Review of the detasseling techniques for maize (*Zea mays* L.) hybrid seed production

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Abstract: Maize (*Zea mays* L.) is a critical staple crop globally, integral to human consumption, food security, and agricultural product stability. The quality and purity of maize seeds, essential for hybrid seed production, are contingent upon effective detasseling. This study investigates the evolution of detasseling technologies and their application in Chinese maize hybrid seed production, with a comparative analysis against the United States. A comprehensive examination of the development and utilization of detasseling technology in Chinese maize hybrid seed production was undertaken, with a specific focus on key milestones. Data from the United States were included for comparative purposes. The analysis encompassed various detasseling methods, including manual, semi-mechanized, and cytoplasmic male sterility, as well as more recent innovations such as detasseling machines, and the emerging field of intelligent detasseling driven by unmanned aerial vehicles (UAVs), computer vision, and mechanical arms. Mechanized detasseling methods were predominantly employed by America. Despite the challenges of inflexible and occasionally overlooked, applying detasseling machines is efficient and reliable. At present, China's detasseling operations in hybrid maize seed production are mainly carried out by manual work, which is labor-intensive and inefficient. In order to address this issue, China is dedicated to developing intelligent detasseling technology. This study emphasizes the critical role of detasseling in hybrid maize seed production. The United States has embraced mechanized detasseling. The application and development of manual and mechanized detasseling were applied later than those in the United States, but latest intelligent detasseling technologies first appeared in China. Intelligent detasseling is expected to be the future direction, ensuring the quality and efficiency of hybrid maize seed production, with implications for global food security.

Keywords: detasseling technique, detasseling machine, UAVs, intelligent agriculture, maize hybrid seed production
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1 Introduction

Maize (*Zea mays* L.) is one of the most important food crops in the world[1]. Hybrid seed production in crops is based on the principle that dominant genes express favorable traits, whereas recessive genes express unfavorable traits, thus utilizing heterosis to combine the desirable characteristics of parents and improve crop quality, yield, and resistance[2,3]. As a typical allogamous crop, maize exhibits inbreeding depression and heterosis, making it to be one of the most successful crops for treating heterosis. In China, hybrid maize accounts for approximately 98% of the total maize-planting area[4]. However, hybrid maize seeds can only be planted in one generation because the manifestation of heterosis diminishes after the second generation. Consequently, annual maize seed production has become crucial.

The four major indicators for measuring the quality of seeds obtained from hybrid seed production are bud rate, moisture, cleanliness, and purity, among which purity is themost crucial[5]. Detasselling is the most critical and challenging step in maize seed production. During hybrid seed production, several rows of female parents were planted alternately with one row of male parents. The tassels of the female parents must be detasselled before pollening or silking to ensure that they only receive pollen from the male parent's tassel, resulting in hybrid seeds. The timely removal of tassels is crucial for maintaining seed purity. Successful detasseling ensures purity, enhances lodging resistance, reduces nutrient consumption, improves ventilation and light transmission conditions, and decreases the probability of pests and diseases.

Because the agronomic technical requirements for maize detasseling are very strict, the detasseling operation period is limited to only 7-10 d. The detasselling process must be executed with utmost precision and thoroughness. Failure to perform timely and accurate detasselling during field seed production can result in a

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high rate of self-pollination, which significantly restricts the purity of maize seeds. Manual detasselling has traditionally been the predominant method since the beginning of maize hybrid seed production in China. However, this manual approach is time-consuming, inefficient, and labor-intensive, with unsatisfactory results. With the advancement of agricultural mechanization and automation, detasseling machines that can accurately and efficiently remove tassels have emerged. Mechanized detasseling offers clear advantages, such as high efficiency, strong mobility, and less dependence on natural conditions[6,7]. Manual detasseling is inevitably replaced by mechanized detasseling.

The evolution of maize detasseling technology has progressed through various stages, starting with artificial detasseling and transitioning towards semi-mechanized detasseling, cytoplasmic male sterility, and ultimately mechanized detasseling. With the rapid development of artificial intelligence and unmanned aerial vehicle (UAV) technology, Chinese researchers have begun to explore intelligent detasseling methods that utilize UAVs and artificial intelligence. This study aims to review the development and key technologies of maize detasseling in the maize seed production industry while comparing its application process with that of the United States, focusing on key points from the perspective of China.

2 Semi-mechanized detasseling and cytoplasmic male sterility

With the global promotion of agricultural mechanization and automation, the maize industry has witnessed the emergence of semi-mechanized detasseling and the utilization of cytoplasmic male sterility (CMS) to address the agronomic requirements of detasseling. Advancements have aimed to improve the low efficiency and labor-intensive nature of manual detasseling.

2.1 Semi-mechanized detasseling

The semi-mechanized detasseling method was first introduced by the United States, which involved the invention of a three-wheeled self-propelled machine with a high clearance. The machine was equipped with six person-carrying frames on its chassis, allowing workers to stand on the frames for manual detasseling operations[8]. The transmission system of this model consisted of a belt, drive chain, and three traveling wheels that enable slow movement across the field. Compared with manual detasseling method, the semi-mechanized approach reduces the reliance on human labor and thereby improves operational efficiency.

The Second generation of the semi-mechanized detasseling machine was upgraded in the United States[8]. This version featured a diesel engine as the power system. The walking system was transformed into a four-wheel system to provide improved stability during operation. Additionally, a sunshade canopy has been added. Compared to the first generation, the second-generation detasseling machine exhibits improved stability during operation and higher detasseling efficiency.

When semi-mechanized detasseling machines emerged in the United States, China was in the phase of maize hybrid breeding and application. The operation of removing maize tassels in China primarily relied on manual detasseling during this period.

Semi-mechanized detasseling is an initial attempt to incorporate machinery into maize detasseling operations, which combines human labor and machine power, resulting in higher efficiency compared with the manual detasseling method. Despite this not completely replacing manual labor, it lays the foundation for the subsequent development fully mechanized detasseling methods.

2.2 Cytoplasmic male sterility method

Cytoplasmic male sterility (CMS) is a sterility regulated by the interplay between nuclear and cytoplasmic sterile genes. Its distinctive feature includes the ability to establish a coordinated system involving sterile, maintainer, and restorer lines, thus harnessing heterosis in hybrid production through the three-line method. By incorporating CMS into crossbreeding programs, the need for manual detasseling can be circumvented, resulting in reduced labor and resources. Simultaneously, this approach ensures the purity of the hybrid seeds and enhances crop yield[9].

Maize was one of the earliest crops to utilize male sterility characteristics to prevent self-pollination. The emergence of the first maize male-sterile hybrid in 1950 prompted studies of cytoplasmic male sterility in maize. By 1970, approximately 85% of the national maize planting area in the United States was occupied by hybrid varieties that utilized sterile cytoplasmic male lines. There are three major types of maize CMS based on their responses to specific restorers: CMS-T, CMS-S, and CMS-C. During this time, most sterile lines used were CMS-T, which refers to T-type cytoplasmic male sterile lines. However, the invasion of T-type cytoplasm by the bipolaris maydis T race resulted in a devastating outbreak of maize bipolaris maydis T race, leading to significant losses in maize production[10]. Since 1970, breeding experts in various countries have selected new sterile lines, and China is one of the countries that conducted early studies on the breeding of new male sterile lines.

Despite with the efforts of breeding experts to develop new types of sterile seeds, identifying robust restorers and effective maintainers of sterile lines remains time-consuming and requires significant financial resources. Consequently, the application of CMS is challenging. For maize seed production, the physical removal of tassels is still crucial.

3 Development of key technologies for mechanized detasseling

Mechanized detasseling technology and detasseling agricultural machinery, capable of essentially replacing manual detasseling, have been developed in the United States and China. The key technologies involved in mechanized detasseling primarily focus on cutting and extracting the key components of detasseling, a parallel four-bar profiling control system, and a maize plant height detection system that utilizes a photoelectric sensor to sense plant height.

3.1 Key components for detasseling

Various devices, such as rotary horizontal blades, sickle mowers, and shredding apparatus have been used to remove maize tassels. However, these devices damage maize plants, harming the top leaves enveloping the tassels that are indispensable for plants' growth and development.

Therefore, mechanical devices suitable for maize detasseling during the seed production process have been invented. At present, two main types of detasseling are utilized at the detasseling end of typical machines: cutting and extraction. The cutting-type detasseling end uses a knife to rotate or reciprocate to remove the tassels. The extraction-type detasseling end clamps the tassels and separates them from the plant through the rotation of the roller.

3.1.1 Cutting type detasseling device in the United States

A detasseling device employing clamping and cutting composed of a fixed blade, clamping wheel, frame, hydraulic motor, tension spring, flexible transmission shaft, divider, transmission chain, and grain guide plate is shown in Figure 1. During the detasselling operation, the clamping wheel rotates to generate frictional contact. The straw dividers converge the maize towards the center, guiding it into the frictional zone of the clamping wheels, where the maize tassels and their associated stems and leaves are cut off[11].

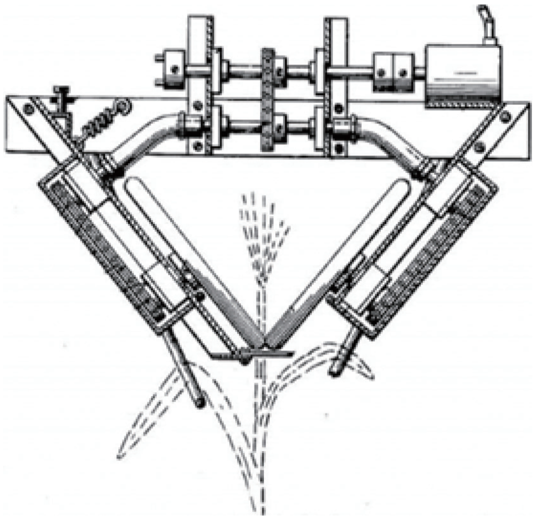

Figure 1 Clamping cutting detasseling mechanism[11]

An air-assisted maize detasselling device comprises a frame, transmission shaft, paddle wheel, vertical plate, divider, conduit with nozzles, and a bow-shaped cushion plate, as shown in Figure 2. During operation, the drive shaft drives the paddle wheel to rotate and generate airflow, which is sprayed from the nozzle along the conduit to spread the top blades. After leaving the airflow area, the vertical plate maintained the plant in the above state. Moreover, this device can effectively reduce the damage to maize top leaves by separating the tassels and top leaves[12].

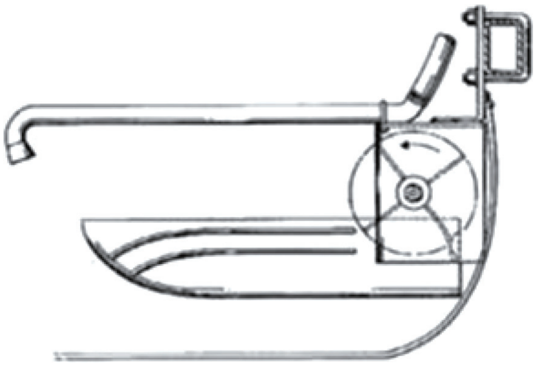

Figure 2 Air-assisted maize detasseling device[12]

Figure 3 shows a physical image of the cutting-type detasseling device attached to the 204SP detasseling machine[13].

3.1.2 Extraction type detasseling device in the United States

A belt-extraction-type detasseling device is shown in Figure 4. The device consists of a frame, hydraulic motor, elastic belt, grain divider, blade-pressing roller, and pressing wheel. During operation, the hydraulic motor drives the blade-pressing roller and elastic belt to rotate, and the grain divider gathers the maize plants in the middle. The tassels were separated from the leaves by using a blade-pressing roller. Moreover, they enter the clamping area composed of two elastic belts, and the two blade-pressing rollers are conical and rotate downward relatively; the two elastic belts rotate in reverse, with a low front end and a high rear end. The tassels were pulled out, thrown on the ground, or recycled[14].

Figure 3 Cutting type detasseling device of 204SP detasseling machine[15]

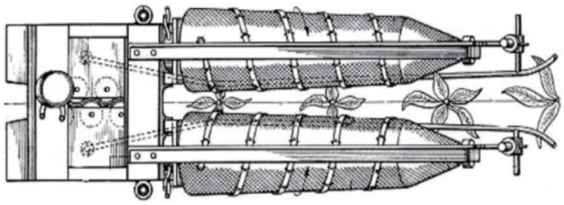

Figure 4 Belt-extraction type detasseling device[14]

An inflatable-tire-extraction type detasseling device, comprises a grain divider, driven shaft, hydraulic motor, frame, roller, driving shaft, and fixed frame, as shown in Figure 5. The driving shaft is parallel to the driven shaft and inclined toward the lower rear of the fixed frame, with two rollers installed at the end of the shaft. The plane formed by the two axes is inclined outward and downward relative to the frame[16].

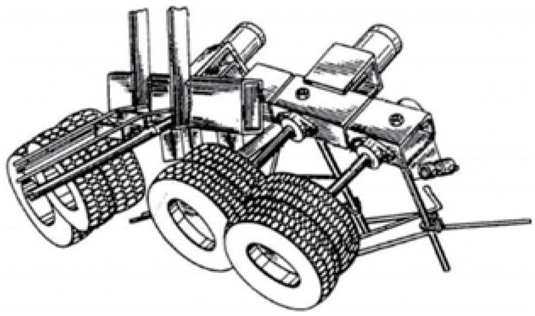

Figure 5 Inflatable-tire-extraction type detasseling device[16]

During the operation, the grain divider gathers the plants towards the center and enters the contact area formed by the roller, which drives the tassels to separate from the plants and throws them between the rows. The design of the roller space was conducive for throwing the extracted maize tassels backward.

Figure 6 shows the extraction-type detasseling mechanism

Figure 6 Extraction type detasseling device of 204SP detasseling machine[15]

attached to the 204SP detasseling machine(Manufacturer, city, country)[15].

3.1.3 Cutting type detasseling device in China

A self-propelled and leap-type maize detasseling machine with replaceable detasseling ends has been designed according to the actual seed production environment and detasseling agronomic requirements in Xinjiang. It can be equipped with both cutting and extraction type detasseling ends[17].

The cutting type detasseling end comprises a hydraulic motor, knife frame, cutter, cross beam, guard plate, and tassel guide rod. The double-sided blades installed on the knife frame have an acute angle that could cut tough tassels in a sliding manner without bending them.

During operation, the tassel guide rod gathers the tassels far away from the middle, reducing the damage to the maize leaves with the cooperation of the guard plate and ensuring efficient and high-quality removal of maize tassels.

A 3QXZ-8 self-propelled leap-type maize detasselling machine driven by a hydraulic motor has been designed[18]. The cutting-type detasseling device with circular knives was improved on the device designed by Lu.

The device consists of a: 1. Shift lever, 2. Cutter head, 3. Blade, 4. Shield, 5. Hydraulic motor, 6. Connecting rod. The cutting-line spacing could be adjusted by changing the position of the cutter head fixed to the connecting rod. Three double-sided blades with sharp angles are distributed evenly on the cutter head. Compared to the detasseling machine designed in[17], it has enhanced mobility and higher operational efficiency.

3.1.4 Extraction type detasseling device in China

The extraction type detasseling device adopts the clamping extraction principle and comprises: 1. Tassel extraction wheel, and 2. Tassel guide rod, 3. Cross beam, 4. Suspension arm, 5. Guard plate, 6. Fixed plate, 7. Hydraulic motor[17].

During operation, the tassel guide rod gathers the tassels from both sides of the row towards the center and forcibly extracts the tassels under the pressure of the wheels. However, owing to the high speed and the abundance of leaves, there is a risk of leaf damage. To address this issue, a leaf guard plate was designed to reduce the mechanical damage to the leaves.

The extraction-type tassel-removal component of 3QXZ-8 self-propelled leap-type maize detasselling machine is composed of: 1. Driving wheel 2. Driven wheel 3. Support seat 4. Connecting rod 5. Hydraulic motor 6. Shift lever[18].

During operation, the driving wheel shaft rotates in the direction of the arrow in the figure under the power of the hydraulic motor, and the driven wheel rotates with the driving wheel under the action of friction caused by the close-contact rollers. When the maize tassels are in contact with the roller, they are squeezed and pulled out by the wheel.

Differing from the wheel-based extraction-type detasseling devices mentioned before that remove maize tassels by rotating the roller, a flexible disk-extraction-type detasseling device was designed. The device is composed of: 1. Grain divider 2. Expansion roller 3. Flexible disc 4. Drive motor 5. Compression Spring 6. Compression roller 7. Installation frame[19].

A photograph of the extraction-type tassel-removal component attached to the 3XZG-8YA self-propelled maize detasseling machine (Chinese Academy of Agricultural Mechanization Science Group Co., Ltd., China) was designed. Experimental validation has confirmed that the optimal detasseling mechanism inclination angle falls within the range of 27°-30°. When using a tire tread pattern resembling a gemstone pattern, the highest detasseling rate and the minimum leaf loss rate can be achieved[20].

Extraction-type detasseling devices, which can pull out the tassels once, are mainly used to detect varieties with long tassels during seed production. During the operation of the flexible disc extraction-type detasseling device, the rubber joint twists, deforms, and age affect the detasseling quality. Cutting-type detasselling devices are suitable for use with various short tassels. Despite working reliably, it will cut other leaves, allowing the tassels to grow again; thus, it must be cut again[21]. There are advantages and disadvantages using the cutting- and extraction-type detasseling devices. Different detasseling devices must be selected to adapt to the actual maize-planting situation in the field.

3.2 Profiling mechanism

The height of maize plants can vary owing to factors such as seed quality and growth environment. When using a detaseling machine, maintaining a specific range of relative positions between the detasseling apparatus and maize plants is crucial to achieve optimal detasseling results. Therefore, the height of the detasseling device must be adjusted according to the height of the plant to ensure that it is positioned correctly. In addition, it is crucial to maintain a constant inclination angle of the extractor because this contributes to a higher detasseling rate and reduces leaf loss.

Currently, the mechanical profiling control mechanism of the detasseling components in typical detasseling machines adopts a parallel four-bar structure, as shown in Figure 7[22-24].

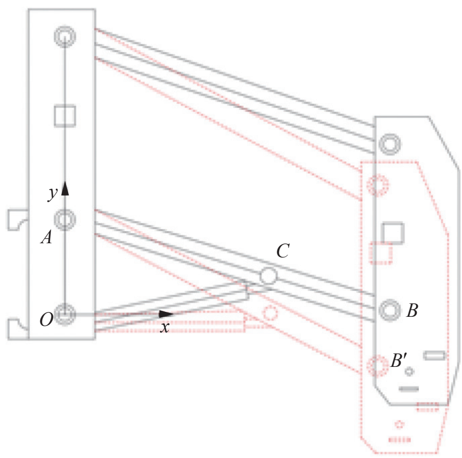

Figure 7 Four-bar linkage mechanism

To establish a rectangular coordinate system XOY, take the hinge point O between the hydraulic cylinder and the frame as the coordinate origin and the horizontal and vertical directions as axes x, y, respectively. The y-axis represents the fixed side of the parallel four-bar structure and the movement of point B along the y-direction, y represents the movement of the detasseling ends along the y-direction.

From the kinematic relationship of the mechanism, we can get formula:

$$Y_B = L_{OA} - L_{AB}\frac{L_{OA}^2 + L_{AC}^2 - L_{OC}^2}{2L_{OA}L_{AC}} \tag{1}$$

where, Y_B is the ordinate of point B, mm, L_{OA} is the length between OA, mm, L_{AB} is the length between AB, mm, L_{AC} is the length between AC, mm, and L_{OC} is the length of OC, which is the total length of hydraulic cylinder, mm.

When the point B moves continuously to B', the ordinate of the point B' is

$$Y_{B'} = L_{OA} - L_{AB}\frac{L_{OA}^2 + L_{AC}^2 - (L_{OC}^2 + s)^2}{2L_{OA}L_{AC}} \tag{2}$$

$$s = vt \tag{3}$$

where, s is the expansion and contraction quantity of the oil cylinder; the expansion is positive, and the contraction is negative, mm; v is the movement speed of the oil cylinder, mm/s; t is the adjusted execution time, s.

The vertical displacement of the point B is

$$Y_{B'} - Y_B = L_{AB}\frac{2L_{OC}^2 vt + v^2t^2}{2L_{OA}L_{AC}} \tag{4}$$

From Equations (2) and (4), the adjustment amount of the detasseling component in the vertical direction is affected by the current value of L_{OC}, cylinder motion speed v, adjusted execution time t and cylinder motion state.

The profiling control mechanism cooperates with the height recognition device of the photoelectric sensor to adjust the height of the detasseling ends and achieve an accurate detasseling operation.

3.3 Plant height recognition technology

In the maize detasseling process, it is crucial to detect the height of plants to ensure that the detasseling ends are in optimal working positions. However, during detasseling operations, tassels are often concealed by leaves; thus, the height of the tassels and their associated stems and leaves must be identified. This section focuses on the height recognition technology used in typical detasseling machines.

A contact-based height detection system for detasseling machines was invented, comprising a sensing rod, swinging arm, frame, and microswitch. During the operation, if the plant height is appropriate, the swinging arm will not contact the microswitch[25]. If the plant is too short, the swinging arm will rotate downward and trigger the microswitch on the right, causing the detasseling mechanism to move downward. Similarly, when the plants are too tall, the pivot arm will also rotate upward, triggering the microswitch on the left side, and causing the detasseling mechanism to move upward. The TS2 detasseling machine (Oxbo, USA) is equipped with retroreflective photoelectric sensors. In this device, each set of detection units has two pairs of retroreflective photoelectric sensors- one above and one below. Each sensor pair emits a beam of light between its emitter and receiver. When the beam of light is obstructed, the receiver does not receive the light signal, and the maize plant is detected. The 204SP detasselling machine is equipped with a reflective height detection device[15]. Each group of this device consists of two sets of reflective high-intensity LED sensors installed at the upper and lower ends of a fixed frame. The emitter of the sensor emits a beam of light that reflects off a reflective plate and returns to the receiver. When the male ears obstruct the light beam, the receiver does not receive the light, and this way, the presence of the male ears is detected.

The '3QXZ-6 seed corn detasseling machine' (Chinese Academy of Agricultural Mechanization Science Group Co., LTD, China)[22] is equipped with a pair of vertically placed 42FRU-9200TTL (NPN-type) photoelectric sensors. The height of maize tassels is determined by the switch signals generated when the plant obstructs these sensors. The height detection system of the '3XZG-8YA self-propelled corn emasculation machine'[21] uses reflective photoelectric sensors, consisting of upper and lower detectors.

The height recognition technologies used on detasseling machines at present primarily adopt the detection mechanisms based on photoelectric sensors. These devices determine the relative height of the plant through the occlusion of the maize plant to the light while the profiling mechanism cooperates for subsequent adjustment.

3.4 Typical maize detasseling agricultural machines and their development

3.4.1 Maize detasseling machine in America

The 204SP detasselling machine[15] shown in Figure 8 is a specialized maize detasseling machine. The entire machine adopts four-wheel hydraulic drive, with a chassis ground clearance of 1930 mm and an adjustable row spacing range of 214.6-304.8 cm, and can be equipped with cutting-type and extraction-type detasseling devices. The Oxbo TS2 Detasseler (Oxbo, USA)[6] is designed to perform the tasks of cutting and pulling more accurately. It can be equipped with either cutting-type or extraction-type detasseling components, all of which are hydraulically driven. PDF752D (Big John, USA)[26] is a multifunctional machine for detasseling and pesticide application in maize. It can be employed for both complete detasseling operations and pest control spraying in maize fields. The ground clearance of the chassis is 1850 mm, and the wheelbase adjustment range is 200-260 mm. It can be equipped with an extraction-type detasseling component, allowing for detasseling operations in 12 rows. In addition to the United States, France also possesses a mature detasseling machine, the BD864[6], as shown in Figure 9. The entire machine utilizes hydraulic transmission technology, with a chassis ground clearance of 2100 mm and a wheelbase adjustment range of 200-300 cm. It can be equipped with cutting-type or extraction-type detasseling components, supporting a maximum of 9 rows for detasseling operations. The machine is equipped with a corn plant height detection and shape-mimicking control system, along with a visual operating terminal.

Figure 8 204SP detasseling machine[15]

Figure 9 BD864 detasseling machine[6,27]

3.4.2 Maize detasseling machines in China

China has previously imported detasseling machines from the

United States, such as the 4WD 2204 TURBO, PDF752, and 204SP. However, these machines require even maize growth and are expensive with inconvenient maintenance, making them less favorable for farmers to purchase and widely adopt. To address this issue, China has independently designed detasseling machines that are suitable for China's maize-planting mode and environment.

OK104-3CX self-propelled maize-detasseling machine (Jiuquan Aoke seed machinery Co., LTD, China) is a dedicated maize-detasseling machine with eight sets of detasseling ends, as shown in Figure 10[28]. The entire machine adopted hydraulic transmission technology, and the arrangement of the detasseling ends is similar to that of PDF752D. 3QXZ-6 seed maize detasseling machine[22] was designed to improve the mechanical level. The equipment comprised a profiling mechanism, hydraulic driving system, and plant-profiling controlled system. The profiling mechanism was configured in the form of a parallelogram. The roller was powered by the load-sensing hydraulic system, and the adjustment of height was controlled by a cylinder driven through a proportional control hydraulic system. '3QXZ-8 self-propelled and leap-type corn emasculation machine'[18] is powered by a hydraulic motor that enables it to traverse the cornfield. Additionally, it can adjust the position of the emasculation device based on the row spacing and the growth height of the plants. Depending on the growth characteristics of the female parent and the requirement for removal, it have the option to use either Circular knives detasseling equipment or Roller detasseling equipment. The conducted tests indicate a 90% success rate, with 4% experiencing leakage and 6% being damaged. 3XZG-8YA self-propelled maize detasseling machine[21] have a smooth operation process, and the detasseling effect meets the requirements of industry standards.

Figure 10 OK104-3CX detasseling machine[29]

The aforementioned Chinese, American, and French maize detasseling machines, along with their specific applications and technical indicators, are summarized in Table 1.

Table 1 Typical maize detasseling machines and their parameters

Model	Row spacing/ cm	Plant spacing/ cm	Chassis ground clearance/ mm	Wheel tread/ mm	Detasseling lines	Detasseling height/ cm
OK104-3CX	--	--	1930	1900-2300	8	--
3QXZ-6	60	20	--	--	6	--
3QXZ-8	40-80	--	--	--	8	160-250
3XZG-8YA	30-70	--	1850	2600-3300	8	--
204SP	51-76	--	1930	215-305	18	0-1676
Oxbo TS2	51-76	--	--	--	20	--
PDF752D	40-90	--	1850	200-260	8	--
BD864	--	--	2100	200-300	9	--

After mechanical detasselling, rechecking it manually and promptly was crucial. Furthermore, a working face was generated in the field[30]. If there are tassels, they are easy to find, and the difficulty of manual rechecking is significantly reduced.

4 Development and application of key technologies and equipment for intelligent detasseling

Certain issues and inadequacies remain in the maize seed production process, whether it involves manual or ground-mechanized detasseling. Manual detasselling is time-consuming, laborious, and inefficient. The operational effects of mechanized detasseling are affected by terrain, planting density, and other factors, leading to omission detasseling, incorrect detasseling, and a low success rate of mechanized detasseling.

With the continuous promotion of modern agriculture and the rapid development of computer vision, UAVs, mechanical arms, and other technologies, artificial intelligence technology can be considered for use in the field of tassel identification and unmanned precision detasseling in the future.

Figure 11 shows a prototype of the detasseling UAV. The equipment is based on a four-rotor UAV equipped with a lightweight tassel-removal component and a visual camera.

Figure 11 Detasseling UAV

This section describes the key technologies involved in unmanned precision intelligent detasseling, including tassel identification, path planning, robot arm design and control, and collection of tassels after their removal.

4.1 Maize tassel detection for detasseling

UAVs can cover a variety of areas in a short time and obtain image information through various sensors, such as RGB (Red, Green, Blue), multispectral, and hyperspectral cameras, which is crucial for the development of intelligent agriculture to take advantage of image recognition technology that can extract key crop information and identify and locate crops from UAV remote sensing images. Image-recognition technology has many applications in agriculture. For example, it is used for wheat sun[31,32], cotton[33-35], and maize pest identification[36] to prevent infestations in advance, and it is also used for accurate harvesting of strawberries[37], kiwis[38], and other fruits. Furthermore, it assists in identifying and grading peanuts[39], mushrooms[40] and other crops automatically. Additionally, it enables monitoring the developmental stages of wheat[41] and rice[42,43]. Currently, there are many studies on the application of machine learning algorithms to identify maize tassels worldwide.

Computer vision technology and support vector machine methods were utilized to detect and locate the cutting positions of maize tassels[44]. Using shape and texture features, the hierarchical clustering method was used to fuse multiple detections of the same tassel; the correct detection rate of this method was 81.6%, which proved the feasibility of using regular color images to detect maize cuttings. Tang et al.[45] proposed a maize tassel recognition and location method based on binocular stereo vision technology. They used a binocular camera to collect maize tassel images on the left and right sides, converted them to the HIS (Hue, Saturation, Intensity) color space to preprocess the image of maize tassel rows, and segmented the images of tassels based on the segmentation algorithm of regional growth and a certain threshold to obtain the three-dimensional spatial coordinates of maize tassels. In 2015, Lu et al.[46] proposed an automatic fine-grain machine vision system named mTASSEL, which combines multiple feature views and different conduction views to reduce the impact of environmental changes on maize tassels and built a relatively large-scale maize tassel dataset. Furthermore, the proposed model was 26% better than the other models.

A maize Tassel Counting model based on a depth convolution neural network named TasselNet was proposed, which created the maize tassel counting dataset (MTC) and verified that the performance of TasselNet is far superior to other algorithms on the MTC dataset[47]. Liu et al.[48] compared the performance of Faster R-CNN with ResNet and VGGNet as backbones using images from UAVs, mobile phones, and MTC. Moreover, ResNet, as a feature extraction network, was better at identifying maize tassels. Zhou et al.[49] created a Maize Tassel Detection Counting dataset (MTDC) by supplementing bounding box annotations with MTC. Therefore, he proposed an evaluation criterion for maize tassel detection methods based on target detection and regression counting, evaluated four models of RetinaNet, YOLOv3, Faster R-CNN, and FaceBoxes.

Achieving automatic network model requires large amounts of labeled data and calculations for training. However, such data are often challenging to obtain from agricultural fields. Crop targets in the field environment are usually small and large in number; therefore, it is time-consuming to generate marker datasets. Kumar et al.[50] proposed a pixel-based segmentation method and a maize tassel detection method based on *k*-means clustering and an adaptive threshold to solve this problem[51]. Compared to the You Only Looking Once and Faster R-CNN models, they have the advantages of shorter training time and lower computational complexity. Alzadjali et al.[52] proposed two automatic tassel-detection methods based on UAV images and customized the evaluation standard for maize tassel recognition which is more suitable for target detection in agricultural environments. Yu et al.[53] compared the differences in the tassel segmentation accuracy of four models: PspNet, DeepLab V3+, SegNet, and U-Net. The U-Net model achieved the highest tassel segmentation accuracy for maize varieties across different growth periods, demonstrating good universality and robustness and providing an effective method for maize tassel detection. After proving that the U-Net model can perform effective tassel segmentation on RGB images, the U-Net model with Vgg-16 and MobileNet as the feature extraction networks was compared with the tassel segmentation accuracy of RGB images in complex situations[54]. Moreover, the VGG16 feature extraction network yielded higher accuracy.

Despite object detection methods with anchor frames achieving higher recognition accuracy, they rely on complex anchor frame designs and intricate network structures. However, algorithms without anchor frames have certain advantages because they simplify the non-maximum suppression process. Yang et al.[55] proposed an improved CenterNet model that is a typical representative anchor-free target detection algorithm. They removed the last layer of the feature extraction backbone network, introducing coordinate information as a feature layer into the last high-resolution deconvolution layer, which enhanced position sensitivity and improved the accuracy of maize tassel detection. Experimental results confirmed that the improved CenterNet model achieved a recognition accuracy that was 3.42% higher than that of YOLOv4 and 26.22% higher than that of Faster R-CNN with anchor frames. YOLO_X, which incorporates anchor-free mechanisms and decoupled heads, outperformed other models in the YOLO series[56]. Wang et al.[57] applied transfer learning to achieve high-precision recognition of maize tassels using the Faster R-CNN, SSD, and YOLO_X object detection models. Analysis of the detection performance of different models revealed that the use of transfer learning significantly enhanced the results, with YOLO_X demonstrating the best performance.

Research on maize tassel recognition using computer vision focused on the tassels that had already lost powder and did not address the requirement of detasseling before pollination during the maize hybrid breeding process. Future research on maize tassel recognition through image analysis should pay more attention on identifying tassels before they lose their pollen.

4.2 Path planning

Path planning is a key technology used in UAV research. The path planning of the detasseling operation and the path planning of plant-protection UAVs were optimal in farmland scenarios. Therefore, path planning for plant-protection UAVs provides valuable insight into the path planning of maize-detasseling UAVs. UAV path planning involves planning the optimal or suboptimal operation route based on specific operation requirements, flight energy consumption, and operation efficiency under the conditions of meeting environmental, self-performance, and task constraints.

In recent years, unmanned aerial vehicles (UAVs) have emerged as one of the most challenging and promising research directions in the field of aeronautics. Despite limited research on maize detasseling UAV operations, the technology of agricultural UAV, such as plant protection UAVs[58-60], has developed rapidly and has been applied in fields including crop seeding, agricultural data collection, topping, pruning, livestock tracking, and crop pest control[61,62].

There are two operational scenarios for detasseling UAVs: one of which the maize plants are not detasseled by the detasseling machines, and the entire process of detasseling is accomplished by the UAV. The other is where the detasseling machines perform the initially detassel, and the UAVs perform secondary tassel removal to remove any missed tassels. Path planning for the entire process of detasseling by UAVs falls under the category of full-coverage path planning. There are two main types of full-coverage path-planning algorithms. The first is intelligent optimization-based path-planning algorithms, such as the ant colony optimization (ACO) algorithm[63], genetic algorithm (GA)[64], and particle swarm optimization (PSO) algorithms[65]. The other is graph-based path-planning algorithms, which rely on graph search techniques such as the A^* algorithm[66] and artificial potential field (APF) algorithms[67,68]. The principles, comparative advantages, and disadvantages of these algorithms are listed in Table 2 for reference.

Owing to the limitations in battery energy density technology, the endurance of UAV typically ranges from 25 to 30 min. Achieving a full-length UAV-based detasseling task can be challenging because of these limitations. In scenarios where only secondary detasseling is required, the entire field does not need to be covered because it is sparse. However, the objective was to minimize energy consumption and travel distance. UAVs must navigate through and remove dispersed and missed tassels to address discrete points. This optimization problem can be abstracted as a (TSP)[69]. Currently, two main categories of algorithms exist for solving the TSP. The first is the exact algorithm, which aims to determine the global optimal solution by exhaustively exploring the entire solution space. However, as the problem size increases, the computational complexity increases exponentially because of combinatorial explosion, making it challenging to complete the search within a reasonable timeframe. The second is a heuristic algorithm that does not require to explore the entire solution space. Instead, they started with a feasible solution and iteratively improved it until it approximated the global optimal solution with minimal error. Examples of heuristic algorithms include the simulated annealing algorithm and ant colony algorithm. The Simulated Annealing algorithm is known for its asymptotic convergence because it can obtain a global optimal solution with a certain probability[70,71]. Zhang et al.[72] has improved the stability and solution quality of the Ant Colony algorithm by adaptively adjusting its parameters and pheromone update strategies based on changes in population similarity. Zhao et al.[73] introduced an enhanced Ant Colony optimization algorithm that incorporated a forgetfulness factor in artificial ants, addressing stagnation and premature convergence issues in the Ant Colony algorithm when solving the traveling salesman problem, resulting in a shorter runtime and superior results.

Table 2 Advantages, and disadvantages of path planning algorithm

Algorithm	Advantages	Disadvantages
Dijkstra algorithm	The shortest path can be found	It cannot handle the negative weight edges
A* algorithm	Fast discovery of the shortest path	It has Poor adaptability to dynamic environments
Rapidly-exploring Random Trees (RRT) algorithm	Adaptability to complex environments and the algorithm is easy to implement	The path is not optimal and has poor convergence
Artificial Potential Field algorithm	Real-time performance and smooth path	Susceptibility to local optima outside the target point
Ant Colony Optimization algorithm	Strong search capability and good robustness	Requires a lot of iterations and has poor parallelism
Genetic algorithm	Effective global search capability and easy to expand	Computational cost and poor interpretability
Particle Swarm Optimization (PSO) algorithm	Simple computation and fast convergence	Poor adaptability and sensitive to parameters

In complex and dynamic real-world scenarios such as time-sensitive detasseling operations across vast farmlands, the use of multiple UAVs working in a coordinated manner significantly improves operational efficiency, reducing the time required for specific field tasks[74]. The problem of multidrone cooperative operation has received considerable attention from researchers. Kan et al.[75] introduced an algorithm for multi-drone collaborative path planning in agricultural drone operations based on an improved particle swarm optimization. This algorithm optimized the return order and return point locations for each UAV. Zhang[76] proposed an APF-DQN model and an improved Self-Organizing Map (SOM) to enhance the success rate of multi-drone missions. They addressed the problem of multi-drone convergence and task allocation using a combination of Deep Q-Learning (DQN) and an artificial potential field algorithm. The multiple traveling salesman problem (MTSP), which is a generalization of the classical TSP, was adapted by Ji et al.[77] to address the problem of multidrone collaborative path planning with target localization. They decomposed the problem into an MTSP and a coarse-grained point-allocation problem around the targets. Furthermore, they proposed the heuristic and approximate algorithms for MTSP, resulting in a simulation-verified algorithm that reduced the average energy consumption by 21%[78]. These approaches demonstrate the significance of multi-drone cooperation in addressing complex, large-scale agricultural tasks, such as maize tassel removal, and highlight the value of innovative optimization algorithms and techniques for improving the overall operational efficiency.

Numerous studies on UAV path planning have been conducted. However, the existing issues include suboptimal optimization objectives, slow algorithm convergence, and inadequate adaptability to dynamic path planning. When addressing the challenge of UAV path planning in maize detasselling operations, it is crucial to draw from existing path-planning algorithms, combine multiple algorithms, and thoroughly consider constraints such as terrain, battery capacity, operational efficiency, and real-time dynamic planning requirements to formulate the optimal operational path.

4.3 Design and control for mechanical arms

With the rapid development and growing maturity of aerial robotics technology, multi-rotor UAVs have found extensive applications in fields such as agricultural and forestry plant protection, power inspection, aerial mapping, and environmental monitoring[79,80]. However, these applications primarily involve environmental sensing rather than active environmental manipulation. To address this issue, numerous studies have focused on equipping unmanned aircraft with mechanical arms or end effectors. The mechanical arm and end effector are operational devices for performing mechanical tasks involving repetition, high strength, or dangerous conditions. Achieving unmanned operations with precision requires specialized end effectors. The design of UAV precision operations, which involve mechanical arms and end effectors, draws inspiration from the structural principles of cutting and extracting the components of ground-based detasseling machines. Furthermore, this design must also consider the payload constraints of the UAV and aim for lightweight components. In addition, a collection mechanism must be designed to recover the removed tassels simultaneously.

When using a UAV for detasseling, a stable relative position between the mechanical arm and maize tassels must be maintained while also controlling the UAV's flying attitude. This stability ensures that the depth of tassel cutting remains relatively constant or that the tassels are extracted without causing harm to the leaves. The precision control of a UAV's detasseling mechanical arm can be inspired by research on mounting mechanical arm systems for rotor-based UAVs and is applicable to the precise control of detasseling arms on drones.

In China, research on rotary-wing flight mechanical arms began relatively late, and few studies have been conducted in this area. Bai[81] built a rotor–flight manipulator system on a JR260 aircraft helicopter platform (Jiangsu Jincheng Aviation Technology Co., LTD, China). They designed a dynamic inverse autonomous flight control system based on neural-network compensation. However, the practical application of this system is less than ideal, primarily because of the significant influence of neural network error compensators on the online learning of the model. Zhong et al.[82] proposed a dynamic center-of-gravity compensation strategy to solve the interference caused by the regular motion of a manipulator on the center of gravity of a UAV. However, the selection of the model parameters had a substantial impact on the results because it relied on estimating the center of gravity using a dynamic model. Quan[83] designed a six-DOF series-connected rotary-wing flight manipulator. However, this system lacks robustness and requires a calibration board. Sun et al.[84] established a kinematic model for a rotary-wing flight mechanical arm system equipped with a four-degree-of-freedom series-connected mechanical arm. They controlled the translation of the system in the image space and the rotation in the Cartesian space. They proposed a layered task combination control algorithm for redundant systems to enhance flight attitudes. Meng et al.[85] addressed the issue of contact operations during the movement of mechanical arms in a rotary-wing flight. They introduced a force and position hybrid controller to maintain continuous contact with the target and the contact force. The effectiveness of this approach is experimentally validated.

Pounds et al.[86] used UAVs equipped with mechanical grippers to perform hovering target manipulations. They also designed a PID controller to stabilize the system altitude. Cataldi et al.[87] proposed an impedance control scheme to reduce the interaction forces between the end effector and the environment. Orasg et al.[88] applied traditional proportional-integral-derivative (PID) controllers to control a system based on real operational scenarios. They validated the system's stability by executing tasks such as grabbing, inserting, and rotating. Jafarinasab et al.[89] designed a model-based underactuated rotary-wing flight mechanical arm using an adaptive motion controller. They used two control schemes to separately control the UAV and manipulator to ensure normal operation of the manipulator in both the joint space and task space.

Studies on the control of rotor aerial manipulator systems can serve as references for the design and precise control of aerial manipulators for maize-detasseling UAVs. When designing a robot arm for unmanned detasseling operations, it is crucial to prioritize a lightweight design and mitigate interference from wind conditions to advance the implementation, application, and development of UAV detasseling technologies.

4.4 Tassel recovery device

The removed tassels are scattered disorderly among rows of maize, and some of them are not dropped on the ground but hung on the plant, affecting the normal growth of maize plants and causing a risk of self-pollination. Wang et al. designed a maize detassel and tassel return harvesting table, which has the function of maize detasseling and tassel recovery after detasseling[90]. The schematic of the trial production prototype consists of: 1. Maize plant 2. Maize detassel and tassel return harvesting table 3. Cab 4. Cab lifting system 5. Tyre 6. Outrigger 7. Hydraulic system 8. Engine 9. Fuel tank 10. Walking chassis 11. Spraying rack. The maize detassel and tassel return harvesting tables comprised of 12. Profiling mechanism 13. Clamping recovery device 14. Cutting-type detasseling device 15. Storage box. The clamping recovery device comprised a 16. Hydraulic motor 17. Clamping recovery roller; and 18. Bearing seat 19. Electric push rod 20. Loose leaf folding 21. Support guard plates. During operation, the maize plants converged on the contact surface of the two rollers under the effect of the divider. In the clamping state, the cutting-type detasseling device cuts the maize tassels. The moved tassels fall into the storage box owing to the inertial force of the roller clamping, completing the mechanization of maize detasseling and recovery.

5 Discussion

Detasseling is essential in maize seed production. The quality of detasseling directly affects the purity and quality of maize seeds, thus influencing the success of seed production and ultimately contributing to a high maize yield[91].

Limitations and challenges must be addressed in mechanized detasselling[92]. The future direction of detasseling in the maize industry lies in intelligent detasseling, which presents various challenges, such as identifying tassels that still contain pollen but are obscured by leaves of the same color[93,94]. Therefore, researchers are working on locating the tassel coordinates through image recognition and determining the optimal operation path using flight path planning and UAV cluster control algorithms. The design of a lightweight detasseling manipulator that can be mounted on a UAV and accurately controlled is crucial for efficient, intelligent detasseling operations, drawing on the structural principles of the cutting- and extraction-type detasseling components of the ground detasseling machine and existing research on the rotor flight manipulator system.

6 Conclusions

This study analyzed the development and application of detasseling technology in Chinese hybrid maize seed production and compared it with the United States at key points. Manual and mechanized detasselling have some drawbacks. Recent advancements in detasseling technology, known as intelligent detasseling. This approach integrates technologies, such as UAV, robot arms, and deep learning, representing an inevitable trend and crucial direction for the future development of detasseling operations in the maize seed production industry. Future development trends in the maize seed industry will involve the creation of intelligent and lightweight detasseling agricultural machinery that is cost-effective, easy to operate, and capable of performing intelligent detasseling operations.

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