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Mechanized technologies for scaffolding cultivation in the kiwifruit industry: A review

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ABSTRACT

The success of organic and green agricultural fruit production depends on quality and cost. As the kiwifruit industry becomes ever more commercialized, it is in the interests of the industry to mechanize production, which can promote industrialization and improve industrial value and market prospects. Currently, New Zealand, Italy, Chile, and China carry out research into the mechanism of kiwifruit production. This review describes in detail the current state of the art of pollination, harvesting and grading equipment, including detection and identification, non-destructive end effector, harvesting robots and grading devices. Process technologies that include artificial pollination, harvest mechanization, grading and standardization of production problems are analysed and compared. These problems directly affect the quality of kiwifruit products. Finally, to solve the various problems that the kiwifruit industry experiences, it is necessary to accelerate the development of mechanized kiwifruit production, realize the mechanization of information acquisition and standardization in order to advance precision agriculture and agricultural wisdom for the future. Mechanization of the kiwifruit industry must adapt to adjustments in how China's economic structure develops.

Contents

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1. Introduction

The current global production of kiwifruit (*Actinidia deliciosa*) stands at 4.3 million metric tons (tonnes), led by China with 56% of the total [1]. In order of production output, Italy, New Zealand, Chile, Greece, France, Turkey, Iran, Japan and the USA are the next highest producers. In recent years, China's kiwifruit industry has developed rapidly, and it has the largest cultivated area of kiwifruit [2]. Kiwifruit production has become a highly lucrative business with a considerable economic value [3].

The kiwifruit yield in China, however, is well below the world average and lags behind that of New Zealand and Chile in particular. While studies have recognized that China has the largest planted area of kiwifruit of any country, its development of mechanized harvesting lags well behind that of most other producers [4]. Along with the development of kiwifruit pollination, harvesting, grading, cultivation and management, a large number of other problems need to be resolved and the kiwifruit industry as a whole developed further.

The increasing mechanization of the kiwifruit industry is playing an important role in current agricultural practices, which has brought many benefits but has also created its own problems.

2. Mechanization of the kiwifruit

The various stages in the kiwifruit production process consist of planting, harvesting, grading, processing and main production. Base on the production plant scale and requirements imply steps of production difficulty by urgency and other factors [5]. The mechanization of kiwifruit production must consider, among other factors, the level of economic benefit that it might bring. The production process can be divided into the planting, harvesting and post-harvest stages, as shown in Fig. 1. The fruit industry as a whole has already developed a standard that includes a greater level of mechanization [6]. The mechanization of kiwifruit production would reduce labour, improve work efficiency and also reduce production costs.

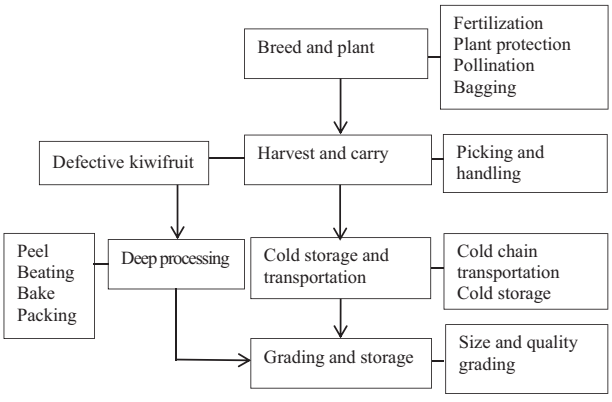


Fig. 1 – Processes in the kiwifruit industry.

2.1. World kiwifruit production

Both the total global cultivated area and the yield of kiwifruit continue to increase, while the quantity of labour engaged in its production is decreasing. In order to realize the maximum development of the kiwifruit industry, some key links in the production process need to be introduced by means of mechanization to improve work efficiency and promote industrial development. At present, the mechanization of the planting stage has basically been realized, but global efforts to solve the questions of pollination, picking, grading and other mechanical technical problems have so far failed completely. Several factors are to blame for this situation. First, as kiwifruit pollination uses the method of artificial pollination, it is difficult to achieve a high standard, which is directly related to the size and quality of kiwifruit. The provision of services for pollination has also now become a new orchard industry, thus the mechanization of kiwifruit pollination is gradually becoming more important. Second, the picking of kiwifruit uses artificial picking widely, which makes it an annual problem for the industry as extra labour is needed to harvest the crop. Finally, the grading classification of kiwifruit size and quality prior to sale determines the sale price.

2.2. Kiwifruit production in New Zealand

New Zealand's kiwifruit production is famous all over the world and uses a higher level of mechanization than in other countries [7]. The advantage that New Zealand has achieved in this field puts it at the head of the international kiwifruit industry, and it has achieved considerable scale, standardization and market share [8]. Possessing highly favourable conditions of soil, sunshine, rainfall and temperature, a comprehensive analysis of fruit planting combined with harvesting during the optimum harvesting season, kiwifruit production management there is more advanced than in any other country. Mechanical equipment used in the production process employs electric vehicles, tractors, refrigerated trucks for transporting, spraying and drilling, as well as other modern management concepts of orchard fertilization. Since 2010, several New Zealand universities have participated in studies of pollination and harvesting [4]. However, the

Table 1 – Mechanization of the kiwifruit industry in China.

Project period	Situation	Level of mechanization	Questions
Planting	Few realised	20%	Planting and protection machinery
Pollination	Artificial pollination	N/A	Artificial pollination
Harvesting	Artificial harvesting	N/A	Without harvesting machinery
Grading	Size grading	N/A	Without quality inspection grading

mechanization of pollination and picking has not yet been implemented.

2.3. *Kiwifruit production in China*

Kiwifruit production in China focuses on the use of cultivation machinery and equipment in orchards, which includes farming machinery, plant protection machinery, transport machinery, as well as machinery for irrigation and the spreading of fertilizer. In addition, farmers use artificial labour, to complete pollination and harvesting. In the sorting of kiwifruit, grading machinery can grade fruits for commercial processing post fruit picking. Studies are underway into the mechanical development of kiwifruit [9]. The state of mechanization in the Chinese kiwifruit production industry is given in Table 1.

At present, the development of mechanization in the kiwifruit industry is hindered by technical difficulties in harvesting, grading and pollination. It should be pointed out that current studies are focused on harvesting and grading of the mechanization. In essence, the kiwifruit industry in China should pay close attention to these key technologies and the theoretical studies that underpin them in order to promote standardization, mechanization and industrialization.

3. Status of research into the mechanization of kiwifruit production

The key technical problems are mechanical, mainly the lack of pollination, picking, grading and other automated equipment. It is essential that kiwifruit scientists participate in the mechanization process as soon as possible. At present, the mechanization of kiwifruit production is minimal–only a few kiwifruit enterprises have launched semi-automatic or manually operated auxiliary equipment, as shown in Table 2. However, laboratory studies into some of these technologies are underway.

3.1. *Status of research into the mechanization of pollination*

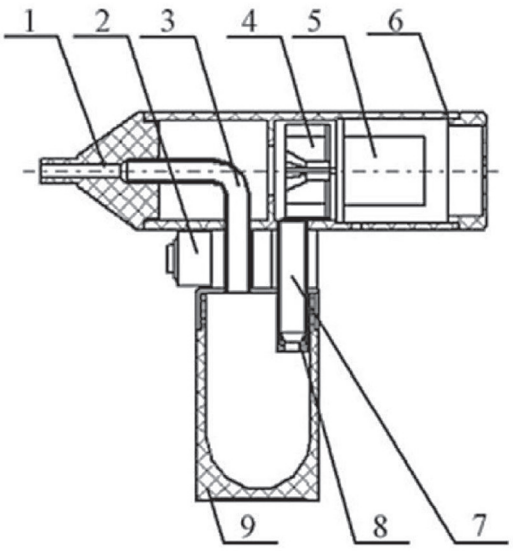
The mechanization of pollination is an important part of the overall mechanization of kiwifruit production. Mechanical pollination can improve the quality of pollination. Kiwifruit tree are dioecious plants, and therefore requires flower pollen to be collected and applied artificially over a wide area of cultivation [10]. This has become an indispensable part of kiwifruit production, and the high level of development of mechanization has achieved high standards of pollination for kiwifruit.

Producers in New Zealand, Japan and other countries use artificial pollination as the means to selectively pollinate kiwifruit flower in orchards [11]. Research into plant pollination for kiwifruit tree has led to flower identification technologies, and experiments have yielded good pollination results using sensors and advanced nozzle systems [12,13]. By using hydraulic spray and air dusting technologies for mechanical pollination, the air dusting technique has been widely applied using an improved pressure sprayer, saving considerable time when compared with artificial pollination [11].

The methods of mechanical pollination used in China include mainly hydraulic and pneumatic systems. Hydraulic pollination does not produce consistent results due to the uneven distribution of pollen particles in suspension. Wind causes pollen to speed from the nozzle and be evenly dispersed according to the orientation of the airflow, the stigma is pollinated directly at the nozzle, and the remainder of the pollen is dispersed as a suspension in the air. Natural wind drift influences how the pollen drifts down to the stigma of the pistil to complete the pollination process [14,15]. A handheld kiwifruit wind pollination machine consists of a powder box, nozzle, shell, centrifugal fan, motor, air duct, control buttons and other parts, as shown in Fig. 2. The main factors that influence the air-assisted pollination machine include nozzle diameter, motor voltage and shrink tube diameter.

Table 2 – Machine products of kiwifruit cultivation.

Equipment	Application	Company	Country
Conveyance truck and grading machine	Transport Classification	Zespri®	New Zealand
Packaging and conveyance	Storage	Origine	Italy
Grading on line machine	Classification	Qifeng Fruit	China
Pollination machine	Pollination	Sichuan Longmen	China

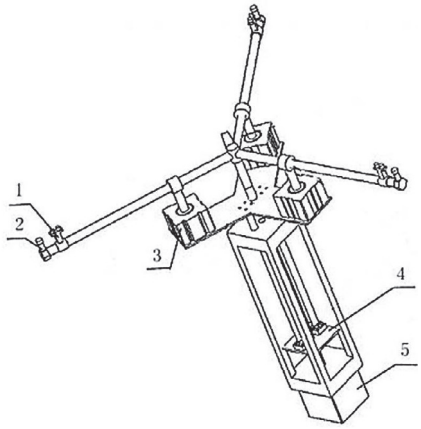


1. Jet tube; 2. Switch; 3. Pipe; 4. Centrifugal fan; 5. Motor; 6. Shell; 7. Air duct; 8. Shrinkage pipe; 9. Dust hopper

Fig. 2 – Handheld air-assisted pollination device.

Cui designed a pollination end effector [16], with a mechanism that includes arrive equipment and a spray injector [17]. The end effector prototype has an effective stroke of 200 mm, a tuning mechanism that allows a maximum adjustment of up to 60 mm and a uniformity of the end effector that can pollinate in orchards, as shown in Fig. 3. Patents related to nozzle spraying pollination of kiwifruit exclude precise regulation and dusting because of interference by natural wind conditions [17]. The pollination end effector can be adjusted to achieve full pollination [18,19]. However, these pollination machines that are covered by the patents generally perform with low efficiencies, but irrespective of the utilization rate of the pollinating tool [20].

In short, current pollination machines cannot realize automated pollination, and need to be manually operated. The spray device of the pollination machine uses a nozzle to control the flow of liquid, but the nozzle ruptures the liquid droplet, and the droplet is distributed over the surface of the female flowers during pollination. Currently, hand-operated pollination machines are needed to carry out artificial pollination, and there is a need to develop proper and reproducible spraying standards by developing intelligent control of the spraying parameters of these machines. In addition, obtaining accurate positioning of the pollinated flowers is the key to ensuring precise artificial pollination using pollen guns. This is important in kiwifruit research to determine the factors influencing the mechanism of pollination. Pollination equipment has an important role to play in the development of automatic pollination of dioecious kiwifruit vines and can improve the quality and the success rate of pollination.



1. Distance sensor; 2. Spray body; 3. Thin cylinder; 4. Adjustable gap slide block; 5. Closed institutions

Fig. 3 – Pollination end effector prototype.

3.2. *Status of research into the mechanization of harvesting*

At present, kiwifruit picking relies mainly on manual labour and is time-consuming work [4]. Research into the mechanization of kiwifruit harvesting began in recent decades. Scarfe invented an autonomous kiwifruit picking robot at Massey University in New Zealand [21]. The robot possessed a machine vision control system and a mobile vehicle, with four mechanical arms that could pick simultaneously. A prototype harvesting robot for kiwifruit orchards is shown in Fig. 4(a). Cui developed a kiwifruit harvesting robot at Northwest Agriculture and Forestry University, Shaanxi Province, China, which included an end effector, visual system, control system, mechanical arm and vehicle [22] . By means of machine vision, it could recognize the location of kiwifruit during the day, and during the night in an illuminated environment [23,24], and could recognize kiwifruit calyx clusters using a convolutional neural network [25]. The picking end effector was designed based on the results of research into non-destructive picking. The kiwifruit harvesting robot is shown operating in an orchard [26,27] in Fig. 4(b).

Chen invented an automated kiwifruit picking end effector [28], composed of a clamping device, cutting device, detection device and chassis shell, as shown in Fig. 5. Chen has recently invented an updated end effector, which comprises mechanical devices and a sensing system [29]. Cui has invented a new kiwifruit picking method whereby the picking robot platform can perform mechanical picking of kiwifruit using mechanical and control systems [30], as shown in Fig. 6. Cui also invented a picking manipulator that uses a sensor control system to send commands to the finger clip of the kiwifruit picking manipulator [31] and uses a multi-fruit automatic picking end effector to improve efficiency [32,33]. Yang invented a kiwifruit picking robot with a retractable arm array that improves on the efficiency of the single-arm picking robot giving a multi-arm machine that can operate efficiently [34,35]. Using a telescopic arm approach operating at different heights allows adjustment of the position of the kiwifruit picking machine.

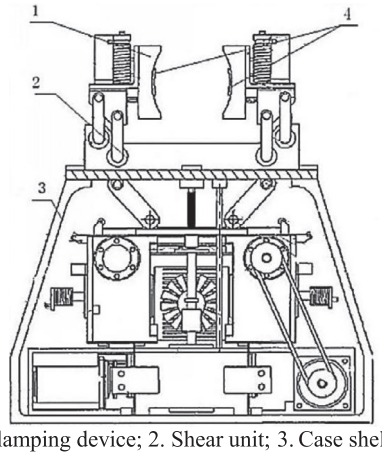
Based on the growth and physical characteristics of kiwifruit, using a picking robot is highly suited to the scaffolding cultivation of kiwifruit. The harvesting robot uses sensing information for kiwifruit identification, and the end effector and mobile vehicle perform a non-destructive pick. Moreover, in order to coordinate the approach of the manipulator, the

(a) Kiwifruit harvesting robot in New Zealand[4]

(b) Kiwifruit harvesting robot in China

1. End effector; 2. Machine vision; 3. Control box; 4. Vehicle; 5. Mechanical arm

Fig. 4 – Kiwifruit picking robot platform.



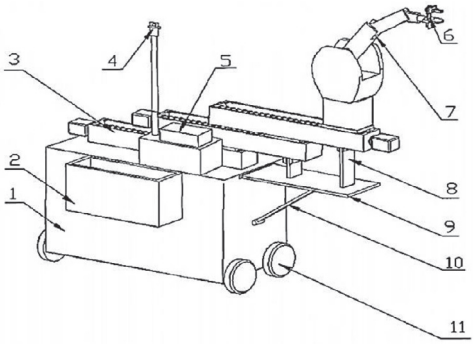
1. Clamping device; 2. Shear unit; 3. Case shell; 4. Detection device

Fig. 5 – Automatic kiwifruit picking end effector.

location of the target fruit depends on the quality of machine vision, the ability of the end effector to complete non-destructive picking and navigation of the vehicle to the next picking area [36,37]. However, these common problems experienced with harvesting robots mean that they are inefficient at present, system integration and the application of complex operation are both difficult, and there is a lack of generality in the study of picking robot multi-target recognition and multi-robot cooperative operation. The robustness of the identification and control algorithm of the latter can be improved by artificial intelligence, making the picking robot adaptive to complex environments. If the main technological problems can be solved, these machines will realize the full potential of automated kiwifruit harvesting.

3.3. *Status of research into the mechanization of grading*

The New Zealand 'Zespri' kiwifruit brand is the most typical example of the developed industry. This company exports 400,000 tonnes of high-quality kiwifruit to more than 60 countries and regions and has more than 30% of global exports of the Hayward variety kiwifruit [38]. The profitability per unit area and per unit weight of the kiwifruit yield is much higher in New Zealand than in other countries, the main reason being the fact that in New Zealand kiwifruit are graded for size and quality before sale. In Japan, research into fruit grading equipment is in an advanced state [39,40]. Equipment that employs machine vision detection systems can sort fruit



1. Vehicle; 2. Kiwifruit basket; 3. Sliding platform; 4. Camera; 5. Control computer; 6. End effector; 7. Manipulator; 8. Plate; 9. Platform; 10. Frame; 11. Wheel

Fig. 6 – Kiwifruit picking robot and picking method.

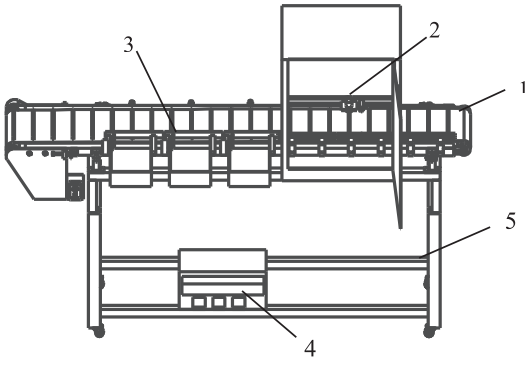
according to size and surface defects, and by means of this pipeline of sorting equipment, fruit can be packed according to customer demand before entering the supermarket.

Selection of quality-grade kiwifruit can improve the value of sales in China. Cui explored the automatic grading and surface defect detection of kiwifruit. His grading system was able to detect the size of kiwifruit using a small mobile grading system in the lab [41,42], as shown in Fig. 7. Fu carried out a comprehensive evaluation index and principal component analysis of kiwifruit cluster quality using a single camera in his kiwifruit grading method [26]. In addition, Guo used near-infrared hyperspectral imaging technology for detecting early latent damage in kiwifruit and near-infrared diffuse reflectance spectroscopy for recessive damage detection [43–45]. A hyperspectral non-destructive grading test has been proposed to determine the soluble solids content of kiwifruit to determine both internal and external injury to kiwifruit before separation [46].

Xu invented a kiwifruit grading device [47], consisting of a storage device, a one-way positioning and grading conveyance system, processing system, control system and grading system, which could act as a simple and convenient classification device for kiwifruit to improve classification accuracy and efficiency, as shown in Fig. 8. Fu contrived a kiwifruit grading device, including a feeding conveyor belt to grade and classify kiwifruit by means of separation [48]. Yang created the taper drum computer monitoring speed grading device [49], which has a mechanism that removes kiwifruit hair without extrusion or damage by a combination of centrifugal force and the workings of a soft brush.

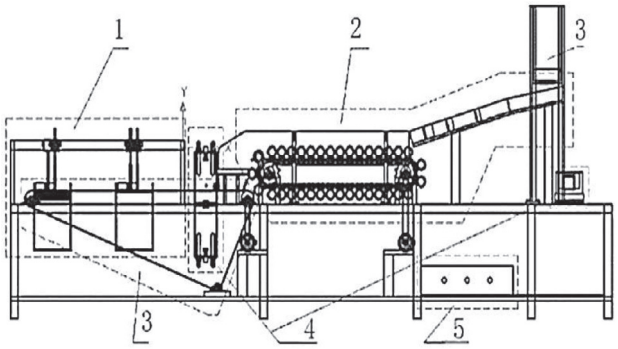
At present, kiwifruit grading devices cannot be fully automated and must resort to some level of manual operation. Research, both domestically and overseas, into fruit grading includes studies into fruit shape, size and detection of surface defects. Because of differences in shape, colour and other characteristics, grading equipment used for other kinds of fruit is unsuitable for detecting surface defects in kiwifruit. Interior damage detection and classification of acidity and soluble solids content are still at the research stage. Spectral imaging technology has made advancements in fruit detection, and the use of principal components analysis is increasing. This investment of research into the study of fruit quality should increase inspection standards, practical grading and the quality of testing equipment.

Finally, mechanization of the various processes used in the kiwifruit industry should also contribute to the advancement of research into machine learning and image processing. Data obtained from these technologies can provide accurate information about fruit growth and internal quality etc. and can provide the basis for technologies to manufacture intelligent



1. Transportation agency; 2. Appearance quality inspection agencies; 3. Separate actuator; 4. Control system; 5. Frame

Fig. 7 – Schematic of small portable kiwifruit online detection and classification system.



1. Kiwifruit; 2. Feeding conveyor belt; 3. Separation of conveyor belt; 4. Baffle; 5. Grade control

Fig. 8 – Kiwifruit grading device.

agricultural equipment. The realization of mechanization is the carrier of technological integration, which, combined with research and development into agricultural equipment, will improve the level of mechanization of kiwifruit production in China.

4. Analysis and discussion

Currently, there is some mechanized processing of the planting, pollination, harvesting, grading and storage stages in kiwifruit production. The attention of developing machnilization for kiwifruit insdustry is to decrease expenditure and win the advantages through efficient and low-cost field operations in kiwifruit and flower detection, automated pollination, harvesting and grading. From theses what has been discussed that the mechanisms and technologies used for kiwifruit harvesting in both the lab and in commercial orchards. In different aspect, related researches are concluded in Tables 3–5. The scientific paper has been extensively reviewed since these systems are crucial components determining whether or not a kiwifruit industry machine can successfully face its performance demands.

First and foremost, the kiwifruit technology is designed for lab use, such as image processing, manipulation, end effector controls, vehicle motion guidance and control [24]. Mechanized kiwifruit production equipment in fields needs to be able to sense its environment and avoid collisions with tree root ridges, the canopy column and other structures of

Table 3 – Kiwifruit pollination machines.

Reference	Detection accuracies and hardware	Computer and communication	Control system
Naik and Rana [12]	89.63%; Spray pollination device		
Ding et al. [14]	57.66%; Handheld wind pollinator		
Ding et al. [15]	67.11%; Handheld wind pollinator		
Guo [16]	19.99% (coverage on water-sensitive test paper); Robot spray pollination end effector		Microcontrollers: STC89C52RC single control

Table 4 – Kiwifruit harvesting machines.

Reference	Detection accuracies and hardware	Computer and communication	Control system
Scarfe et al. and Scarfe [4,21]	83.56% ; Detection 2HID camera, 3.6 mm, 3-D detection; Navigation LiDAR	PC	PC Sobel
Zhan et al. [50]	96.70%; 1 camera	PC	PC Adaboost HSI, L * a * b
Cui et al. [23]	89.10%; 1 CCD camera	PC	PC, 0.9 * R-G, Hough
Fu et al. [1]	88.30%; 1 CCD camera	PC	PC
Fu et al. [3]	96.00%; End effector	51 single control	51 single control
Li et al. [51]	Cartesian coordinates	PC and PLC	PC
Wang et al. [52]	Kinect sensor, Error: 2 mm, 0.5 s	PC and Kinect sensor	PC
Fu et al. [1]	94.30%; 1 CCD camera	PC	PC HSV
Mu et al. [22]	90.00%; Kinect sensor	51 single control	PC 51 single control
Fu et al. [27]	94.30%; 1 CCD camera	PC	PC Hough
Fu et al. [25]	89.29%; 1 CCD camera	PC	PC CNN

Table 5 – Kiwifruit grading machines.

Reference	Detection accuracies and hardware	Computer and communication	Control system
Cui et al. [53]	1 CCD camera and Fujinon HF16HA-1B camera	PC	
Scarfe [4]	98%; 1 camera	PC	PC
Fu et al. [26]	98.30%; 1 CCD camera	PC	
Qu et al. [54]	96.30%; 1 CCD camera	PC	PC

growing kiwifruit in a typical scaffolding canopy [4]. The scientific equipment and associated algorithms installed in a kiwifruit machine are crucial for the successful recognition of kiwifruit. The majority of components in scientific equipment consists of CCD or sensors, and many complex image processing algorithms cannot abtain dependable, real-time performance at the natural environment.

Second, it is important that artificial intelligence and machine vision strengthen research into the mechanization of kiwifruit production. Then, studies should help to strengthen research into machine learning and image processing, which can accurately detect the position and internal quality of kiwifruit growth. To produce fruits in high yields as the breakthrough point, combining advanced practical and economic methods will develop conditions that are suitable for conditions in which agricultural equipment must operate in China. Ensuring food security and sustainable production of agricultural fruit to high standards is very important for the future. The development of mechanized 'precision agriculture' is necessary to realize the production and application of agricultural machinery. The development model of the agricultural industrial chain in China will also need to be further studied, to adapt to changes in the structure of the agriculture industry.

Third, the production of electric machinery used in kiwifruit vine cultivation can improve the efficiency of the industry and reduce environmental pollution. The advantages of electric machinery include energy-saving and environmental protection, but the disadvantages include short battery life, reduced power and reduced torque. In the future, to solve the problem of variable control strategy driven by electric motors, the operating time of agricultural machinery must be restricted, at different temperatures in different environments for the evaluation of consumption, the effective operation of the battery with the length of time of detection and feedback.

In China, the 'No. 1 document' of the central government has pointed out that the development of intelligent agricultural equipment is essential. Automatic adjustment, according to changes in job requirements, is controlled by artificial intelligence, and intelligent agricultural machinery will complete different production operations. According to factors in the cultivated environment, the sensors have been equipped with a wide variety of intelligent agricultural machinery for monitoring the operating environment and automatically adjusting the working conditions to ensure the safety and reliability of agricultural machinery and equipment. Automatic control and computer vision algorithms for intelligent agricultural equipment using mature methods in the field of artificial intelligence, combined with detection and internet technology applied to 'big data' in the process of kiwifruit pollination, will lead to improvements in the stability and robustness of harvesting and grading equipment and reduce operating costs.

5. Conclusions

The development of mechanization in kiwifruit production reflects the development level of agricultural engineering in China, despite the gap in the popularization rate of agricultural machinery compared with developed countries, and progress in the development of agricultural equipment will eventually catch up with that of other countries. The following aspects need to be researched further: (1) the facility of pollination, harvesting and grading processes in kiwifruit production facility can basically realize the mechanization, and scientific research institutes should increase their research funding in this field; (2) the development of agricultural robots needs to focus on agronomic production to enable the production of high-yield fruit suitable by advanced, practical and economic agricultural equipment; (3) the promotion of mechanization as the basis for the development of precision agriculture.

Agricultural engineers and researchers should pay close attention to the combination of multiple methods of cooperation with enterprises in the implementation of agricultural equipment products. Studies of the way in which agricultural products are developed should stress the importance of adjusting the industrial structure to adapt to agriculture in China.

Conflict of interest

The authors declare no competing financial interests.

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