Design and experiment of ground jujube picker based on bionic mechanism

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Abstract: In view of the issues like easy to damage jujube, low efficiency and difficult to separate jujube and impurity for mechanized picking of ground jujube under thick planting mode, a bionic arm ground jujube picker was designed on the basis of analyzing jujube planting mode and jujube characteristics, the structural parameters of its key components were determined, and a characteristic model for airflow in the internal flow field of the cleaning system and a movement trajectory model of the gathering device were established. A quadratic orthogonal center composite test was carried out to establish the regression models between influencing factors and the performance of the picker, and analyze the influence law of these factors on the picker, in which ground jujubes were taken as the picking object, the forward speed of the picker, the fan speed, and the height of the picking mouth from the ground were taken as the influencing factors, and the picking rate and the impurity rate were taken as the performance indexes of the picker. The optimal combination of parameters was determined by multi-objective optimization (MOD): the forward speed of the picker was 0.47 m/s, the fan speed was 3025.76 r/min, and the height of the picking mouth from the ground was 84.20 mm. At this time, the picking rate of the picker was 94.00%, and the impurity rate was 2.30%. According to test verification, the test results and optimization results were consistent, meeting the requirements of mechanized picking of ground jujube.

Keywords: jujube picker, Fluent simulation, test design, cleaning system
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1 Introduction

There is a long history of planting jujube in China, and there are many kinds of jujube with high nutritional value, containing a large number of vitamins and mineral elements, enjoying the reputation of "natural vitamins"[1-4]. Xinjiang is suitable for the growth of jujube due to its abundant sunlight, large diurnal temperature variation, and long frost-free period[5]. By the end of 2020, the output of jujubes in Xinjiang amounted to 3.8124 Mt, accounting for about 50% of the total domestic output, making it the main producing area of jujubes in China. The harvest of jujube in Xinjiang is mainly based on mechanical vibration and artificial picking. Both ways require artificial picking when some jujubes fall to the ground during the maturity period, resulting in high labor cost. Also, it overlaps with the harvesting period of maize and cotton, resulting in a large amount of wastage and recovery difficulties. These factors all seriously restrict the rapid development of jujube industry in Xinjiang[6,7]. Based on this, it is of great value and significance to study a ground jujube picking machine.

There are not many studies on jujube harvesting machinery in foreign countries[8], as jujube is planted in fewer areas abroad, and it is only planted in small quantities in a few countries such as South Korea and Japan. Lee (Chungnam National University, South Korea) explored a fully hydraulic self-propelled jujube harvester based on canopy vibration, which provides little reference as the Korean jujube planting pattern differs greatly from the dwarfing and dense planting pattern in Xinjiang, China[9]. Churchill used a scraper conveying method to accomplish the citrus harvesting. However, this machinery has high requirements for the ground flatness and easily causes missed picking and fruit damage, and it is mainly used to pick fruits with hard peels[10]. Therefore, the bulky fruit harvesting machinery in foreign countries is not suitable for the harvesting of jujube in the dwarf planting pattern in China.

In China, there is a larger jujube planting area, so the research on jujube harvesting has gone further. Li et al.[11] designed a sweeping-air suction jujube picker, featuring a disc-type sweeping device, which has a small operating area and low efficiency when harvesting jujube. Fu Wei applied vertical double drum vibration picking device, which separates jujube and branches based on the vibration principle. The advantage is that the jujube harvester straddles the jujube tree to harvest the jujube at one time. However,

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its weakness includes poor stability after raised, damage to the jujube tree due to the characteristics of machine harvesting, and inability to pick jujube falling on the ground[12]. Ding et al.[13] optimized the vibration frequency of the vibration device in order to improve the vibration harvesting efficiency of the jujube picker, established the kinetic model of the vibration system and jujube tree, and obtained the following parameters: 2.7 rad/s for angle of rotation of the vibration device and 16.9 Hz for vibration frequency. Then, he carried out ADAMS kinematics simulation, which showed that the jujube picking rate reached more than 90% when the motor speed was 25.0-26.5 r/min, and the vibration frequency was 16.5-17.4 Hz, and the damage rate of jujubes in the harvesting process was less than 8%. It has the advantage of shaking off jujube by the optimal excitation frequency, thus reducing the damage to the jujube tree; its disadvantage is that the rigid connection between the device and the jujube tree causes damage to both the machine and the three bark, and inability to pick jujube on the ground[13]. Fu et al.[14] established the double-pendulum vibration model of jujube "branch-stalk-fruit" according to the change of instantaneous acceleration in the vibration process, analyzed the intrinsic frequency of system vibration, and carried out the frequency scanning test using the vibration test system. They found that the resonance frequency of jujube trees was concentrated in the range of 12-24 Hz; according to relevant tests and calculations, the maximum instantaneous inertia force of jujube was greater than the maximum tensile force of the stalk, which was 6 N. The test showed that the force transmission effect was good in the process of vibration harvesting at 7 mm amplitude and 17 Hz frequency. The cleaning system is the main device of the jujube picker for the purpose of efficiently separating jujubes and impurities. It is determined through pre-tests that the forward speed of the machine is 0.3-0.6 m/s, the fan speed is 2900-3100 r/min, and the airflow velocity of the cleaning system is 32 m/s[15,16].

Accordingly, there is an urgent need to develop a ground jujube picking machine for dwarfing and thick planting mode in Xinjiang, and to promote the mechanization of jujube harvesting. Therefore, a ground jujube picker combining pneumatic and mechanical mode was designed, which adopts a human-like arm to gather ground jujubes into strips, and then collects them in pneumatic mode. It can effectively separate broken soil, twigs and leaves through secondary screening.

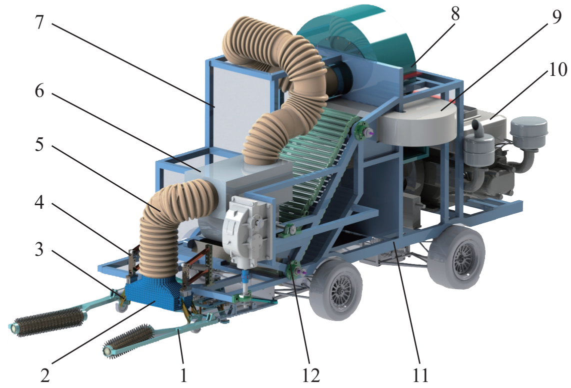
2 Overall structure and working principles

2.1 Overall structure

Figure 1 shows the structure of the ground jujube picker based on bionic mechanism, which combines pneumatic and mechanical mode. It is mainly composed of a frame, gathering device, pick-up unit, collection device, cleaning system, wind power system, transmission system, among others.

2.2 Working principles

When the jujube picker is working, the negative-pressure airflow formed by centrifugal fan running at the air inlet is transmitted to the picking mouth through the air duct and the jujube screening box, where the jujubes and impurities are separated; then, the jujubes are discharged from the bottom of the box and transferred to the collection box by the conveyor belt; when the jujubes enter into the collection box from the top of the conveyor belt, the air discharged from the air outlet will be used to clean the remaining jujube leaves in the jujube screening box for the second clearing of impurities (mainly jujube leaves), thus accomplishing the picking and cleaning of the jujubes.

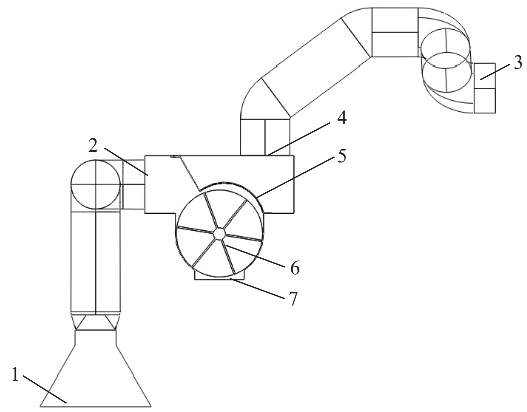


1. Gathering device 2. Air suction picking mouth 3. Feeler mechanism 4. Vibration damping mechanism 5. Rubber duct 6. Jujube screening box 7. Collection box 8. Fan 9. Wind control device 10. Diesel engine 11. Frame 12. Screening mechanism

Figure 1 Overall structure of ground jujube picker

2.3 Working principle of the cleaning system

The cleaning system has the functions of selecting jujubes and impurities, separating impurities and air, and it is the key working part of pickers combining pneumatic and mechanical mode. Its structure diagram and physical drawing shown in Figures 2 and 3, composed of jujube screening box inlet, filter screen, deflector, impurity air-lock valve and jujube air-lock valve, jujube outlet, among others. The deflector is located between the jujube screening box inlet and filter screen of the cleaning system, which is used to change the motion characteristics of air in the cleaning system. When the cleaning system is working, the impurity air-lock valve and the jujube air-lock valve can discharge jujubes and impurities in real time, while maintaining the airtightness of the cleaning system.



1. Air inlet of cleaning system, 2. Cleaning system box body, 3. Air outlet of cleaning system, 4. Jujube screening box outlet, 5. Filter screen, 6. Impurity air-lock valve and jujube air-lock valve, 7. Jujube outlet

Figure 2 Structure diagram of jujube screening box in the cleaning system

When the system is in operation, jujubes and impurities enter into the jujube screening box inlet of the cleaning system under the action of negative-pressure airflow. Due to the joint action of the impurity air-lock valve and the filter screen, the air flow trajectory in the cleaning system is changed; under the action of aerodynamics and the filter screen, jujubes settle in the cleaning system, and then they are discharged from the cleaning system through the jujube air-lock valve, and then fall on the conveyor belt, which transports the jujubes into the collection box. Under the action of aerodynamics and the filter screen, one part of the impurities is directly carried out through the air flow over the filter screen, and the other part is blocked by the filter screen, and then discharged from the cleaning system through the impurity air-lock valve, thus accomplishing the cleaning of jujube and impurities.

Figure 3 Physical drawing of cleaning system

2.3.1 Cleaning system

In order to improve the effect of jujube settlement and impurity screening, the airflow velocity in the cleaning system should be greater than that of the impurities but less than that of jujube suspension. Therefore, the relevant structural parameters of the cleaning system can be designed according to the airflow velocity in the system. In the area of cleaning system, the Mach number of air is much less than 1, so air can be considered as an incompressible fluid[17]. At the same time, the exchange and leakage of air between the air-lock valve in the cleaning system and the external environment are ignored.

According to the previous studies[18,19] and the working parameters of the picker matched with the ground jujube screening system based on bionic mechanism, it is known that the air velocity at the inlet of the cleaning system is 27-45 m/s, the suspension speed of jujube is 17.2-21.4 m/s, and the suspension speed of jujube leaves and branches is 0.5-2.2 m/s and 1.2-3.2 m/s, respectively. In order to bring impurities out of the cleaning system, the average air velocity in the system should be greater than 3.2 m/s.

2.3.2 Determination of curve equation of deflector

For some jujubes that enter the cleaning system from the air inlet of the jujube screening box and are difficult to settle, compared with impurities, they have large and small resistance, so it is difficult to have them settled. Therefore, jujubes directly collide with the filter screen at the outlet, which will cause further damage to the jujubes[20,21], and even lead to deformed jujubes getting caught in the filter screen, which will reduce the working efficiency of the cleaning system and affect the sale of jujubes. Therefore, the deflector is designed between the air inlet of the jujube screening box and the filter screen, and the incomplete elastic collision between the deflector and the jujubes changes their trajectory, which makes the jujubes settle quickly. According to the theorem of momentum and impulse, the smaller the change of velocity direction when jujubes collide with the deflector, the more beneficial it is to reduce the damage of jujubes. Also, the secondary damage caused by the collision of jujubes with the filter screen after crossing the deflector is avoided, and the minimum speed change direction is that the jujubes collide with the deflector and converge on the track at the top of the impurity air-lock valve and the jujube air-lock valve. Shi et al.[15] determined that the shape of the deflector is elliptic curve by mathematical knowledge, so the deflector curve presents an angle with the horizontal plane.

In order to analyze the elliptic equation and inclination angle of the deflector surface, the coordinate system *OXY* is established with the center position of the air inlet of the jujube screening box as the coordinate origin $O(0,0)$, the X-axis parallel to and the Y-axis perpendicular to the air inlet of the jujube screening box. The schematic diagram of the elliptic curve equation of the deflector is shown in Figure 4. At any point $M(x_i,y_i)$, the elliptic curve equation is established as follows:

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}=1 \tag{1}$$

$$\begin{cases} a^2=\dfrac{1}{4}\left(\sqrt{(x_{c1}-x_i)^2+(y_{c1}-y_i)^2}+\sqrt{(x_{c2}-x_{c1})^2+(y_{c2}-y_{c1})^2}\right)^2 \\ b^2=\dfrac{1}{4}((x_{c1}-x_i)^2+(y_{c1}-y_i)^2-(x_{c2}-x_{c1})^2+(y_{c2}-y_{c1})^2) \end{cases} \tag{2}$$

$$\frac{\left(x_i\cos\theta-y_i\sin\theta-\dfrac{\sqrt{(x_{c2}-x_{c1})^2+(y_{c2}-y_{c1})^2}}{2}\right)^2}{a^2}+\frac{(y_i\cos\theta-x_i\sin\theta)^2}{b^2}=1 \tag{3}$$

where, a and b are respectively the length of the major and minor semi-axis of the ellipse, m; θ is the included angle between the elliptic equation and the horizontal plane, (°).

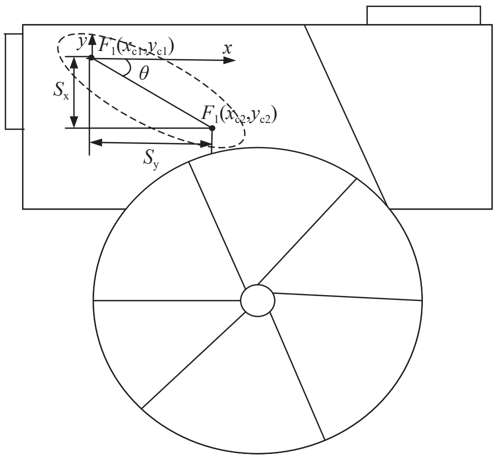


Figure 4 Schematic diagram of deflector curve

In the coordinate system established, the coordinate of F_1 (x_{c1}, y_{c1}) is (0, 0), the projected length of the inlet from the top of the impurity air-lock valve and the jujube air-lock valve on the X-axis is designed as 0.25 m, and y_{c2}=0.25tanθ. By substituting the above values into Equation (3), the simplified deflector equation is as follows:

$$\frac{(4x_i\cos\theta-4y_i\sin\theta-0.25)^2}{\sqrt{x_i^2+y_i^2}-\sqrt{0.25^2+(0.25\tan\theta)^2}}+\frac{4(x_i\sin\theta-y_i\cos\theta)}{x_i^2+y_i^2-\left[0.25^2+(0.25\tan\theta)^2\right]}=1 \tag{4}$$

$$\theta=\arctan\frac{S_y}{S_x} \tag{5}$$

According to the physical knowledge, ignoring the action of airflow except the drag force, jujube makes a quasi-projection motion after entering the cleaning system. The tangent equation of jujube trajectory is established[22].

$$\begin{cases} a_i = \dfrac{\mathrm{d}v}{\mathrm{d}t} \\ m_i a = \sin\gamma m_i g + F_i \end{cases} \tag{6}$$

where, a_i is jujube acceleration, m/s^2; v is jujube speed, m/s; m_i is mass of jujube, kg, g is acceleration of gravity, m/s^2; t is time, s, γ is the included angle between the movement direction of jujube i and the horizontal direction, (°). F_i is the drag force on jujubes, N, which is calculated as follows[4]:

$$F_i = \frac{C_i}{8}\rho_{\rm air}\left|\cos\gamma v_{\rm air} - v_i\right|(\cos\gamma v_{\rm air} - v_i)(\pi d_i^2) \tag{7}$$

$$C_i = \begin{cases} \dfrac{24}{Re_p},\ (1 \le Re_p) \\ \dfrac{24(1+0.15Re_p^{0.687})}{Re_p},\ (1 < Re_p < 10^3) \\ 0.44,\ (Re_p > 10^3) \end{cases} \tag{8}$$

where, $\rho_{\rm air}$ is air density, here it is taken as 1.205 kg/m^3; $v_{\rm air}$ is air flow rate, m/s; d_i is projection diameter of the jujube perpendicular to relative velocity direction, m; C_i is flow resistance coefficient (determined by Reynolds number of particles)[23,24]; Re_p is Reynolds number obtained by introducing porosity.

$$Re_p = \frac{\varepsilon\rho_{\rm air}\left|\mu_{\rm air} - v_i\right| d_i}{v_{\rm air}} \tag{9}$$

where, ε is porosity, %; $\mu_{\rm air}$ is air dynamic viscosity, here it is taken as 14.8×10^{-6} m^2/s. According to the simultaneous Equations (8) and (9), the calculated Reynolds number is greater than 10^3, which belongs to the turbulence model. By substituting c_i = 0.44 Substituting into (7) and associating (6) yields, we can get the following:

$$F_i = 0.055\left|\cos\gamma v_{\rm air} - v_i\right|(\cos\gamma v_{\rm air} - v_i)(\pi d_i^2) \tag{10}$$

According to the jujube motion trajectory equation, the trajectory equation in the horizontal direction is:

$$s_x = v_0 t + \frac{1}{2}\frac{\cos\gamma F_i}{m_i}t^2 \tag{11}$$

The trajectory equation in the vertical direction is:

$$s_y = \frac{1}{2}\left(\frac{\sin\gamma F_i}{m_i} + g\right)t^2 \tag{12}$$

where, $v_{\rm o}$ is the initial velocity of jujube, m/s.

The test shows that when jujube enters the cleaning system, the maximum initial velocity is 6.5 m/s, and θ=9.43° according to Equations (9)-(11), that is, the angle between the deflector and the horizontal plane is 9.43°.

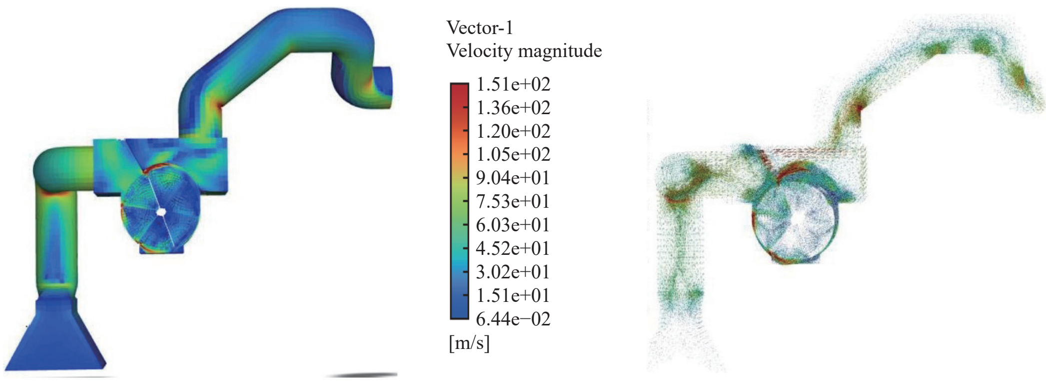
2.3.3 Modeling and simulation analysis of cleaning system

The cleaning system model built in Solidworks2021 is transformed into parasolid.x_t format, and then imported into ANSYS/mech module for grid division, and saved as .msh format, and then imported into ANSYS/Fluent module for simulated calculation. The inlet airflow velocity is set to 40 m/s, and the outlet velocity is set to 30 m/s. The key simulation parameters are set as listed in Table 1.

Table 1 Fluent simulation settings

Parameter	Option	Parameter	Option
Calculation pattern	Three-dimensional double precision	Velocity and pressure coupling	SIMPLE
Solver	Pressure based solver	Element gradient interpolation method	Least-squares Cell Based
Solving model	VOF model	Discretization scheme of pressure modification coefficient	Body Force Weighted
Viscosity model	Standard k-ε turbulence model	Initialization	Mixed initialization
Flow model	Transient flow	Time step	0.0001 s
Discretization scheme of convective term	Second order upwind	Material	Air

In order to study the air motion characteristics in the cleaning system, Fluent 2022 software was used to simulate and analyze the internal flow field of the cleaning system, and the results are shown in Figure 5.



a. Cloud diagram of airflow velocity b. Vector diagram of airflow velocity

Figure 5 Fluid simulation analysis results of the cleaning system

The gas movement characteristics are the key to analyze the movement characteristics of the jujube during the picking process of the air-suction pickup machine. The airflow velocity cloud diagram of the device in the fluid domain is shown in Figure 5a. It can be seen that the airflow is mainly concentrated in the air inlet and outlet of the cleaning system, which is more favorable for the removal of impurities. In addition, the airflow velocity increases first and then decreases after entering the cleaning system, which is conducive to the settlement of the jujube. The maximum airflow velocity appears in the middle part of the deflector and the exhaust fan and the jujube exhaust fan, which is conducive to the airflow carrying light impurities over the exhaust fan and the jujube exhaust fan. The airflow velocity vector is shown in Figure 5b.

Figure 5b is the airflow velocity vector diagram of the cleaning system. The airflow trajectory at the front and lower ends of the deflector and the exhaust fan and the jujube exhaust fan changes, which can effectively guide the jujube settlement. The airflow gathers below the deflector and changes sharply, which is more conducive to carrying impurities across the top of the exhaust fan and the jujube exhaust fan. A small amount of impurities enter the impurity exhauster and the jujube exhauster due to the obstruction of the jujube. Under the action of the difference in the proportion of jujube and impurity, some of the impurities are excluded by the impurity exhauster, and the other part is carried to the filter by the rotation of the impurity exhauster and the jujube exhauster, and is excluded by the filter to achieve secondary cleaning. Therefore, the simulation analysis results of the flow field of the cleaning system show that the characteristics of the airflow movement inside the system are in line with the expected results.

2.3.4 Determination of jujube suspension speed

When jujubes are sucked up by negative pressure formed by the picker, they are suspended in the airflow and remain relatively static with the ground, and the airflow velocity at this time is the

suspension speed of jujubes. According to the stress analysis of jujubes, they are subjected to gravity, attractive force and air resistance, so the critical suspension speed of jujube is as follows[25]:

$$\begin{cases} v_{\text{critica}} = \sqrt{\dfrac{8m_{\max}g - 2\pi g\rho_{air}xy^2}{\pi C_d\rho_{air}y^2}} \\ v = Kv_{\text{critica}} \end{cases} \tag{13}$$

where, C_d is resistance constant; ρ_{air} is air density, kg/m³; x is the minor axis diameter of jujube, m; y is the major axis diameter of jujube, m; v_{critical} is the theoretical airflow velocity, m/s; v is the actual airflow velocity, m/s; $m_{\max}$ is the maximum mass of jujube, kg; g is the acceleration of gravity, m/s²; and K is the reliability constant of jujube suction.

In order to reduce the error caused by factors such as shape and size of jujube and collision, the range of K is 1.8-2.0, and K=2. According to the suspension characteristics and experiments of jujube[26-28], the critical suspension speed of jujube is determined to be 20.94 m/s, and the actual airflow velocity is finally determined to be greater than 30 m/s taking into account the influence of various factors on jujube suspension.

3 Overall test

3.1 Test conditions

The performance test of jujube picker was carried out on October 28, 2023, in Group 2, Brigade 8 of Yixilaimuqi Township, Wensu County, Akesu Prefecture. The test area was 300 m long and 32 m wide, where jujube trees were spaced by 4 m, and the average spacing of the plants was 2 m, and the variety was grey jujube, with a moisture content of 31.05%. The main test was the performance test of the cleaning system, as shown in Figure 6.

a. Before picking b. After picking

Figure 6 Jujube test site

3.2 Test method

According to research from Zhang et al.[25], it is found that when the forward speed of the jujube picker is higher than 0.7 m/s, not all jujubes on the ground can be picked up, which makes it difficult to screen jujubes and impurities, and the picking efficiency is even lower when the forward speed is lower than 0.3 m/s. When the fan speed is higher than 3100 r/min, a large number of jujubes are picked up in a short time, which causes accumulation of a large number of jujubes in the cleaning system, thus making it difficult to separate jujubes from impurities. When the fan speed is lower than 2900 r/min, the cleaning system has poor working performance and poor picking effect. According to the pre-tests, the airflow velocity is the key factor to determine the separation and picking efficiency of jujubes and impurities. In the field work, the optimal working state of the jujube picker is determined by the separation effect of jujubes and impurities. Therefore, it is determined that the air flow rate is adjusted by the speed of variable frequency fan. The fan speed range is 2900-3100 r/min, the air flow rate range is 27-45 m/s, and the forward speed of the picker is 0.3-0.7 m/s. According to DG/T 188-2019 *Fruit Picker*, Q/XNJ 001-2017 *Self-propelled Air Suction Jujube Picker* and GB/T5667-2008 *Productive Testing Methods for Agricultural Machinery*, the field test is carried out. Before the test, relevant parameters of the jujube picker are adjusted to meet the test requirements. The test factors are determined, including forward speed of the picker, fan speed, height of the picking mouth from the ground, and the test indexes are impurity rate and picking rate, where impurity rate is the ratio of the mass of impurities to that of harvested jujubes, and picking rate is the ratio of the mass of harvested jujubes to that of ground jujubes. The test indexes are determined by Equations (14)-(15). The test is repeated for 3 times, and the result is the arithmetic average.

$$\eta_0 = \frac{\sum_{i=1}^{3} m_0}{\sum_{i=1}^{3} m_{R0} + \sum_{i=1}^{3} m_0} \tag{14}$$

$$\eta_d = \frac{\sum_{i=1}^{3} m_d}{\sum_{i=1}^{3} m_{R0} + \sum_{i=1}^{3} m_d} \tag{15}$$

where, η_0 is impurity rate, %; m_0 is the mass of impurities discharged from the impurity air-lock valve, kg; m_{R0} is the mass of harvested jujubes, kg; η_d is picking rate, %; m_d is the mass of jujubes discharged from the impurity air-lock valve, kg.

3.3 Test program

In order to investigate the influence law of test factors on test indexes, a quadratic orthogonal center composite test was carried out using the Central Composite Design module of the Design-Expert 12 software, with the factor intervals shown in the ranges described in section 3.2 and the test factor level codes listed in Table 2.

3.4 Test results and analysis

According to the theory of Central Composite Design in Design-Expert 12 software, forward speed of picker, fan speed, height of the picking mouth from the ground are defined as the influencing factors for the response surface test, while impurity rate and picking rate are defined as the response values. The parameters

are modified by the quadratic regression orthogonal test program with 3 factors and 5 levels. Orthogonal test program and the results are listed in Table 3. The test consists of a total of 20 groups. From the test results, jujube picker has an impurity rate of 1.7%-9.6% and picking rate of 82.9%-94.5%.

Table 2 Test factor level

Level	Factor		
	Forward speed Forward speed/m·s^{-1}	Fan speed Fan speed/r·min^{-1}	Height of picking mouth from the ground x_2/mm
Upper asterisk arm (1.682)	0.67	3099.2	98.82
Upper level (1)	0.6	3060	92
Zero level (0)	0.5	3000	82
Lower level (–1)	0.4	2945	72
Lower asterisk arm (–1.682)	0.33	2905.8	65.18

Table 3 Test program and results

Test code	Influencing factor			Response indicators	
	Forward speed A	Fan speed B	Height of picking mouth from the ground C	Picking rate Q/%	Impurity rate M/%
1	–1	–1	–1	88.8	3.1
2	1	–1	–1	82.9	8.8
3	–1	1	–1	88.7	2.4
4	1	1	–1	88.1	4.1
5	–1	–1	1	88.7	2.0
6	1	–1	1	83.6	8.5
7	–1	1	1	87.3	1.7
8	1	1	1	88.8	4.0
9	–1.68	0	0	86.5	3.0
10	1.68	0	0	82.9	9.6
11	0	–1.68	0	86.8	7.4
12	0	1.68	0	90.8	2.7
13	0	0	–1.68	87.3	3.2
14	0	0	1.68	89.8	2.0
15	0	0	0	94.5	3.2
16	0	0	0	94.3	3.5
17	0	0	0	93.4	2.5
18	0	0	0	93.9	3.3
19	0	0	0	94.2	3.2
20	0	0	0	93.8	3.6

3.4.1 Significance test and regression model

The multiple regression fitting analysis is performed by Design-Expert 12 software according to the test data in Table 3[29,30,31,32], and a regression model is established for the quadratic response surface of jujube impurity rate and picking rate on the three independent variables, namely forward speed of the picker, fan speed and height of the picking mouth from the ground, and an ANOVA is performed, as shown in Equations (16)-(17) and Table 3.

$$Q = 94.01 - 1.18A + 1.14B + 0.3005C + 1.49AB + 0.3625AC - 0.1625BC - 3.26A^2 - 1.81B^2 - 1.9C^2 \tag{16}$$

$$M = 3.23 + 2.00A - 1.33B - 0.3089C - 1.02AB + 0.1750AC + 0.075BC + A^2 + 0.5613B^2 - 0.305C^2 \tag{17}$$

where, Q is jujube picking rate, %; M is impurity rate, %.

According to ANOVA in Table 4, the p value of the model of picking rate and impurity rate of jujube in the response surface model is less than 0.0001 (p<0.01), which indicates that the regression model is highly significant; the p value of the loss of fit terms is 0.1293 and 0.5714, respectively, which is not significant, indicating that there are no unconsidered factors affecting the test indexes; and the coefficient of determination R^2 is 0.9887 and 0.9875, respectively, which indicates that the model can be fit to the test results of 98.87% and 98.75%, respectively. With the above test results, it can be known that the relevant parameters of the machine can be optimized by the model. In the jujube picking rate model, A, B, AB, A^2 and B^2 have highly significant influence on the regression model (p<0.01), while AC and BC have no significant influence on the regression model (p>0.05); in the jujube impurity rate model, A, B, AB, A^2 and B^2 have highly significant influence on the regression model (p<0.01), while AC and BC have no significant influence on the regression model (p>0.05). The optimized equations with the insignificant regression terms removed are shown in Equations (25) and (26).

Table 4 ANOVA of jujube picking rate and impurity rate

Source of variation	Picking rate				Impurity rate			
	Sum of squares	*df*	*F*	*p*	Sum of squares	*df*	*F*	*p*
Model	272.77	9	97.04	<0.0001**	109.10	9	87.83	<0.0001**
A	19.11	1	61.18	<0.0001**	54.57	1	395.42	<0.0001**
B	17.88	1	57.26	<0.0001**	24.00	1	173.90	<0.0001**
C	1.23	1	3.95	0.0118*	1.30	1	9.44	0.0118*
AB	17.70	1	56.68	<0.0001**	8.40	1	60.90	<0.0001**
AC	1.05	1	3.37	0.2123	0.245	1	1.78	0.2123
BC	0.2113	1	0.6764	0.5806	0.045	1	0.3261	0.5806
A^2	153.04	1	490.01	<0.0001**	14.50	1	105.09	<0.0001**
B^2	47.17	1	151.03	0.0002**	4.54	1	32.89	0.0002**
C^2	51.89	1	166.15	0.0109*	1.34	1	9.71	0.0109*
Residual	3.12	10			1.38	10		
Lack of fit residual	2.33	5	2.96	0.1293	0.6318	5	0.8442	0.5714
Pure error	0.7883	5			0.7438	5		
Total	275.89	19			110.48	19		

Note: ** indicates highly significant (p<0.01); * indicates significant (p<0.05)

$$Q= 94.01-1.18A+1.14B+0.3005C+1.49AB-3.26A^2-1.81B^2-1.9C^2 \quad (18)$$

$$M= 3.23+2.00A-1.33B-0.3089C-1.02AB+A^2+0.5613B^2-0.305C^2 \quad (19)$$

The test of the regression coefficients in Equations (18)-(19) concludes that the primary and secondary factors affecting the picking rate and impurity rate are: forward speed, fan speed, and height of picking mouth from the ground.

3.4.2 Effect analysis of test factors

In the evaluation of jujube picking performance indexes, picking rate and impurity rate are key performance indexes of the machine. According to the established regression model of picking rate and impurity rate, one of the test factors is set to zero level, and the response surface and contour map are drawn, as shown in Figures 7 and 8.

As shown in Figures 7a and 8a, when the height of the picking mouth from the ground is at the central level (82 mm), the picking rate first increases and then decreases with the increase of forward speed and fan speed. The impurity increases with the increase of forward speed, but decreases with the increase of fan speed, impurity rate decreases. This is because with the increase of forward speed and fan speed, a lot of jujubes and impurities are drawn into the screening system, while the fan speed increases to blow the leaves out of the screening system, increasing the picking rate; when the forward speed and fan speed continue to increase, the machine continues to draw in jujubes and impurities, and the screening system is full, in which case the gap between jujubes and impurities becomes small and not conducive to the separation, and therefore the picking rate becomes smaller. With the increase of fan speed and wind force, leaves and other objects are blown out of the screening system to reduce the impurity content. When the forward speed is small (less than 0.5 m/s), it has little influence on picking rate and impurity rate. When the forward speed is large (>0.5 m/s), it has great influence on picking rate and impurity rate.

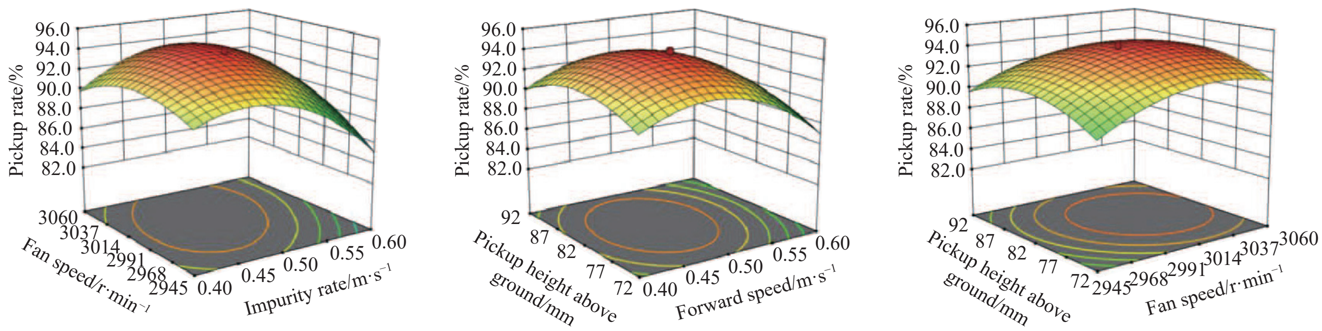
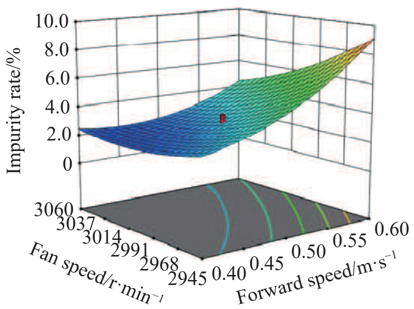


Figure 7 Influence of various factors on picking rate

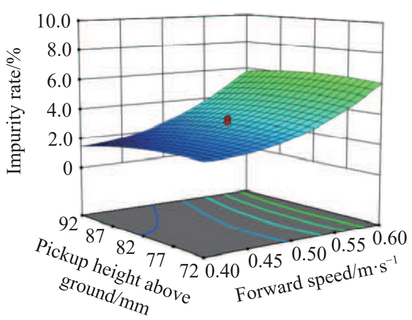
As shown in Figures 7b and 8b, when the fan speed B is at the central level (3000 r/min), the picking rate first increases and then decreases with the increase of forward speed and height of picking mouth from the ground, while the impurity rate always increases. This is because as the forward speed and the height of picking mouth from the ground increase, the machine draws a lot of jujubes and impurities into the screening system. The picking rate increases first when the screening system is not full and has the optimal screening efficiency; but when the screening system is full as the machine continues to draw in jujubes and impurities, the gap between them negatively affects the separation, so the picking rate decreases, and the impurity rate increases as leaves and other objects cannot be blown out of the screening system. When the forward speed is small (less than 0.5 m/s), it has little influence on picking rate and impurity rate. When the forward speed is large (greater than 0.5 m/s), it has great influence on picking rate and impurity rate.

As shown in Figures 7c and 8c, when the forward speed is at the central level (0.5 m/s), the picking rate increases first and then decreases with the increase of fan speed and height of picking mouth from the ground, while the impurity rate always decreases. This is because as the fan speed and the height of picking mouth from the ground (picking area) increase, the machine draws a lot of jujubes and impurities into the screening system. The picking rate increases first when the screening system is not full and has the optimal screening efficiency; but when the screening system is full

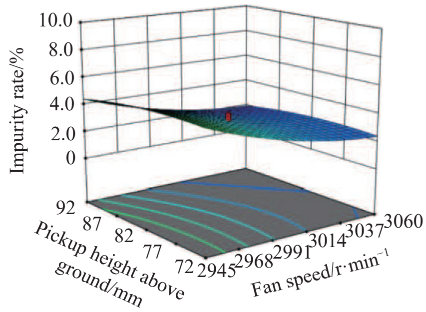
as the machine continues to draw in jujubes and impurities, the gap between them negatively affects the separation, so the picking rate decreases. With the increase of fan speed and wind force, leaves and other objects are blown out of the screening system to reduce the impurity content. When the fan speed is small (less than 3000 r/min), it has a great influence on picking rate and impurity rate. When the fan speed is large (greater than 3000 r/min), it has little influence on picking rate and impurity rate.



a. $M(A,B,0)$



b. $M(A,0,C)$



c. $M(0,B,C)$

Figure 8 Influence of various factors on impurity rate

3.4.3 Parameter optimization

When the forward speed is 0.4-0.6 m/s, the fan speed is 2945-3060 r/min, and the height of picking mouth from the ground is 72-92 mm, the main objective function method in multiple response is used to optimize the influencing factors, namely forward speed, fan speed and height of picking mouth from the ground, and picking rate and impurity rate are used as performance index functions for optimization solution. The objective function and constraints are as follows:

$$\begin{cases} \max Q \\ \min M \\ Q > 93\% \\ M < 3\% \\ \text{s.t.} \begin{cases} 0.33 \text{ m/s} \leq A \leq 0.67 \text{ m/s} \\ 2905.8 \text{ r/min} \leq B \leq 3099.2 \text{ r/min} \\ 65.18 \text{ mm} \leq C \leq 98.82 \text{ mm} \end{cases} \end{cases} \tag{20}$$

In order to achieve the optimal working performance of the ground jujube picker, the influencing factors in the test are optimized. For the optimal working parameters of the picker, optimization solution is obtained by Design-Expert 12 data processing software, which results in the optimal parameter combination of the influencing factors: forward speed 0.47 m/s, fan speed 3025.76 r/min, height of picking mouth from the ground 84.20 mm. The predicted values of the objective function are: 94.00% and 2.30% for picking rate and impurity rate, respectively.

3.5 Test verification

In order to verify the optimization results of the working parameters of jujube picker and the operational performance of the cleaning system, test verification is repeated five times with the above optimal parameter combination, as shown in Figure 9, and the results are arithmetic average. The test concludes that the average picking rate is 93.7%, which is greater than 93.0%, and the average impurity rate is 2.5%, which is less than 3.0%. It can be seen that the test results and optimization results are consistent, meeting the requirements of mechanized picking of ground jujube.

a. Before field picking test

b. After field picking test

Figure 9 Field test

4 Conclusions

(1) According to the requirements for picking up jujube and jujube characteristics, a ground jujube picker was designed, which adopted the air suction method. The parameters of the key components were determined, and relevant calculations were carried out on the suspension speed of jujubes and the gathering device. Also, the key factors affecting the picker performance are defined as follows: forward speed, fan speed, and height of picking mouth from the ground.

(2) The performance of the ground jujube picker based on bionic mechanism in the field was mainly evaluated by two indexes, namely picking rate and impurity rate. The main influencing factors for the working indexes are forward speed of the picker, fan speed and height of the picking mouth from the ground. The picker draws in jujubes through the negative pressure airflow formed by centrifugal fan, and carries out the first jujube and impurity separation in the cleaning system, after which the jujubes are transmitted to the collection box through the conveyor belt, and enter into the collection box from the top of the conveyor belt. The remaining jujube leaves in the jujube screening box are cleaned by airflow for secondary cleaning, thus accomplishing the picking and cleaning of jujubes.

(3) The quadratic orthogonal center composite test was performed. The regression model was established between the performance indexes of the picker and various test factors, and the influence of these factors on response indicators was analyzed based on the response surface. The optimal combination of working parameters was determined by multi-objective optimization (MOD): forward speed 0.47 m/s, fan speed 3025.76 r/min, height of picking mouth from the ground 84.20 mm. In this case, the performance indexes of the picker are 94.00% for picking rate and 2.30% for impurity rate.

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