DESIGN AND EXPERIMENT OF A SELF-PROPELLED JUJUBE COLLECTION STRIP PICK-UP MACHINE
/
自走式红枣集条捡拾机的设计与试验

Fengkui ZHANG[1,2], Wenxi SHAO [1,2], Jikui ZHU [1,2], Ting ZHANG[1,3], Shijie ZHAO[1,3], Ping LI [1,2*]

[1)] College of Mechanical and Electrical Engineering, Tarim University, Alar 843300, Xinjiang, China;

[2)] Modern Agricultural Engineering Key Laboratory at Universities of Education Department of Xinjiang Uygur Autonomous Region, Tarim University, Alar 843300, Xinjiang, China

[3)] Key Laboratory of Tarim Oasis Agriculture (Tarim University), Ministry of Education, Tarim University, Alar 843300, Xinjiang, China

Corresponding Author: Ping Li, Email: lpdyy716@163.com

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ABSTRACT

Aiming at the problems of single mechanical performance, multi-person operation and low operation efficiency of air-suction jujube harvesting in China, combined with the requirements of mechanized jujube harvesting in Xinjiang, this study designed a self-propelled jujube collection strip pick-up machine. The machine is mainly composed of crawler chassis, landing jujube collection strip device, separation and impurity removal device and hydraulic system. According to the jujube planting mode, the size of the crawler chassis is 1780 mm × 1650 mm × 310 mm. In order to simulate the effect of artificial collecting strips, a reciprocating collecting strip blowing head was designed with a height of 15 cm from the ground, a horizontal and vertical angle of 35° and 15° respectively. The model of the collecting fan is selected as 9-19-4A; the fluid simulation analysis of the separation and impurity removal box is carried out to verify the rationality of the box structure design. The performance of the picker was tested by pick-up efficiency, cleanliness, breakage, and impurity rates. The results show that when the forward velocity was about 0.40 m·s^{-1}, the average pick-up efficiency could reach 752.7 km·h^{-1}, the average pick-up cleanliness rate was 95.66 %, the average breakage rate was 2.68 %, and the average impurity rate was 3.64 %. The self-propelled jujube collection strip pick-up machine designed in this experiment meets the requirements of mechanized harvesting of jujube and can realize single-person remote control operation.

摘要

针对我国气吸式红枣收获机械性能单一、需多人同时操作以及作业效率低等问题，结合新疆红枣机械化收获作业要求，本研究设计一种自走式红枣集条捡拾机。该机主要由履带底盘、落地红枣集条装置、分离除杂装置和液压系统等组成。根据红枣种植模式设计履带底盘外形尺寸为 1780 mm×1650mm×310 mm；为模拟人工集条效果，设计往复式集条吹头距地高度 15cm、水平和竖直夹角分别为 35°和 15°；选取集条风机型号为 9–19–4A；对分离除杂箱箱体进行流体仿真分析，验证箱体结构设计合理性；通过捡拾效率、拾净率、破损率和含杂率来检验捡拾机作业性能。结果表明：前进速度约为 0.40m·s-1 时，平均捡拾效率可达 752.7 km·h-1，平均捡净率为 95.66%，平均破损率为 2.68%，平均含杂率为 3.64%。本试验设计的自走式红枣集条捡拾机符合红枣机械化收获作业要求，可实现单人远程遥控操作。

INTRODUCTION

Currently, landing jujube harvest operations in China are mainly comprised of the sectional type operation mode of gathering strips, followed by concentrated harvest, which first uses domestic fire fans to collect scattered jujubes on the ground into heaps or strips. Finally, air-absorbing jujube harvesting machinery and equipment were used to gather the harvest *(Zhang et al., 2021)*. This operation method improved the mechanization level and efficiency of landing jujube harvesting to a certain extent and reduced the cost of production. Still, there are problems, such as the need for multiple people to operate the machine and the working link being verbose simultaneously *(Chen et al., 2020; Yuan et al., 2022)*.

Fengkui Zhang, Master, Lecturer; Wenxi Shao, Graduate student; Jikui Zhu, Lecturer; Ting Zhang, Graduate student; Shijie Zhao, Graduate student; Ping Li, PhD, Professor.

The research on foreign forest fruit harvesting equipment started earlier than that in China. There are many studies on shaking forest fruit harvesting equipment *(Homayouni, 2021; Sola-Guirado, et al., 2017; Afsah-Hejri, et al., 2022)*, such as blueberry, citrus and so on *(Brondino et al., 2021; Ghonimy et al., 2019)*. When harvesting fruits with small particle size, the principle of negative pressure suction is generally used to reduce the damage rate of fruit epidermis *(Shuib et al., 2018)*. The development of modern agriculture is transforming from manual harvesting to sustainable automation *(Kootstra et al., 2021)*. Especially in the mechanization of fruit harvesting, it has begun to focus on economic performance research *(Bernardi et al., 2021; Grupioni et al., 2020)*. With the rapid development of orchard intelligence, orchard picking robots have made positive progress in fruit recognition and positioning *(Kim et al., 2020)*, path planning *(Kurtser and Edan, 2020)*, pose adjustment *(Yeshmukhametov et al., 2020)*, and flexible grasping *(Ben-Shahar et al., 2020)*. However, there are still problems such as low efficiency and difficulty in meeting the actual needs of fresh fruit picking *(Davidson et al., 2020; Fu et al., 2020; Davidson et al., 2020)*.

The planting area and yield of jujubes in China rank first in the world. There is relatively much research on jujube harvesting machinery and equipment. However, the harvesting principle and device structure are similar to those of foreign forest fruit harvesting machinery and equipment due to the late research on forest fruit harvesting machinery and equipment. For the harvesting operation of ground jujube, there are many problems, such as poor applicability and a single function *(Wang et al., 2021)*. Compared with mechanical principle harvesting machinery and equipment, its advantages are: good applicability and flexibility, low picking, and low breakage rates *(Yuan et al., 2021)*. However, most of them are small jujube harvesting machinery, and productivity cannot meet the requirements when working in the field. Before the operation, the landing jujube must be artificially gathered into piles or strips, and the function only meets picking, transportation, separation, and impurity removal. Therefore, it is necessary to improve and optimize such mechanical equipment according to the local conditions and human resources *(Yamin et al., 2022; Yamin et al., 2022)*.

A self-propelled jujube-collecting strip picker was designed in this study based on the analysis of the problems mentioned above and connected with the previous research basis and research data. It can complete the harvesting operation of jujube between under the tree and row middle using the air-blowing principle and the reciprocating collection strip mechanism. The performance parameters of the pick-up machine were verified by the operation performance test of the pick-up machine to provide references for research on jujube harvesting machinery.

MATERIALS AND METHODS

Main planting pattern and mechanized harvesting operation requirements

The planting area and yield of Xinjiang jujube are the first in China. The jujube planting industry uses 4/5 of the available planting regions in Xinjiang, mainly distributed in southern Xinjiang *(Editorial Committee of Xinjiang Statistical Yearbook, (2021))*. In the harvest time, landing jujube is more than 60% of the total, and finally, the artificial tap down on the ground to collect together and complete the harvest operation. The parameter table of the jujube planting pattern is shown in Table 1. Wide-row close planting (trunk shape) and wide-narrow intercropping (open center shape) are two main planting patterns in the jujube high-quality producing areas of Southern Xinjiang for convenient mechanized operation and management. There are characterized by wide row spacing, high crown height and fixed stem, and sparse lateral branches. These two planting patterns benefit the mechanized process and improve the final fruit quality. The wide-row close planting (trunk shape) and wide-narrow intercropping (open center shape) planting modes were selected as the design basis to improve the applicability and versatility of the designed self-propelled jujube collection strip pick-up machine.

Table 1

The parameter table of the jujube planting pattern

Tree shape	Seed spacing /(m^{-1})	Row spacing /(m^{-1})	Crown height /(m^{-1})	Heading height /(m^{-1})
Trunk shape	0.8–1	1.6–2	< 1.5	0.4–0.6
Open Center shape	1.5–2	3–3.5	2.5–3	0.5–0.8

The operation process of landing jujube mechanical harvesting conduct an inter-row landing jujube collection strip and jujube under the tree blow to the inter-row firstly. Then, pick-up, transportation, separation, and impurity removal for the jujube of the collection strip are performed. Finally, the jujube was collected into the fruit collection box.

The whole structure and technical parameter

The structure of the self-propelled jujube collection strip pick-up machine is shown in Figure 1. The apparatus mainly comprises a crawler walking system, chassis frame, hydraulic system, remote control operating system, landing jujube collection strip device, jujube under the tree blowing device, a separation and impurity removal device, picking and conveying pipe, suction blower, transmission mechanism, etc. The landing jujube collection strip device comprises a collection strip blowing head, collection strip fan, reciprocating collection strip mechanism, and copying collection stripboard. The jujube under the tree blowing device is composed of under-tree jujube blowing head, flexible pipe, blowout fan, etc. The main technical parameters of the whole machine are shown in Table 2.

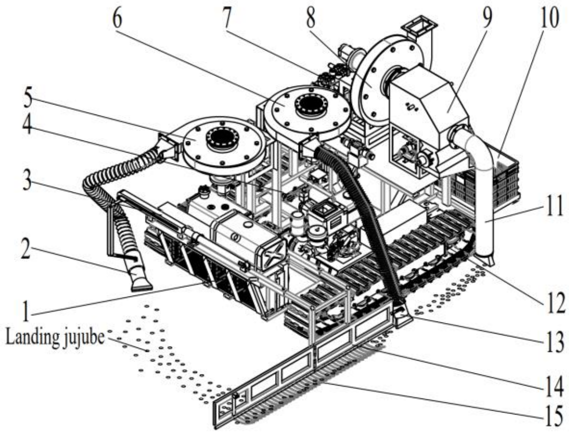


Fig. 1 - Structural diagram of the self-propelled jujube collecting strip pick-up machine

1. chassis frame; 2. collection strip blowing head; 3. reciprocating collection strip mechanism; 4. hydraulic system; 5.collection strip fan; 6. blowout fan; 7. remote control operating system; 8. suction blower; 9. separation and impurity removal device; 10. fruit collection box; 11. picking and conveying pipe; 12. crawler walking system; 13. under-tree jujube blowing head; 14. copying collection stripboard; 15. lock chain

Table 2

Key technical parameters of the self-propelled jujube collecting strip pick-up machine

Parameters	Design Values
Machine size (L × W × H)/ (mm × mm × mm)	2000 × 1500 × 1300
Overall weight / kg	1250
Matched power / kW	23
Operation width / mm	1500–2000
Operating speed / km·h $^{-1}$	0–5
Pick-up efficiency / kg·h $^{-1}$	≥ 700
Pick-up cleanlily rate / %	≥9 0
Breakage rate / %	≤ 3
Impurity rate / %	≤ 5

Working principle

When the self-propelled jujube collecting strip pick-up machine works between rows in the jujube garden (Figure 2), the effect is best when the copying collection strip board of the pick-up machine is adjusted to 3-5 cm from the left jujube trunk between rows. The collection strip blowing head in the front of the pick-up machine blows the landing jujube in the front working area from the right side to the bottom of the left copying collection strip board under the action of the reciprocating collection strip mechanism and intercepts. It collects the strip through the lock chain. The jujube of the collection strip is picked up by picking and conveying pipes and transported to the separation and impurity removal device. The jujube is separated from the impurities under airflow, self-weight, and obstructive board and is discharged into the fruit collection box through the unloading impeller.

The lightweight impurities with small floating speed, such as blades and others, move with the suction airflow, and are discharged from the outlet of the suction blower after being broken by the choppy roll. Heavy impurities, such as soil and others can be discharged through the railing gap of the discharge port during the jujube removal process. During the whole operation process, the under-tree jujube blowing head on the left side of the pick-up machine blows out the jujube under-tree under the action of the blowout fan to the left row of the landing jujube harvest operation. After completing the left side of the inter-row landing jujube harvesting operation, the pick-up machine can be turned to the right side of the inter-row operation and finally achieve the landing jujube harvesting operation of the inter-row.

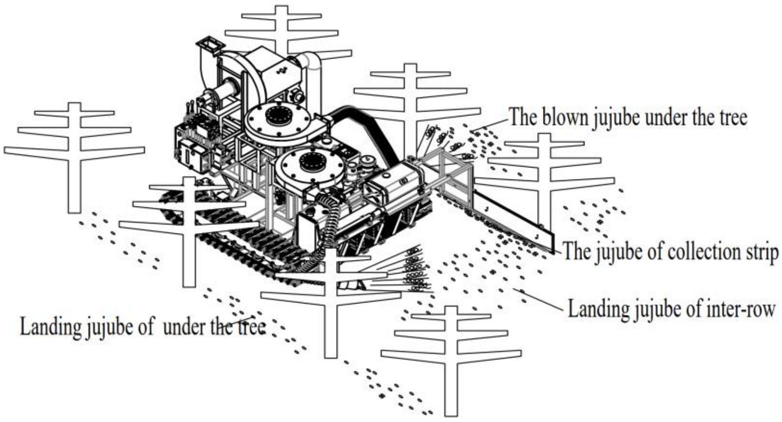


Fig. 2 - Working principle of the self-propelled jujube collecting strip pick-up machine

Design of critical components
Self-propelled crawler chassis

The crawler chassis has the advantages of reducing ground pressure and improving traffic ability *(Zhang et al., 2023)*, and it can better adapt to the operating conditions of sand-land in Southern Xinjiang. The pick-up machine must overcome the driving resistance and steering resistance at the same time. The power consumed by the steering resistance was much larger than the linear driving resistance. Steering of the crawler chassis is achieved by changing the driving force on the driving wheels on both sides to achieve different speeds *(Wang et al., 2021; Du et al., 2023; Vladislav, 2023)*. Figure 3 shows the force analysis of the contact area with the ground when the chassis turns. O is the steering center point of the crawler chassis, and O' is the geometric center point of the crawler chassis.

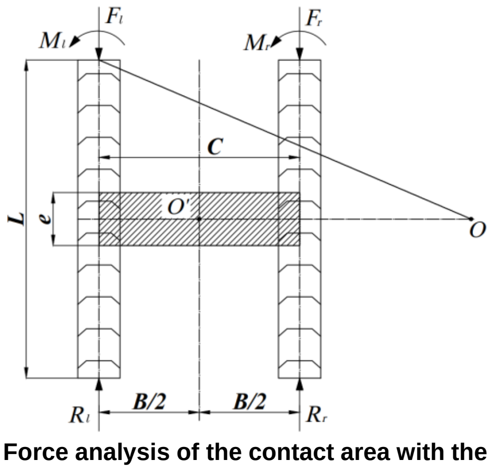


Fig. 3 - Force analysis of the contact area with the ground

The equilibrium conditions for turning are as follows:

$$F_l = \frac{fG}{2}\left(1 + \frac{2C}{B}\right) \tag{1}$$

$$F_r = \frac{fG}{2}\left(1 - \frac{2C}{B}\right) \tag{2}$$

where:

F_l is the crawler steering resistance of the left side, Pa;

F_r is the crawler steering resistance of the right side, Pa;
f is the coefficient of rolling resistance, it is 0.12;
G is the total gravity of the crawler chassis, N;
C is the transverse eccentric distance, it is 0.708 m; B is the center distance of crawler, it is 1.416 m.

The grounding pressure of the crawler on both sides is as follows:

$$P_{al} = \frac{G}{2bL}\left(1+\frac{2C}{B}\right) \tag{3}$$

$$P_{ar} = \frac{G}{2bL}\left(1-\frac{2C}{B}\right) \tag{4}$$

where:

P_{al} is the crawler grounding pressure of the left side, Pa,
P_{ar} is the crawler grounding pressure of the right side, Pa,
b is the width of crawler contact ground, it is 0.24 m,
L is the length of crawler contact ground, it is 1.4 m.

The steering torque moment of crawler chassis M is:

$$M = M_l + M_r \tag{5}$$

$$M_l = \frac{\mu GL}{8}\left(1+\frac{2C}{B}\right)\left[1-\left(\frac{2e}{L}\right)^2\right]^2 \tag{6}$$

$$M_r = \frac{\mu GL}{8}\left(1-\frac{2C}{B}\right)\left[1-\left(\frac{2e}{L}\right)^2\right]^2 \tag{7}$$

where:

M is the steering torque moment of the crawler chassis, N·m;
M_l is the steering torque moment of the crawler chassis of the left side, N·m;
M_r is the steering torque moment of the crawler chassis of the right side, N·m;
μ is the coefficient of steering resistance, it is 0.7; e is the longitudinal eccentricity distance, it is 0.297 m.

The steering torque moment and power of the drive wheel when the crawler drive chassis turns left are as follows:

$$F_l = \frac{fGL}{2}\left(1+\frac{2C}{B}\right)+\frac{\mu GL}{4B}\left[1-\left(\frac{2e}{L}\right)^2\right]^2 \tag{8}$$

$$F_r = \frac{fGL}{2}\left(1-\frac{2C}{B}\right)-\frac{\mu GL}{4B}\left[1-\left(\frac{2e}{L}\right)^2\right]^2 \tag{9}$$

$$M_{max} = \left(F_{lmax}+F_{rmax}\right)r \tag{10}$$

$$W_{max} = \left(F_{lmax}+F_{rmax}\right)v \tag{11}$$

where:

M_{max} is the maximum driving moment of the crawler driving wheel, N·m;
W_{max} is the maximum driving power of the crawler driving wheel, kW;
r is the pitch radius of the driving wheel, it is 0.12 m;
v is the line speed of the driving wheel, it is 0.415 m·s^{-1}.

The full load quality of the pick-up machine is 1250 kg. According to the calculation, the maximum driving moment of the chassis drive wheel is 649.27 N·m, and the maximum power is 10.82 kW.

The self-propelled crawler chassis comprises a hydraulic motor, driving wheel, tensioning wheel, bearing wheel, etc., as shown in Figure 4.

Two hydraulic motors drive the driving wheel with a power of 6 kW and an operating speed of 155 – 775 $r \cdot min^{-1}$ to realize the movement and spot turn of the pick-up machine. The driving wheel adopts the rear type to reduce the height of the entire machine. The pitch tooth meshing mode fixes the crawler and the driving wheel to ensure that the track does not fall off. According to the row spacing of the wide-row close planting (trunk shape) and wide-narrow intercropping (open center shape) planting modes, the dimension of the crawler chassis was designed to be 1780 mm × 1650 mm × 310 mm (L × W × H).

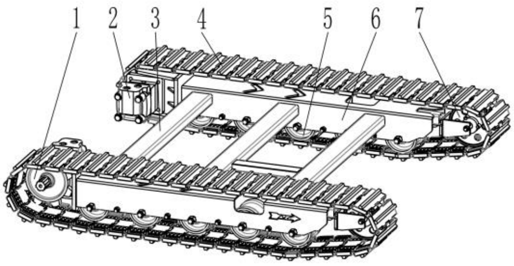


Fig. 4 - Structure diagram of self-propelled crawler chassis

1. Driving wheel; 2. Hydraulic motor; 3. Balance beam; 4. Crawler; 5. Bearing wheel fixing plate; 6. Bearing wheel; 7. Tensioner wheel

The landing jujube collection strip device and under-tree jujube blowing device

The landing jujube collection strip and under-tree jujube blowing device are composed of a collection strip blowing head, reciprocating frame, adjusting mechanism, collecting strip fan, expansion frame, copying collection strip board, blowout fan, under-tree jujube blowing head, etc., as shown in Figure 5. The landing jujube collection strip device realizes reciprocating motion by controlling the hydraulic cylinder to make the adjusting mechanism on the reciprocating frame drive the collection strip blowing head to simulate the effect of a manual collection strip. The adjusting mechanism can adjust the height and horizontal and vertical angle of the collection strip blowing head from the ground. The expansion frame can adjust the protrusion distance of the copying collection strip board to control the width of the collection strip operation to apply to different work plots. The under-tree jujube blowing device discharges the positive pressure airflow through the blowout fan and the under-tree jujube blowing head. According to the previous research results of the team, the design of the strip blowing head was 15 cm from the ground height, the horizontal and vertical angles were 35° and 15°. The operation effect is the best when the forward speed is 1.5 km/h, and the picking rate can reach 93.99 %. The landing jujube under the tree is blown to the row under positive pressure airflow to realize the blowing operation of the jujube under the tree. The under-tree jujube blowing head is installed on the left side of the end of the copying collection strip board to prevent the reduction of picking efficiency caused by blowing out the collected jujube.

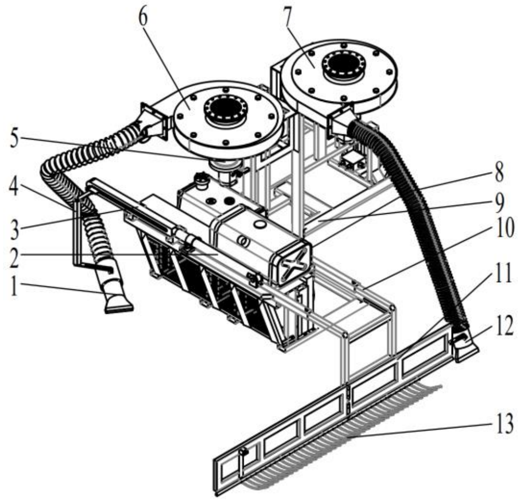


Fig. 5 - The landing jujube collection strip and under-tree jujube blowing device

1. Collection strip blowing head; 2. Hydraulic cylinder; 3. Reciprocating frame; 4. Adjusting mechanism; 5. Hydraulic motor; 6. Collecting strip fan; 7. Blowout fan; 8. Flexible pipe; 9. Frame; 10. Expansion frame; 11. Copying collection stripboard; 12. Under-tree jujube blowing head; 13. Lock chain

By setting up the air-blowing collection strip test device and conducting the orthogonal test in the soil through the laboratory of Tarim University, the orthogonal test showed that the operation effect was the best when the collection strip blowing head from the ground was 15 cm, and the horizontal and vertical angles were 35° and 15°. The forward velocity was 1.5 km·h^{-1}, and the pick-up cleanlily rate could reach 93.99%. The air-blowing collection strip test device is shown in Figure 6.

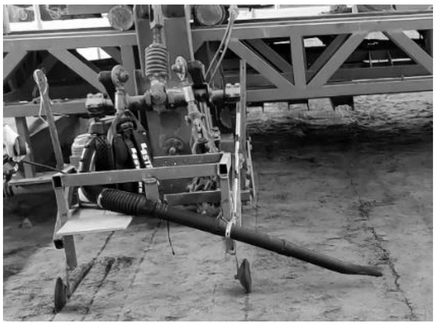


Fig. 6 - Air-blowing collection strip test device

Collection strip fan type selection

The model of the collecting fan can be selected by the air volume required for the operation. The operating air volume includes the operating loss air volume and the air volume required to move the landing jujube to the baffle *(Zhang et al., 2022; Yu et al., 2020)*. The operation air volume can select the model of the collection strip fan. The operation air volume includes the operational waste air volume, and the air volume of the landing jujube moves to the collection stripboard.

(1) Operating air volume calculation

The previous experimental observation found that when the jujube is affected by airflow, the jujube with different initial states will eventually roll with the long axis as the axis. Therefore, the long-axis section is used as the wind surface for calculation, and the air volume is as follows:

$$Q_0 = K \cdot L \cdot \rho \cdot v \cdot Q \tag{12}$$

where: Q_0 is the demand air volume of the collector bar, m^3·h^{-1};

K is the airflow coefficient, due to fan losses and airflow losses in the air, so the airflow coefficient is introduced, generally 1.3–1.6;

ρ is the concentration of landing jujube, pcs/m^2;

v is pick-up machine forward speed, km·h^{-1}.

The air volume required for a single jujube to roll to the baffle is:

$$Q = v_0 \tag{13}$$

where:

v_0 is airflow velocity, m·s^{-1};

A is the cross-sectional area of jujube subjected to wind, m^2.

(2) Wind pressure calculation of fan operation

The total pressure of the fan is composed of static and dynamic pressures. Thus, there are the following formulas:

$$P = P_S + P_D \tag{14}$$

$$P_S = \frac{\varepsilon v_0 \rho_a}{2} \tag{15}$$

$$P_D = \frac{{v_0}^2 \rho_a}{2} \tag{16}$$

where:

P is the full pressure of the fan, Pa;

P_S is the static pressure of the fan, Pa; P_D is the dynamic pressure of the fan, Pa;

ε is the inherent resistance coefficient *(Yang and Wang, 2016)*, 1.35;

v_0 is the airflow velocity, m·s^{-1}; ρ_a is the air density, kg·m^{-3}.

The pressure loss along the way should also be considered in the fan type selection, and it can be obtained from the following formula:

$$\Delta P_m = \frac{\lambda}{de} \cdot \frac{v^2}{2} \rho l \tag{17}$$

$$\lambda = K \cdot \frac{0.0134}{D^{\wedge 0.284}} \tag{18}$$

where:

de is the equivalent diameter of the blowing pipe, m, round blowing pipe de = d; v is airflow velocity in the tube, m·s^{-1}; ρ is the air density, kg·m^{-3}; l is the length of the blowing pipe, m; λ is resistance friction coefficient, as the blowing pipe is in the resistance square zone (it is the ratio of velocity to kinematic viscosity greater than 2.7×10^6); K is the equivalent friction coefficient of the inner wall of the blowing pipe, according to the roughness of the value, here is 0.15; D is the diameter of blowing pipe, m.

The dynamic pressure loss of the fan was 1506.25 Pa, the static pressure loss was 2033.44 Pa, and the pressure loss along the way was 90.26 Pa when the length of the blowing pipe was 1.5 m and the total pressure was 3629.95 Pa. Therefore, the air volume and total pressure of the collection strip fan should be higher than the calculated data *(Chen et al., 2022).* The fan model was 9–19–4A, which was selected during the "Fan Selection" stage.

Separation and impurity removal device

The separation and impurity removal device comprises a discharge fence, discharge impeller, separation and impurity removal box, chain wheel drive mechanism, suction, and supply fan, fan connecting shaft, and hydraulic motor, as shown in Figure 7. During the operation, the suction blower rotates to generate negative-pressure suction airflow inside the separation and impurity removal box. The jujube enters the separation and impurity removal box from the gathering process, conveying hoses and falling into the unloading impeller. From the unloading outlet through the fence the jujube falls into the fruit collection box. In the gathering process and conveying, the floating speed of lightweight impurities, such as blades and others are small, move with suction airflow, and are discharged from the outlet of the suction blower after being broken by the choppy roll. Heavy impurities, such as soil and others can be discharged through the railing gap of the discharge port during the jujube removal process.

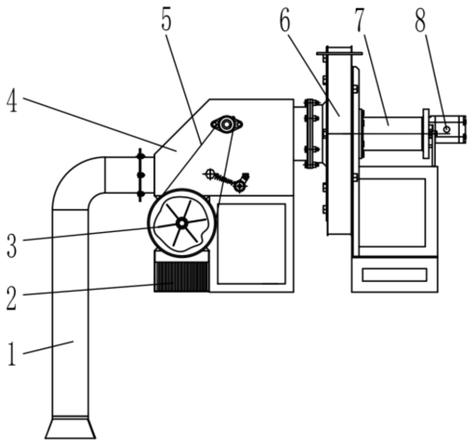


Fig. 7 - Separation and impurity removal device

1. picking up and conveying hoses; 2. unloading fence; 3. unloading impeller;4. separation and impurity removal box; 5. chain wheel drive mechanism; 6. suction blower;7. fan connecting shaft; 8. hydraulic motor

Hydraulic transmission system

The hydraulic transmission system consists of walking and activity systems, as shown in Figure 8. Two traveling motors are connected in parallel in the hydraulic transmission system, and the walking dual pump supplies the oil. The throttle size can control motor speed. The driving motor of the suction strip fan is parallel to the driving motor of the blowout fan. The unloading driving motor is similar to the driving motor of the suction blower, and the speed control valve can control the hydraulic flow rate. The speed of the hydraulic motor can be controlled, and the dual-activity pump supplies the oil.

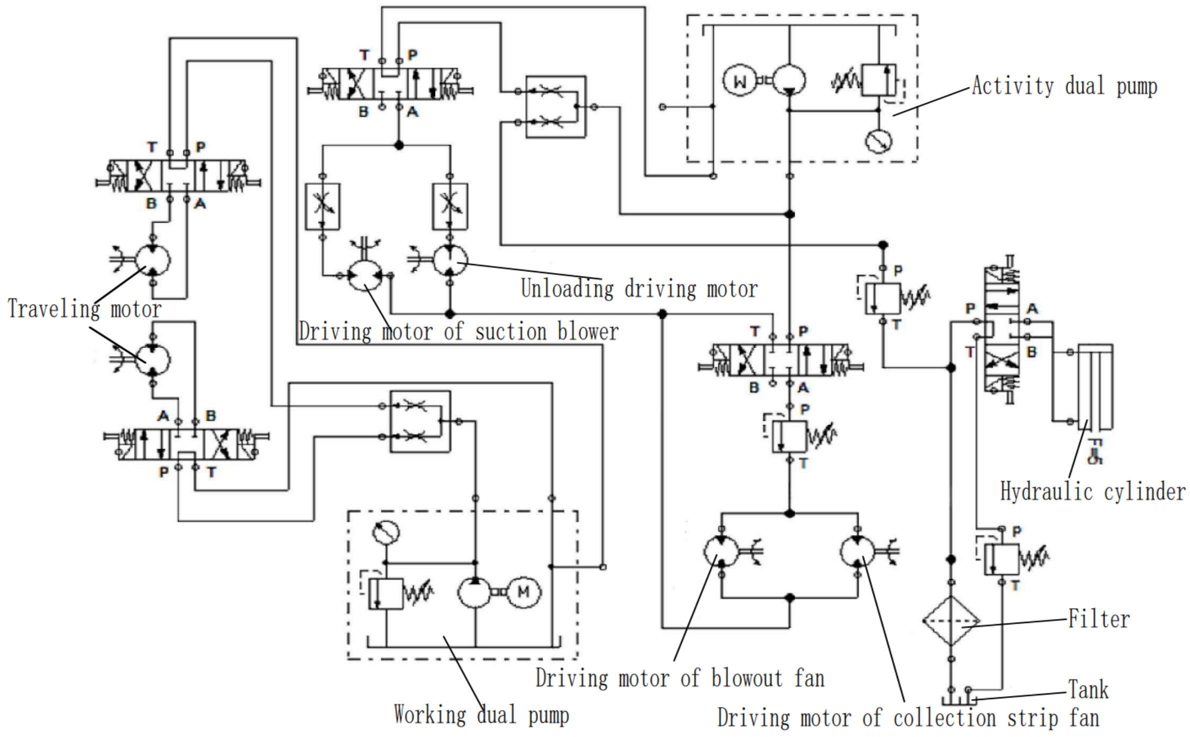


Fig. 8 - Hydraulic transmission system

The reciprocating collection strip mechanism realizes automatic reciprocating linear motion by pushing and pulling the hydraulic cylinder. A three-position four-way electromagnetic directional valve and travel switch control the pushing and pulling of the hydraulic cylinder. When the switch is started during operation, the three-position four-way electromagnetic directional valve is powered at the left valve position, the hydraulic oil enters the left chamber of the hydraulic cylinder, and the hydraulic cylinder is extended at this time. When switch two is fully extended, the right valve of the three-position four-way electromagnetic directional valve is electrified, and the hydraulic oil enters the rod cavity and lets the piston rod return. When the piston rod of the hydraulic cylinder is completely returned, switch one is touched to control the hydraulic cylinder to return, and an operation cycle process is completed.

Separation and impurity removal box

The separation and impurity removal box comprises three parts: a separation chamber, a crushing impurity chamber, and an unloading chamber. The separation chamber reduces the airflow velocity by suddenly increasing the volume and cooperates with the baffle plate to separate the jujube from the impurities. The choppy roll in the crushing impurity chamber crushes the light impurities, such as jujube leaves, through high-speed rotation to be discharged from the outlet of the suction blower. The unloading chamber separates the jujube and heavy impurities through the unloading fence and puts them into the fruit collection box, while ensuring the airtightness of the box. The separation and impurity removal box is shown in Figure 9.

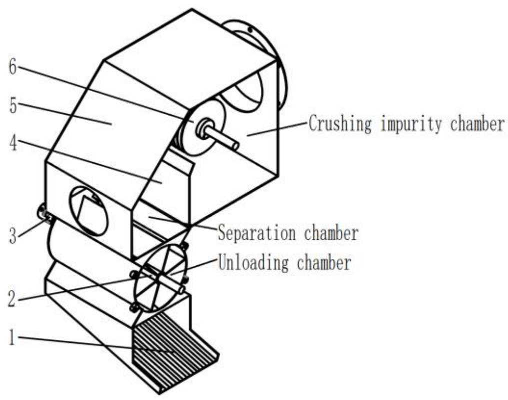


Fig. 9 - Separation and impurity removal box

1. Unloading fence; 2. Unloading impeller; 3. Servo motor; 4. Baffle plate; 5. Box shell; 6. Choppy roll

Operation performance test

Experiment conditions

The operation performance test of the self-propelled jujube collection strip pick-up machine (Figure 10) was carried out in the experimental center of Tarim University of Alar city, Xinjiang Province, China, on 15 August 2022. A flat ground with a length of 50 m and a width of 5 m was selected as the test area for operation performance, and three repeated tests were conducted. Before the experiment, the forward velocity of the pick-up machine was adjusted to about 0.4 m·s^{-1}. A 30 m × 1.5 m landing jujube working belt was arranged in the test area of operational performance. The mass ratio of jujubes to impurities was 4:1. The jujubes with pests and surface damage need to be removed to reduce the impact on the test and reflect the actual performance parameters of the pick-up machine.

Fig. 10 - The operation performance test of the self-propelled jujube collection strip pick-up machine

Test methods

According to the test method of *DG/T 188–2019 "Fruit Picker," (2019)* test indexes, such as picking efficiency, picking rate, damage rate, and impurity rate, were proposed as the performance assessment criteria of the self-propelled jujube collection strip pick-up machine.

(1) Picking efficiency γ

The pick-up machine was operated to harvest the jujube in the selected operation area. After the operation, the jujube in the fruit collection box was weighed and recorded as x_i. Due to the uneven distribution of scattered jujubes on the ground, the time spent on harvesting operations within the area of the completed work was recorded by a timer s_i.

$$\gamma = \frac{x_i}{s_i} \tag{19}$$

where:

γ is picking efficiency, kg·h^{-1};

x_i is weighing the quality of jujube in the fruit collection box, kg;

s_i is time spent on harvesting operations, h.

(2) Pick-up cleanlily rate λ

After the operation of the pick-up machine is completed, the landing jujube that is not collected strip and picked up by the pick-up machine in the operation area, has the weight recorded as y_i..

$$\lambda = 1 - \frac{y_i}{x_i + y_i} \times 100\% \tag{20}$$

where:

λ is pick-up cleanliness rate, %;

y_i is weighing the quality of un-collected strip and un-picking jujube, kg.

(3) Breakage rate ε

The jujube fruit in the fruit collecting box was selected, weighed and recorded as z_i.

$$\varepsilon = \frac{j_i}{z_i} \times 100\% \tag{21}$$

where:

ε is the breakage rate, %; j_i is weighing the quality of broken jujube, kg.

(4) Impurity rate μ

The mixture in the fruit collection box was weighed and recorded as a_i.

$$\mu = \frac{z_i}{a_i} \times 100\% \tag{22}$$

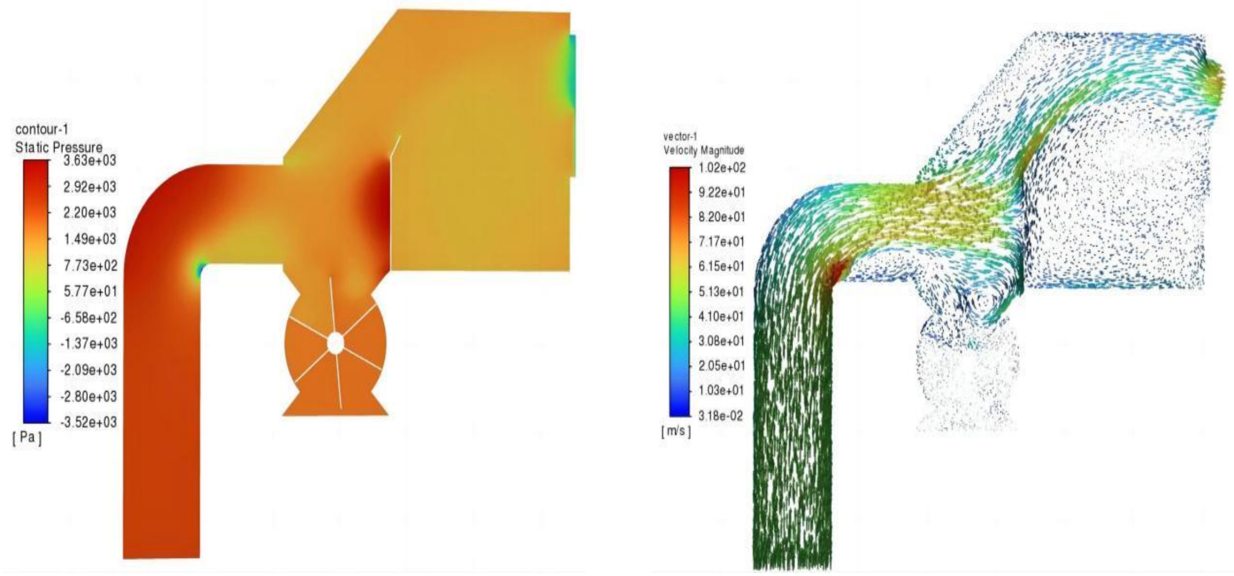
where:

μ is the impurity rate, %; z_i is the impurity weighing quality, kg.

RESULTS AND ANALYSIS

Numerical simulation of internal airflow field in the box

A fluid simulation analysis of the box was conducted to verify the rationality of the design of the separation and impurity removal box. Only the grids at the unloading chamber and the baffle plate are encrypted when meshing to explore the airflow state of the box and the conveying hoses and reduce the simulation time. The grids at the unloading chamber, the outer wall of the box, and the conveying hoses were sparse, and the number of grids divided was 246,000. The standard k-ε model was used to set the parameters, the inlet pressure was 0 Pa, the outlet pressure was -1200 Pa, the unloading chamber was set as the rotating area, the speed was 30 r·min^{-1}, and the rest areas were the static area. The simulation results are shown in Figure 11.



a) b)

Fig. 11 - Distribution diagram of pressure and velocity in the center section of the separation and impurity removal box

a) Pressure nephogram; b) Air velocity trajectory vector diagram

The airflow velocity and pressure distribution of the separation and impurity removal box and the pick-up conveying pipe are relatively uniform, as shown in Figure 11. There are slight losses at the bend pipe, baffle plate, and unloading chamber, which can be ignored. The overall airflow trajectory vector distribution of the unloading chamber is reasonable, and the vortex phenomenon appears on the upper right of the unloading chamber, which is more convenient for the jujube to enter the unloading chamber. The airflow vector in the unloading chamber is weak, which has little effect on the movement of the jujube, indicating that the influence of the rotation of the unloading impeller on the airflow inside the box can be ignored. In summary, the design of the box structure is reasonable.

Experiment results and analysis

The prototype operation performance test showed that the overall performance of the pick-up machine was relatively stable, and each device could work normally. The general operation effect was good, as it could meet the harvesting requirements.

According to the above pick-up machine test method, the picking efficiency, net pick-up rate, breakage rate, and impurity rate of each test area were calculated, and the average values of the three test results were taken. The average picking efficiency of the jujube garden of the pick-up machine is about 752.7 kg·h^{-1}, the average pick-up cleanlily rate is approximately 95.66%, the average breakage rate is about 2.68%, and the average impurity rate is about 3.64%, which meets the design requirements. The experimental results are shown in Table 3.

Table 3

Experimental results

Area Number	Pick-up efficiency (kg·h^{-1})	Pick-up cleanlily rate /%	Damage rate/%	Impurity rate/%
1	749.6	94.61	2.67	3.58
2	756.3	96.46	2.85	3.71
3	752.2	95.93	2.52	3.64

CONCLUSIONS

(1) Aiming at the problems of a single function of air-suction jujube harvesting machinery and equipment, simultaneous operation of multiple people, and low efficiency of field operation, combined with the planting mode and mechanized harvesting requirements of jujube high-quality production areas in Southern Xinjiang, a self-propelled jujube collection strip pick-up machine was designed. The whole machine had a compact structure and could be operated by a single person. It could complete the collection strip, picking, separation, and impurity removal of the landing jujube. It could be remotely controlled to reduce the harm of dust to people during operations.

(2) Through the design calculation and test of the critical devices and components, the size of the crawler chassis was designed to be 1780 mm long, 1650 mm wide, and 310 mm high to ensure the suitable trafficability of the pick-up machine in the garden. Through experiments, it is concluded that when the collection strip blowing head from the ground was 15 cm, the horizontal was 35°, the vertical angle was 15°, and the forward velocity was 1.5 km·h^{-1}, the pick-up cleanlily rate could reach 98.84%. The internal flow field of the separation and impurity removal box was simulated and analyzed to verify that the box structure design was more reasonable.

(3) The operation performance test of the pick-up machine shows that the overall performance is stable and the operation effect was satisfactory. It can meet the requirements of the mechanized harvesting operation of the landing jujube, and the performance index parameters meet the design requirements. The picking efficiency was 752.7.2 kg·h^{-1}, the pick-up cleanliness rate was 95.66%, the breakage rate was 2.68%, and the impurity rate was 3.64%.

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