The Positive and Negative Synergistic Airflow-Type Jujube Fruit Harvester (P-N JH)

Hongzhen Xu *, Yong Hua, Jie He and Qingli Chen

College of Mechanical and Control Engineering, Guilin University of Technology, Guilin 541006, China; 2018012@glut.edu.cn (Y.H.); xu_hz086@163.com (J.H.); timesea1572037232@163.com (Q.C.)
* Correspondence: 2018013@glut.edu.cn

Abstract: Low operation efficiency and poor working performance are the main reasons that restrict the application of pneumatic date pickers. In this study, it is proposed to use positive pressure air flow blowing and negative pressure air flow suction to pick jujube fruit and to use inertia air flow to remove impurities and design a positive and negative collaborative air flow type date fruit harvester (P-N JH). The second-order regression model of test factors and response indexes was established by using the central composite design method, and the operating performance of P-N JH was evaluated and comprehensively optimized, and the optimal combination of operating parameters was obtained: positive pressure wind speed, negative pressure wind speed, and travel speed were 16.8 m·s⁻¹, 34.0 m·s⁻¹, and 1.5 m·s⁻¹, respectively. In addition, the verification test results show that the pickup rate, impurity rate, damage rate, and operating efficiency are 97.21%, 2.15%, 1.08%, and 2170 kg/h, respectively. The operating performance of P-N JH not only meets the requirements of jujube picking but also significantly improves the operating efficiency compared with the traditional air-suction jujube harvester. This study can provide theoretical and technical reference for the harvesting of air-suctioned dates; it also provides a new way of thinking for jujube fruit picking.

Keywords: jujube fruit; pickup; pneumatic; parameter optimization

1. Introduction

Jujube fruit (Ziziphus jujube Mill.) have rich nutrition and important medical care functions [1,2]. They are usually planted in China, Pakistan, Iran, Lebanon, the Korean peninsula, and Northern India [3], among which China is the largest output and export of jujube fruit countries in the world. Due to the natural conditions of large temperature difference and arid climate, Xinjiang province is an important area for high-quality jujube fruit with 3.81 million tons output, about 50% of the total output of China [4]. The jujube fruit are mainly processed into dried jujube fruit and jujube products. Hence, the method of natural air drying on the tree after maturity was usually adopted to reduce the moisture content and further improve nutritional composition in the Xinjiang province [5]. The jujube fruit will fall off naturally in large quantities [6] in harvest periods. At present, the jujube fruit harvesting method is: (a) to knock off the remaining jujube fruit on the tree, (b) together with the naturally shedding jujube fruit to the middle of the jujube fruit row to form a “jujube fruit belt”, and (c) pick up the jujube fruit manually or mechanically. Manual pick up jujube fruit have the problems of low efficiency, high cost, and high labor intensity, which is difficult to meet the jujube fruit harvesting needs of the Xinjiang province [7,8]. To solve the problem of manually picking up jujube fruit, experts have developed a variety of types of jujube fruit pick up machine. According to the operation principle, which can be divided into mechanical ground jujube fruit pick up machine [9–12] and pneumatic ground jujube fruit pick up machine [13–16], the picking device needs to go deep into the soil to shovel or pick up the jujube fruit as the mechanical ground-based jujube picker operates, which has higher requirements for the ground flatness and soil type of the jujube fruit...
garden, which limits its promotion and application. The pneumatic ground jujube fruit pick up machine is the hot spot of current research. The working principle is to suction ground jujube fruit through the negative pressure airflow formed by the centrifugal fan, and then to remove the impurities through the cleaning device. Due to the rapid dissipation of negative pressure airflow [17], small effective action area, and collision between jujube fruit and the cleaning device, there are some problems, including low operation efficiency, low clean rate, containing more impurities, and high damage rate.

The existing research results showed that when increasing the initial kinetic energy of materials [18,19], changing the operation form and/or parameters of the negative pressure airflow can effectively improve operation efficiency and working performance before picking up materials. The inertial airflow technology that is used in the fluid dynamics and inertia differences between materials and impurities [20–22] was usually used to remove impurity of agricultural materials. However, the application of the removal impurities that contained jujube fruit has not attracted the attention of experts. Hence, the device with high efficiency for picking up jujube fruit and high quality for cleaning jujube fruit and impurities, as well as a new type of jujube fruit harvester need to be developed urgently.

Therefore, the positive and negative synergistic airflow-type jujube fruit harvester (P-N JH) was designed, which picks jujube fruit through the method of positive pressure airflow blowing and negative pressure airflow suction, and the inertial airflow principle was used to remove impurities. The focus is on the evaluation and comprehensive optimization of the operational performance of the P-N JH through the second-order regression model of experimental factors and response indexes. This study is expected to solve the bottleneck problem of jujube gas absorption and can provide a new method for jujube harvesting.

2. Materials and Methods
2.1. Materials

The field tests of P-N JH performance were carried out at the 10th regiment jujube fruit mechanization demonstration base in the Alar city, Xinjiang province (longitude: 81°29′58.98″, latitude: 40°34′5.30″) on 22–30 November 2021. The experimental jujube fruit garden area is 226 m long and 86 m wide. The row spacing, the average plant spacing, the average height of the jujube tree, and the crown width are 3 m, 1.5 m, 3.2 m, and 2.6 m, respectively. The jujube tree age is 9 years old, and the plant variety is Xinzheng Grey Jujube, with a yield of 9750 kg/ha. The long axis and short axis of jujube fruit were measured with a DL91150 digital vernier calipers (maximum measurement length: 150 mm, measurement accuracy: 0.02 mm), the main distribution range of the long-axis size of jujube fruit is 28.81–29.34 mm, with a mean value of 29.08 mm and a standard deviation of 3.06 mm; the main distribution range of the short-axis size is 20.69–21.05 mm, with a mean value of 20.87 mm and a standard deviation of 2.02 mm. The average moisture content of wet base of jujube fruit at harvest dates is 48.54 ± 4.21%, which was measured with a Sartorius MA100 electronic rapid moisture tester (measurement accuracy: 0.001 g, moisture content accuracy: 0.01%, Sartorius Germany). In addition, the instruments used in the tests include a TCS-60 electronic platform scale (measuring accuracy: 2 g, Shanghai Yousheng Weighing Instrument Co., Ltd., Shanghai, China) and a SYT-2000V intelligent digital pressure anemometer (pressure range: 0–±2000 Pa, airflow speed range: 0–40 m/s, resolution: 0.01 m/s) [23].

2.2. Design of the P-N JH
2.2.1. Structure

Figure 1 shows the structure of the P-N JH, which mainly consists of a diesel engine power generation system, control cabinet, inertial airflow cleaning system, positive and negative synergistic airflow pick up device, jujube fruit conveying device, transmission mechanism, and caterpillar walking chassis.
Figure 1. Structure of the positive and negative synergistic airflow-type jujube fruit harvester (P-N JH). 1. negative pressure airflow pipe; 2. diesel engine power generation system; 3. positive pressure airflow pipe; 4. control cabinet; 5. inertial airflow type cleaning system; 6. air distribution and regulation device; 7. centrifugal fan; 8. jujube fruit conveying device; 9. turnover basket; 10. negative synergistic airflow pick up device; 11. gear motor; 12. jujube guide slot; 13. frame; 14. transmission mechanism; 15. caterpillar walking chassis.

The key devices of the P-N JH were the positive and negative synergistic airflow device and inertial airflow cleaning system. The function of the positive and negative synergistic airflow device was to pick up jujube fruit on the ground, and its structure and parameters were shown in Figure 2a, mainly including the negative pressure airflow mouthpiece, negative pressure airflow mouth, positive pressure airflow mouthpiece, positive pressure airflow mouth, connector, etc. The function of the inertial airflow system was to remove impurities contained in picked-up jujube fruit, and its structure was shown in Figure 2b, which mainly consists of the materials inlet, diversion surface, regulating plate, roller screen, airflow outlet, etc.

Figure 2. The key device of the positive and negative synergistic airflow-type jujube fruit harvester (P-N JH): (a) working principle of pneumatic pickup, and (b) operation principle diagram of the inertial airflow cleaning system. 1. negative pressure airflow mouthpiece; 2. positive pressure mouth; 3. ground; 4. positive pressure airflow direction; 5. jujube fruit; 6. jujube fruit movement direction; 7. negative pressure airflow direction; 8. materials inlet; 9. diversion surface; 10. jujube fruit closed-air aspirator; 11. regulating plate; 12. impurities closed-air aspirator; 13. roller screen; 14. materials outlet.

The positive and negative synergistic airflow device was installed on the frame through the connector, and the connector with profiling function can ensure that the negative pressure airflow mouth was in close contact with the ground. The outlet of the inertial airflow cleaning system was connected to the air inlet of a centrifugal fan, and the materials inlet was connected with the negative pressure airflow mouthpiece through the negative
pressure airflow pipe (D = 0.20 m). The positive pressure airflow mouthpiece was connected to the air distribution and regulation device installed on the centrifugal fan outlet through the positive pressure airflow pipe (D = 0.15 m). The diesel engine power generation system provides power for the running of the P-N JH and working parts, and the control cabinet regulates the travel speed of the machine and the running parameters of each working part.

2.2.2. Working Principle

During the centrifugal fan running, the negative pressure airflow was formed at negative pressure airflow mouth, and the positive pressure airflow was formed at the positive pressure airflow mouth. The strip-shaped positive pressure airflow mouth presents a certain angle with the P-N JH forward direction and the ground. With the P-N JH forward, jujube fruit and impurities were successively concentrated in the acting force area of negative pressure airflow by the positive pressure airflow and were suctioned by the negative pressure airflow. Then the jujube fruit and impurities will enter the inertial airflow cleaning system. The running trajectory of jujube fruit and impurities will change due to the difference of fluid dynamics and inertia characteristics of jujube fruit and impurities [24]. The jujube fruit were discharged from the jujube fruit closed-air aspirator and fell into the jujube guide slot and were then transported to the turnover basket through the jujube fruit conveying device. The impurities that passed through the regulating plate were blocked by the roller screen and discharged to the garden ground by the impurities closed-air aspirator. After that, the process of picking up and cleaning was completed.

2.2.3. Technology Parameters

The main technical parameters of the P-N JH were shown in Table 1.

Table 1. Technology parameters of the positive and negative synergistic airflow-type jujube fruit harvester (P-N JH).

| Items                              | Values/Type         |
|------------------------------------|---------------------|
| Rated power/kW                     | 40                  |
| Unity machine dimensions (Length × width × height)/ (mm × mm × mm) | 2840 × 1320 × 1710 |
| Centrifugal fan model              | YS-47               |
| Travel speed/(km/h)                | 0–3 (continuously variable) |
| Operation width/m                  | ≤0.65               |
| Pick up rate/%                    | ≥96                 |
| Impurities rate/%                  | ≤3                  |
| Damage rate/%                     | ≤1.5                |

2.3. Tests Methods and Performance Evaluation

The P-N JH performance tests were carried out according to the GB/T5667-2008 “Agricultural Machinery Production Test Method” and DG/T 188-2019 “Fruit Picker” standard [25,26]. Several test areas with thirty meters and intervals areas of three meters were divided by tape measures at the rows and marked with colored flags. In addition, the impurities in the jujubes collected by the machine are mainly jujube leaves and jujube hangings; to avoid the influence of adjacent test results, the jujube fruit and impurities in the interval areas were removed manually. The tests were carried out after the operation parameters were adjusted to the conditions required, and the operation time of each test area was recorded. After the tests, the picked-up jujube fruit, unpicked-up jujube fruit, impurities, and damaged jujube fruit were carefully collected by hand and their mass were recorded as $N_{tp}$, $N_{up}$, $N_{pi}$, and $N_{pd}$, respectively.

According to the test standards of jujube fruit harvesting performance and the actual requirements of jujube fruit harvester [27], the pickup rate, impurities rate, damage rate, and operation efficiency were determined as the evaluation indexes of the P-N JH operation performance. The pickup rate was the ratio of the picked-up jujube fruit mass to the unpicked-up jujube fruit mass. The impurities rate was the ratio of the impurities mass...
contained in the jujube fruit to the picked-up jujube fruit mass. The damage rate was the ratio of the damaged jujube fruit mass, which were caused by machine operation, to the picked-up jujube fruit mass [28]. The operation efficiency was the ratio of the picked-up jujube fruit mass of pure operation time. Since jujube fruit were approximately evenly distributed in the jujube fruit garden, it was more meaningful to test the operation efficiency at the optimal operating performance of the P-N JH. The operation efficiency can be calculated according to the traveling speed and the pickup rate.

The pickup rate, impurities rate, breakage rate, and operation efficiency of the P-N JH were calculated according to Equations (1)–(4).

\[ \eta_{pr} = \frac{N_{up}}{N_{tp}} \times 100 \]  
\[ \eta_{ir} = \frac{N_{ip}}{N_{tp}} \times 100 \]  
\[ \eta_{dr} = \frac{N_{pd}}{N_{tp}} \times 100 \]  
\[ \xi = \frac{N_{tp}\eta_{pr}}{t} \]

where: \( \eta_{pr} \) was the pickup rate, %; \( N_{up} \) was the mass of unpicked jujube fruit by the P-N JH, kg; \( N_{tp} \) was the mass of picked-up jujube fruit by the P-N JH, kg; \( \eta_{ir} \) was the impurities rate, %; \( N_{ip} \) was the impurities mass that was contained in the picked-up jujube fruit, kg; \( \eta_{dr} \) was the damage rate, %; \( N_{pd} \) was the mass of damaged jujube fruit by the P-N JH, kg; \( \xi \) was the operation efficiency, %; \( t \) was pure operation time, s.

2.4. Experimental Data Process

According to the working process analysis and the pre-tests of the P-N JH, the function of the positive pressure airflow is to blow the jujube fruit along the ground to the suction port of the negative pressure airflow, which mainly affects the movement of the jujube fruit. The negative pressure airflow speed should ensure the normal operation of picking and conveying jujube fruits, which mainly affects the suction process of jujube fruit [29].

The travel speed of the harvester affects the relative motion state of the machine and jujube fruits, which directly affects the working efficiency. Therefore, the positive pressure airflow velocity, negative pressure airflow velocity, and travel speed were the main factors affecting the operation performance. The positive pressure air velocity is adjusted by changing the air outlet flux of the fan through the air distribution adjustment device; its measurement position was the position where the positive pressure airflow duct was close to the outlet of the centrifugal fan. The negative pressure airflow velocity is adjusted by the frequency converter in the control cabinet to control the rotational speed of the centrifugal fan, its measurement position was the middle position of the feed inlet of the air cleaning device. The travel speed is adjusted by the frequency converter to control the motor speed of the crawler chassis. According to the corresponding relationship established between the motor frequency of the crawler chassis and the travel speed of the harvester, the travel speed of the harvester can be measured, and the time taken by the harvester from the start to the end of the operation is recorded by a stopwatch. Table 2 presents the factors and interval levels for the performance evaluation tests of the P-N JH, and their interval levels were obtained through pretests.
Table 2. Factors and interval levels for the performance evaluation tests of the positive and negative synergistic airflow-type jujube fruit harvester (P-N JH).

| No. | Factors                        | Interval Levels          |
|-----|--------------------------------|--------------------------|
| 1   | Positive airflow velocity A/(m·s⁻¹) | 14~26                    |
| 2   | Negative airflow velocity B/(m·s⁻¹) | 24~36                    |
| 3   | Travel speed C/(m·s⁻¹)             | 0.9~1.8                  |
| 4   | Performance indexes               | pickup rate, impurities rate, damage rate |

The interval levels of experimental influencing factors A, B, and C were encoded according to the central composite design method [24,25]. Table 3 shows the levels of the factors for the performance evaluation tests.

Table 3. Factors and levels for the performance evaluation tests of the positive and negative synergistic airflow-type jujube fruit harvester (P-N JH).

| Level | Positive Airflow Velocity A/(m·s⁻¹) | Negative Airflow Velocity B/(m·s⁻¹) | Travel Speed C/(m·s⁻¹) |
|-------|-------------------------------------|-------------------------------------|------------------------|
| −1.682| 10.93                               | 25.27                               | 0.59                   |
| −1    | 14.00                               | 28.00                               | 0.90                   |
| 0     | 18.50                               | 32.00                               | 1.35                   |
| 1     | 23.00                               | 36.00                               | 1.80                   |
| +1.682| 26.07                               | 38.73                               | 2.11                   |

According to the experiment factors and level values in Table 3, the pickup rate, impurities rate, and damage rate were taken as response indexes. The central composite design method of design expert 10.0.3 software was used to design the three-factor and five-level central composite experiment scheme [30,31]. A total of twenty test groups that included five groups zero estimation errors and fifteen groups physical prototype tests were carried out, according to the experiment scheme. The experimental schemes and results were shown in Table 4. The interval values of the pickup rate, impurities rate, and damage rate were 97.38~99.81%, 0.88~3.21%, and 0.18~1.48%, respectively.

Table 4. Experimental factors and indexes.

| No. | Positive Airflow Velocity A/(m·s⁻¹) | Negative Airflow Velocity B/(m·s⁻¹) | Travel Speed C/(m·s⁻¹) | Pickup Rate(%) | Impurities Rate(%) | Damage Rate(%) |
|-----|-------------------------------------|-------------------------------------|------------------------|----------------|-------------------|----------------|
| 1   | 14.00                               | 28.00                               | 0.90                   | 99.55          | 1.86              | 0.66           |
| 2   | 23.00                               | 28.00                               | 0.90                   | 99.24          | 1.08              | 0.88           |
| 3   | 14.00                               | 36.00                               | 0.90                   | 98.69          | 2.94              | 1.27           |
| 4   | 23.00                               | 36.00                               | 0.90                   | 99.31          | 2.68              | 1.30           |
| 5   | 14.00                               | 28.00                               | 1.80                   | 98.21          | 2.10              | 0.18           |
| 6   | 23.00                               | 28.00                               | 1.80                   | 98.72          | 1.23              | 0.38           |
| 7   | 14.00                               | 36.00                               | 1.80                   | 97.61          | 2.02              | 1.13           |
| 8   | 23.00                               | 36.00                               | 1.80                   | 98.99          | 2.16              | 1.12           |
| 9   | 10.93                               | 32.00                               | 1.35                   | 97.38          | 1.86              | 0.99           |
| 10  | 26.07                               | 32.00                               | 1.35                   | 98.23          | 0.89              | 1.18           |
| 11  | 18.50                               | 25.27                               | 1.35                   | 99.75          | 0.88              | 0.37           |
| 12  | 18.50                               | 38.73                               | 1.35                   | 99.09          | 3.21              | 1.48           |
| 13  | 18.50                               | 32.00                               | 0.59                   | 99.81          | 2.54              | 0.85           |
| 14  | 18.50                               | 32.00                               | 2.11                   | 98.62          | 2.21              | 0.33           |
| 15  | 18.50                               | 32.00                               | 1.35                   | 99.11          | 1.77              | 0.90           |
| 16  | 18.50                               | 32.00                               | 1.35                   | 98.98          | 1.72              | 0.94           |
| 17  | 18.50                               | 32.00                               | 1.35                   | 99.18          | 1.35              | 0.93           |
Table 4. Cont.

| No. |  | Factors | Indexes |
|-----|---|---------|---------|
|     | Positive Airflow Velocity | Negative Airflow Velocity | Travel Speed | Pickup Rate(%) | Impurities Rate(%) | Damage Rate(%) |
|     | A/(m·s⁻¹) | B/(m·s⁻¹) | C/(m·s⁻¹) |             |                |                |
| 18  | 18.50     | 32.00    | 1.35     | 99.04       | 1.68           | 0.87           |
| 19  | 18.50     | 32.00    | 1.35     | 99.11       | 2.12           | 0.92           |
| 20  | 18.50     | 32.00    | 1.35     | 99.13       | 1.76           | 0.91           |

3. Results and Discussion

The analysis module of design-expert 10.0.3 software was used to perform the regression variance analysis of the pick rate, impurities rate, and damage rate. The second-order response model of test factors and test indexes was established according to the results of the variance analysis. Then, the second-order response models were drawn on the response surface diagram to intuitively analyze the influence of factor interaction on test indexes.

3.1. Pickup Rate

Table 5 shows the regression variance analysis for the pickup rate. The model F value of 256.97 implies the model is significant. The model P value of less than 0.001 indicates the model terms are significant. The lack of fit F value of 3.4 implies that the lack of fit is not significant relative to the pure error. In this case, A, B, C, AC, BC, A², B², and C² are extremely significant model terms, and AB is the non-significant model terms.

Table 5. Regression variance analysis for the pickup rate.

| Source    | Sum of Squares | DF | Mean Squares | F Value | p Value |
|-----------|----------------|----|--------------|---------|---------|
| Model     | 25.55          | 9  | 2.84         | 256.97  | <0.001 **|
| A         | 0.70           | 1  | 0.70         | 63.41   | <0.001 **|
| B         | 11.80          | 1  | 11.80        | 1068.52 | <0.001 **|
| C         | 2.18           | 1  | 2.18         | 197.68  | <0.001 **|
| AB        | 0.020          | 1  | 0.020        | 1.81    | 0.2082 NS |
| AC        | 1.79           | 1  | 1.79         | 161.66  | <0.001 **|
| BC        | 0.64           | 1  | 0.64         | 57.79   | <0.001 **|
| A²        | 4.040          | 1  | 4.04         | 366.11  | <0.001 **|
| B²        | 4.81           | 1  | 4.81         | 435.05  | <0.001 **|
| C²        | 0.050          | 1  | 0.047        | 4.26    | 0.0061 **|
| Residual  | 0.11           | 10 | 0.011        |         |         |
| Lack of fit| 0.090        | 5  | 0.017        | 3.40    | 0.1025 NS |
| Pure error| 0.030          | 5  | 0.0050       |         |         |
| Cor total | 25.66          | 19 |             |         |         |

where: ** denotes the extremely significant factors (p ≤ 0.01); NS denotes the non-significant factors (p > 0.05).

The second-order response model for the pickup rate is:

\[ \eta_{pr} = 59.35 + 0.69A + 2.38B - 10.99C - 0.0028AB + 0.23AC + 0.16BC - 0.026A^2 - 0.036B^2 + 0.28C^2 \] (5)

Figure 3 shows the response surfaces graph of the interaction influence of positive pressure airflow velocity, negative pressure airflow velocity, and travel speed on the pickup rate. Figure 3a shows the response surfaces graph of the interaction influence between the positive pressure airflow velocity and the negative pressure airflow velocity on the pickup rate, as the travel speed is placed in the middle level (1.35 m·s⁻¹). The pickup rate first increases rapidly, and then the increases tend to be stable, with an increase in the negative pressure airflow velocity. The pickup rate increases first and then decreases gradually, with the increase in the positive pressure airflow velocity. The pickup rate
reaches the maximum value of 99.8%, as the positive pressure airflow velocity is about 19.0 m·s⁻¹, and the negative pressure airflow velocity is the maximum value. The reason is that the greater the negative pressure airflow velocity, the greater the force on jujube, so the higher the pickup rate. The jujube fruit may be difficult to be effectively blown to the negative pressure airflow mouth, as the positive pressure airflow velocity is too small. The jujube fruit may be blown away from the negative pressure airflow mouth, as the positive pressure airflow velocity is too high, which is difficult to capture or be picked up by the negative pressure airflow, which also reduces the pickup rate. The pickup rate of this paper is 96.8%–99.8%, which is higher than that of the air suction jujube fruit harvester studied by Zhang et al. [15,16], in which the pickup rates of Jun jujube and grey jujube are 92.20% and 90.65%, respectively. On the one hand, the positive pressure airflow increased the kinetic energy of jujube fruit while entering the negative pressure airflow mouth. On the other hand, the jujube fruit that are difficult to suck can be picked up by the action of the positive pressure airflow, which improves the pickup rate.

![Figure 3. Response surfaces graph of the interaction factors for the pickup rate: (a) influence of interaction factors between the positive airflow velocity and the negative airflow velocity, (b) influence of interaction factors between the positive airflow velocity and the travel speed, and (c) influence of interaction factors between the negative airflow velocity and the travel speed.](image)

Figure 3b shows the response surfaces graph of the interaction influence between positive pressure airflow velocity and travel speed on the pickup rate, as the negative pressure airflow velocity is placed in the middle level (32.0 m·s⁻¹). The pickup rate decreases gradually with the increase in the travel speed, as the positive pressure airflow velocity is less than 19.0 m·s⁻¹. The pickup rate does not change significantly with the travel speed increase, as the positive pressure airflow velocity is greater than 19.0 m·s⁻¹. The pickup rate increases rapidly at first and then decreases slightly with the increase in the positive pressure airflow velocity, as the travel speed is greater than 1.4 m·s⁻¹. The pickup rate increases slightly at first and then decreases gradually, as the travel speed is less than 1.4 m·s⁻¹. The maximum pickup rate is about 99.8%, as the travel speed and the positive pressure airflow velocity are 0.9 m·s⁻¹ and 17 m·s⁻¹, respectively. Wu et al. [32,33] also found that the overall removal efficiency decreased with the increase in the travel speed of the vehicle when they studied the pickup head performance of the road sweeper. The reason is that the spatial position was jointly affected by the travel speed of the P-N JH and the movement speed of jujube fruit, as the positive pressure airflow blows the jujube fruit. The jujube fruit may lag into the action range of the negative pressure airflow mouth, resulting in the reduction in the cleaning rate.

Figure 3c shows the response surfaces graph of the interaction influence between negative pressure airflow velocity and travel speed on the pickup rate, as the positive pressure airflow velocity is placed in the middle level (18.5 m·s⁻¹). With the decrease in the travel speed, the pickup rate increases gradually, and with the increase in the negative pressure airflow velocity, the pickup rate increases gradually. The maximum pick up is
about 99.8%, as the travel speed and the negative pressure airflow velocity are 0.9 m s\(^{-1}\) and 34 m s\(^{-1}\), respectively. This conclusion that the pickup rate gradually increases with the increase in the negative pressure airflow velocity is the same as the research result of Zhang et al. [13]. The reason is that the greater the negative pressure airflow speed, the stronger the force on jujube fruit. Hence, the pickup rate is higher.

3.2. Impurities Rate

Table 6 shows the regression variance analysis for the impurities rate. The model F value of 13.79 implies the model is significant. The lack of fit F value of 0.90 implies it is not significant relative to the pure error. In this case, only B is the extremely significant model term; A, C, AB, BC, C\(^2\) are the significant model terms; AC, A\(^2\), B\(^2\) are the non-significant model terms.

Table 6. Regression variance analysis for the impurities rate.

| Source      | Sum of Squares | DF | Mean Squares | F Value | p Value |
|-------------|----------------|----|--------------|---------|---------|
| Model       | 7.11           | 9  | 0.79         | 13.79   | <0.001 **|
| A           | 0.85           | 1  | 0.85         | 14.78   | 0.0032 * |
| B           | 4.06           | 1  | 4.06         | 70.88   | <0.001 **|
| C           | 0.19           | 1  | 0.19         | 3.29    | 0.010 *  |
| AB          | 0.29           | 1  | 0.29         | 5.11    | 0.047 *  |
| AC          | 0.012          | 1  | 0.012        | 0.21    | 0.66 NS  |
| BC          | 0.42           | 1  | 0.42         | 7.30    | 0.022 *  |
| A\(^2\)     | 0.18           | 1  | 0.18         | 3.21    | 0.10 NS  |
| B\(^2\)     | 0.22           | 1  | 0.22         | 3.86    | 0.078 NS |
| C\(^2\)     | 0.83           | 1  | 0.83         | 14.55   | 0.0034 * |
| Residual    | 0.57           | 10 | 0.057        |         |         |
| Lack of fit | 0.27           | 5  | 0.054        | 0.90    | 0.54 NS  |
| Pure error  | 0.30           | 5  | 0.060        |         |         |
| Cor total   | 7.69           | 19 |              |         |         |

\[ R^2 = 0.9254; R^2_{adj} = 0.8583; C.V. = 12.58\%; R_{Pred} = 0.6690. \]

where: ** denotes the extremely significant factors (\(p \leq 0.01\)); * denotes the significant factors (0.01 < \(p \leq 0.05\)); NS denotes the non-significant factors (\(p > 0.05\)).

The second-order response model for the impurities rate is:

\[ \eta_{ir} = 8.21 - 0.21A - 0.38B + 0.244C + 0.011AB + 0.019AC - 0.13BC - 0.0058A^2 + 0.0075B^2 + 1.19C^2 \]  

(6)

Figure 4 shows the response surfaces graph of the interaction influence of the positive pressure airflow velocity, negative pressure airflow velocity, and travel speed on the impurities rate. Figure 4a shows the response surfaces graph of the interaction influence between positive pressure airflow velocity and negative pressure airflow velocity on the impurities rate, as the travel speed is placed in the middle level (1.35 m s\(^{-1}\)). With the increase in the negative pressure airflow velocity, the impurities rate gradually increases, which has the same results as Zhang et al. [13]. The reason may be that with the higher negative pressure airflow velocity, more impurities will be sucked into the inertial airflow cleaning device, resulting in the increase in impurities rate. The impurities rate decreases gradually with the increase in the positive pressure airflow velocity. The reason is that the positive pressure airflow velocity is greater, the ability to blow out the impurities is stronger, which reduces the impurities rate of the picked up jujube fruit. The lowest impurities rate is about 0.6%, as the negative pressure airflow velocity is the lowest value and the positive pressure airflow velocity is the highest value.

Figure 4b shows the response surfaces graph of the interaction influence between positive pressure airflow velocity and travel speed on the impurities rate, as the negative pressure airflow velocity is placed in the middle level (32.0 m s\(^{-1}\)). With the increase in the travel speed, the impurities rate first decreases and then increases slowly, which is the
same as the research result of Zhang et al. [13]. The lowest impurities rate is about 1.4%, as the travel speed and the positive pressure airflow velocity are 1.4 m·s\(^{-1}\) and 23 m·s\(^{-1}\).

Figure 4c shows the response surfaces graph of the interaction influence between negative pressure airflow velocity and travel speed on the impurities rate, as the positive pressure airflow velocity is placed in the middle level (18.5 m·s\(^{-1}\)). The impurities rate increases rapidly with the increase in the negative pressure airflow velocity, as the travel speed is less than 1.5 m·s\(^{-1}\), and the increased trend changes slowly, only increasing from 1.4% to about 2.3%, as the travel speed is greater than 1.5 m·s\(^{-1}\). The impurities rate first decreases slowly and then increases slightly with the decrease in the travel speed, as the negative pressure airflow velocity is less than 32.0 m·s\(^{-1}\), and the impurities rate first decreases rapidly and then the decreases tend to be stable with the increase in the travel speed, as the negative pressure airflow velocity is greater than 32.0 m·s\(^{-1}\). The reason may be that the time and force acting on impurities becomes longer and larger, as the air velocity is high and the traveling speed is low. As a result, there are many impurities with large specific gravity, which are difficult to be effectively cleaned, resulting in the rapid increase in the impurities rate.

![Graph of response surfaces](image)

**Figure 4.** Response surfaces graph of the interaction factors for the impurities rate: (a) influence of interaction factors between the positive airflow velocity and the negative airflow velocity, (b) influence of interaction factors between the positive airflow velocity and the travel speed, and (c) influence of interaction factors between the negative airflow velocity and the travel speed.

### 3.3. Damage Rate

Table 7 shows the regression variance analysis for the damage rate. The model F value of 684.36 implies the model is significant. The lack of fit F value of 0.19 implies that it is not significantly relative to the pure error. In this case, A, B, C, AB, \(A^2\) are the extremely significant model terms; BC, \(C^2\) are the significant model terms; AC and \(B^2\) are the non-significant model terms.

**Table 7.** Regression variance analysis of damage rate.

| Source  | Sum of Squares | DF | Mean Squares | F Value  | p Value |
|---------|----------------|----|--------------|----------|---------|
| Model   | 2.27           | 9  | 0.25         | 684.36   | <0.001 ** |
| A       | 0.040          | 1  | 0.042        | 114.72   | <0.001 ** |
| B       | 1.54           | 1  | 1.54         | 4183.60  | <0.001 ** |
| C       | 0.35           | 1  | 0.35         | 940.29   | <0.001 ** |
| AB      | 0.020          | 1  | 0.020        | 54.31    | <0.001 ** |
| AC      | 0.00045        | 1  | 0.00045      | 1.22     | 0.29 NS  |
| BC      | 0.054          | 1  | 0.054        | 147.87   | 0.040 *  |
| \(A^2\) | 0.055          | 1  | 0.055        | 148.06   | <0.001 ** |
| \(B^2\) | 0.00035        | 1  | 0.00035      | 0.95     | 0.35 NS  |
| \(C^2\) | 0.19           | 1  | 0.19         | 504.19   | 0.042 *  |
Table 7. Cont.

| Source         | Sum of Squares | DF | Mean Squares | F Value | p Value |
|----------------|----------------|----|--------------|---------|---------|
| Residual       | 0.0037         | 10 | 0.00037      |         |         |
| Lack of fit    | 0.00060        | 5  | 0.00012      | 0.19    | 0.95 NS |
| Pure error     | 0.0031         | 5  | 0.00062      |         |         |
| Cor total      | 2.27           | 19 |              |         |         |

$R^2 = 0.9984; R^2_{adj} = 0.9969; C.V. = 2.18\%; R_{pred} = 0.9960.$

where: ** denotes the extremely significant factors ($p \leq 0.01$); * denotes the significant factors (0.01 < $p \leq 0.05$); NS denotes the non-significant factors ($p > 0.05$).

The second-order response model of the damage rate is:

$$\eta_{br} = -0.95 - 0.0061A + 0.054B - 0.24C - 0.0028AB - 0.0037AC + 0.046BC + 0.0030A^2 + 0.00031B^2 - 0.56C^2 \quad (7)$$

Figure 5 shows the response surfaces graph of the interaction influence of positive pressure airflow velocity, negative pressure airflow velocity, and travel speed on the damage rate. Figure 5a shows the response surfaces graph of the interaction influence between positive pressure airflow velocity and negative pressure airflow velocity on the damage rate, as the travel speed is placed in the middle level (1.35 m·s$^{-1}$). The damage rate increases rapidly with the increase in the negative pressure airflow velocity and gradually decreases with the increase in the positive pressure airflow. The minimum damage rate is 0.5%, as the negative pressure airflow velocity is 28 m·s$^{-1}$ and the positive pressure airflow velocity is 14 m·s$^{-1}$. The reason may be that when the negative pressure airflow speed is greater, the force on the jujube fruit is greater, and the jujube fruit enter the inertial airflow cleaning system faster, so the damage rate caused by collision in the settlement process will increase. The negative pressure airflow velocity is higher and the damage rate is also higher, which is a similar trend to Zhang et al. [15]. The reason is that the greater the airflow speed, the greater the force on jujube fruit, and, therefore, the collision between jujube fruit and contact material causes more serious damage.

Figure 5b shows the response surfaces graph of the interaction influence between positive pressure airflow velocity and travel speed on the damage rate, as the negative pressure airflow velocity is placed in the middle level (32.0 m·s$^{-1}$). With the travel speed increase, the damage rate decreases slowly at first and then decreases rapidly. With the decrease in the negative pressure airflow velocity, the damage rate gradually decreases and then becomes stabilized. The traveling speed is lower, the picked jujube fruit will reduce,
and the obstruction of jujube fruit to the airflow will reduce, which will make the jujube fruit move faster and increase the collision damage.

Figure 5c shows the response surfaces graph of the interaction influence between negative pressure airflow velocity and travel speed on the damage rate, as the positive pressure airflow velocity is placed in the middle level (18.5 m·s⁻¹). The damage rate increases gradually with the increase in negative pressure airflow velocity, as the travel speed is between 0.9 m·s⁻¹~1.8 m·s⁻¹, and the increasing trend is more obvious with the increase in the travel speed. The damage rate decreases rapidly with the increase in the travel speed, as the negative pressure airflow velocity is less than 31.0 m·s⁻¹, and the damage rate decreases slowly with the increase in the travel speed, as the negative pressure airflow velocity is greater than 31.0 m·s⁻¹. The minimum damage rate is 0.3%, as the travel speed and negative pressure airflow velocity are 1.8 m·s⁻¹ and 28 m·s⁻¹.

3.4. Optimal Parameters

To achieve the best operating performance of the P-N JH, the Numerical module in the DesignExpert11.0 software was used according to the actual working conditions and model analysis results. Taking the optimal combination of operating parameters with the maximum pickup rate, the minimum impurity rate, and breakage rate as the set target values, the set objective function values and constraints are:

\[
\begin{align*}
\text{max} (\eta_{pr}) ; \min (\eta_{ir}, \eta_{dr}) \\
\text{s.t.} \quad & 0.9 \leq A \leq 1.9 \\
& 24 \leq B \leq 36 \\
& 14 \leq C \leq 26
\end{align*}
\]

The Optimization module in Design-Expert was used to obtain the optimal combination parameters. The results indicate that the pickup rate, impurities rate, and damage rate were 99.29%, 2.02%, and 1.03%, respectively, as the positive pressure airflow velocity, negative pressure airflow velocity, and forward velocity were 1.5 m·s⁻¹, 34.0 m·s⁻¹, and 16.8 m·s⁻¹, respectively.

3.5. Verification Tests

The P-N JH operating parameters were set as the optimal combination parameters, namely, positive airflow velocity (16.8 m·s⁻¹), negative airflow velocity (34.0 m·s⁻¹), and travel speed (1.5 m·s⁻¹), and the other test conditions were consistent with the test methods in Chapter 2.3. Then, the field validation tests were carried out, to verify the accuracy of the optimal combination parameters and to assess the performance of the P-N JH. The tests were repeated five times, and the arithmetic mean values were taken as the results. The verification test results indicated that the pickup rate, impurities rate, and damage rate were 97.21%, 2.15%, and 1.08%, respectively, and their relative errors between the verification test results and the optimal parameters were 2.09%, 6.44%, and 4.85%. In addition, the operation efficiency was 2170 kg/h, which has improved more than four times than that of the traditional pneumatic jujube fruit pick up machines (100–500 kg/h) [13–16]. One reason is that it not only needs to overcome the gravity of jujube fruit but also needs to provide the drag force required by the acceleration of jujube fruit from rest state to entering the jujube suction tube, when the pneumatic jujube fruit pick up machines were suctioning jujube fruit. The other reason is that the dissipation speed of negative pressure airflow is very fast, resulting in the waste of a lot of negative pressure airflow, so the picking efficiency is low. In this paper, in the process of blowing jujube fruit to the suction mouth of negative pressure airflow through positive pressure airflow, the force of positive pressure airflow acting on jujube fruit is more concentrated, increasing the kinetic energy of jujube fruit. Moreover, the jujube fruit were directly blown to the negative pressure airflow mouth of the positive and negative synergistic airflow device, which can further improve the utilization efficiency of the negative pressure airflow. Therefore, the operation efficiency is significantly improved.
4. Conclusions

To improve the operation efficiency and performance of the pneumatic jujube fruit pick up machines, the P-N JH was designed, and its structure and working principle were described. The performance of the P-N JH was analyzed with a response surface method. The results showed that the pickup rate, impurities rate, and damage rate were 99.29%, 2.02%, and 1.03%, respectively, and the positive pressure airflow velocity, negative pressure airflow velocity, and travel speed were 16.8 m·s⁻¹, 34.0 m·s⁻¹, and 1.5 m·s⁻¹, respectively. In addition, the field validation tests of the P-N JH operation performance were carried out under the optimal factor levels of parameter optimization, and the pickup rate, impurities rate, breakage rate, and operation efficiency were 97.21%, 2.15%, 1.08%, and 2170 kg/h, respectively. Hence, the P-N JH not only meets the design requirements, but also the operation efficiency is significantly improved compared with traditional pneumatic jujube fruit pick up machines.

In the future, this research can be further promoted in two directions. First, a jujube fruit collecting device can be integrated to the P-N JH, so the operation efficiency will be further improved. Second, more P-N JH tests should be carried out, to obtain the operation performance in different jujube fruit varieties and different orchards.

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