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Research on the Adaptive Cleaning System of a Soybean Combine Harvester

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Abstract: This study investigates the adaptive cleaning system of a soybean combine harvester, addressing the issue of low adaptability in matching the cleaning parameters of the air-and-screen cleaning device of domestic combine harvesters to varying soybean extract characteristics. This mismatch results in high cleaning loss and impurity rates during soybean machine harvesting. Through cleaning experiments, we examine the impact on soybean machine harvesting, where the cleaning loss rate accounts for approximately 10.08% of the total loss rate. The weight of the cleaning loss rate is lower than that of the impurity rate. Additionally, we establish a linear relationship between cleaning parameters and the corresponding cleaning loss rate and impurity rate. We design an adaptive control strategy workflow chart and integrate the adaptive cleaning system into the soybean combine harvester. Verification tests confirm the effectiveness of the adaptive control function. Comparative analysis reveals a reduction of 0.19% in cleaning loss rate and 0.98% in impurity rate compared to the air-and-screen cleaning device. The adaptive cleaning system significantly improves cleaning quality during soybean machine harvesting and enhances the intelligent capabilities of the air-and-screen cleaning device. The results provide practical insights and theoretical guidance for the development of high-quality, low-loss cleaning technology in soybean machine harvesting in China.

Keywords: soybean; combine harvester; adaptive cleaning system; cleaning loss rate; impurity rate

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1. Introduction

Cleaning represents a critical phase in the combined harvesting of soybeans, with the air-and-screen cleaning device being a common piece of equipment in soybean combine harvesters for this purpose [1]. The evaluation of cleaning quality relies on two key metrics: the cleaning loss rate and impurity rate associated with the air-and-screen cleaning device [2]. Cleaning parameters are operational settings that can be adjusted on the air-and-screen cleaning device, and their accuracy and level of automation directly influence the quality of the cleaning process [3,4].

In China, the degree of automation in adjusting and controlling cleaning parameters is generally low. Manual adjustments are common, but these tend to be inaccurate, time-consuming, and labor-intensive due to the static nature of the cleaning parameters during harvesting. Given the complexity of working conditions and the significant variation in soybean extract characteristics, the adaptability of the cleaning parameters to these differences is limited. This limitation results in poor cleaning quality during soybean machine harvesting, characterized by high cleaning loss and impurity rates. These issues severely impact the performance of domestic combine harvesters, as well as soybean yield and quality [5–7].

To enhance the adaptability of cleaning parameters and improve the cleaning quality of the air-and-screen cleaning device in combine harvesters, both domestic and international researchers have explored intelligent control systems. Domestically, Xiong et al. [8]

developed a real-time monitoring system for rice–wheat combine harvesters, enabling the monitoring and display of parameters such as cleaning fan speed and tail screen opening. Zhang et al. [9] designed a monitoring system for threshing and cleaning in corn combine harvesters, aimed at monitoring and providing early warnings for key parameters. Jiang et al. [10] introduced a fuzzy controller for centrifugal fans, which adjusts the operating parameters based on the actual conditions of grain combine harvesters. Li et al. [11] developed an intelligent rice and wheat combine harvester cleaning system using drone remote sensing images. The images were used to obtain the distribution of grass-to-grain ratio of crops in the target area. The air separation plate angle, fish scale sieve opening, and fan speed of the combine harvester cleaning system were controlled through an incremental fuzzy control model. Shen et al. [12] designed a hydraulic control system for the corn harvester to achieve hydraulic drive of the cleaning device, and used PLC to achieve real-time monitoring and adjustment of the hydraulic actuator components of the cleaning device. Cai et al. [13] proposed a multi-functional integrated control handle device for combine harvesters, offering control over parameters like fish scale sieve opening, working speed, and air regulating plate, solely through control handles and buttons. Lu et al. [14] developed an electrical control system for the test bench of longitudinal axial rice harvesters, providing real-time data collection and control over operation parameters. Internationally, Mahmoud et al. [15] designed a fuzzy logic controller (FLC) that combined human expert knowledge. The combine harvester can automatically adjust the operating speed, fan speed, threshing drum speed, and concave screen gap based on the grain loss measured at the straw walking device and upper screen position, ensuring that the grain loss of the combine harvester during field operation is minimized. Geert et al. [16] collected a large amount of knowledge about the working principles of cleaning devices using data-based models. Based on experimental data and fuzzy modeling techniques, the optimal and non-optimal operating conditions were determined, and a fuzzy control system was implemented that combined the inputs of experienced operators with the data-based models. This approach enabled the combine harvester to cope with different soil, climate, and crop conditions, and to be capable of harvesting different crops under different environmental conditions. Maertens et al. [17] predicted internal separation behavior through crop yield and grain flow measurements to address the lack of efficiency measurement sensors in combine harvesters. An overview of existing monitoring devices for the separation process of commercial combine harvesters was provided. Actual measurements and feasibility studies were conducted under different crop conditions for cutting width, crop yield, and separation degree to evaluate instantaneous separation. A data-driven method based on gradient recursive identification technology was proposed to analyze the online behavior of the separation and cleaning systems. Dimitrov et al. [18] studied a fuzzy expert system for intelligent decision support in combine harvesters, modeling adjustable operating parameters, including operating speed, threshing drum speed, and centrifugal fan speed. They selected an optimal model suitable for the complex and variable field operations of combine harvesters. Yuri et al. [19] introduced advanced electric control technology to precision agriculture systems in modern combine harvesters, facilitating automatic adjustments of operating parameters based on the combine harvester's field conditions, achieving electric and hydraulic control of parameters like reel speed, header screw conveyor speed, threshing drum speed, fan speed, and fish scale sieve opening. Gundoshmian et al. [20] proposed a three-layer perceptron neural network combined with a backpropagation training algorithm to establish a performance model for combine harvesters, allowing for efficient prediction of combine harvester performance under different conditions.

After conducting a comprehensive analysis of the current research status, both domestically and internationally, it becomes evident that there is a notable dearth of studies focusing on the comprehensive control, monitoring, and real-time display of cleaning parameters within the field operations of grain combine harvesters in domestic research. Furthermore, the scope of control variables for cleaning parameters remains limited. In China, research on the adaptive control function of air-and-screen cleaning devices is under-represented, and the examination of cleaning parameters is often narrowly focused, thus precluding the realization of multi-parameter adaptive control. Conversely, abroad, the application of intelligent control technology in combine harvesters predominantly centers on the precise monitoring and display of cleaning operation performance. These technologies adjust the machine's operating parameters automatically and intelligently when harvesting various crops under diverse field conditions, ensuring that the equipment maintains an optimal operating state. Internationally, advanced combine harvesters have successfully achieved intelligent control and high-quality, high-efficiency cleaning operations for large feed-rate air-and-screen cleaning devices.

In response to the aforementioned analysis, this article proposes an investigation into the adaptive cleaning system of soybean combine harvesters. Such a study is both necessary and urgently needed to address the issues encountered by domestic soybean combine harvesters employing air-and-screen cleaning devices. The objective of this research is to reduce the cleaning loss rate and impurity rate during soybean machine harvesting, enhance the adaptability of cleaning parameter matching to varying characteristics of soybean extracts, and improve overall cleaning quality. The study includes an exploration of the influence of cleaning parameters on cleaning quality, the design of an adaptive control strategy workflow chart, integration of the adaptive cleaning system into soybean combine harvesters, and verification and comparative analysis of the system's effectiveness and superiority. The proposed system allows for the multi-parameter adjustability and measurability of cleaning parameters, as well as the optimization of field cleaning parameters for soybean combine harvesters. This study effectively enhances the adaptability of cleaning parameter matching to the distinct characteristics of soybean extracts, leading to a reduction in the cleaning loss rate and impurity rate during soybean machine harvesting. This improvement is expected to positively impact soybean yield and quality per unit area, with significant implications for soybean safety and the development of the soybean industry. The study also contributes to the enhancement of the intelligent capabilities of air-and-screen cleaning devices, aligning with the trend of intelligent development in combine harvesters. It holds practical significance in advancing the full mechanization of domestic soybean production and promoting technological progress within the domestic harvesting machinery industry, thereby accelerating the modernization of agriculture in the country.

2. Multi-Parameter Adjustable Measurable Cleaning System

The multi-parameter adjustable and measurable cleaning system comprises an air-and-screen cleaning device, a cleaning parameter control system, a cleaning quality monitoring system, and a power and control system. The overall structure is depicted in Figure 1. The air-sieve cleaning device includes a frame, a fan, a cleaning screen, a grain-collecting screw conveyor, and a re-stripping screw conveyor. This forms the fundamental structure of a multi-parameter adjustable and measurable cleaning system. The cleaning parameter control system includes devices for controlling the cleaning screen crank speed, fan speed, damper opening, and fish scale sieve sheet opening. These devices enable continuous adjustment control and real-time monitoring of cleaning parameters. The cleaning quality monitoring system comprises two components: a cleaning loss rate monitoring system located below the tail of the cleaning screen at the impurity discharge outlet of the air-and-screen cleaning device and an impurity rate monitoring system positioned beneath the grain outlet in the grain box. These systems facilitate real-time monitoring of the cleaning loss rate and impurity rate. The power and control system is composed of a power supply, a display terminal, a controller, a GPS receiver, a voltage converter, and integrated circuits. This system provides power, regulates the entire machine, monitors operating speed in real-time, controls the display terminal for cleaning parameters, and handles signal transmission. It also enables the reception, storage, and display of various data, including cleaning parameters, cleaning quality evaluation indicators, and power consumption on the terminal [21].

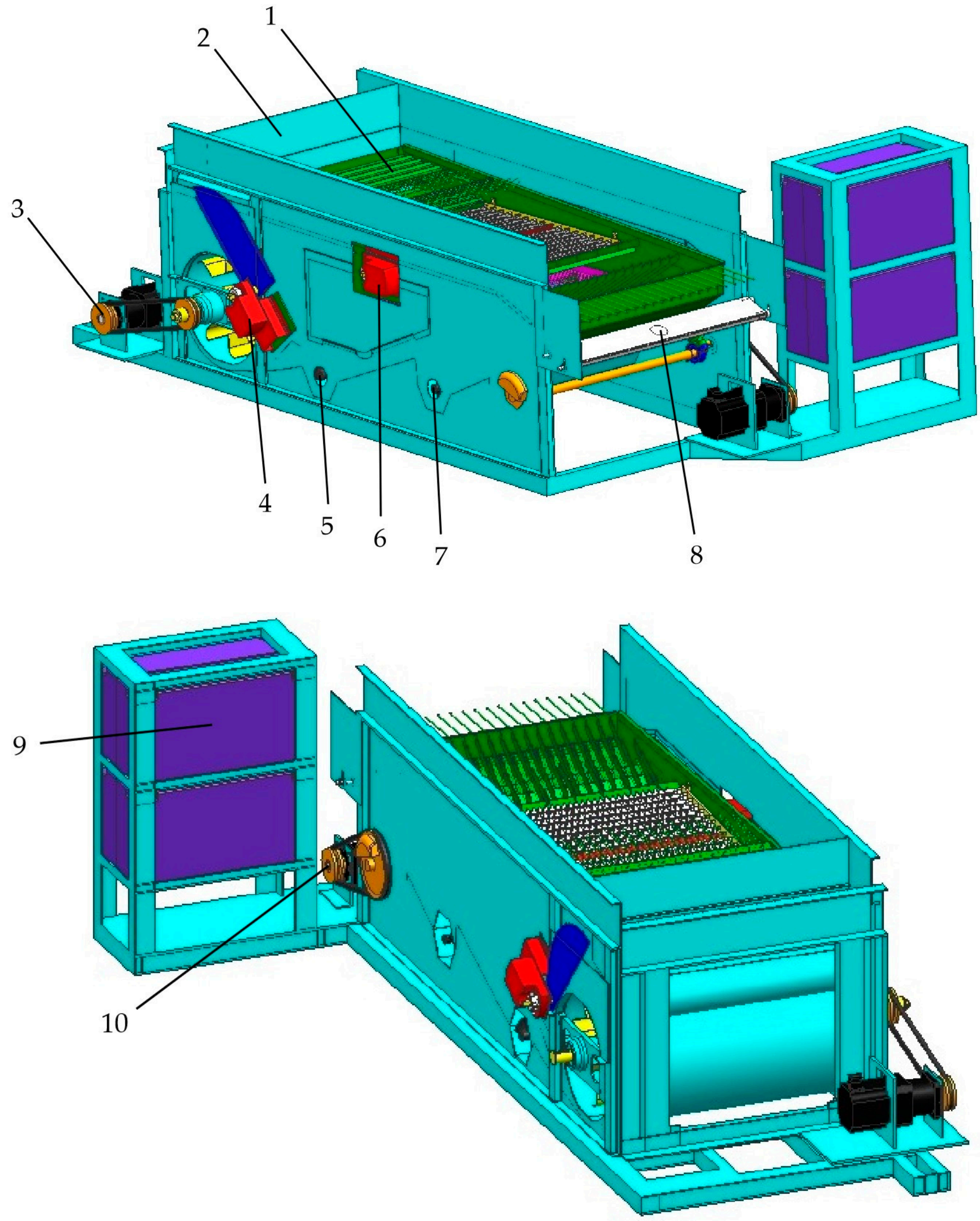

Figure 1. Overall structure of the multi-parameter adjustable and measurable cleaning system. 1. Cleaning sieve. 2. Frame. 3. Fan speed control device. 4. Air door opening control device. 5. Grain collecting screw conveyor. 6. Fish scale sieve sheet opening control device. 7. Repeated screw conveyor. 8. Cleaning loss rate monitoring system. 9. Power supply. 10. Cleaning sieve crank speed control device.

3. Influence of Cleaning Parameters on Cleaning Quality

3.1. Cleaning Test and Evaluation Index

3.1.1. Pilot Items

The cleaning test items are shown in Table 1.

Table 1. Cleaning test items.

NO.	Name	Time	Place
1	Air-and-screen cleaning device test	October 2020	Soybean Test Base, Hedong District, Linyi City, Shandong Province, China
2	Single factor test		

3.1.2. Test Parameters

In Table 2, we present the soybean characteristic parameters, harvester structure, operation parameters, and the optimal combination of cleaning parameters, drawing upon relevant studies and previous research [21–26].

Table 2. Test parameters.

Category	Name	Parameter
Soybean characteristic parameters	Varieties	Lindou 10
	Grass-to-grain ratio	1.64
	Moisture content of grain/(%)	15.2
	100 grain weight/(g)	39.8
	Plant height/(mm)	922
	Bottom pods height/(mm)	170
	Diameter of canopy surface/(mm)	232
Harvester structural parameters	Model	4LZ-4.0
	Type	Full feed track type
	Rated power/(kW)	72.9
	Outline size/(mm)	5620 × 2810 × 2990
	Roller length/(mm)	2210
	Roller diameter/(mm)	620
	Roller type	Single longitudinal axial flow
	Swath/(mm)	2300
Harvester operation parameters	Feed auger speed/(r/min)	185
	Conveyor chain rake speed/(r/min)	440
	Threshing drum speed/(r/min)	600
	Reel speed/(r/min)	44
The best combination of cleaning parameters for soybean machine harvesting	Operation speed/(km/h)	6
	Fish scale screen sheet opening/(mm)	32
	Damper opening/(°)	17
	Fan speed/(r/min)	1310
	Cleaning screen crank speed/(r/min)	410

3.1.3. Evaluation Indexes

(1) Sample collection method of evaluation index.

Both the air-and-screen cleaning device and the single-factor test employ a real-time cleaning quality monitoring system to record data for cleaning quality evaluation indices during the harvesting process. Upon completion of the air-and-screen cleaning device test, the tester manually collects 1 m^2 samples of residual loss from the test area corresponding to each test serial number.

(2) Analysis method of evaluation index.

Following established studies, the total loss rate, cleaning loss rate, and impurity rate are computed using Equation (1) and Equation (2), respectively [27].

$$\begin{cases} Y_0 = \frac{W_{ss}}{W_{ss}+W_{sh}} \times 100\% \\ Y_1 = \frac{W_{sq}}{W_{ss}+W_{sh}} \times 100\% \\ W_{ss} = W_{sq} + W_{sy} - W_{sz} \end{cases} \tag{1}$$

$$Y_2 = \frac{W_{zz} - W_{zq}}{W_{zz}} \times 100\% \tag{2}$$

where Y_0 represents total loss rate in %; W_{ss} is soybean loss in g/m^2; W_{sh} is soybean harvest in g/m^2; Y_1 denotes cleaning loss rate in %; W_{sq} is cleaning loss in g/m^2; W_{sy} is residual loss in g/m^2; W_{sz} is natural dropping amount in g/m^2; Y_2 is impurity rate in %; W_{zz} is sample quality in g; W_{zq} is sample quality after impurity removal in g.

3.1.4. Test Process

The evaluation of cleaning parameters for soybean machine harvesting is conducted using a multi-parameter adjustable measurable cleaning system and a supporting harvester. The test site is depicted in Figure 2.

Figure 2. Lindou 10 test site.

3.2. Evaluation Index Weight

3.2.1. Industry Standards

In accordance with the pertinent literature, the industry standard for evaluating soybean machine harvesting is presented in Table 3 [27].

Table 3. Industry standard of soybean machine harvesting evaluation index.

Evaluation Indexes	**Total Loss Rate Y_{0s}/(%)**	**Impurity Rate Y_{2S}/(%)**	**Cleaning Loss Rate Y_{1s}/(%)**
Level	≤ 5	≤ 3	≤ 0.5

3.2.2. Air-and-Screen Cleaning Device Test

The air-and-screen cleaning device test covers a distance of 80 m and includes 16 groups of evaluation indices. The average values for the cleaning loss rate, impurity rate, and total loss rate across these 16 groups are obtained, as detailed in Table 4.

Table 4. Air-and-screen cleaning device test data.

Name	**Cleaning Loss Rate Y_1/(%)**	**Impurity Rate Y_2/(%)**	**Total Loss Rate Y_0/(%)**	**Cleaning Loss Rate as a Percentage of Total Loss Rate Y_3/(%)**
Parameter	0.38	2.66	3.75	10.08

3.2.3. Cleaning Loss Rate as a Percentage of Total Loss Rate

The percentage of the cleaning loss rate relative to the total loss rate is computed using Equation (3), as illustrated in Table 4. According to Equation (4), the industry standard for the cleaning loss rate in soybean machine harvesting is $Y_{1s} \leq 0.5\%$, as shown in Table 3.

$$Y_3 = \frac{W_{sq}}{W_{ss}} \times 100\% \tag{3}$$

$$Y_{1s} = Y_3 \times Y_{0s} \tag{4}$$

Y_3 represents the cleaning loss rate as a percentage of the total loss rate as a percentage (%), Y_{1s} is the industry standard for the cleaning loss rate in soybean machine harvesting as a percentage (%), Y_{0s} is the industry standard for the total loss rate in soybean machine harvesting as a percentage (%), W_{sq} is the cleaning loss in grams per square meter (g/m^2), and W_{ss} is the soybean loss in grams per square meter (g/m^2).

3.2.4. Weight

Drawing from relevant studies, the evaluation indices and weights for the grain combine harvester are presented in Table 5 [28].

Table 5. Evaluation index and weight of grain combine harvester.

Evaluation Indexes	Total Loss Rate	Crushing Rate	Impurity Rate
Weight	0.7	0.2	0.1

Comparing Tables 4 and 5, the cleaning loss rate comprises approximately 10.08% of the total loss rate. The weight for the total loss rate is 0.7, while the weight for the impurity rate is 0.1, with no consideration for the crushing rate. Using Equation (5), the weight conversion yields a weight of about 0.4 for the cleaning loss rate (W_1) and about 0.6 for the impurity rate (W_2), demonstrating that the weight relationship between the cleaning loss rate (Y_1) and the impurity rate (Y_2) in the quality evaluation index for soybean machine harvesting and cleaning is such that Y_1 weight < Y_2 weight.

$$\begin{cases} W_0 = Y_3 \times 0.7 + 0.1 \\ W_1 = \frac{Y_3 \times 0.7}{W_0} \\ W_2 = \frac{0.1}{W_0} \end{cases} \tag{5}$$

W_0 represents the sum of the weight of the initial cleaning loss rate and impurity rate. Y_3 represents the percentage of cleaning loss rate to total loss rate as a percentage (%), W_1 is the weight of the cleaning loss rate, and W_2 is the weight of the impurity rate.

3.3. Linear Relationship between Parameter and Index

3.3.1. Single Factor Test

The single factor test involves adjusting the level of one cleaning parameter while keeping the other three parameters constant. This process is repeated at five different levels, with each test group conducted at a distance of 25 m [27]. In alignment with the relevant literature and prior research on cleaning parameters, combined with the adjustment range of the cleaning parameters for the multi-parameter adjustable measurable cleaning system, the selected cleaning parameter levels are outlined in Table 6, and the data for the single factor test are presented in Table 7 [21–26].

Table 6. Cleaning parameter level.

Level	Fish Scale Screen Sheet Opening A /(mm)	Damper Opening B /(°)	Fan Speed C /(r/min)	Cleaning Screen Crank Speed D /(r/min)
1	22	0	1200	300
2	25	5	1300	350
3	28	10	1400	400
4	31	15	1500	450
5	34	20	1600	500

Table 7. Single factor test data.

NO.	Fish Scale Screen Sheet Opening A/(mm)	Damper Opening B/(°)	Fan Speed C/(r/min)	Cleaning Screen Crank Speed D/(r/min)	Cleaning Loss Rate Y_1/(%)	Impurity Rate Y_2/(%)
1	22	17	1310	410	0.22	1.66
2	25	17	1310	410	0.19	1.83
3	28	17	1310	410	0.09	3.70
4	31	17	1310	410	0.02	4.64
5	34	17	1310	410	0.01	4.91
6	32	0	1310	410	0.08	10.80
7	32	5	1310	410	0.12	6.94
8	32	10	1310	410	0.18	4.11
9	32	15	1310	410	0.25	3.78
10	32	20	1310	410	0.35	0.85
11	32	17	1200	410	0.07	10.83
12	32	17	1300	410	0.21	4.26
13	32	17	1400	410	0.36	2.35
14	32	17	1500	410	0.43	2.12
15	32	17	1600	410	0.71	1.38
16	32	17	1310	300	0.04	7.03
17	32	17	1310	350	0.16	2.72
18	32	17	1310	400	0.38	2.57
19	32	17	1310	450	0.83	2.05
20	32	17	1310	500	0.95	0.85

3.3.2. Linear Relationship

Based on previous research, the adjustment range for cleaning parameters ensures that the evaluation index values do not fall below zero. Origin 9.1 software is used to analyze the data from the single factor test, which provides the maximum adjustment range for the four cleaning parameters. Additionally, the linear equations and numerical ranges corresponding to the two evaluation indices are determined, as presented in Table 8 [21].

Table 8. Linear equation and numerical range of evaluation index corresponding to cleaning parameters.

Name	Fish Scale Screen Sheet Opening A/(mm)	Damper Opening B/(°)	Fan Speed C/(r/min)	Cleaning Screen Crank Speed D/(r/min)
Maximum adjustment range	0~43	0~90	0~3000	0~1500
Y_1 linear equation	$Y_1 = -0.01967A + 0.65667$	$Y_1 = 0.0134B + 0.062$	$Y_1 = 0.0015C - 1.744$	$Y_1 = 0.00498D - 1.52$
R^2	0.90	0.96	0.95	0.94
Impact on Y_1	Monotonically decreasing	Monotonic increase	Monotonic increase	Monotonic increase
Corresponding Y_1 range/%	0.65667~0	0.062~1.268	0~2.756	0~5.95
Y_2 linear equation	$Y_2 = 0.31033A - 5.34133$	$Y_2 = -0.4612B + 9.908$	$Y_2 = -0.02104C + 33.644$	$Y_2 = -0.02606D + 13.468$
R^2	0.92	0.92	0.66	0.70
Impact on Y_2	Monotonic increase	Monotonically decreasing	Monotonically decreasing	Monotonically decreasing
Corresponding Y_2 range/%	0~8.00286	9.908~0	33.644~0	13.468~0

4. Adaptive Control Strategy

4.1. Fuzzy Grade Interval and Adjustment Step

4.1.1. Fuzzy Rule

To facilitate the implementation of an adaptive control strategy, the monitoring range for evaluating the cleaning quality of soybean machine harvesting is subjected to a fuzzy process. Both Index Y_1 and Index Y_2 employ the same fuzzy rule design method. Four cleaning parameters correspond to seven fuzzy rules: ZO (no adjustment), PS (positive small step adjustment), PM (positive middle step adjustment), PB (positive big step adjustment), NS (negative small step adjustment), NM (negative middle step adjustment), and NB (negative big step adjustment). The fuzzy grade intervals for the evaluation indices, determined by these rules, are categorized into four grades: grade 0, grade 1, grade 2, and grade 3. The fuzzy grade intervals for the two evaluation indices align with the fuzzy rules for the four cleaning parameters, as shown in Table 9 [29–34].

Table 9. Fuzzy rules of cleaning parameters corresponding to fuzzy grade interval of evaluation index.

Fuzzy Grade Interval of Evaluation Index	Y_1 Corresponding Fuzzy Rules for 4 Parameters				Y_2 Corresponding Fuzzy Rules for 4 Parameters			
	A	B	C	D	A	B	C	D
Level 0 interval	ZO	ZO	ZO	ZO	ZO	ZO	ZO	ZO
Level 1 interval	PS	NS	NS	NS	NS	PS	PS	PS
Level 2 interval	PM	NM	NM	NM	NM	PM	PM	PM
Level 3 interval	PB	NB	NB	NB	NB	PB	PB	PB

4.1.2. Fuzzy Grade Interval and Adjustment Step Division

To determine the fuzzy grade intervals and corresponding adjustment step sizes, we reference the industry standards for soybean machine harvesting cleaning: $Y_{1s} \leq 0.5\%$ for cleaning loss rate and $Y_{2s} \leq 3\%$ for impurity rate, as listed in Table 3. We also consider the linear equations and numerical ranges for cleaning parameters presented in Table 8 and the fuzzy rules for cleaning parameters from Table 9. The fuzzy grade intervals for the evaluation indices Y_1 and Y_2, and the values for the adjustment step sizes of the four cleaning parameters, are established. Grade 0 for Y_1 and Y_2 correspond to the intervals [0, 0.5] and [0, 3], respectively, with the maximum values set to 100%, as indicated in Table 10.

Table 10. Fuzzy grade interval of evaluation index and adjustment step of corresponding cleaning parameters.

Interval Progression	Adjusting Direction	Y_1 Interval/(%)		Y_2 Interval/(%)		Y_1 Corresponding Adjustment Step Size				Y_2 Corresponding Adjustment Step Size			
0	Incoherent	0	0.5	0	3	0	0	0	0	0	0	0	0
1	0	0.5	a_1 (0.56)	3	a_2 (5)	L_{A11} (4)	L_{B11} (−5)	L_{C11} (−50)	L_{D11} (−15)	L_{A21} (−7)	L_{B21} (5)	L_{C21} (100)	L_{D21} (80)
2	0	a_1 (0.56)	b_1 (0.62)	a_2 (5)	b_2 (7)	L_{A12} (7)	L_{B12} (−10)	L_{C12} (−90)	L_{D12} (−25)	L_{A22} (-13)	L_{B22} (9)	L_{C22} (200)	L_{D22} (155)
3	0	b_1 (0.62)	100	b_2 (7)	100	L_{A13} (10)	L_{B13} (−15)	L_{C13} (−130)	L_{D13} (−30)	L_{A23} (−19)	L_{B23} (13)	L_{C23} (300)	L_{D23} (230)

Based on the previous study, the influence order of the four cleaning parameters on the cleaning loss rate Y_1 is as follows: cleaning screen crank speed (D) > fan speed (C) > damper opening (B) > fish scale screen sheet opening (A). The influence order on the impurity rate Y_2 is: fish scale screen sheet opening (A) > damper opening (B) > fan speed (C) > cleaning screen crank speed (D) [22].

In line with the influence order of the four parameters on Y_1 (D > C > B > A), when Y_1 exceeds grade 0, parameter D is adjusted first. If the desired effect is not achieved, parameters C, B, and A are adjusted in succession.

Examining Table 8, we find that the parameter with the smallest adjustment range for Y_1 is A, with a range of 0 to 0.65667. To ensure that parameter A can be adjusted in all grade intervals, we set the condition $b_1 < 0.65667$, with the range 0.5 to 0.65667 covering a length of about 0.15. To allow the other three parameters to effectively divide the adjustment step size into three intervals, we set the constraint "interval range not less than 0.05." Therefore, the length of the grade 1 interval for Y_1 is 0.06, grade 2 is 0.56 to 0.62, and grade 3 is 0.62 to 100. As such, a_1 is set to 0.56 and b_1 is 0.62. Following the same method, we determine that a_2 is 5 and b_2 is 7. For Y2, grade 1 covers 3 to 5, grade 2 is 5 to 7, and grade 3 is 7 to 100.

Analyzing the adjustment step for parameter A, we calculate the step length for grade 0 [0, 0.5] of Y_1 to be approximately 25. When adjusting Y_1 from grade 1, 2, and 3 to 0.5 using parameter A, the minimum adjustments for Y_1 are 0.06, 0.12, and 0.15667, respectively. Corresponding adjustment steps for parameter A when transitioning Y_1 from grade 1, 2, and 3 to grade 0 are calculated as 3, 6, and 7.4, respectively. The adjustment step range for parameter A based on grade 1 of Y_1 is 3 to 28, grade 2 is 6 to 31, and grade 3 is 7.4 to 32.4. Within this range, the step size can be adjusted as needed. In practice, the adjustment step sizes for three fuzzy grade intervals corresponding to parameter A are set to L_{A11} as 4, L_{A12} as 7, and L_{A13} as 10, in accordance with the field operation of the multi-parameter adjustable measurable cleaning system. Using a similar approach, we determine the fuzzy grade intervals for the evaluation index and corresponding adjustment step sizes for the cleaning parameters, as shown in Table 10. Positive adjustment is represented by a positive adjustment step size, and negative adjustment is indicated by a negative step size.

4.2. Adaptive Control Strategy Workflow Chart

The real-time monitoring indexes Y_1 are designated as Y_{1R}, Y_{1R+1}, Y_{1R+2}, Y_{1R+3}, and Y_{1R+4}, while the real-time monitoring indexes Y_2 are denoted as Y_{2R}, Y_{2R+1}, Y_{2R+2}, Y_{2R+3}, and Y_{2R+4}. The industry standard for cleaning loss rate is Y_{1S}, and the industry standard for impurity rate is Y_{2S}. Table 10 illustrates that the qualifying conditions for these two indexes are $Y_{1R} \leq Y_{1S}$ and $Y_{2R} \leq Y_{2S}$, whereas the non-qualifying conditions are $Y_{1R} > Y_{1S}$ and $Y_{2R} > Y_{2S}$. Based on the influence order of cleaning parameters on the quality evaluation index of soybean machine harvesting and cleaning, the optimal combination of cleaning parameters for soybean machine harvesting, the fuzzy grade interval of the evaluation index, the adjustment step for corresponding cleaning parameters, and the weight relationship between cleaning loss rate Y_1 and impurity rate Y_2 of soybean machine harvesting are considered in the design of the workflow for the adaptive control strategy, as shown in Figure 3.

The workflow of the adaptive control strategy for simultaneous monitoring of Y_1 and Y_2 can be given by four parameters. When the real-time monitoring values of Y_1 and Y_2 are more than the 0 level range, the adaptive control of the four parameters is independently and simultaneously carried out. Due to the different ranking of the effects of the four parameters on the two indicators, and the reverse trend of the effects of the four parameters on the two indicators, as shown in Table 8, the regulatory components for these four parameters are unique. Therefore, when adaptively adjusting the four parameters for two indicators simultaneously, there may be situations where the same parameter is adjusted at the same time. For instance, parameter D is adjusted adaptively based on the weight relationship $Y_1 < Y_2$ of the two indicators. Indicator Y_2 undergoes adaptive adjustment for the corresponding adjustment step size of parameter D within the fuzzy level interval. Indicator Y_1 is sorted based on the impact of the four parameters on indicator Y_1 (E > D > C > B), and it automatically selects the next parameter C. This, in turn, completes adaptive adjustment of the fuzzy level interval corresponding to the adjustment step size of parameter C. When adjusting different parameters, they are adjusted simultaneously according to their respective adaptive control strategy workflow.

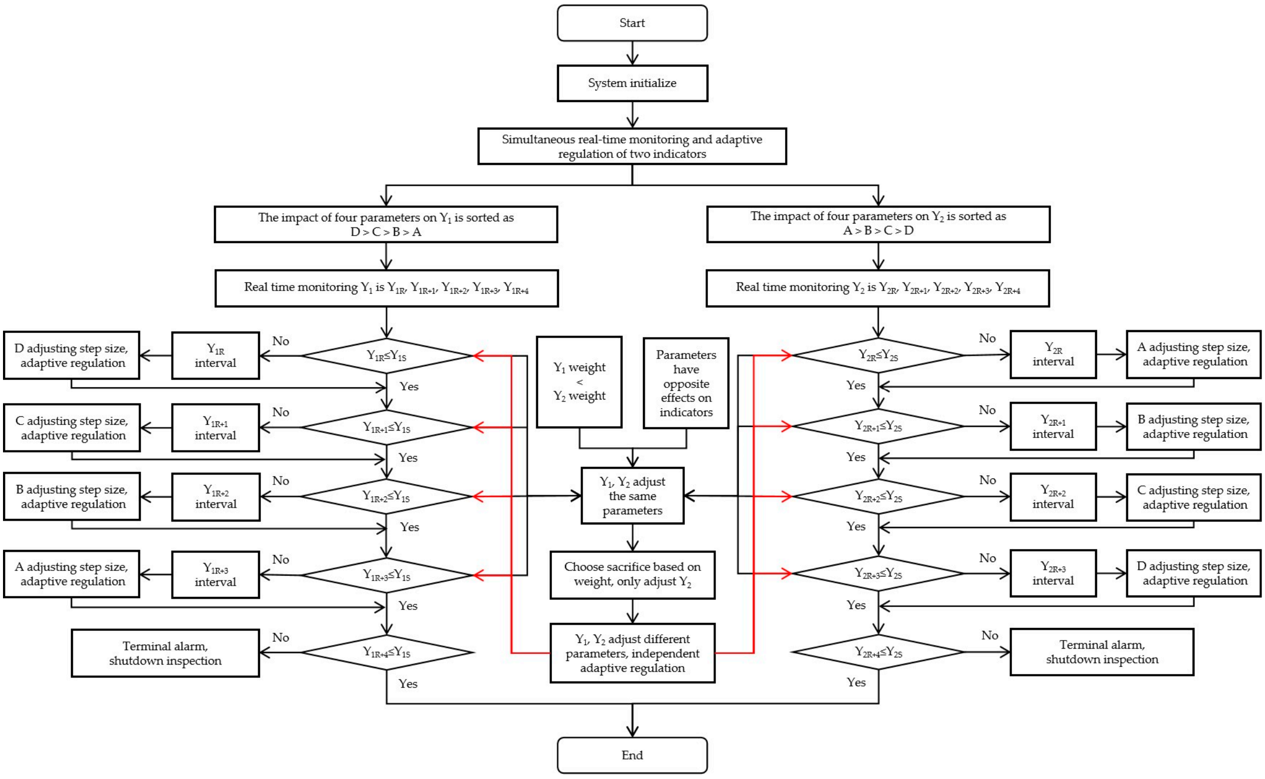

Figure 3. Adaptive control policy workflow.

5. Integration and Test of Adaptive Cleaning System

5.1. Integration and Working Principle of Adaptive Cleaning System

The adaptive cleaning system is integrated based on the multi-parameter adjustable measurable cleaning system and the workflow chart of the adaptive control strategy. The prototype and the supporting harvester are depicted in Figure 4.

When the adaptive cleaning system is engaged in cleaning during soybean machine harvesting, the power and control system provides electrical power to the entire adaptive cleaning system. It displays various parameters and real-time data, such as cleaning parameters and cleaning quality, on the display terminal. The initial value of the best cleaning parameter combination for soybean machine harvesting is set through the display terminal. The cleaning quality monitoring system monitors two evaluation indexes, cleaning loss rate and impurity rate, in real-time and displays them on the display terminal. If these two evaluation indexes exceed the 0 grade, the display terminal employs the adaptive control strategy workflow to determine the fuzzy grade interval in which these indexes are located. It then automatically selects the corresponding cleaning parameters and adjustment step sizes, and controls the multi-parameter adjustable measurable cleaning system to make real-time adjustments to the cleaning parameters. This process ensures that the cleaning parameters adapt to the characteristic differences of soybean extracts, continuously reducing the cleaning loss rate and impurity rate of soybean machine harvesting until both evaluation indexes reach the 0 grade. This maintains the optimal operation state of the air-and-screen cleaning device of the soybean combine harvester and achieves adaptive cleaning, matching the cleaning parameters to the characteristic differences of soybean extracts during soybean machine harvesting.

Figure 4. Prototype of adaptive cleaning system and supporting harvester.

5.2. *Adaptive Cleaning Test*

5.2.1. Pilot Items

Adaptive cleaning test items are shown in Table 11.

Table 11. Adaptive cleaning test items.

NO.	Name	Time	Place
1 2	Verification test Adaptive cleaning system test	October 2020	Soybean Test Base, Hedong District, Linyi City, Shandong Province, China

5.2.2. Test Parameters

The adaptive cleaning test employed Lindou 10 and Lindou 8 soybean varieties. The characteristic parameters of Lindou 8 soybeans used in the test are presented in Table 12, and the characteristics of Lindou 10 soybeans, the structure and operation parameters of the harvester, and the best combination of cleaning parameters for soybean machine harvesting are shown in Table 2 [21–26].

Table 12. Characteristic parameters of Lindou 8 soybean.

Name	Parameter
Varieties	Lindou 8
Grass-to-grain ratio	1.54
Moisture content of grain/(%)	14.9
100 grain weight/(g)	34.2
Plant height/(mm)	938
Bottom pods height/(mm)	176
Diameter of canopy surface/(mm)	205

5.2.3. Test Process

The adaptive cleaning system and supporting harvester were utilized to complete the adaptive cleaning test under the best combination of cleaning parameters for soybean machine harvesting. Initially, Lindou 8 was used for the verification test, followed by separate adaptive cleaning system tests for Lindou 10 and Lindou 8. The test site for Lindou 10 is illustrated in Figure 2, and the test site for Lindou 8 is shown in Figure 5.

Figure 5. Lindou 8 test site.

5.3. Verification Test and Analysis

5.3.1. Verification Test

The adaptive cleaning system's control function was verified in the field operation of soybean combine harvesters. Cleaning loss rate and impurity rate were significantly increased until they surpassed the 0 grade of the two evaluation indexes. Subsequently, the adaptive cleaning system's control function effectively reduced these evaluation indexes. This verified the system's adaptive control function.

The operation speed of the soybean machine harvester is positively correlated with the cleaning loss rate and impurity rate, with increased operation speed leading to higher cleaning loss rates and impurity rates [35–37]. The verification test covered a distance of 100 m, with the harvester initially operating at a speed of 6 km/h for the first 30 m. After reaching 30 m, the operator increased the harvester's speed to 7.5 km/h for the remaining 70 m. The verification test details are presented in Table 13.

Table 13. Validation test design.

Name	Initial Value	Adjustment Range	Working Distance /(m)	Operation Speed/(km/h)	
				Working Distance 0~30 m	Working Distance 30~100 m
Operation speed /(km/h)	6	0~7.5	100	6	7.5
Fish scale screen sheet opening /(mm)	32	0~43			
Damper opening /(°)	17	0~90			
Fan speed /(r/min)	1310	0~3000			
Cleaning screen crank speed /(r/min)	410	0~1500			

5.3.2. Data Analysis

The verification test produced 17 sets of evaluation indexes, and their data trends are displayed in Figure 6. Both the cleaning loss rate and impurity rate exhibited an initial increase followed by a decrease, confirming the effectiveness of the adaptive control function of the adaptive cleaning system.

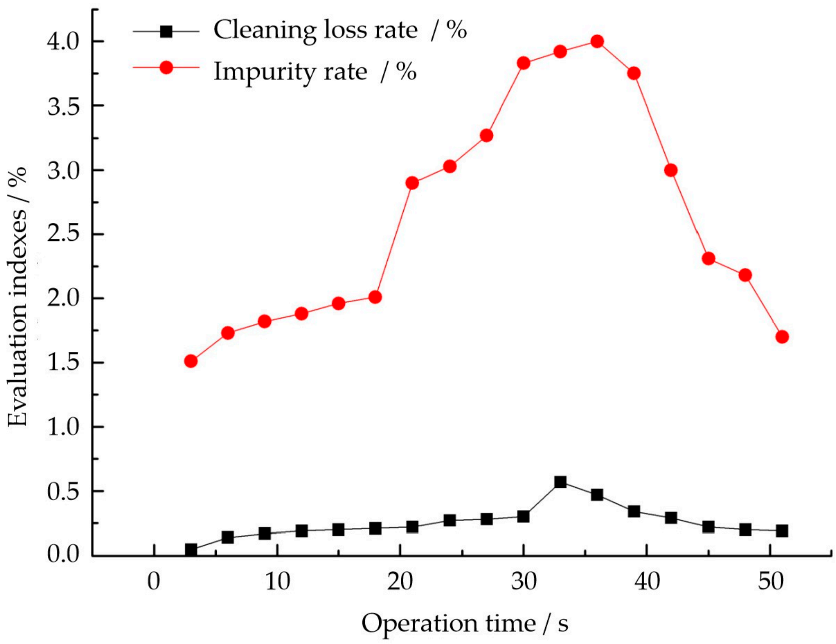

Figure 6. Trend of validation test data.

5.4. Adaptive Cleaning System Experiment and Analysis

5.4.1. Adaptive Cleaning System Test

The operation speed for the adaptive cleaning system test was fixed at 6 km/h, and each test covered a distance of 80 m, resulting in 16 sets of evaluation indexes for each test. The evaluation indexes for Lindou 10 and Lindou 8 were averaged separately, and subsequently, the evaluation indexes for both soybean varieties were averaged. The data from the adaptive cleaning system test are presented in Table 14.

Table 14. Adaptive cleaning system test data.

Name	Cleaning Loss Rate/(%)	Impurity Rate/(%)
Lindou 10	0.18	1.75
Lindou 8	0.20	1.61
Average value	0.19	1.68

5.4.2. Comparative Analysis

Table 4 reveals that the cleaning loss rate in the air-and-screen cleaning device test stands at 0.38%, with an impurity rate of 2.66%. Meanwhile, Table 14 illustrates that the adaptive cleaning system test records a cleaning loss rate of 0.19% and an impurity rate of 1.68%. A comparative analysis of the two evaluation index datasets from the adaptive cleaning system test and the air-and-screen cleaning device test, combined with the industry standards for soybean machine harvest evaluation indexes provided in Table 3, indicates that the cleaning loss rate and impurity rate in the adaptive cleaning system test are reduced by 0.19% and 0.98%, respectively, compared to those in the air-and-screen cleaning device test. Both of these values satisfy the requirements of the industry standards for cleaning loss rate ($Y_{1s} \leq 0.5\%$) and impurity rate ($Y_{2s} \leq 3\%$) in soybean machine harvesting.

6. Conclusions

(1) The effect of cleaning parameters on the cleaning quality of soybean machine harvesting is studied through cleaning experiments. By analyzing the experimental data from the air-and-screen cleaning device, it is determined that the cleaning loss rate for soybean machine harvesting is approximately 10.08%. The industry standard for the cleaning loss rate, Y_{1s}, is set at $\leq$0.5%, and the weight of the cleaning loss rate is less than that of the impurity rate. The linear equations and numerical ranges for the four cleaning parameters corresponding to the cleaning loss rate and impurity rate are obtained by analyzing the single-factor test data using Origin 9.1 software.

(2) The workflow chart for the adaptive control strategy is designed, and the integration of the adaptive cleaning system is explained, along with the operational principles of the adaptive cleaning system for a soybean combine harvester. An established verification method for the adaptive control function of the adaptive cleaning system is proposed, involving a significant increase in the cleaning loss rate and impurity rate of soybean machine harvesting. Analyzing the change trend of the two evaluation indexes for cleaning quality in the verification test confirms the effectiveness of the adaptive control function of the adaptive cleaning system. The adaptive cleaning system test and comparative analysis reveal that the cleaning loss rate and impurity rate in the adaptive cleaning system are reduced by 0.19% and 0.98%, respectively, when compared to the air-and-screen cleaning device.

(3) The cleaning loss rate and impurity rate of the adaptive cleaning system in a soybean combine harvester are lower than those of the air-and-screen cleaning device. The adaptive cleaning system can effectively reduce the cleaning loss rate and impurity rate during soybean machine harvesting. It enhances the adaptability of cleaning parameters to the differences in soybean extract characteristics and the cleaning quality of the air-and-screen cleaning device of the combine harvester. The research conducted in this paper on the adaptive cleaning system for a soybean combine harvester provides a practical reference for the development of high-quality, low-loss cleaning technology for soybean machine harvesting in China.

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