MRP-type grading device for pota-

toes reaches its optimum. With this configuration, the grading accuracy reaches 94.88%, and the grading efficiency is 13.9477 t/h.

(3) Compared with the first-generation grading device, the optimized grading device improved the grading accuracy by 3.84% and the grading efficiency by 12.94%.

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