A REVIEW ON RESEARCH OF MECHANIZED RESIDUAL FILM RECOVERY TECHNOLOGIES AND EQUIPMENT
/
机械化残膜回收技术与装备研究综述

Hongjian ZHANG*[1], Junyi LU[1], Yufeng LI[1], Linlong JING[1], Shuo KANG[1], Jinxing WANG[1]
[1]School of Mechanical and Electronic Engineering, Shandong Agricultural University, Shandong/China
Corresponding author: Hongjian ZHANG
Tel: +8618805488951; E-mail: zhanghongji_an@163.com
DOI: https://doi.org/10.35633/inmateh-79-67

Keywords: *agricultural residual film, mechanized recovery, mechanized film-impurity separation, resource utilization of residual film*

ABSTRACT
Agricultural plastic mulch films have significantly increased crop yields but have also caused severe residual film pollution. This review summarizes the research progress in residual film recovery machinery, intelligent monitoring systems, film–impurity separation technologies, and resource utilization methods, while analyzing the advantages, limitations, and development trends of different technologies. Post-harvest recovery equipment has been widely applied due to its strong adaptability and broad application range, whereas seedling-stage and pre-sowing recovery technologies still require improvements in automation and environmental adaptability. Intelligent monitoring technologies can enhance the evaluation of recovery processes, but their application is restricted by complex field environments. Vibrating, pneumatic, and water-washing separation technologies exhibit advantages in processing capacity, film purity, and impurity removal, respectively. Recycled pelletizing and wood–plastic composites are important resource utilization pathways, but they still face challenges related to cost and performance. In the future, residual film management will develop toward intelligent, efficient, and high-value utilization.

摘要
农业塑料覆盖膜提高了作物产量，但也造成严重的残膜污染。本综述总结了残膜回收机械、智能监测系统、膜杂分离技术及资源利用方法的研究进展，并分析了不同技术的优势、局限性和发展趋势。收获后回收设备因适应性强、应用范围广而得到广泛应用，而苗期和播前回收技术仍需提升自动化和环境适应能力。智能监测技术可提高回收过程评价水平，但复杂田间环境限制其应用。振动、气力和水洗分离技术分别在处理能力、膜纯度和杂质去除方面具有优势。再生造粒和木塑复合材料是重要资源化途径，但仍面临成本和性能挑战。未来残膜治理将向智能化、高效化和高值化方向发展。

INTRODUCTION
In the 20th century, with the rise of the plastics industry, plastic mulch cultivation technology emerged and gradually developed *(Wang et al., 2018; Briassoulis et al., 2013; Wei et al., 2019)*. Japan conducted relatively early research on plastic mulch technology, which greatly promoted crop production. Plastic mulches are widely used in vegetable and fruit production systems across Europe, particularly in Mediterranean countries such as Spain and Italy. Plasticulture is widely adopted in North America for the production of high-value crops such as strawberries, tomatoes and melons. China has a history of about 40 years in the application of plastic mulch cultivation. Among them, the plastic mulch coverage rate of cotton in Xinjiang is 96.6%, and that of peanut and tobacco in Shandong and Hubei reaches 100% *(Chen et al., 2020)*. However, with extensive use and large amounts of plastic mulch left in farmland after harvest (Fig.1(c)), mulch mainly made of polyethylene is difficult to decompose naturally. Inadequate post-treatment by farmers has led to soil and environmental pollution, reducing water infiltration, ventilation and moisture content, hindering water and nutrient transport, causing soil compaction, and inhibiting crop root growth *(Filipe et al., 2023)*. To date, 7.4 million tons of agricultural plastic films are consumed globally each year. Just 10% are recycled and 14% incinerated, while 76% enter landfills or the environment, creating major risks to ecosystems and human health (Fig.1(a)). In Europe, approximately 0.6 million tons of agricultural plastic waste are generated annually, of which about 24% are recycled *(Martín et al., 2018)*.

The U.S. has implemented plastic recycling initiatives, waste mulch film recycling is low (*Sarpong et al., 2024*). Soil residues account for 60%–80% of film mass, so recycling costs exceed regeneration benefits. Farmers use on-farm storage, paid landfilling or open burning, which emits heavy metals and dioxins and pollutes the environment *(Montoya et al., 2018).* The average residual mulch film content in long-term mulched farmland soils of China ranges from 60 to 90 kg/hm². A residual film concentration of 58.5 kg/hm² significantly inhibits crop root growth and hinders water and nutrient transport. (*Li et a., 2023*).

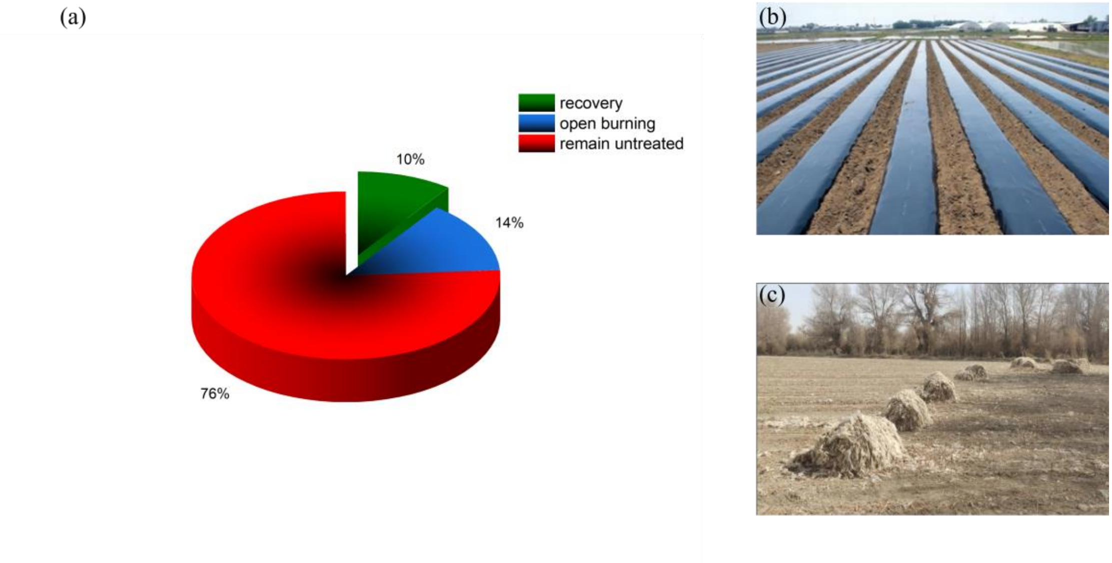

Fig. 1 – Usage of Agricultural Plastic Mulch

(a) The proportions of disposal approaches for waste agricultural plastic films worldwide;
(b) Farmland Mulching; (c) Residual Mulch Accumulation in Farmland

Many reviews have discussed agricultural plastic films regarding their application, degradation, ecological risks and recycling technologies. Some analyzed plastic environmental behavior, while others evaluated residual film recovery machinery. Nevertheless, existing reviews focus merely on pollution assessment or general waste management. Comprehensive summaries of mechanized residual film recovery, intelligent detection, separation and resource utilization are scarce. The integration of recovery machinery with intelligent sensing and automation lacks systematic analysis *(Li et al., 2020; Wang et al., 2026; Yang et al., 2024)*.

This paper focuses on the core technical chain of residual film pollution control and systematically reviews related technologies, including recycling machine classification, intelligent systems, membrane-impurity separation, and resource utilization. It covers the whole-process system of mechanized recovery, intelligent monitoring, impurity separation, and resource regeneration, providing a research basis for technical optimization and equipment development. Systematic literature searches to identify research on agricultural residue film recovery, separation technologies, intelligent monitoring systems, and resource utilization pathways. Literature retrieval was conducted using Web of Science Core Collections, Scopus, ScienceDirect, SpringerLink, and Google Scholar databases. The search strategy combines keywords, including "agricultural plastic film," "residual film," "plastic cover film recycling," "film recycling equipment," "machine vision," "intelligent detection," "plastic separation," and "resource utilization." This review covers studies published between 2000 and 2026. After removing duplicate records, the retrieved articles are filtered according to the title, abstract, and full text, following preset inclusion and exclusion criteria. Subsequently, the selected studies were analyzed to summarize the findings.

KEY LINKS IN MECHANIZED RECYCLING OF RESIDUAL FILM

Farmland residual plastic film mainly includes two types: surface residual film and subsurface tillage layer residual film. Among them, surface residual film is classified into relatively intact film and fragmented film according to its morphology, while residual film in the tillage layer is entirely fragmented. Due to the short laying period and low degree of mechanical property degradation, relatively intact plastic film is relatively easy to recover. In contrast, fragmented residual film is scattered and exhibits severe mechanical property degradation, making it difficult to recover. Thus, fragmented residual film is the main target for residual film recovery.

Based on current practical recovery conditions, residual film collection and operation evaluation, film-impurity separation, and residual film processing and utilization are the key links in mechanized residual film recovery. In terms of mechanized residual film collection, residual film recovery equipment at different stages is used to lift and pick up residual film from both the surface and tillage layer, then transport it to a baling unit to complete baling and recovery *(Zhang et al., 2008a)*. During recovery evaluation, residual film image recognition, machine operation status monitoring, and operation area monitoring are adopted to identify residual film, monitor key components in real time, and detect picked, missed, and repeated areas in the field. In mechanized processing, baled residual film is first separated from straw and sand by film-impurity separation equipment *(Guo et al., 2011c)*, and then made into high-purity raw materials for plastic products through regenerative granulation technology, as shown in Fig. 2.

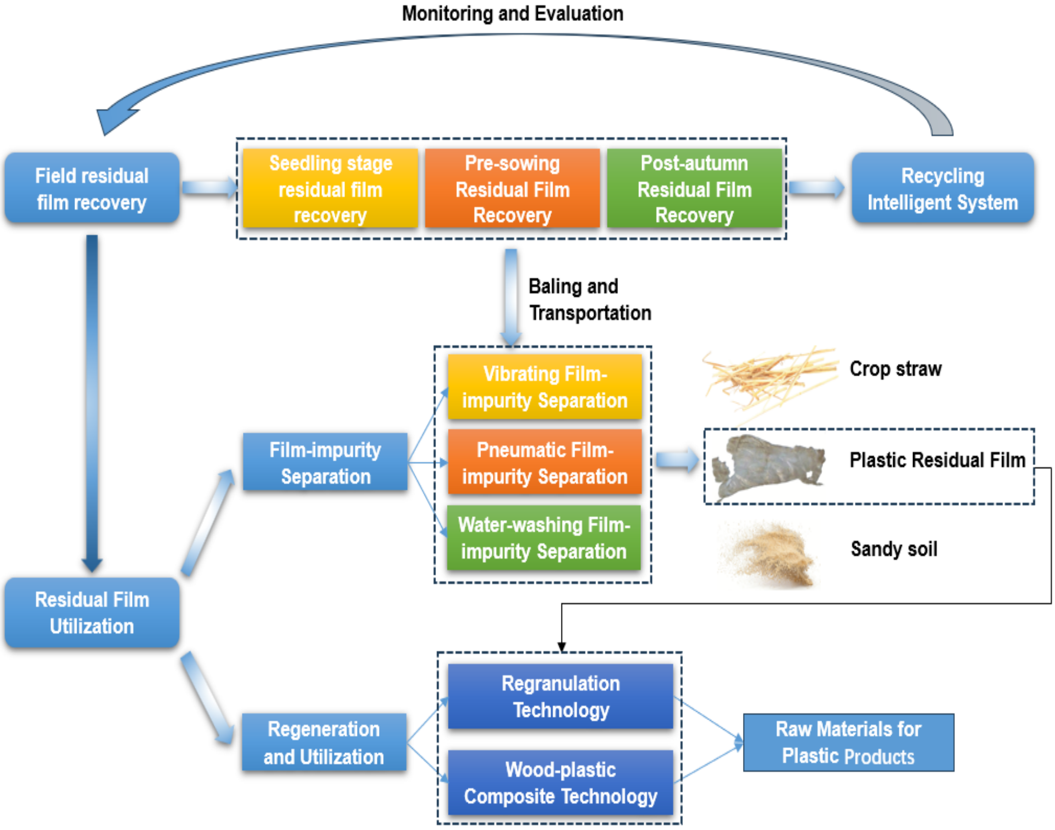

Fig. 2 – Key Processes of Mechanized Residual Film Recovery

MECHANIZED RECOVERY TECHNOLOGY, EQUIPMENT AND INTELLIGENT SYSTEM

In the early 20th century, some developed countries began research on residual film recovery machinery. Since the plastic film they used was generally thicker than 0.20 mm, film-soil separation was mainly achieved by relying on the relatively high tensile strength of the film itself, with research focused on winding mechanisms. Relevant research in China started in the 1980s. Affected by factors such as thin film thickness, low strength and easy damage, research has mainly focused on key components including film lifting and film collection *(Cheng et al., 2023)*. Due to regional agronomic differences, China has various residual film recovery machines, which can be categorized by operating period into seedling-stage, post-harvest and pre-sowing types, with post-harvest machines being the most widely applied. Accordingly, residual film recovery equipment is gradually integrating intelligent technologies, developing monitoring systems for field operation and recovery performance to realize intelligent upgrading *(Kou et al., 2023; Jin et al., 2023a)*.

Seedling-stage Residual Film Recovery Technology and Equipment

In China, residual plastic film is mainly recovered at the seedling stage before the first irrigation, as the film is relatively intact and easy to collect. The mainstream film rolling technology uses the inherent strength of plastic film to meet tension needs during film-soil separation, and is widely used for vegetable film recovery abroad and seedling-stage residual film recovery in China.

Early seedling-stage residual plastic film collectors were mostly semi-automatic, composed of frame, ground wheels, cutting blades, film lifters and cutoff discs *(Liu et al., 2024; Yang et al., 2010; Hu et al., 2016)*. They cut weeds first, lifted the film, and relied on manual pickup, leading to low efficiency. Accordingly, researchers worldwide developed fully automatic machines that wind residual film with rolling rollers and separate it from the soil using the film's inherent tensile force, offering higher efficiency and better adaptability for seedling-stage film recovery, Typical seedling-stage residual film recovery machines from various countries and their operating parameters are listed in Table 1.

Table 1

Representative Seedling-stage Residual Film Recovery Machines and Operating Parameters

Brand	Country	Picture	Operating speed	Working width	Advantages	Disadvantages
PS610 In-Season Plastic-Film Recovery Machine	USA		3–4 km/h	1.5m	It enables efficient pre-recycling with less residual film, intact mulch film, and continuous mechanized operation.	Recovery efficiency decreases under severe film fragmentation or soil embedding conditions.
ROCCA PMR-01 Plastic Mulch Retriever	USA		2–5 km/h	1.5–1.8 m	High-efficiency continuous collection with preliminary film–impurity separation.	Sensitive to film fragmentation and soil adhesion; limited adaptability and high cost.
MSM-3 type seedling-stage residual film recovery machine	CHN		2–3 km/h	1.2-1.8m	It features a compact design, high recovery efficiency, reduced soil contamination, and multi-row operation.	Affected by field conditions, with limited recovery of buried and fragmented film and limited adaptability.
Mulch film winding/recovery device	JPN		0.72–2.88km/h	0.9–1.2 m	Reduces film damage, improving recovery quality and resource-use efficiency.	Poor soil-film separation, low fragmented-film adaptability, low throughput, not for large-scale use.
Jaulent Industrie DTR	FRA		4–8km/h	1.5m	Simple structure, high efficiency, suitable for European vegetable fields, and capable of recovering film and drip lines.	Designed mainly for intact mulch films, with poor adaptability to fragmented films and limited film–soil separation capability.

However, the film-rolling seedling-stage residual film recovery equipment still relies on manual film guiding and unloading, with high labor intensity, low efficiency and insufficient tension control that easily causes film tearing, breaking or residue. To solve this, the floating synchronous film-rolling machine adopts a special mechanism to dynamically adjust the roller's speed and pressure according to real-time film conditions, ensuring uniform film stress and avoiding tearing or breaking *(Zhou et al., 2019)*.

Existing studies show that seedling-stage residual film recovery is mainly suitable for crops like corn with little need for later soil warming. The method varies with crop type, agronomy and production conditions. However, such recovery may increase water demand and soil compaction, especially in arid areas using under-film irrigation. Relevant technologies and equipment remain limited.

Autumn residual film recovery technologies and equipment

Post-harvest residual film recovery refers to the recovery operation conducted after crop harvest and before tillage, mainly targeting the plastic film used in the current season. As this operation is independent of crop harvesting, it avoids impacts on harvesting efficiency and crop quality, making it a widely applied method. However, plastic film is severely aged after harvest and disturbed by straw coverage, increasing operational difficulty.

Dense root stubbles after straw returning also cause fine residual film to hook and adhere, further complicating recovery *(Wang et al., 2017; Wu et al., 2025)*. In response, research institutions have developed corresponding equipment.

Current post-harvest recovery mainly includes two categories: one is single recovery dominated by drum-type devices, and the other is combined recovery integrating film collection, straw crushing and film baling.

1. Drum-type residual film recycler

Drum-type residual film recovery technology uses a toothed drum to collect residual film. As the drum rotates, residual film in the shallow tilled layer is hooked and attached to the teeth, then removed and collected by mechanical stripping or air blowing. According to the relative motion between the pick-up teeth and the drum, such recyclers are divided into concentric drum type and eccentric drum type *(Hu,2021; Zhang et al., 2023a)*.

Figure 4(a) shows the pick-up drum of a concentric drum-type residual film recycler. Its characteristic is that the elastic pick-up teeth are rigidly fixed to the drum body, with no relative movement between them during operation, and their rotational axes remain concentric. The residual film pick-up drum and the film stripping drum rotate in opposite directions. The elastic pick-up teeth on the pick-up drum pick up and clamp residual film from the tilled layer, then convey it to the stripping zone. Under the relative motion of the two drums, residual film attached to the pick-up teeth is effectively stripped by the stripping drum, and finally delivered to the residual film collection device, realizing continuous operations of film pick-up, conveyance, stripping and collection. Figure 4(d) shows the pick-up drum of an eccentric drum-type residual film recycler. Unlike the concentric type, the film pick-up teeth and the roller of the eccentric type can produce controllable relative movement. During operation, the pick-up teeth and the roller undergo periodic radial relative displacement to grasp, carry and separate residual film in the field. When the elastic pick-up teeth are fully extended, they fully contact residual film and complete the grasping operation. As the elastic teeth gradually retract, the grasped residual film moves with the teeth away from the working surface and then returns to the roller surface, creating conditions for subsequent film separation and cleaning.

Fig. 4 – Drum-type residual film recovery machine

(a) Concentric drum pickup structure (Zhang, 2023b). (b) Comb-tooth lifting and pneumatic stripping residual film recovery machine for tillage layer (Liu et al., 2021). (c) FEM-SPH Coupled Roller-Type Residual Film Recovery Machine (Zhang et al., 2024b). (d) Eccentric drum pickup structure (Niu et al., 2023). (e) Eccentric drum pickup structure (Shi et al., 2023). (f) Collecting and Separating Device for Strip Plastic Film Baler (Niu et al., 2017).

2. Combined residual film recovery machine

Combined residual film recovery machines can be divided into combined straw crushing and returning machines with residual film recovery, and combined residual film recovery and film block baling machines. Compared with single residual film recovery, the combined operation mode integrates and optimizes processes, which can effectively reduce field operation times and the interference of straw on film recovery. Meanwhile, it realizes baling of residual film, significantly improves operation stability and simplifies subsequent treatment. Therefore, Chinese researchers have developed various combined residual film recovery machines *(He et al.,2013; Yu et al; 2016; He et al., 2023)*. As shown in Figure 5(c), the 4JMLQ-210 combined straw returning and residual film recovery machine is a tractor-mounted unit with front straw crushing and rear film recovery. During operation, high-speed rotating parts crush straw, break stubbles and level the field, preparing for film recovery. Residual film is then collected by film lifting, pickup and separation mechanisms.

One-pass operation achieves both straw returning and film pollution control. Figure 5(e) shows the MJY-1500 residual film picking and baling machine. It uses three sets of vertical hydraulic cylinders to compact film into square bales. This baler forms bales quickly with a high baling rate. Compared with conventional collection boxes, hydraulic compression greatly increases film density, easing transport and preventing secondary pollution. The structure is simple and reliable.

Fig. 5 – Combined Residual Film Recovery Machine

(a) 4JSM-2200 Combined Straw Returning and Residual Film Recovery Machine (Luo et al., 2024). (b) Second stage chain plate straw crushing and plastic film recycling combined operation machine (Wen et al., 2021). (c) Model 4JMLQ-210 Combined Operation Machine for Straw Returning and Residual Film Recovery (Liu et al., 2024). (d) Cotton Field Mulch Film Recovery Baler (Shi et al., 2025). (e) Model MJY-1500 Residual Film Collecting and Baler Combined Machine (Zhan et al., 2017). (f) Self-propelled Combined Machine for Cotton Stalk Baling and Residual Film Packing (Li et al., 2025)

Technology and Equipment for Pre-sowing Residual Film Recovery

Pre-sowing residual film recovery is performed after tillage and land leveling but before sowing *(Wang et al., 2017)*. It can effectively increase the seedling emergence rate. At this stage, most residual film exists as fragments in the plough layer, making recovery difficult, so the windrowing method is mainly used *(Shen et al., 2024)*. As shown in Figure 6, the machine mainly used is a closely arranged spring-tooth residual film recovery machine. As the key working component, the spring teeth are usually made of manganese alloy materials such as No.60 or No.65 manganese steel, with an arc-shaped structure. During operation, the elastic teeth can pierce the residual film in the field, quickly hook and attach it to the tooth surface, thus completing residual film picking. When the machine reaches the end of the field, the collected residual film is then unloaded. However, most spring-tooth residual film recovery machines only pierce and pick up film, and unloading depends on manual work, which limits efficiency. To solve this problem, researchers have added a film unloading mechanism to the machine, as shown in Figure 6(c), realizing the integration of film picking, stripping and unloading, and effectively improving the automation and recovery efficiency. Compared with other film recovery machines, the spring-tooth type has a low recovery rate of only about 50% and high impurity content. Still, due to its simple structure, low cost and high efficiency, it has been widely used and promoted in northern China such as Xinjiang, Gansu and Inner Mongolia.

Fig. 6 – Closely Arranged Spring-Tooth Residual Film Recovery Machine

(a) Structure of TM-120 Residual Film Recovery Machine (Song et al., 2023).
(b) Standing cotton stalks raking-film machine with wide folding and monomer profiling (Wang, 2018).
(c) Raking-Type Residual Film Recovery Machine with Rotary Film Stripping (Zheng, 2020).

Residual film recycling machines have different application characteristics at different operation stages. Seedling-stage, autumn, and pre-sowing machines are designed for different residual film conditions, but challenges remain in adaptability, separation efficiency, and intelligent operation.

The characteristics, advantages, disadvantages, and development trends of different types of residual film recycling machines are summarized in Table 2.

Table 2

Characteristics and Future Development Trends of Residual Film Recycling Machines at Different Operation Stages

Type	Operation period	Residual film state	Advantages	Disadvantages	Future development directions
Seedling stage residual film recycling machine	Crop seedling stage	Relatively intact film	The residual film can be recovered timely with high film integrity, which reduces subsequent pollution.	Poor adaptability to fragmented film and soil-contaminated film; restricted by seedling crops	Adaptable mechanisms for diverse crops, planting systems, and film conditions.
Autumn residual film recycling machine	Crop postharvest stage	High fragmentati on degree with obvious soil adhesion	It adapts well to fragmented and soil-contaminated films, supports large-scale operations, and is the most widely used residual film recovery equipment.	Fragmented and soil-contaminated films are difficult to separate, and complex structures increase energy consumption and reduce adaptability.	Enhanced separation, efficient fragmented film recovery, and multifunctional development.
Pre-sowing residual film recycling machine	Pre-sowing stage	Severe fragmentati on and increased burial depth	Enables intact film recovery, simplifies film–soil separation, and improves field conditions for subsequent operations.	Complex structure, high energy consumption, and limited field adaptability.	Efficient fragmented film recovery, intelligent operation, and multifunctional development.

Intelligent System for Residual Film Recovery

The intelligent monitoring system for residual film recovery is an integrated intelligent system that integrates sensing, identification, positioning, computing and communication technologies. It mainly fulfills two functions: real-time monitoring of the operating status of key components during the operation of residual film recovery machines, and accurate monitoring of the effective operating area and recovery quality of the equipment.

1. Monitoring System for Key Components of Residual Film Recovery Machines

During operation, key components of residual film recovery machines often suffer from abnormal speed and damage due to entanglement by film and straw. Drive shaft speed directly affects recovery efficiency and quality. Proper speed ensures effective film picking and conveying, while abnormal speed reduces recovery performance. Thus, real-time speed monitoring of rotating parts is essential *(Xu, 2014; Jaumann et al., 2022)*. As shown in Figure 7, mature commercial intelligent monitoring systems from CASE, Massey Ferguson and Precision Planting enable key component monitoring, warning and fault diagnosis for residual film recovery machines, providing important references for China's research. Research on intelligent monitoring for residual film recovery machines in China started late and remains mostly in small-scale experiments. Using the 11FMJ toothed-chain residual film recovery machine, Chinese researchers developed a monitoring system that increased speed monitoring accuracy by 0.25%. They also proposed an STM32F103-based scheme to realize multi-parameter synchronous monitoring for drum-type machines, filling relevant technological gaps *(Ke et al., 2023; Xue et al., 2024)*.

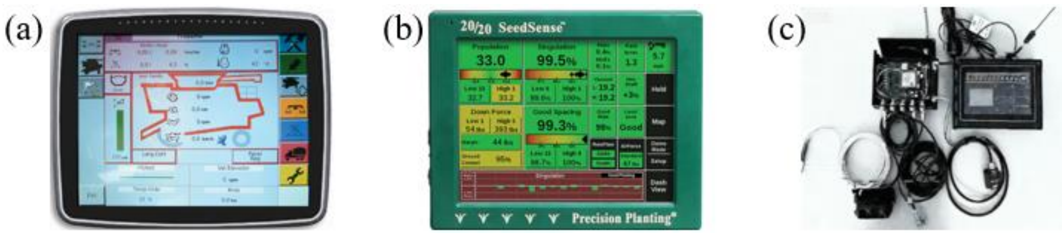

Fig. 7 – Key Component Monitoring System for Residual Film Recovery Machines

(a) FieldStar System (Coena et al., 2008) (b) 20/20 SeedSense System (Ding et al., 2018)
(c) Monitoring System for Key Components of Domestic Residual Film Recovery Machines

2. Residual Film Recovery Machine Operation Effect Monitoring System

The operation performance monitoring system for residual film recovery machines comprises two parts: an effective operation area monitoring system and a residual film image recognition system. Some countries have developed GPS-based agricultural machinery operation area monitoring methods *(Reid et al., 2000; Hamada et al., 2009)*, but these often suffer from overlapping tracks and poor boundary positioning accuracy *(Ji et al., 2012; Zhang et al., 2018)*. China's BeiDou Navigation Satellite System (BDS) has broken the technological monopoly. Its high-precision positioning provides key technical support for accurate monitoring of residual film recovery operation area. Based on BDS, Chinese researchers have developed an effective operation area monitoring system for residual film recovery machines, enabling precise calculation of effective operation area and resolving ineffective operation issues *(Zhao et Al., 2018; Zhang et al., 2020; Wang et al., 2025; Song et al., 2009)*. The residual film image recognition system detects residual films via image capture and computer vision algorithms, allowing quantitative evaluation of recovery performance. Image noise in complex fields greatly reduces model accuracy and robustness. With advances in artificial intelligence, residual film recognition has evolved from traditional machine learning to deep learning. Chinese scholars have developed lightweight detection models that achieve accurate segmentation of residual films in complex field environments while maintaining precision *(Liu et al., 2022; Ding et al., 2024; Zhang et al., 2021c; Zhai et al., 2022; Meng et al., 2025; Lu et al., 2025)*.

3. Challenges of intelligent monitoring systems under field conditions

Although deep learning-based intelligent recognition methods have achieved high detection accuracy under experimental conditions, their practical performance is still significantly affected by complex field environments. First, variations in weather conditions, solar elevation angles, and shadows caused by crops and agricultural machinery lead to constantly changing illumination conditions, thereby affecting image acquisition quality and target feature extraction. This issue is particularly significant for plastic mulch film with strong reflective properties, which is prone to local overexposure and feature loss *(Silwal et al., 2021)*. In addition, after long-term exposure to field environments, residual film surfaces are often covered with dust and soil particles, resulting in changes in their visual and spectral characteristics. These changes reduce the difference between residual film and the surrounding soil background, increasing the difficulty of image segmentation and target recognition. Meanwhile, residual film recovery operations are often accompanied by large amounts of straw and plant residues, which may overlap with residual film in images, causing false detections and missed detections and reducing the reliability of recognition systems *(Milioto et al., 2018).* Furthermore, residual films partially buried in soil generally exhibit incomplete shapes, limited visible areas, and weak visual features, making it difficult for traditional image-based methods to achieve accurate recognition. Therefore, although intelligent monitoring technologies provide a new technical pathway for automated residual film recovery, complex and unstructured field environments remain a major factor restricting their large-scale application *(Murad et al., 2023)*.

Future research should focus on developing recognition models with stronger environmental adaptability and robustness. By integrating multi-source information, including RGB images, hyperspectral data, and environmental sensing data, the accuracy and stability of residual film detection under complex scenarios can be improved. Meanwhile, lightweight deep learning algorithms combined with edge computing technologies should be employed to achieve real-time target recognition. Furthermore, the deep integration of intelligent monitoring systems with automated residual film recovery equipment should be promoted to enable intelligent and autonomous residual film management, as illustrated in Fig. 8.

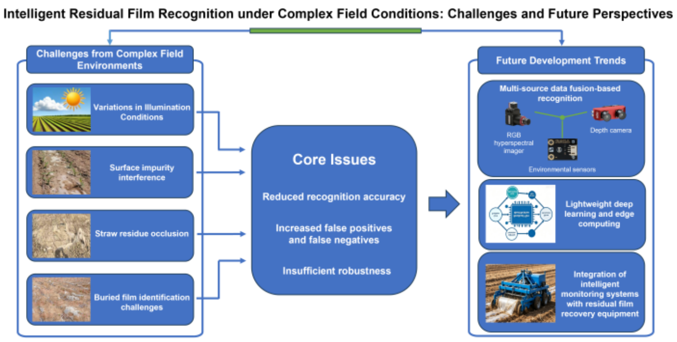

Fig. 8 – Intelligent Residual Film Recognition under Complex Field Conditions: Challenges and Future Perspectives

FILM-IMPURITY SEPARATION AND RESOURCE UTILIZATION

Although there are many types of residual film recovery machines, the recovered film mixtures have similar compositions, mainly consisting of strip or sheet old films, straw and soil clods, with varying proportions of each component. Severe entanglement between straw and residual film makes resource utilization difficult, and manual separation is inefficient and labor-intensive. Meanwhile, random stacking, burying and incineration of recovered residual film cause serious secondary pollution. Therefore, developing high-performance equipment for film-impurity separation and resource utilization is key to solving recycling challenges and achieving comprehensive control of farmland residual film *(Zhang et al., 2018)*.

Film-Impurity Separation Technology and Equipment

China has made initial progress in film-impurity separation technologies and equipment. Based on different power and working media, these technologies are mainly divided into three types: vibrating, pneumatic and water-washing *(Jiang et al., 2026)*.

1. Vibrating Film-Impurity Separation Technology and Equipment

Vibrating separation uses mechanical vibration to generate periodic oscillations, so that residual film and impurities are repeatedly thrown, bounced and slid during vibration. Based on differences in physical properties between film and impurities, they show different motion trajectories, thus achieving effective separation *(Zhang et al., 2022; Wei et al., 2018; Ruj et al., 2015)*. After mechanical recovery of farmland plastic film, the collected film-impurity mixture is complex, containing not only residual film, straw and gravel but also large amounts of soil, with severe soil wrapping on the film being especially prominent *(Guo et al., 2018b; Lubongo et al., 2022)*.To solve the resulting separation difficulties, Chinese scholars have carried out extensive research to improve separation efficiency *(You et al., 2018a; You et al.,2017b; Zhang et al., 2007d; Zhang et al., 2013)*. Figure 9(a) shows a vibrating film-soil separation device for residual film. After natural drying, the film-soil mixture collected from the field is conveyed by a belt to squeeze rollers for pre-compaction. Rotary cutters in the crushing unit then break up entangled straw and soil clods. Finally, the resulting mixture passes through a vibrating screen, which separates the residual plastic film from the soil.

Vibrating separators provide good separation and can effectively sort film from soil and stubble. They are stable, reliable and suitable for large-scale recovery. However, small and fine film pieces easily fall through the screen, lowering purity. They also adapt poorly to clay soil, where screens clog easily and reduce working efficiency.

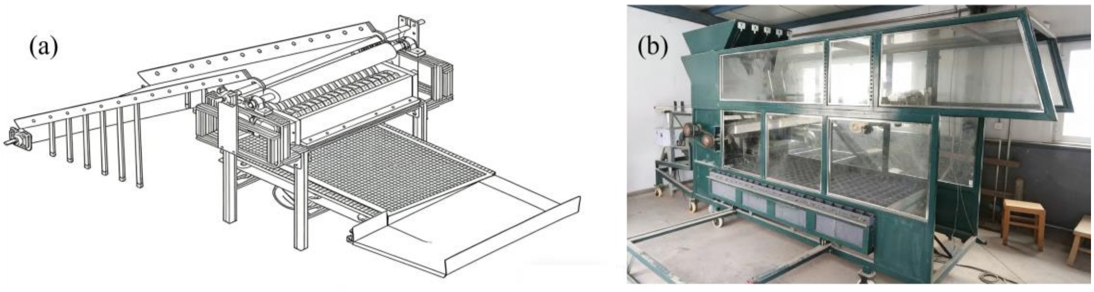

Fig. 9 – Vibrating film-impurity separation equipment

(a) Film-soil separation device (Liu et al., 2025) (b) Staggered Multi-Screen Film-Impurity Soil Removal Device (Peng, 2021)

2. Pneumatic Film-Impurity Separation Technology and Equipment

Pneumatic separation is based on the different responses of materials to airflow. Residual film has low density and low suspension velocity and is easily carried by airflow. In contrast, soil and straw have higher density and higher suspension velocity, so they tend to fall under gravity (*Anchieta e Silva; Shapiro et al., 2005*). By adjusting airflow path and velocity, film can be conveyed to a specific zone and separated *(Ma, 2024; Xie et al., 2024b)*. As shown in Figure 10(a), a pneumatic film-impurity separation device mainly consists of a fan, a rotary drum sieve, blades, a housing, a motor, and a film collection box. During operation, the fan generates airflow while the drum sieve rotates slowly. The residual film mixture (Figure 10(b)) enters the sieve through the inlet and is thrown as the sieve rotates, loosening the film. Due to the different air settling characteristics of residual film and impurities, the film is carried by airflow to the end of the sieve and into the film collection box (Figure 10(c)), while cotton stalks (Figure 10(d)) are pushed by blades to the discharge outlet, completing separation.

However, pneumatic separation requires continuous and sufficient air pressure to produce separating airflow, resulting in high power consumption, especially high energy costs for large-area operations. Restricted by environmental conditions, in humid environments, residual film adheres to impurities, reducing separation accuracy *(Kang et al., 2020; Guo et al., 2020a; Jin et al., 2022b)*.

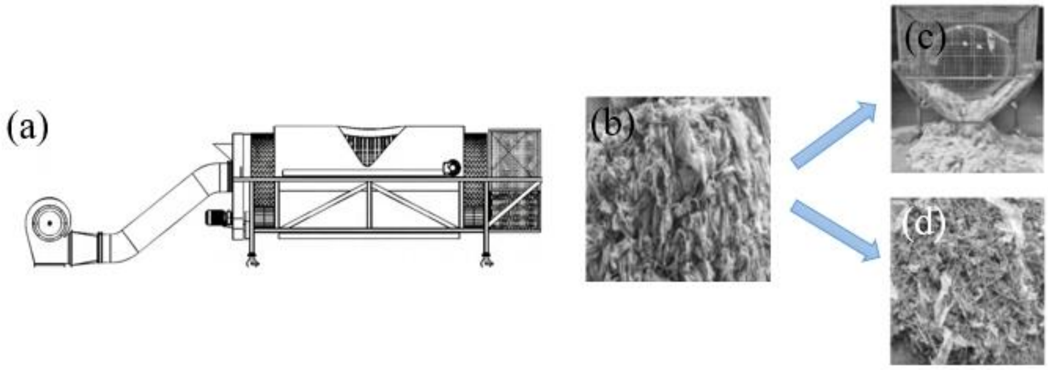

Fig. 10 – Pneumatic residual film-impurity separation device

3. Water-washing film-impurity separation technology and equipment

Water-washing separation uses the large differences in floating and settling behavior of flexible film, straw and soil particles in water. Under water flow impact and agitation, they show different trajectories and settling speeds, realizing efficient film-impurity separation *(Feng et al., 2026)*.

Water-washing separation has unique advantages in film-impurity separation, and researchers have conducted systematic research on relevant equipment. The impeller-driven water-washing separator (Fig. 11(a)) consists of a stalk collection box, stalk collection plate, water level sensor, separation tank, nozzles and water pump. During operation, cotton stalks float, residual film suspends in the middle layer, and soil settles at the bottom under water spraying. The impeller driven by the motor produces spiral thrust to enhance separation efficiency. Stalks and film are collected separately, and water is recycled through the pump. The countercurrent hook-type washing separator (Fig. 11(b)) effectively separates residual film from straw and soil. It overcomes the high soil content of air-separated film and the high energy and water consumption of ordinary washing devices *(Carvalho et al., 2010)*. However, manual removal of film from the hooks reduces separation efficiency.

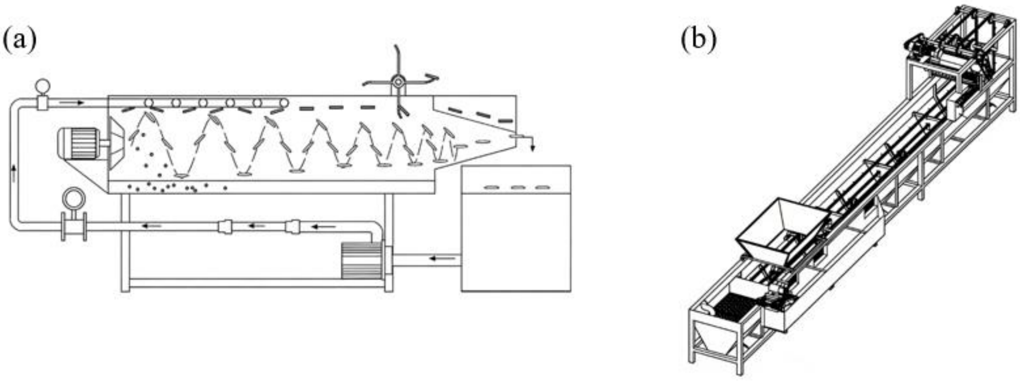

Fig. 11 – Water-washing film-impurity separation device

(a) Impeller-driven water-washing separator for mechanically harvested residual film (He et al., 2020) (b) Countercurrent hook-type washing and separating device for residual film mixture (Xie et al., 2025a)

4. Comparison of Different Film-Impurity Separation Technologies

Table 3

Comparison of different film-impurity separation technologies

Separation technology	Advantages	Limitations	Applicable conditions
Vibrating separation	Simple structure, low energy consumption, high processing capacity, no water requirement	Limited removal ability for fine soil particles and strongly adhered impurities; affected by moisture content	Suitable for preliminary separation and large-scale treatment of relatively clean residual film

Separation technology	Advantages	Limitations	Applicable conditions
Pneumatic separation	High film purity; effective separation of lightweight impurities based on aerodynamic differences	High energy consumption; separation performance affected by material moisture and particle size	Suitable for removing lightweight impurities and improving recovered film purity
Water-washing separation	High separation efficiency; excellent removal of soil and organic impurities	High water consumption; requires wastewater treatment; high operating cost	Suitable for heavily contaminated residual film requiring high-quality recycling

Overall, vibrating separation is characterized by simple structure, low energy consumption, and high processing capacity, while pneumatic separation can improve recovered film purity through airflow classification. Water-washing separation provides superior impurity removal performance but requires considerable water resources and increases treatment costs. Future development of film-impurity separation technologies will focus on improving separation efficiency while reducing energy and resource consumption. Hybrid separation systems integrating vibrating screening, pneumatic classification, and water-assisted cleaning are expected to become a promising approach for handling complex residual film mixtures and achieving efficient, sustainable, and resource-oriented recycling.

Technology and equipment for resource utilization of residual film

Waste agricultural films obtained after film-impurity separation are mainly disposed of through reuse, landfilling, incineration, and resource recycling. Although several pathways have been developed for residual film utilization, their environmental benefits and technical feasibility vary considerably. Direct reuse has the lowest processing requirement and environmental burden, but it requires relatively intact and clean films, limiting its application for highly fragmented agricultural residues. Landfill and incineration can rapidly reduce waste volume; however, landfill may cause long-term environmental risks, while incineration requires strict emission control to avoid secondary pollution. In contrast, recycling and regeneration align with the concepts of sustainable agricultural development and circular economy, making it an ideal disposal method, but they require effective impurity removal and film purification because soil particles and organic residues can deteriorate processing stability and product quality. Wood-plastic composites offer an alternative pathway for low-quality residual films, although the influence of residual soil, additives, and polymer degradation on composite mechanical properties remains a major challenge. Currently, the treatment of waste agricultural films worldwide is gradually shifting toward resource utilization. The core technologies include regenerative granulation technology and wood-plastic composite technology, as shown in Figure 12. *(Zhang et al., 2017; Hu et al., 2019; Madrid et al., 2022).*

Regenerative granulation is a core technology for residual film recycling due to its high efficiency and simple process, which is mainly divided into dry and wet methods. Wet granulation is the mainstream process, using water for cleaning. It achieves high impurity removal and high-quality recycled pellets through crushing, washing, drying, melting and pelletizing, but consumes large amounts of water, requires wastewater treatment, and has high costs, making it suitable for large-scale projects with sufficient water. Dry granulation is water-free and removes impurities via mechanical crushing, friction screening and air separation. It features low energy consumption, low investment and potentially lower environmental impacts, suitable for water-scarce regions *(Lamtai et al., 2023)*, table 4 summarizes the comparison of the two technologies.

Table 4

Comparison between wet and dry granulation technologies for residual film recycling

Technique	Water consumption	Energy consumption	Impurity removal capacity	Product purity
Wet granulation	It requires a large amount of water as the medium and features high water consumption.	The drying step consumes a certain amount of energy.	Impurities can be further eliminated by water washing and centrifugation, and a favorable impurity removal effect can be obtained.	A large proportion of surface impurities can be removed, achieving high product purity.
Dry granulation	It requires no or minimal water, with extremely low water consumption.	It requires relatively high pressure or temperature, leading to high energy consumption.	Surface impurities tend to remain, resulting in inferior impurity removal performance.	Considerable surface impurities remain, leading to low product purity.

Residual film wood-plastic composite technology takes recycled agricultural film as the matrix, blends it with straw, wood chips and additives, and forms products via melt extrusion. The composite material combines plastic's water and corrosion resistance with wood-like appearance, and can be made into garden walkways, pallets, guardrails and building formworks *(Xia et al., 2020; Huang et al., 2021; Nukala et al., 2022)*.

Despite its potential, the application of residual film in wood-plastic composites faces several challenges. Residual soil particles and impurities can interfere with polymer–wood bonding, resulting in reduced mechanical strength and poor processing stability *(Turku et al., 2017; Ribeiro et al., 2023)*. In addition, repeated recycling may cause polymer chain degradation, which decreases tensile strength and impact resistance of composite products. Furthermore, the end-of-life management of wood-plastic composites containing recycled agricultural films remains challenging because their mixed polymer–biomass structure complicates further recycling. Future studies should focus on improving purification technologies, interface modification methods, and circular recycling strategies.

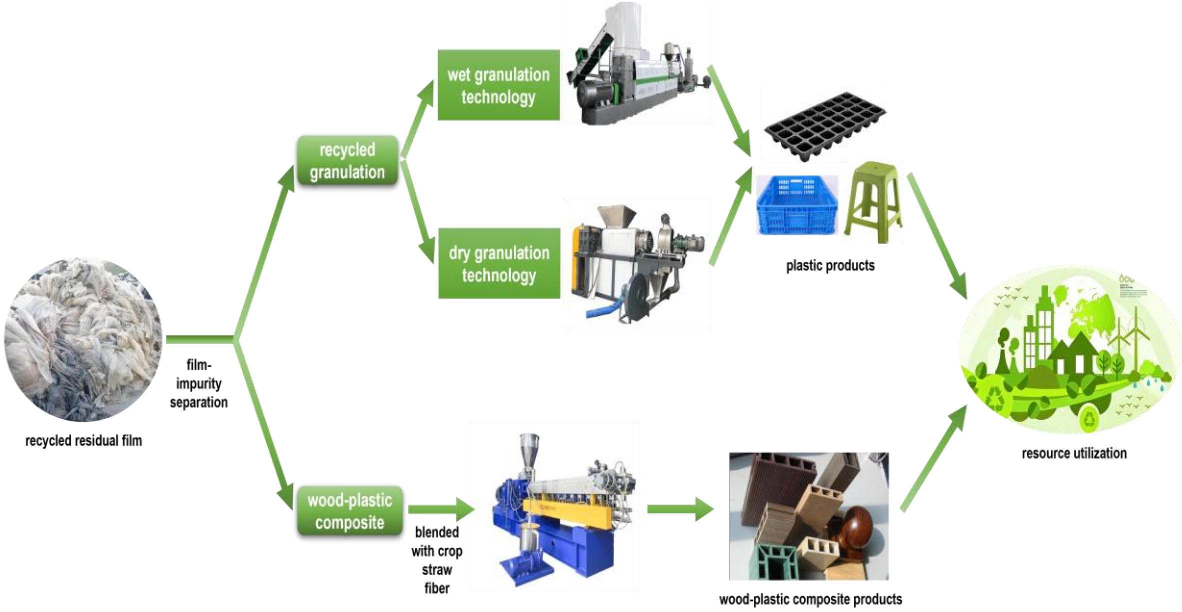

Fig. 12 – Resource utilization technology of residual film

SUMMARY AND OUTLOOK

This paper systematically reviews the core research progress throughout the entire process of farmland residual plastic film pollution control. Based on relevant research and application practices, the main conclusions are as follows: Mechanized recovery of residual film is the core link of pollution control, and an equipment system has been formed covering three key operation periods: seedling stage, post-harvest stage, and pre-sowing stage. Among them, post-harvest recovery is the most widely applied; seedling-stage recovery is developing toward automation; and pre-sowing recovery machinery is extensively used in arid agricultural areas of northern China, yet its recovery rate and automation level need to be improved. The intelligent system for residual film recovery has developed two core monitoring modules, enabling fault early warning, area measurement, and residual film identification. However, it remains in the experimental stage in China, lagging behind the commercialization level of foreign products. Membrane-impurity separation is a prerequisite for the resource utilization of residual film, and three existing types of equipment—vibratory, pneumatic, and water-washing separation—each have their advantages and disadvantages. The core technologies for the resource utilization of residual film are recycled granulation and wood-plastic composite technology, among which wood-plastic composite technology represents an important direction for the high-value utilization of residual film. At present, a full-process technical system has been established and is developing steadily with multi-stakeholder collaboration. Nevertheless, several bottlenecks still exist, restricting its large-scale and efficient application.

In view of the current technical bottlenecks in residual film pollution control and the demand for green and sustainable agriculture, future technologies and equipment will develop toward intelligence, high efficiency, coordination, and high value-added utilization. Key efforts include upgrading mechanized recovery equipment, developing new pickup mechanisms to improve the recovery rate of fragmented residual film, and optimizing combined machines and regionally adapted equipment.

Supported by Beidou navigation, AI and IoT, intelligent recovery technologies will be industrialized, with integrated management platforms and optimized algorithms to promote large-scale application. Membrane-impurity separation technologies and composite equipment will be optimized to solve existing problems, along with water-saving washing technologies to reduce costs. Resource utilization paths will be expanded by optimizing related processes, developing modification technologies, and exploring coordinated utilization with other agricultural solid wastes. Relevant standards and industrial chain mechanisms will be improved to form a sound cycle with government guidance, enterprise leadership and farmer participation, ultimately achieving "reduction, resource utilization and harmless treatment" to support green agriculture and plastic pollution control.

ACKNOWLEDGEMENT

The authors were funded for this project by the Shandong Provincial Key Research and Development Program (2024CXGC010903), the China Agriculture Research System (CARS-27), the Shandong Youth Talent Promotion Program (SDAST2024QTA050), and the Youth Innovation Team Program of Universities in Shandong Province (2023KJ160).

REFERENCES

[1] Anchieta e Silva, F., Cartaxo, A. D. S., Esmeraldo, A. D. D. S. R., Senra, E. M., & Pinto, J. C. (2026). Advancements in plastic waste sorting: A review of techniques and applications. *Processes*. 14(7):1144.

[2] Briassoulis D., Hiskakis, M., Babou, E., (2013). Technical specifications for mechanical recycling of agricultural plastic waste, *Waste Management*, 33(6), 1516-1530.

[3] Cheng, F. P., Tuo, H. Z., Yi, W. Y., Wang, P., Yang, C. M., Zhan, B. T. (2023). Research status and development trend of residual film recycling machinery in cotton field (棉田残膜回收机械研究现状及发展趋势). *Journal of Chinese Agricultural Mechanization.* 44(02):200-207.

[4] Coena, T., Saeysa, W., Missottenb, B., De Baerdemaeker, J. (2008). Cruise control on a combine harvester using model-based predictive control. *Biosystems Engineering,* 106(02),47-55.

[5] Carvalho, T., Durão, F., Ferreira, C. (2010). Separation of packaging plastics by froth flotation in a continuous pilot plant. *Waste Management*. 30:2209-2215.

[6] Ding, Y. C., Zhang, L. L., Yang, J. Q., Zhu, K. (2018). Sensing device improvement and communication design on sowing monitoring system of precision planter for rapeseed (油菜精量直播机播种监测系统传感装置改进及通信设计). *Transactions of the Chinese Society of Agricultural Engineering.* 34(14):19-26.

[7] Ding, Y. J., Yang, W. T., Zhao, Y. L. (2024). Apple Leaf Spot Segmentation Model Based on Consistency Semi-supervised Learning (基于一致性半监督学习的苹果叶片病斑分割模型研究). *Transactions of the Chinese Society for Agricultural Machinery.* 55(12):314-321.

[8] Feng, Z., Kan, Z., Wu, G. D., Peng, H. J., Meng, H. W., Zhang, B. C. (2026). Numerical Simulation and Experiment of Turbulent Flow Membrane Debris Separation Device (扰流式碎后膜杂分离装置数值模拟与试验). *Transactions of the Chinese Society for Agricultural Machinery.* 57(04):257-267.

[9] Filipe, S.; Mourão, P.M.; Couto, N.; Tranchida, D. (2023). Towards a Sustainable Future: Advancing an Integrated Approach for the Recycling and Valorization of Agricultural Plastics. *Polymers*, 15(23), 4529.

[10] Guo, W. S., He, X. W., Wang, L., Zhao, P. F., Hu, C., Hou, S. L., Wang, X. F. (2020). Development of a comb tooth loosening and pneumatic stripping ploughlayer residual film recovery machine (梳齿松土气力脱膜式耕层残膜回收机研制). *Transactions of the Chinese Society of Agricultural Engineering.* 36(18):1-10.

[11] Guo, W. S., Jian, J. M., San, Y. L., Li, G., Gao, M. Q., Hou, S. L. (2018). Design and Experimental Optimization of 4CML-1000 Type Chain Rake Film Recycling Machine (4CML-1000 型链耙式残膜回收机设计与试验优化). *Transactions of the Chinese Society for Agricultural Machinery.* 49(02):66-73.

[12] Guo, W. S., Kan, Z., Zhang, R. Y., Guo, S. X., An, H. L., Cong, T. D. (2011). Analysis of material character based on mesh roller-type cotton and film remnant separator (基于网式滚筒棉秆残膜分离装置的物料特性分析). *Transactions of the Chinese Society of Agricultural Engineering.* 27(S2):1-5.

[13] Hamada, Y., Matsuo, Y., Yamashita, T. (2009). Agricultural vehicle navigation system: Development of a guidance information display. *Japan Agricultural Research Quarterly.* 43(3):187-192.

[14] He, H. M., Hu, B., Li, J. H., Cai, H., Luo, X. (2020). Research and Experiment of the Machine Collecting Residual Film in the Impeller-driven Washing Separation Device (叶轮驱动式水洗分离装置残膜回收机的研究与试验). *Journal of Agricultural Mechanization Research.* 42(09):151-155.

[15] He, Y. C., Wang, X. J., Wang, J. L., Cao, S. L., Wang, M., Liu, Y. (2013). Research and Design of Cotton Plastic Film Collector&Field Straw Chopper Combined Machine after Autumn (棉花秋后残膜回收与茎秆粉碎联合作业机设计). *Acta Agriculture Boreali-occidentalis Sinica.* 22(08):199-204.
[16] He, Y. Z., Lu, Y. T., Wang, M., Ying, Y. K., Wang, J. L., Qin, C. M., Xue, L. (2023). Development and test of 4MKJ residual film recycling and straw crushing integrated machine (4MKJ 残膜回收打捆与秸秆粉碎联合作业机的研制与试验). *Xinjiang Agricultural Mechanization.* (02):7-8+22.
[17] Hu, B. Q., Zhu, D. G., Yang, Y. F. (2018). Design of the Main Structure of Plastic Film Collector for Toabcco at Seedling Stage (苗期烟草残膜回收机主要结构设计). *Journal of Anhui Agricultural Sciences.* 44(10):251-253.
[18] Hu, C., Wang, X. F., Chen, X. G., Tang, X. Y., Zhao, Y., Yan, C. R. (2019). Current situation and control strategies of residual film pollution in Xinjiang (新疆农田残膜污染现状及防控策略). *Transactions of the Chinese Society of Agricultural Engineering.* 35(24):223-234.
[19] Hu, G. F. (2021). Design of Farmland Residual Film Recycling Machine and Parameter Optimization of Key Components (农田残膜回收机设计与关键部件的参数优化). [Master's thesis]. Hunan Agricultural University.
[20] Huang, X. Y., Pan, L. W., Tan, L., Wang, H. (2021). Study on Reuse Techniques of Hot Air Melting of Waste Plastics (热风熔融废旧塑料再生利用技术研究中国塑料). *China Plastics*. 35(08):195-199.
[21] Ji, B. B., Li, J., Yang, Y. P., Zhang, S. (2012). A Real-time Measurement Based on GPS Which Was Designed for Calculating the Harvest Area of Combine (基于 GPS 的联合收割机作业面积实时测算装置设计). *Journal of Chinese Agricultural Mechanization.* (06):89-92.
[22] Jiang, S. Q., Zhang, H. D., Hua, Y. J. (2016). Research on location of residual plastic film based on machine vision (基于机器视觉的残膜定位方法研究). *Journal of Chinese Agricultural Mechanization.* 37(11):150-154.
[23] Jiang, W. J., Du, Y. K., Fang, W. Q. (2026). Research progress and prospects of cotton field residue film recycling machines (棉田残膜回收机械研究进展与展望). *Journal of Chinese Agricultural Mechanization.* 47(02):14-20.
[24] Jin, W., Ding, Y. C., Nong, F., Zhang, X. J., Bai, S. H. (2023). Design and Test of Excavating and Conveying Device with Vibrating Chain Tooth and Bar for Residual Film-Soil-Straw (振动链齿杆式残膜-土-秸秆挖掘输送装置设计与试验). *Transactions of the Chinese Society for Agricultural Machinery.* 54(11):71-82.
[25] Jin, W., Zhang, X. J., Ding, Y. C., Bai, S. H., Liu, W. P., Zhou, X. C. (2022). Experiment on Suspension Separation of Residual Film and Impurity Based on EDEM-Fluent Coupling (基于 EDEM-Fluent 耦合的残膜-杂质悬浮分离试验). *Transactions of the Chinese Society for Agricultural Machinery.* 53(04):89-98.
[26] Jaumann, M., Olcay, E., & Oksanen, T. (2022). Condition monitoring using convolutional neural network in agricultural machinery-use case: disc mower. *IFAC-PapersOnLine.* 55(32):235-240.
[27] Kang, J. M., Zhang, H., Zhang, G. H., Du, H. Y., Peng, Q. J., Song, Y. M. (2020). Aerodynamic characteristics of residual film materials and test of membrane separation device (残膜物料气动特性及膜杂分离装置试验). *Journal of Chinese Agricultural Mechanization.* 41(01):167-172.
[28] Ke, Z. R. (2023). Design of on-line monitoring system for field operations of the tooth chain type residual film recovery machine (齿链式残膜回收机田间作业在线监测系统设计). [Master's thesis]. Ningxia University.
[29] Kou, J. L., Wang, J. K., Wang, L., Zhao, Y. M. (2023). Integrating clamping finger-chain residual film recycling and straw crushing return to cotton field (棉田夹指链式残膜回收-秸秆粉碎还田联合作业装置). *Transactions of the Chinese Society of Agricultural Engineering.* 39(23):14-22.
[30] Li, D., Zhao, W. Y., Xin, S. L., Liu, X. L., Qu. H., Xu, Y. (2020). Current situation and prospect of recycling technology of farmland residual film (农田残膜回收技术研究现状与展望). *Journal of Chinese Agricultural Mechanization.* 41(05):204-209.
[31] Li, K. K. (2023). *Theoretical Analysis and Experimental Research on the Stripping and Impurity Removal Device for Spring-Tooth Residual Plastic Film Collector (弹齿式残膜回收机脱膜除杂装置理论分析与试验研究).* [Master's thesis]. Shandong University of Technology.
[32] Li, T., Zhang, H. C., Wang, X. Y., Wang, X. X., Liu, X. F., Liu, C.H., Kang, J. M., Li, G. M. (2025). Development of Self-propelled Combined Operation Machine for Cotton Stalk Baling and Residual Film Packing (自走式棉秆打捆-残膜打包联合作业机研制). *Transactions of the Chinese Society for Agricultural Machinery.* 56(07):424-433.

[33] Liu, E. S. (2021). *Optimal Design of Residual Film Recovery Machine with Comb-Tooth Film Lifting and Pneumatic Film Stripping (梳齿起膜-气吹脱膜式残膜回收机优化设计).* [Master's thesis]. Tarim University.
[34] Liu, J. H., Quan, L. Z. (2025). Design and experiment of a vibratory separation device for residual plastic film and soil (残膜-土壤振动分离装置设计与试验). *Agricultural Engineering and Equipment.* 52(03):1-4.
[35] Liu, X. H., Tian, X. L., Zhao, Y., Li, Y. C., Ma, H. Z. (2024). Research on Film Collection Device of Residual Film Recycling Machine (残膜回收机集膜装置研究). *Agricultural Engineering.* 14(01):5-14.
[36] Liu, Y. L., Zhang, T. Y., Jiang, M., Li, B., Song, J, L. (2022). Review on Non-destructive Detection Methods of Grape Quality Based on Machine Vision (基于机器视觉的葡萄品质无损检测方法综述). *Transactions of the Chinese Society for Agricultural Machinery.* 53(S1):299-308.
[37] Lu, J. D., Zhai, Z. Q., Meng, Q. J., Miao, L. P., Chen, Y. Zhang, R. Y. (2025). Surface Residual Film Recognition Method Based on Vehicle-mounted Imaging and Deep Convolutional Neural Networks (基于车载成像与深度卷积神经网络的地表残膜识别方法). *Transactions of the Chinese Society for Agricultural Machinery.* 56(05):26-37+70.
[38] Luo, W. J., Zhang, H. C., Liu, X. F., Zhang, L., Zhou, X. (2024). Research of combined operation machine for secondary throwing straw crushing and residual film recovery (二次抛送式秸秆粉碎残膜回收联合作业机研究). *Xinjiang Agricultural Sciences.* 61(S1):142-146.
[39] Lamtai, A., Elkoun, S., Robert, M., Mighri, F., & Diez, C. (2023). Mechanical recycling of thermoplastics: A review of key issues. *Waste*. 1(4):860-883.
[40] Lubongo, C., Alexandridis, P. (2022). Assessment of performance and challenges in use of commercial automated sorting technology for plastic waste. *Recycling*. 7(2):11.
[41] Ma, Z. (2024). *Design and test of wind power-vibration type residual film-impurity (风振式残膜杂质分离装置设计与试验)*. [Master's thesis]. Shenyang Agricultural University.
[42] Meng, Q. J., Zhai, Z. Q., Zhang, L. P., Lu, J. D., Wang, H. T., Zhang, R. Y. (2025). Recognition Method of Cotton Field Surface Residual Film Based on Improved YOLO 11 (基于改进 YOLO11 的棉田地表残膜识别方法). *Transactions of the Chinese Society for Agricultural Machinery.* 56(05):17-25+48.
[43] Milioto, A., Lottes, P., & Stachniss, C. (2018). Real-time semantic segmentation of crop and weed for precision agriculture robots leveraging background knowledge in CNNs. *IEEE International Conference on Robotics and Automation (ICRA)*, 2229-2235.
[44] Murad, N. Y., Mahmood, T., Forkan, A. R. M., Morshed, A., Jayaraman, P. P., & Siddiqui, M. S. (2023). Weed detection using deep learning: A systematic literature review. *Sensors.* 23(7): 3670.
[45] Madrid, B., Wortman, S., Hayes, D. G., DeBruyn, J. M., Miles, C., Flury, M. (2022). End-of-life management options for agricultural mulch films in the United States—a review. *Frontiers in Sustainable Food Systems*. 6:921496.
[46] Martín Martín, A., Orduna-Malea, E., Thelwall, M. (2018). Google Scholar, Web of Science, and Scopus: A systematic comparison of citations in 252 subject categories. *Scientometrics*. 116: 1-30.
[47] Montoya, F. G., Alcayde, A., Baños, R., et al. (2018). A fast method for identifying worldwide scientific collaborations using the Scopus database. *Telematics and Informatics*. 35(1): 168-185.
[48] Niu, A., Wu J., Zhao X. (2023). Infrared Spectrum Analysis of Degradation Characteristics of PPC Plastic Film Under Different Covering Methods (不同覆盖方式下 PPC 地膜降解特性红外光谱分析). *Spectroscopy and Spectral Analysis.* 43(02):533-540.
[49] Niu, Q., Ji, C., Zhao, Y., Chen, X., Zheng, X., Li, H. (2017). Design and Experiment on Collecting and Separating Device for Strip Plastic Film Baler (条状残膜打捆机集膜分离装置设计与试验). *Transactions of the Chinese Society for Agricultural Machinery.* 48(05):101-107.
[50] Nukala, S. G., Kong, I., Kakarla, A. B., Kong, W., & Kong, W. (2022). Development of wood polymer composites from recycled wood and plastic waste: thermal and mechanical properties. *Journal of Composites Science*. 6(7):194.
[51] Peng, X. B. (2021). *Design and experiment of alternated multi-sieve device with function of separating soil from residual film mixture (交替多筛式残膜混合物土膜分离装置设计与试验).* [Master's thesis]. Shihezi University.
[52] Reid, J. F., Zhang, Q., Noguchi, N., Diskin, M. D. (2000). Agricultural automatic guidance research in North America. *Computers and Electronics in Agriculture.* 25(1-2):155-167.
[53] Ribeiro, L. S., Stolz, C. M., Amario, M., Silva, A. L. N. D., & Haddad, A. N. (2023). Use of post-consumer plastics in the production of wood-plastic composites for building components: a systematic review. *Energies*. 16(18):6549.

[54] Ruj, B., Pandey, V., Jash, P., & Srivastava, V. K. (2015). Sorting of plastic waste for effective recycling. *International Journal of Applied Science and Engineering Research.* 4(4):564-571.

[55] Shen, S. L., Zhang, J. X., Jiang, Y. X., Wang, Y. C., Liu, X. F., Li, J. M., Dong, W. H. (2024). Tensile Properties of Residual Film in Tillage Layer Based on Discrete Element Method (基于离散元法的耕层残膜拉伸性能研究). *Transactions of the Chinese Society for Agricultural Machinery.* 55(07):132-141.

[56] Shi, M. W., Wang, M. G., Wang, W., Li, Z. G., Wang, L., Zhang, H. J. (2025). Design and Experiment of Integrated Machine for Cotton Stalk Crushing and Residual Film Recycling and Baling (棉秆粉碎-残膜回收打捆一体机设计与试验). *Transactions of the Chinese Society for Agricultural Machinery.* 56(12):397-406.

[57] Shi, Z., Zhang, X., Cheng, J., Zhou, X., Zhang, C. (2023). Design and test of film transfer and unloading device of vertical double-row chain residual film recycling machine (垂直双排链式残膜回收机输膜卸膜装置设计与试验). *Agricultural Research in the Arid Areas.* 41(03):257-265.

[58] Song, J. H., Zhao, L. Y., Wu, M. Q. (2009). Research and Design of Intelligent Operation Area Measurement System for Agricultural Machinery (农机智能作业面积测量系统研究与设计). *Farm Machinery.* (11):92-94.

[59] Song, Z. T., Guo, J. J., Wen, H. J. (2023). Design and test of film-hanging conveyor belt of rotary-tooth residual film recycling machine (旋齿式残膜回收机挂膜输送带设计与试验). *Xinjiang Agricultural Mechanization.* (04):34-37.

[60] Silwal, A., Parhar, T., Yandun, F., Baweja, H., & Kantor, G. (2021). A robust illumination-invariant camera system for agricultural applications. *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 3292-3298.

[61] Sarpong KA, Adesina FA, DeVetter LW, Zhang K, DeWhitt K, et al. (2024). Recycling agricultural plastic mulch: limitations and opportunities in the United States. *Circular Agricultural Systems* 4: e005.

[62] Shapiro, M., Galperin, V. (2005). Air classification of solid particles: a review. *Chemical Engineering and Processing: Process Intensification.* 44(2):279-285.

[63] Turku, I., Keskisaari, A., Kärki, T., Puurtinen, A., & Marttila, P. (2017). Characterization of wood plastic composites manufactured from recycled plastic blends. *Composite Structures*. 161:469-476.

[64] Wang, D. Y., Zhang, R. Y., Duan, H. W., Zhai, Z. Q., Fu, Y. X., Meng, Q. J. (2024). Design and Research of Effective Working Area Monitoring System for Residual Film Recycling Machine (残膜回收机有效作业面积监测系统设计研究). *Journal of Agricultural Mechanization Research.* 47(01):54-60.

[65] Wang, G., Wang, Q., Tian, Z. H., Ji, D., Liu, F. B. (2026). Research Progress of Farmland Plastic Film Recycling Device (农田残膜回收装置研究进展). *Journal of Agricultural Mechanization Research.* 1-8[2026-03-30].

[66] Wang, J., Ghimire, R., Fu, X., Sainju, U. M. Liu, W. Z. (2018). Straw mulching increases precipitation storage rather than water use efficiency and dryland winter wheat yield. *Agricultural Water Management.* 206:95-101.

[67] Wang, K. (2018). *Design and study on standing cotton stalks raking-film machine with wide folding and monomer profiling (宽幅折叠单体仿形直立棉秆搂膜机设计与研究).* [Master's thesis]. Shihezi University.

[68] Wang, P. Z., Wu, X. M., Zhang, F. G., Huang, H. G., Yu, L. H., Nie, Y. (2017). Design and performance test of comb-type automatic profiling residual film collecting machine (梳齿式自动仿形残膜捡拾机设计及性能试验). *Acta Tabacaria Sinica.* 23(03):56-62.

[69] Wang, X., Zhang, T., Li, S. J., Sun, W., Wang, L. J. (2017). Experimental study on increasing yield and efficiency of mechanical potato planting with whole black film mulching technology (黑色全膜覆盖马铃薯机械种植增产增效试验研究). *Journal of Chinese Agricultural Mechanization.* 38(06):89-93.

[70] Wei, B. Q., Shan, Z. H. (2019). Types of Mulch and Research Progress (地膜类型及研究进展). *West Leather.* 41(17):53-55.

[71] Wei, Z. C., Li, H. W., Sun, C. Z., Li, X. Q., Liu, W. Z., Su, G. L., Wang. F. M. (2018). Improvement of potato harvester with two segment of vibration and wave separation (振动与波浪二级分离马铃薯收获机改进). *Transactions of the Chinese Society of Agricultural Engineering.,* 34(12):42-52.

[72] Wen, H., Gou H., Chen X. (2021). Development of a two-stage chain-plate combined machine for straw crushing and plastic-film recovery (二阶链板式秸秆粉碎地膜回收联合作业机的研制). *Agricultural Development & Equipment,* 235(07):40-41.

[73] Wu, Z. X., Ma, S. H., Ren, W., Han, X. J., Wang, K. L., Lan, W. Q. (2025). Research status and prospects of domestic residual film recycling machine pickup device (国内残膜回收机捡拾装置研究现状及展望). *Xinjiang Agricultural Mechanization.* (04):40-44+49.

[74] Xia, Y., Liu, Z. Y., Zhu, C. (2020). Mechanical Properties Repair Method and Processing Technology of Waste Plastic Regeneration Granulation (废旧塑料再生造粒力学性能修复方法及加工工艺). *China Resources Comprehensive Utilization.* 38(03):96-98.

[75] Xie, J. H., Liu, W., Cao, S. L., Huang, W. R., Zhang, J., Li, Y. Z., Meng, Q. H. (2025). Design and Test of Countercurrent Hook-type Residual Film Mixture Cleaning and Separation Device (逆流钩拽式残膜混合物清洗分离装置设计与试验). *Transactions of the Chinese Society for Agricultural Machinery.* 56(06):397-408.

[76] Xie, J. H., Li, Y. Z., Liu, Y. C., Zhang, J., Du, Y. K., Shi, X. (2024). Design and Test of Segmented Drum Pneumatically Assisted Potosia brevitarsis Larva Residual Film Mixture Separation Device (分段滚筒式气力辅助白星花金龟幼虫转化残膜混合物分离装置设计与试验). *Transactions of the Chinese Society for Agricultural Machinery.* 55(11):329-341+428.

[77] Xu, B. (2014). *Research on Real-time Measurement of Torque and Speed of Transmission Shaft of Micro Combine (微型联合收割机传动轴转矩转速实时测量装置的研究).* [Master dissertation]. Southwest University.

[78] Xue, D. Q., Dong, Z. S., Zhang, J. X. (2024). Design and Experiment of Stress and Strain Monitoring System for Key Components of Drum Film Recovery Machine (滚筒式残膜回收机关键部件应力应变监测系统设计与实验). *Journal of Nanyang Institute of Technology*. 04.009.

[79] Yang, L., Liu, J., Zhang, D. X., Hou, S. L., Xu, F. (2010). Cotton seedling-stage mulch film recycler (棉花苗期地膜回收机设计与试验). *Transactions of the Chinese Society for Agricultural Machinery.* 41(S1):73-77.

[80] You, Z. Y., Hu, Z. C., Wu, H. C., Zhang, Y. P., Yan, J. C., Yan, W., Zhou, X. X. (2017). Design and experiment of 1MCDS-100A typed shovel-sieve residual film recovery machine (1MCDS-100A 型铲筛式残膜回收机的设计与试验). *Transactions of the Chinese Society of Agricultural Engineering.* 33(09):10-18.

[81] You, Z. Y., Wu, H. C., Chen, Y. Q., Hu, Z. C., Tan, L. K., Peng, B. L., Zhang, J. L. (2018). Design and experiment on double-sieve-driving apparatus for film-soil separation and transportation (双筛体驱振式膜土分离与输送装置设计与试验). *Journal of Chinese Agricultural Mechanization.* 39(11):4-11.

[82] Yu, Y. H., Chen, X. G., Wen, H. J. (2016). Development and experiment of straw chopping and plastic filmstrip-collection combined machine (秸秆粉碎与残膜集条联合作业机的研制与试验). *Transactions of the Chinese Society of Agricultural Engineering.* 32(24):1-8.

[83] Yang, S. M., Wang, B. X., Ru, S. F., Chen, X. G., Yan, L. M., & Wu, J. L. (2024). Review of agricultural plastic film recycling equipment from China (中国农田农膜回收装备综述). *INMATEH-Agricultural Engineering*. 74(3):683-698.

[84] Zhai, Z. Q., Chen, X. G., Qiu, F. S., Meng, Q. J., Wang, H. Y., Zhang, R. Y. (2022). Detecting surface residual film coverage rate in pre-sowing cotton fields using pixel block and machine learning (基于像素块和机器学习的播前棉田地表残膜覆盖率检测). *Transactions of the Chinese Society of Agricultural Engineering.* 38(06):140-147.

[85] Zhan, Y., Zheng, X., Chen, X. G., Niu, Q., Ji, C., Zhou, D. X. (2017). Design and test of CMJY-1500 type plastic film residue collecting and balling machine (CMJY-1500 型农田残膜捡拾打包联合作业机设计与试验). *Transactions of the Chinese Society of Agricultural Engineering.* 33(05):1-9.

[86] Zhang, D. H., Ma, Y. H., Guan, F., Wang, Q., Zheng, T. (2018). Agricultural Machinery Operation Area and Track Monitoring Management System Based on GPS (基于 GPS 的农机作业面积与轨迹监测管理系统). *Geospatial Information.* 16(02):68-70+11.

[87] Zhang, D., Liu, H. B., Ma, Z. M., Tang, W. X., Wei, T., Yang, H. D., Li, J. G., Wang, H. Y. (2017). Effect of Residual Plastic Film on Soil Nutrient Contents and Microbial Characteristics in the Farmland (残膜对农田土壤养分含量及微生物特征的影响). *Agricultural Engineering Technology.* 39(14):49-50.

[88] Zhang, J., Yang, W. Z., Xie, X. Y., Mu, D. H., Zhang, J. (2013). Design and Experimental Research on Separating Used Plastic Film from Soil and Transporting Used Plastic Film Mechanism (膜土分离与输送装置的设计及试验研究). *Agricultural Science & Technology and Equipment.* (02):29-30+33.

[89] Zhang, L., Wu, B. T., Xie, J. X., Zhang, H. D., Huang, J. Q., Li, M. (2020). Design and test on agricultural machinery operation area management system of Beidou navigation (北斗导航农机作业面积管理系统设计与试验). *Journal of Chinese Agricultural Mechanization.* 41(12):139-146.

[90] Zhang, X. J., G, L., Shi, Z. L., Yan, J. S., Liu, X. P., Zhang, C. S., Liu, L. (2024). Structural optimization and test of the roll type tillage residual film recovery components using FEM-SPH coupling (基于 FEM-SPH 耦合的卷辊式耕层残膜回收部件结构优化与试验). *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE).* 40(10): 55-65.

[91] Zhang, X. J., Huang, S., Jin, W., Yan, J. S., Shi, Z. L., Zhou, X. C., Zhang, C. S. (2021). Identification Method of Agricultural Film Residue Based on Improved Faster R-CNN (基于改进 Faster R-CNN 的农田残膜识别方法). *Journal of Hunan University (Natural Sciences).* 48(08):161-168.

[92] Zhang, X. J., Wu, C. W., Wang, W., Ma, S. H., Wang, X. F. (2008). Design and Experiment on the Zigzag Scraper Transportation Device for Remnant Plastic Film and Stubble (锯齿刮板式残膜根茬输送装置设计与试验). *Transactions of the Chinese Society for Agricultural Machinery.* (09):49-51.

[93] Zhang, X. J., Wu, C. W., Wang, X. D., Ma, S. H., Wang, X. F. (2007). Motion simulation and analysis of separating sieve mechanism for scrap plastic film (残膜分离筛机构的运动仿真与分析). *Transactions of the Chinese Society of Agricultural Engineering.* (07):113-116.

[94] Zhang, Y. M., Shen, L. X. (2018). Pollution of Residual Film in Farmland Soil and Countermeasures (农田土壤残膜污染及防治对策). *Tianjin Agricultural Sciences.* 24(02):86-90.

[95] Zhang, Z. (2023). *Study on the mechanism of picking up and recovering the residual film of sowing layer based on arc-shaped nail-tooth roller (基于弧钉齿滚筒的播种层残膜捡拾回收机理研究).* [Doctoral dissertation]. Shihezi University.

[96] Zhang, Z., Li J., Wang X., Zhao Y., Xue S., Su Z., Liang J. (2023). Design and test of 1SMB-3600A type fragmented mulch film collector for sowing layer soil (1SMB-3600A 型播种层碎膜捡拾机设计与试验). *Soil and Tillage Research.* 225:105555.

[97] Zhao, Y. D., Tu, J. Y. (2018). Intelligent Surveying and Mapping System of Forest Inspection Based on Beidou Satellite (基于北斗卫星的林业巡检智能测绘系统). *Transactions of the Chinese Society for Agricultural Machinery.* 49(07):177-185.

[98] Zheng, S. Q. (2020). *Design and experiment of spring tooth type rotary unloading mulch film residue collector (弹齿式旋卸残膜捡拾机设计与试验).* [Master's thesis]. Shihezi University.

[99] Zhou, L., Tang, W., Xie, J. H. (2019). Present Research Situation and Existing Problems of Residue Film Collectors (残膜捡拾机研究现状及存在问题). *Xinjiang Agricultural Mechanization.* (05):13-15+32.