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Optimization Experiment and Analysis of Pneumatic Sorting for Multiscale Fresh Tea Leaves

Xiaoling Zhang
Jiaxing Vocational and Technical College, Intelligent Manufacturing Institute, Jiaxing, China

Chao Li
Laiwu Vocational and Technical College, Department of Artificial Intelligence, Institute of Applied Electronics, Jinan, China

Xu Zhang and Xinyu Zhu
Huzhou Vocational and Technical College, Huzhou 313000, China

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Abstract. **To solve the problems of low sorting rates in pneumatic sorting of multiscale fresh tea leaves and easy loss of fresh leaves in repeated experiments, a double negative pressure port noncoaxial adjacent bench was used as the research object. A 1:1 fresh tea leaf model was used to replace real fresh tea leaves. Through single-factor experiments and Box-Behnken response surface methodology, the effects of the rotation speed of the porous turntable, horizontal distance from the falling position of fresh tea leaves to the negative pressure ports, and running speed of the conveyor belt on the sorting rate were investigated. Single-factor experiments determined the effective range of each factor, and response surface methodology optimized the parameters to obtain the optimal combination. The rotation speed of negative pressure port A was 38 rpm and that of negative pressure port B was 28 rpm. The horizontal distances were as follows: L_A = 48 mm and L_B = 69 mm. The conveyor belt speed was 0.3 m/s. Under these parameters, the average sorting rate reached 80.6%, including 85.4% for one-bud–two-leaf leaves and 75.8% for single leaves, which were significantly higher than the initial sorting rate of 67.5%. An analysis of variance showed that the conveyor belt speed had the most significant effect on the sorting rate (F = 378.32), and there was a significant horizontal distance × conveyor belt speed interaction. This study provides a theoretical basis and technical support for the development of automatic and precise sorting equipment for fresh tea leaves.**

Precision grading of fresh tea leaves is a key preliminary link in the tea processing industry chain. The sorting accuracy directly determines the quality grade, flavor characteristics, and economic value of terminal tea products (Guang et al. 2025; Liu et al. 2023; Tang 2024; Zou 2023). With the upgrading of China's tea industry toward large-scale and automated development, the traditional manual sorting mode has resulted in difficulty meeting the needs of modern production because of its low efficiency, strong subjectivity, and easy damage to fresh leaves (Nie 2021; Xiao 2022; Xu 2022). Pneumatic sorting technology has become the mainstream technical path for grading multiscale fresh tea leaves because of its advantages of noncontact operation, no mechanical damage, and high sorting efficiency. However, its technical bottlenecks require correction through practical applications (Huang et al. 2023; Jiang et al. 2025; Lv et al. 2022; Wei 2024; Xue et al. 2020).

Currently, the pneumatic sorting technology for fresh tea leaves has two main problems. First, the sorting rate is generally low. Because of the unreasonable collaborative matching of key operating parameters of existing equipment, such as the rotation speed of negative pressure ports, the falling position of fresh leaves, and the conveyor belt speed, it is easy to incur the phenomenon of grading mixing of fresh tea leaves of different scales, resulting in insufficient sorting purity of target fresh leaves. Second, in the process of repeated experiments, real fresh tea leaves are prone to mechanical damage as well as water loss and deterioration caused by repeated adsorption, falling, manual statistics, and other operations, which not only affect the accuracy and repeatability of experimental data but also greatly increase the experimental cost. In addition, the influence of different placement methods of negative pressure ports (such as vertical type, coaxial relative type, noncoaxial adjacent type, etc.) on the sorting effect is significant to pneumatic sorting equipment with a double negative pressure port structure. The selection of the optimal structure and optimizing operating parameters have become the key to improving sorting performance (Gan et al. 2023; Wang et al. 2021; Zhou 2023).

Our research team previously conducted systematic preliminary experiments involving the pneumatic sorting bench with double negative pressure ports. By comparing the sorting effects of five placement structures (vertical type, noncoaxial relative type, noncoaxial adjacent type, coaxial relative type, and coaxial adjacent type) of double negative pressure ports, it was found that under the condition of a negative pressure difference of 380/320 Pa, the double negative pressure port noncoaxial adjacent bench had the highest average sorting rate of 67.5%. Its initial operating parameters were as follows: rotation speed of the porous turntables of both negative pressure ports, 30 rpm; horizontal distance from the falling position of fresh tea leaves to one side of the negative pressure port, 70 mm; and conveyor belt speed, 0.25 m/s. However, an obvious grading mixing problem under this parameter combination persisted, and the loss rate of real fresh tea leaves was as high as more than 20%, which seriously restricted the depth of parameter optimization and the reliability of experiments. To solve the problem of fresh leaf loss, the research team innovatively used a 1:1 fresh tea leaf model to replace real samples. This model is highly consistent with real fresh tea leaves in physical form and weight distribution, and it can withstand long-term repeated experiments, effectively eliminating the interference of fresh leaf damage on experimental results and providing a stable test basis for multifactor parameter optimization (Zhang et al. 2024a, 2024b, 2024c, 2024d; Zhang et al. 2025).

Based on the previous research foundation, this study used the double negative pressure port noncoaxial adjacent bench as the core research object and the 1:1 fresh tea leaf model as the test carrier. By focusing on three key influencing factors, the rotation speed of the porous turntable (differentiated setting of double negative pressure ports), horizontal distance from the falling position of fresh tea leaves to the negative pressure ports (L_A/L_B), and running speed of the conveyor belt, a two-step method of "single-factor experiment—response surface optimization" was adopted. First, single-factor experiments were conducted to determine the effective regulation range of each factor and exclude invalid parameter intervals. Then, based on the Box-Behnken response surface methodology, multifactor combination experiments were designed to construct a regression model of the sorting rate and each parameter, explore the interaction mechanism between factors, and screen the optimal parameter combination. This study aimed to break through the technical bottlenecks of low sorting rates and poor parameter coordination of traditional pneumatic sorting, realize the precise grading of multiscale fresh tea leaves, and provide a theoretical basis and technical

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X.Z. is the corresponding author. E-mail: 401787180@qq.com.

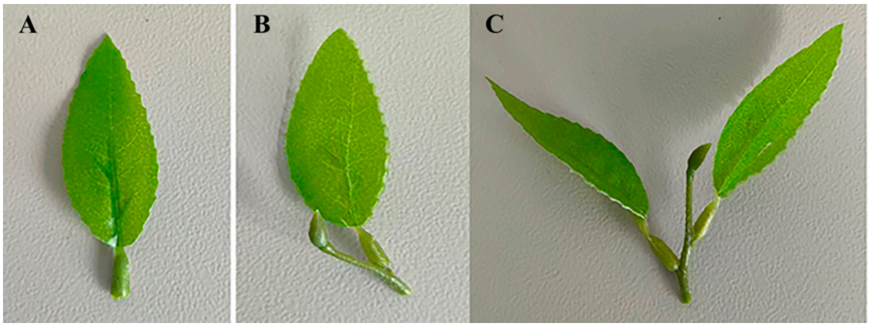

Fig. 1. Fresh tea leaf models used in the bench test. (**A**) Single leaf. (**B**) One-bud–one-leaf. (**C**) One-bud–two-leaf. Thirty leaves of each type are shown.

support for the structural design, parameter debugging, and industrial application of automatic sorting equipment for fresh tea leaves to promote the intelligent upgrading of the tea processing industry.

Experimental Materials and Methods

Experimental materials

According to the previous research of our research team, because of the need for multiple repeated experiments during the main experiment, the fresh tea leaves were mostly damaged during repeated sorting and manual statistics, which affected the experimental results. Therefore, in this study, our research team used a 1:1 fresh tea leaf model as a substitute. As a result, repeated experiments could be conducted for a long time without worrying about experimental errors caused by the loss of fresh tea leaves. Figure 1 shows the multiscale fresh tea leaves selected in the experiment.

Experimental design

Figure 2 shows the bench experiments constructed by the research team based on different placement positions of double negative pressure ports. The bench test equipment is mainly composed of a negative pressure fan (380/320 Pa), tea dropping chamber (made of acrylic transparent plates), porous turntable [created using three-dimensional (3D) printing], negative pressure baffle (created using 3D printing), variable-speed rotating motor and its control system, and speed-adjustable conveyor belt.

The research team counted the average sorting effect of different placement positions of double negative pressure ports through various previous bench tests. It was concluded that when the pressure difference of the double negative pressure fan was 320/380 Pa, the double negative pressure port noncoaxial adjacent type had the best sorting effect, with an average sorting rate of 67.5%. At that time, the equipment operating parameters were as follows: rotation speed of the porous turntables of the double negative pressure ports, 30 rpm; initial falling position of fresh tea leaves from the conveyor belt, center position of the adjacent negative pressure port; horizontal distance from the other side to the negative pressure port, 70 mm; rotation speed of the conveyor belt, 0.25 m/s; pressure values of the double negative pressure ports, 380/320 Pa. In summary, this study aimed to optimize the design of the double negative pressure port noncoaxial adjacent type to improve the sorting rate.

Experimental Analysis and Optimization

Single-factor experiments

The tea sorting rate is an index to measure the proportion of tea leaves effectively separated according to specific quality standards during the tea sorting process, thus reflecting the accuracy and effectiveness of tea sorting equipment expressed as follows:

$$\varphi = \frac{A}{W} \times 100\%$$

where A is the actual number of tea leaves that meet the target standards after sorting and W is the total number of tea leaves sorted.

Single-factor experiment of the rotation speed of a double negative pressure porous turntable. When our research team studied the double negative pressure port vertical bench test (Fig. 2A), experiments showed that the optimal sorting rate was obtained when the rotation speed of the porous turntables of both negative pressure ports was 30 rpm. Based on previous research, when the negative pressure value and the initial horizontal distance from the falling position of fresh tea leaves to the negative pressure port were constant, the adsorption rate of fresh tea leaves gradually decreased as the initial horizontal distance from the falling position of fresh tea leaves to the negative pressure port increased. In this experiment, different rotation speeds were set for the double negative pressure ports. The port with a closer vertical distance to the conveyor belt was defined as the upper negative pressure port, and the port with a farther vertical distance to the conveyor belt was defined as the lower negative pressure port. Combinations were as follows: combination 1, negative pressure port A rotation speed of 20 rpm and lower negative pressure port B rotation speed of 30 rpm; combination 2, negative pressure port A rotation speed of 30 rpm and negative pressure port B rotation speed of 30 rpm; combination 3, negative pressure port A rotation speed of 30 rpm and negative pressure port B rotation speed of 20 rpm; combination 4, negative pressure port A rotation speed of 30 rpm and negative pressure port B rotation speed of 40 rpm; and combination 5, negative pressure port A rotation speed of 40 rpm and negative pressure port B rotation speed of 30 rpm. These combinations were used to determine the rotation speed range of the porous turntable. The rotation speed of the porous turntable was measured with a tachometer (Delixi Electric Co., Ltd., Zhejiang, China) (Fig. 3A). The sorting rate was used as the experimental index to determine the influence of the rotation speed of the porous turntable on sorting. Each experiment was repeated four times, and the average value was used (Fig. 3B).

The experimental results are shown in Table 1. The sorting rate of combination 5 was higher than that of the other four, and the sorting rate of combination 1 was the lowest. An analysis of each single-factor experimental group showed that with combination 1, the upper negative pressure port had a negative pressure value of 380 Pa and a slow rotation speed, resulting in a long adsorption time. The strong adsorption force and long rotation time would adsorb both one-bud–two-leaf and one-bud–one-leaf leaves, leading to no purity in the upper grading; furthermore, the lower negative pressure port had a negative pressure value of 320 Pa and a medium rotation speed (i.e., weak adsorption force and medium adsorption time). Single leaves can be adsorbed, but one-bud–one-leaf leaves cannot be adsorbed because of their medium weight, resulting in only single leaves in the lower grading and one-bud–one-leaf leaves mixed into the upper group. For combination 2, during the strong adsorption of the upper port, one-bud–two-leaf and one-bud–one-leaf leaves were adsorbed, while the weak adsorption of the lower port could only adsorb single leaves. For combination 3, the upper negative pressure port could adsorb one-bud–two-leaf leaves, but one-bud–one-leaf leaves were still adsorbed because of sufficient adsorption force and insufficient centrifugal force; furthermore, the lower negative pressure port had a long adsorption

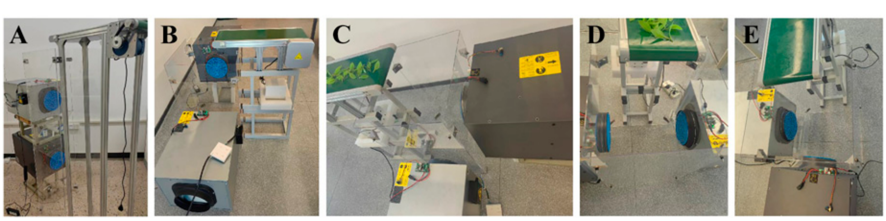

Fig. 2. Bench test design based on different placement positions of double negative pressure ports. (**A**) Double negative pressure port vertical bench test. (**B**) Double negative pressure port noncoaxial relative type. (**C**) Double negative pressure port noncoaxial adjacent type. (**D**) Double negative pressure port coaxial relative type. (**E**) Double negative pressure port coaxial adjacent type.

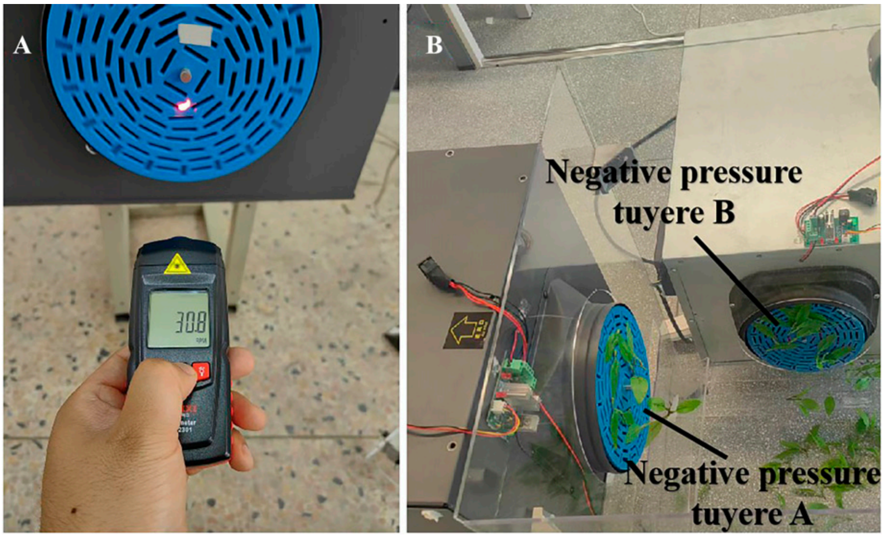

Fig. 3. Single-factor experiment involving different rotation speeds of porous turntables of the double negative pressure port noncoaxial adjacent type.

Table 1. Single-factor experimental results of different rotation speeds of porous turntables.

	Rotary speed of the multihole turntable (rpm)		
No.	Negative pressure tuyere A	Negative pressure tuyere B	Avg adsorption rate (%)
1	20	30	51.6
2	30	30	67.5
3	30	20	70.7
4	30	40	59.6
5	40	30	73.4

time, and the weak adsorption force could adsorb one-bud–one-leaf leaves, but single leaves were also adsorbed for a long time because of extremely low resistance, resulting in material mixing in both grades. For combination 4, the upper negative pressure port had insufficient centrifugal force, and the resistance of one-bud–one-leaf leaves was less than the adsorption force of the upper port, leading to the adsorption of one-bud–one-leaf leaves; furthermore, the lower negative pressure port had an extremely short adsorption time, and single leaves could be adsorbed, but one-bud–one-leaf leaves could not be stably adsorbed because of insufficient adsorption time, resulting in a low adsorption rate. For combination 5, the upper negative pressure port had sufficient adsorption force to achieve precise adsorption, and the adsorption time was suitable. The high rotation speed shortened the adsorption time to avoid excessive adsorption of one-bud–one-leaf leaves, and the shedding was stable. The centrifugal force of 40 rpm was sufficient to make the adsorbed one-bud–two-leaf leaves fall off quickly without residue; furthermore, the lower negative pressure port avoided mixing single leaves, and single leaves were not adsorbed and fell naturally. Single leaves were not adsorbed by the double negative pressure ports and were collected separately.

Single-factor experiment of the horizontal distance from negative pressure ports. To explore the influence of the initial falling position of fresh tea leaves and the distance from the porous turntable on the sorting performance, the distance from the falling position of fresh tea leaves to the porous turntable was used as the experimental factor. The center line of the conveyor belt was used as the reference. The horizontal distance from the center line of the conveyor belt to negative pressure port A was defined as L_A, and the distance to negative pressure port B was defined as L_B (Fig. 4). When the negative pressure value and the rotation speed of the porous turntable were constant, the adsorption rate of fresh tea leaves

Table 2. Single-factor experimental results of the horizontal distance from negative pressure ports.

	Horizontal distance from negative pressure port (mm)		Avg adsorption rate
No.	L_A	L_B	(%)
1	70	50	58.6
2	70	70	67.5
3	50	70	71.3
4	50	50	60.1

gradually decreased as the initial horizontal distance from the falling position of fresh tea leaves to the negative pressure port increased. However, if the distance from the conveyor belt to the negative pressure suction port was too close, then it was difficult to sort multiscale fresh tea leaves. In summary, the distances in this study were set as follows: group 1, L_A = 70 mm and L_B = 50 mm; group 2, L_A = 70 mm and L_B= 70 mm; group 3, L_A = 50 mm and L_B = 70 mm; group 4, L_A = 50 mm and L_B = 50 mm.

The experimental results are shown in Table 2. According to the sorting rate, group 3 had the best sorting effect, and group 1 had the worst sorting effect. An analysis of each single-factor experimental group was conducted. In group 1, for negative pressure port A, one-bud–two-leaf leaves required "strong adsorption and timely adsorption," but because of the large distance, one-bud–two-leaf leaves were easily adsorbed by the lower port B. However, the weak adsorption of negative pressure port B could not stably adsorb the heaviest one-bud–two-leaf leaves, resulting in chaotic sorting of one-bud–two-leaf leaves. The strong adsorption force of A also tended to overly adsorb single leaves and mix with one-bud–two-leaf leaves, eventually leading to chaotic adsorption and failure to achieve the purpose of sorting. In group 2, the distances between negative pressure port A and negative pressure port B were the same. When

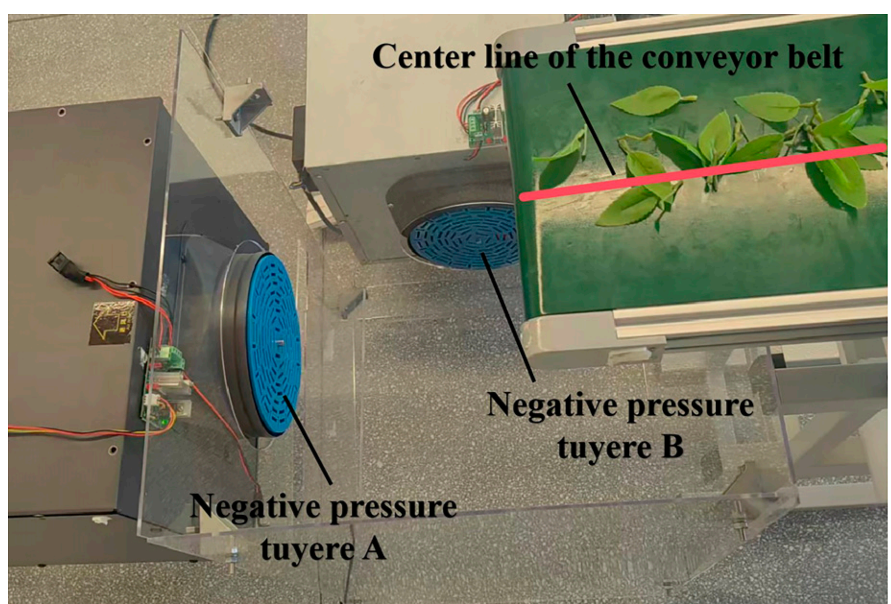

Fig. 4. Determination of the horizontal distance from negative pressure ports.

one-bud–two-leaf leaves were adsorbed by negative pressure port A, one-bud–one-leaf leaves were easily cross-adsorbed by negative pressure port A or B, resulting in grading mixing of one-bud–two-leaf and one-bud–one-leaf leaves. For single leaves, the strong adsorption force of negative pressure port A tended to overly adsorb single leaves and mix them into the sorting of negative pressure port A. In group 3, because the distance of negative pressure port A was closer than that of negative pressure port B and the negative pressure adsorption was strong, it adsorbed one-bud–two-leaf, one-bud–one-leaf, and single leaves. However, because of the large number of adsorbed one-bud–two-leaf leaves, the space of the porous turntable was occupied, so one-bud–one-leaf and single leaves were not adsorbed and continued to fall. Negative pressure port B, with lower negative pressure than that of negative pressure port A, mainly adsorbed relatively light single leaves, and one-bud–one-leaf leaves fell to the bottom. For group 4, the distances between negative pressure port A and negative pressure port B were both close. The strong suction of negative pressure port A mainly adsorbed one-bud–two-leaf leaves, which was similar to group 3. However, the adsorption of negative pressure port B was relatively chaotic. Compared with group 3, negative pressure port B adsorbed one-bud–one-leaf and single leaves, which made it difficult to achieve the sorting effect.

Single-factor experiment of the conveyor belt running speed. To explore the influence of the conveyor belt running speed on the double negative pressure noncoaxial adjacent sorting, the conveyor belt running speed was used as the experimental factor and a single-factor experiment was conducted. In the preliminary experiments of our research team, it was found that the slower the conveyor belt running speed, the better the double negative pressure adsorption sorting effect, but the efficiency was lower. Therefore, under the premise of meeting the sorting rate, the production efficiency should be improved as much as possible. According to the experiment, when the conveyor belt running speed was 0.25 m/s, the sorting rate was good. Therefore, 0.25 m/s, 0.40 m/s, 0.55 m/s, and 0.70 m/s were selected as the conveyor belt speeds.

The experimental results are shown in Table 3. The average sorting rate of experimental group 1 was the best. The fresh tea leaves stay above the negative pressure ports for the longest time. The negative pressure port A of 380 Pa had sufficient time to adsorb the "heaviest and most difficult to adsorb" one-bud–two-leaf leaves, and the negative pressure port B of 320 Pa also had sufficient time to adsorb the "medium weight" one-bud–one-leaf leaves. The adsorption effect between the negative pressure and the materials was the most sufficient, so the sorting rate was the highest. The speed of experimental group 2 was faster than that of experimental group 1, the residence time of fresh tea leaves at the negative pressure ports was shortened, and some one-bud–two-leaf/one-bud–one-leaf leaves left the adsorption area without being fully adsorbed by the negative pressure because of "insufficient adsorption time," resulting in a decrease in the sorting rate. However, because of the low speed increase, the sorting efficiency was improved. In experimental group 3, the speed was further increased, and the residence time was significantly shortened. At that time, the adsorption force of the negative pressure was difficult to overcome the resistance of fresh tea leaves in a very short time, especially for one-bud–two-leaf leaves, which are heavy and require stronger adsorption force and longer time. A large number of target fresh tea leaves left the conveyor belt "too late" to be adsorbed, and the sorting rate dropped to 50.7%.

The sorting rate of experimental group 4 was the lowest. The residence time of fresh tea leaves at the negative pressure ports was the shortest, and the negative pressure had insufficient time to act on the materials. Even the strong adsorption force of negative pressure port A had difficulty adsorbing one-bud–two-leaf leaves in a very short time. The weak adsorption force of negative pressure port B had more difficulty adsorbing one-bud–one-leaf leaves, so the adsorption rate dropped to the lowest rate.

Table 3. Single-factor experimental results of the conveyor belt running speed.

No.	Conveyor belt running speed (m/s)	Avg adsorption rate (%)
1	0.25	67.5
2	0.40	65.4
3	0.55	50.7
4	0.70	41.3

Table 4. Response surface experimental design.

Factors	Level		
	−1	0	1
Negative pressure port A/B multihole turntable speed (rpm)	30/30	30/20	40/30
Falling position is the horizontal distance from the negative pressure port L_A/L_B (mm)	50/50	50/70	70/70
Speed of the conveyor belt (m/s)	0.25	0.40	0.55

Response surface methodology experiment and analysis

Determination of response surface factors. According to the results of single-factor experiments, three levels with good results from each single-factor experiment were selected, and response surface methodology was used to design the experiments. Based on the central composite design principle of Box-Behnken, three factors with significant effects on double negative pressure sorting were selected for the experiments. Each factor was designed with three levels (i.e., a three-factor three-level combination experiment was conducted) (Table 4).

Analysis of response surface experimental results. In this experiment, the Box-Behnken design in response surface methodology was selected. Each numerical factor was set to three levels, five center points were set, and a total of 17 groups of experiments were conducted. The number of multiscale fresh tea leaves in the experiment was the same as aforementioned, and the average sorting rate was used as the experimental result. The experimental scheme and results are shown in Table 5.

Figure 5 shows the analysis of variance (ANOVA) of the experiment. The model's F-value of 80.73 and $P < 0.0001$ indicated that the model is extremely significant, can effectively explain the changes in the experimental index, and can be used for subsequent factor analysis and response prediction. A significance analysis of each factor was conducted. Factor A had an F-value of 73.08 and

Table 5. Experimental scheme and results.

No.	A: Negative pressure port A/B multihole turntable speed (rpm)	B: Falling position is the horizontal distance from the negative pressure port L_A/L_B (mm)	C: Speed of the conveyor belt (m/s)	Y: Avg sorting rate (%)
1	30/30	50/50	0.40	64.4
2	40/30	50/50	0.40	66.7
3	30/30	70/70	0.40	66.2
4	40/30	70/70	0.40	69.4
5	30/30	50/70	0.25	67.6
6	40/30	50/70	0.25	71.2
7	30/30	50/70	0.55	62.5
8	40/30	50/70	0.55	64.3
9	30/20	50/50	0.25	68.9
10	30/20	70/70	0.25	68.7
11	30/20	50/70	0.55	61.2
12	30/20	70/70	0.55	63.6
13	30/20	50/70	0.40	70.3
14	30/20	50/70	0.40	70.1
15	30/20	50/70	0.40	69.8
16	30/20	50/70	0.40	69.3
17	30/20	50/70	0.40	69.5

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	147.65	9	16.41	80.73	< 0.0001	significant
A-Negative pressure port A/B multi-hole turntable speed	14.85	1	14.85	73.08	< 0.0001	
B-The fall position is LA/LB away from the negative pressure port horizontally	5.61	1	5.61	27.61	0.0012	
C-The speed of the conveyor belt	76.88	1	76.88	378.32	< 0.0001	
AB	0.2025	1	0.2025	0.9965	0.3514	
AC	0.8100	1	0.8100	3.99	0.0861	
BC	1.69	1	1.69	8.32	0.0235	
A^2	5.69	1	5.69	28.00	0.0011	
B^2	16.22	1	16.22	79.80	< 0.0001	
C^2	21.08	1	21.08	103.73	< 0.0001	
Residual	1.42	7	0.2032			
Lack of Fit	0.7425	3	0.2475	1.46	0.3525	not significant
Pure Error	0.6800	4	0.1700			
Cor Total	149.07	16				

Std. Dev.	0.4508		**R^2**	0.9905
Mean	67.28		**Adjusted R^2**	0.9782
C.V. %	0.6701		**Predicted R^2**	0.9132
			Adeq Precision	29.7910

Fig. 5. Analysis of variance (ANOVA) of the regression model.

$P < 0.0001$, which is extremely significant. Factor B had an F-value of 27.61 and $P = 0.0012$, which is significant. Factor C had an F-value of 378.32 and $P < 0.0001$, which is extremely significant and has the greatest influence. These findings indicate that all three main factors had significant effects on the response value. From the interaction of factors, only the factor B × factor C interaction had a significant effect on the response value, and other interactions were not significant. A significant quadratic nonlinear relationship was observed between the three factors and the response value; in other words, the influence of factors on the response was not only linear but also had a curvilinear change trend.

The coefficient of determination R^2 of the model was 0.9905, indicating that the model could explain more than 99.05% of the changes in the response value, a high correlation between the predicted value and actual value, and the experimental error was small. The adjusted R^2 was 0.9782, and the fitting degree was still at a high level, indicating that the model was not distorted because of overfitting. The predicted R^2 was 0.9132, and the difference from the adjusted R^2 was less than 0.2, indicating that the fitting effect of the model on the training data were highly consistent with the prediction effect on new data, and there was no overfitting caused by too many independent variables or complex models. At the same time, the model had a very high goodness of fit, with both close to 1, indicating that the model had a strong ability to explain the variation of the response variable. The adjusted R^2 was close to R^2, indicating that most of the independent variables introduced in the model were effective and did not contain too many irrelevant or redundant variables. The adequate precision value was 29.7910, which was much greater than 4, indicating that the model had a high signal-to-noise ratio, the precision of the experimental design was sufficient, and it could effectively distinguish between factor effects and random errors.

Analysis of the influence of interactive factors on experimental indicators. Figure 6 shows the contour diagram and response surface diagram of factor A and factor B, where factor A is the negative pressure port A/B multihole turntable speed and factor B is the falling position horizontal distance from the negative pressure port.

Regarding the interaction and influence trend of factors, the response surface was "arch-shaped," indicating a significant quadratic nonlinear relationship between factor A and factor B on the sorting rate. The contour lines were not perfect circles, indicating a weak interaction between factor A and factor B. When factor A and factor B changed synergistically within a certain range, the sorting rate first increased to a peak and then gradually decreased; in other words, there was an optimal combination of factor A and factor B to maximize the sorting rate. The density of contour lines reflects the "influence sensitivity" of factors on the sorting rate. The denser the contour lines, the more significant the fluctuation of the sorting rate caused by small changes in factors in this interval; otherwise, the influence is relatively gentle. In the high sorting rate area (orange interval in Fig. 6), the contour lines are relatively dense, indicating that the parameter adjustment of factor A and factor B in this interval has a more significant impact on the sorting rate. The peak area of the response surface (orange–red interval in Fig. 6) corresponds to the optimal combination of factor A and factor B with the highest sorting rate. Combined with the "center of the closed circle" of the contour lines, it can be initially judged that when factor A and factor B are near this closed circle, the sorting rate of fresh tea leaves is optimal.

Figure 7 shows the contour diagram and response surface diagram of factor A and factor C, where factor A is the negative pressure port A/B multihole turntable speed and factor C is the conveyor belt speed.

Regarding the interaction and influence trend of factors, the response surface is an "arched convex surface," indicating that there is a significant quadratic nonlinear relationship between factor A and factor C on the sorting rate. The contour lines are not perfect circles, reflecting a weak interaction trend between factor A and factor C. The sorting rate shows a trend of "first rising and then falling" with the synergistic change of factor A and factor C. When factor A and factor C are adjusted within a certain range, the sorting rate first rises to a peak and then gradually decreases, indicating that there is an optimal combination of factor A and factor C to maximize the sorting rate. The density of contour lines reflects the influence sensitivity. The contour lines in the high sorting rate area (red interval in Fig. 7) are denser, indicating that small changes in factor A and factor C in this interval will cause significant fluctuations in the sorting rate. The contour lines in the low sorting rate area (green interval in Fig. 7) are sparse, and the influence is relatively gentle. The peak area of the response surface (red interval in Fig. 7) and the "center of the closed circle" of the contour lines correspond to the optimal combination of factor A and factor C with the highest sorting rate. When factor A and factor C are in this area (Fig. 7), the sorting rate of fresh tea leaves can reach a high level of more than 70%.

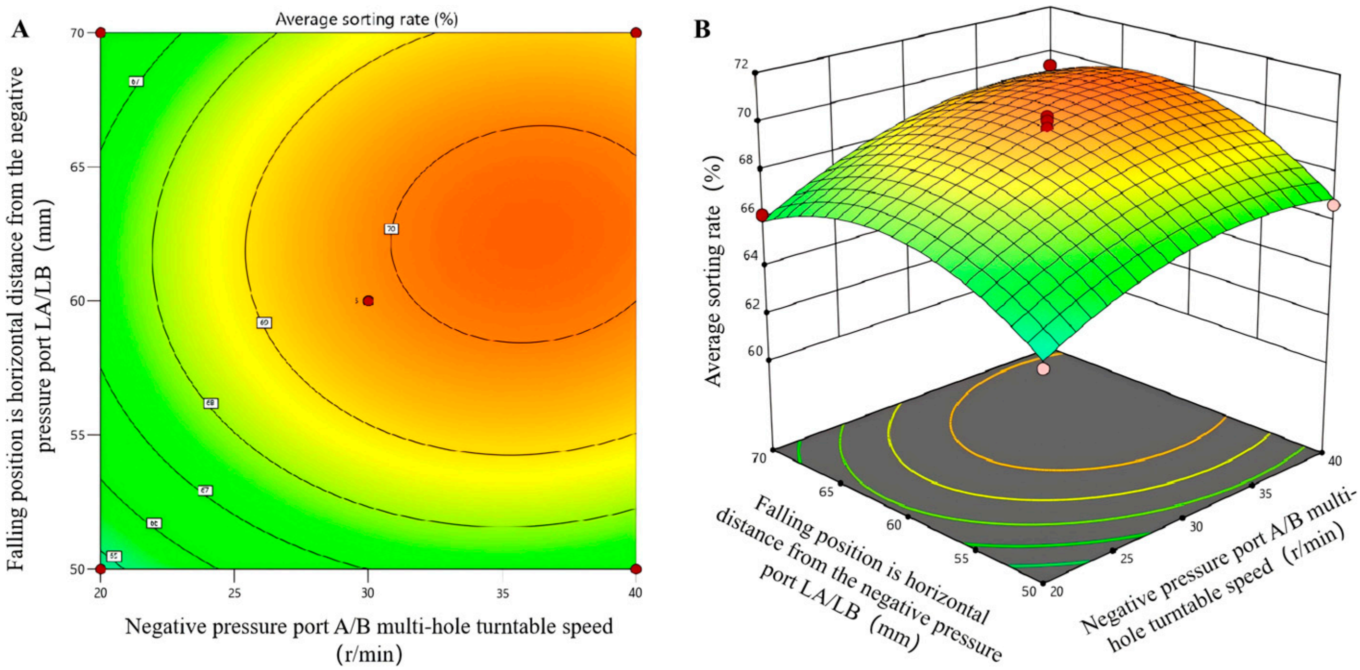

Fig. 6. Contour diagram and response surface diagram of factor A and factor B.

Figure 8 shows the contour diagram and response surface diagram of factor B and factor C, where factor B is the falling position horizontal distance from the negative pressure port and factor C is the conveyor belt speed.

The response surface diagram shows that the response surface is an "arched convex surface," indicating that there is a significant quadratic nonlinear relationship between factor B and factor C on the sorting rate. The contour lines are not perfect circles but show obvious "deformed circles," reflecting a significant factor B × factor C interaction. The sorting rate shows a clear trend of "first rising and then falling" with the synergistic change of factor B and factor C. When factor B and factor C are adjusted within a certain range, the sorting rate first rises to a peak and then gradually decreases, indicating an optimal combination of factor B and factor C to maximize the sorting rate. The contour lines in the high sorting rate area (red interval in Fig. 8) are extremely dense, indicating that small changes in factor B and factor C in this interval will cause significant fluctuations in the sorting rate. The contour lines in the low sorting rate area (green and blue intervals in Fig. 8) are relatively sparse, and the influence of factors on the sorting rate is more gentle. The peak area of the response surface (red core interval in Fig. 8) and the "center of the closed circle" of the contour lines correspond to the maximum sorting rate interval. When factor B and factor C are near this closed circle (Fig. 8), the sorting rate of fresh tea leaves can exceed 70%, reaching the optimal level in the experiment.

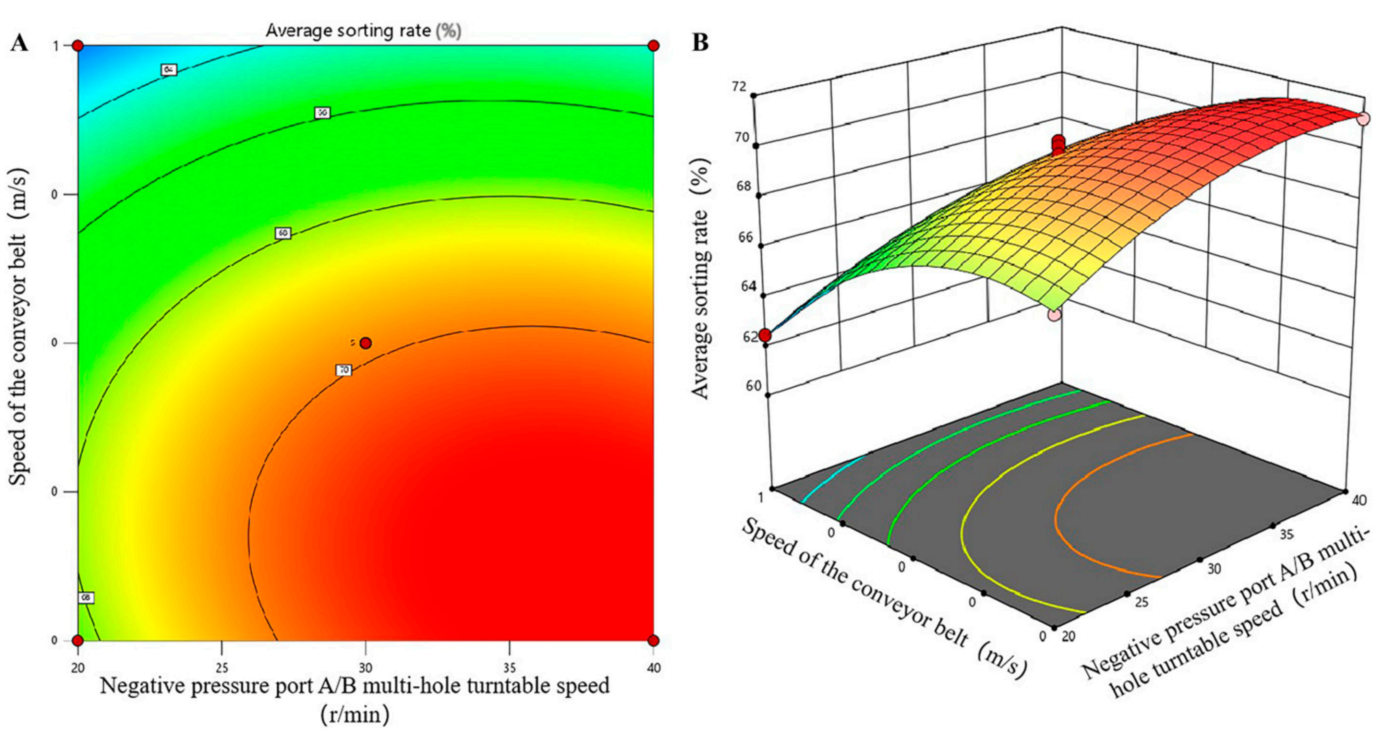

Fig. 7. Contour diagram and response surface diagram of factor A and factor C.

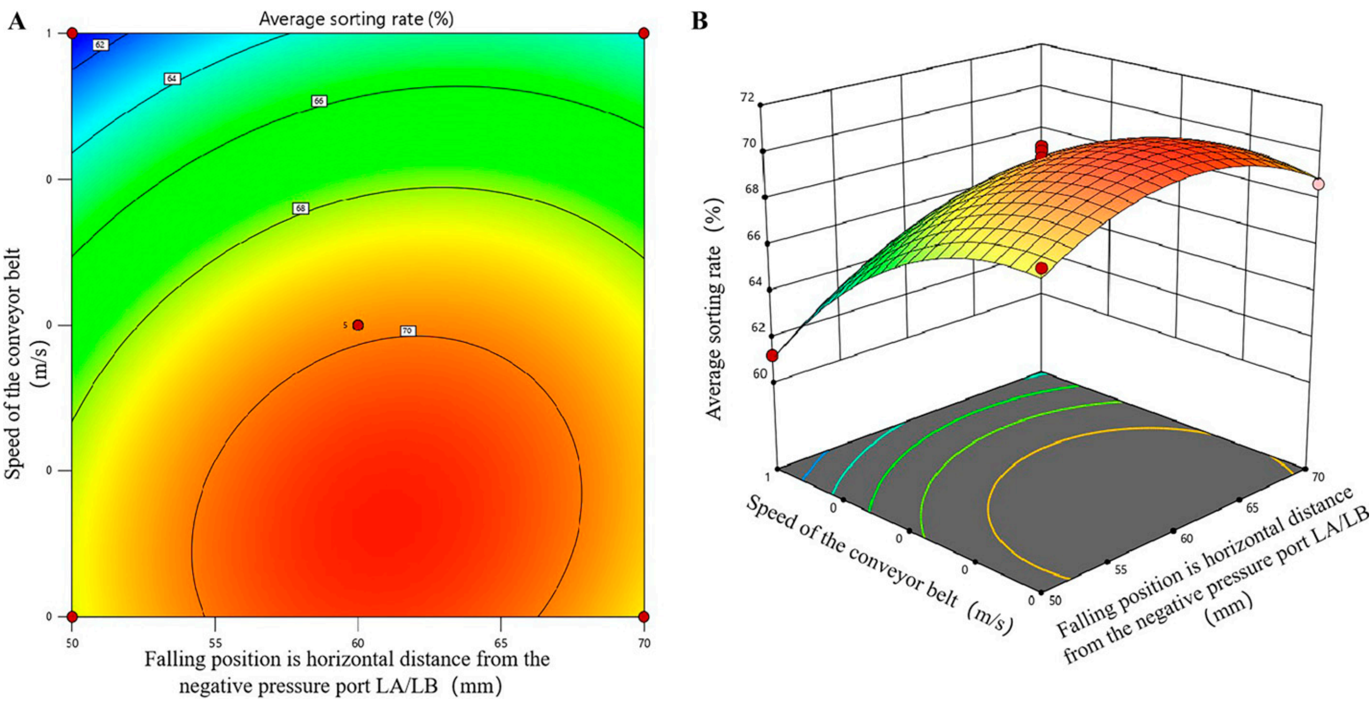

Fig. 8. Contour diagram and response surface diagram of factor B and factor C.

Experimental optimization

According to the aforementioned analysis of the influence of interactive factors on experimental indicators, the optimal parameters for a sorting rate ≥70% are as follows: factor A, the rotation speed of negative pressure port A ranges from 35 to 40 rpm, and the rotation speed of negative pressure port B ranges from 28 to 32 rpm; factor B, LA = 48 to 52 mm and LB = 68 to 72 mm; and factor C, 0.25 to 0.35 m/s. Using the optimization function of Design-Expert software, with the goal of maximizing the sorting rate, the factors were optimized to obtain the following optimal parameters: factor A, rotation speed of negative pressure port A = 38 rpm, rotation speed of negative pressure port B = 28 rpm; factor B, LA = 48 mm and LB = 69 mm; and factor C, 0.3 m/s. The measured average sorting rate was 80.6%, where negative pressure port A mainly adsorbed one-bud–two-leaf leaves, and the sorting rate of one-bud–two-leaf leaves was 85.4%. Negative pressure port B mainly adsorbed single leaves, with a sorting rate of 75.8%.

Discussion

This study used the double negative pressure port noncoaxial adjacent bench as the research object to solve the problems of low sorting rates and easy loss of fresh tea leaves in repeated experiments during the pneumatic sorting of multiscale fresh tea leaves. Through single-factor experiments and response surface methodology optimization, the key factors affecting the sorting effect and the optimal parameter combination were clarified, and the sorting rate was significantly improved from 67.5% initially to 80.6%. This provides a theoretical basis and technical support for the development and application of automatic and precise sorting equipment for fresh tea leaves.

Differential regulation effect of porous turntable rotation speed. The results of single-factor experiments show that the asymmetric setting of the rotation speeds of the double negative pressure ports is better than the symmetric setting, which is closely related to the physical properties of fresh tea leaves and the adsorption–centrifugal balance mechanism. The upper negative pressure port needs to accurately adsorb the heaviest one-bud–two-leaf leaves. A higher rotation speed not only avoids excessive adsorption of one-bud–one-leaf leaves by shortening the adsorption time but also uses sufficient centrifugal force to make the adsorbed one-bud–two-leaf leaves fall off quickly and reduce residue. The lower negative pressure port mainly adsorbs single leaves, and a medium rotation speed can balance the adsorption force and residence time, avoiding single leaves being adsorbed for a long time because of low resistance or one-bud–one-leaf leaves being unable to be stably captured because of insufficient adsorption force. The combination of 38 rpm (port A) and 28 rpm (port B) determined by response surface optimization further verifies the importance of differential rotation speed regulation for improving sorting purity. Its core logic is to achieve the stratification of fresh tea leaves of different scales in adsorption priority through the matching of rotation speed and negative pressure value.

Spatial adaptability of the horizontal distance from negative pressure ports. The horizontal distance (LA/LB) between the initial falling position of fresh tea leaves and the negative pressure ports directly affects the action intensity and coverage range of the negative pressure field. In the single-factor experiment, the combination of LA = 50 mm and LB = 70 mm had the best sorting rate (71.3%). This is because this distance setting allows the upper negative pressure port (strong adsorption) to preferentially capture the near-field one-bud–two-leaf leaves, while the lower negative pressure port (weak adsorption) reduces the false adsorption of one-bud–two-leaf leaves through a longer horizontal distance and accurately captures the single leaves during the falling process. If LA and LB are too close, then the adsorption areas of the double negative pressure ports will overlap, leading to grading mixing of one-bud–one-leaf and single leaves; if LA is too far, then the adsorption force of the upper negative pressure port on one-bud–two-leaf leaves will attenuate, resulting in chaotic sorting. The optimized parameters of LA = 48 mm and LB = 69 mm through the response surface further refine the spatial adaptability relationship, indicating that the horizontal distance between the falling position of fresh tea leaves and the negative pressure ports needs to be gradient-matched according to the negative pressure intensity to maximize the use of the differential adsorption effect of the negative pressure field.

Dominant influence of the conveyor belt speed. The results of the ANOVA show that the F-value of the conveyor belt running speed is as high as 378.32, which is the most significant factor affecting the sorting rate ($P < 0.0001$). This result is highly consistent with the essential characteristics of pneumatic sorting. The adsorption process of fresh tea leaves requires a certain negative pressure action time. When the conveyor belt speed is 0.25 m/s, one-bud–two-leaf and one-bud–one-leaf leaves can have sufficient time to be adsorbed by the corresponding negative pressure ports, and the sorting rate reaches 67.5%. When the speed increases to 0.70 m/s, the adsorption time is greatly shortened, and even the strong negative pressure port is difficult to overcome the inertial resistance of fresh tea leaves, and the sorting rate drops sharply to 41.3%. However, considering the actual production efficiency, the intermediate speed of 0.3 m/s selected after response surface optimization not only retains a high sorting rate but also avoids the efficiency loss caused by too low speed, achieving a balance between sorting accuracy and production efficiency. This finding suggests that in the design of pneumatic sorting equipment, the conveyor belt speed should be dynamically adjusted as a core parameter and adjusted in real time according to the scale distribution of fresh tea leaves.

Conclusions

This study concluded the following through single-factor experiments and response surface methodology optimization. First, the double negative pressure port noncoaxial adjacent structure has the best sorting effect after parameter optimization. The key influencing factors are sorted by significance as follows: conveyor belt running speed, porous turntable rotation speed, and horizontal distance from the falling position of fresh tea leaves to the negative pressure ports. Second, the optimal operating parameters are as follows: rotation speed of negative pressure port A, 38 rpm; rotation speed of negative pressure port B, 28 rpm; LA, 48 mm; LB, 69 mm; and conveyor belt speed, 0.3 m/s. At that time, the average sorting rate reached 80.6%, realizing the precise grading of one-bud–two-leaf, one-bud–one-leaf, and single leaves. Third, differential rotation speed regulation, gradient matching of horizontal distance, and dynamic balance of conveyor belt speed are the core mechanisms to improve sorting accuracy and efficiency. This optimization scheme effectively solves the problems of serious grading mixing and low efficiency of traditional sorting and provides key technical references for the industrial application of fresh tea leaf sorting equipment.

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