Current status of orchard mechanization technologies and key development priorities in the 15th Five-Year Plan period

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Abstract: Orchard mechanization technologies are a key driver of progress in the fruit industry. Their advancement enhances operational efficiency, reduces labor intensity, and minimizes the waste of agricultural inputs. This study reviewed the current regional status of orchard mechanization in China and introduced advanced technologies for mechanized orchard production. The whole mechanized production technology for orchard was analyzed across four core dimensions, including digital orchard scenario reconstruction, autonomous navigation, under-canopy mechanized operations, and tree-oriented mechanization technologies. Furthermore, a comparative analysis was conducted on cutting-edge technologies used in similar types of equipment across four critical operational stages (power platforms, weeding, plant protection, and harvesting), and their respective advantages and limitations in various application contexts were also analyzed. Then, several key problems hindering further development were identified, including limited standardization for mechanization compatibility, significant equipment shortages in hilly and mountainous areas, insufficient integration of advanced technologies into orchard machinery, an aging and undereducated rural workforce, and an underdeveloped system of socially-supported agricultural machinery services. Finally, in view of these problems, six strategic development priorities for the orchard mechanization in the 15th five-year plan period were put forward, including promoting the integration of standardized orchard construction and agricultural machinery systems, overcoming bottlenecks of mechanized equipment, upgrading intelligent equipment in gentle slope orchards, strengthening the application of intelligent technologies in modern standardized orchards, attracting and training highly educated fruit professionals, and strengthening the construction of socialized agricultural machinery service systems.

Keywords: orchard mechanization, intelligent, production management, main problems, development focus
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1 Introduction

Since 1993, when China became the world's largest fruit-producing country, its fruit cultivation area and total output have grown rapidly. Today, fruit production ranks as the third-largest sector in China's crop industry, following grains and vegetables. According to the China Statistical Yearbook, by 2022, the national fruit cultivation area had reached approximately 13 million hectares, with a total output of 313 Mt[1]. A Strategic Study on the High-Quality Development of China's Fruit Industry further reports that, as of 2020, China led the world in both cultivation area and production volume for major fruits such as citrus, watermelon, apple, melon, peach, pear, and strawberry. However, in terms of yield per unit area, China ranked only between sixth and tenth globally, indicating that future productivity gains will largely depend on the adoption of advanced production technologies, particularly full-process mechanization.

Hilly and mountainous regions are critical to China's agricultural output, especially for fruit cultivation, which accounted for approximately 8.1 million hm^2 in these areas by 2022[2]. According to the 2021 Annual Report on Agricultural Mechanization Statistics, staple grain crops such as wheat, rice, and maize have already achieved high mechanization levels, with national comprehensive mechanization rates exceeding 85%. In contrast, the mechanization level of orchards remains substantially lower, with a national average of only around 30%. This sharp disparity highlights not only a significant technological gap between fruit and grain production systems but also considerable potential for advancing mechanization technologies tailored to the complex terrain of orchards[3].

Orchard production involves a diverse array of operations, including soil preparation, canopy management, pest and disease control, irrigation, and harvesting. Key tasks such as power-driven operations, ridge formation, weeding, soil mounding, fertilization, pruning, thinning of flowers and fruits, bagging, pollination, crop protection, and physical pest control are integral to these processes[4]. In some areas—particularly soil preparation, crop protection, and irrigation—a transition from conventional to intelligent mechanized systems has already taken place. However, canopy management and harvesting remain highly labor-intensive and technically challenging, with mechanization levels still

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relatively low.

In recent years, successive releases of China's No. 1 Central Document—the nation's top-level policy directive on agriculture and rural development—have strongly emphasized the acceleration of agricultural mechanization and the adoption of intelligent technologies. Sustained policy support, coupled with targeted subsidies, has significantly facilitated the dissemination and application of relevant mechanization technologies within the fruit production sector.

2 Overall level of orchard mechanization in China

The mechanization level in hilly and mountainous orchards remains substantially lower than that in plain regions. Detailed quantitative data are provided in Figure 1.

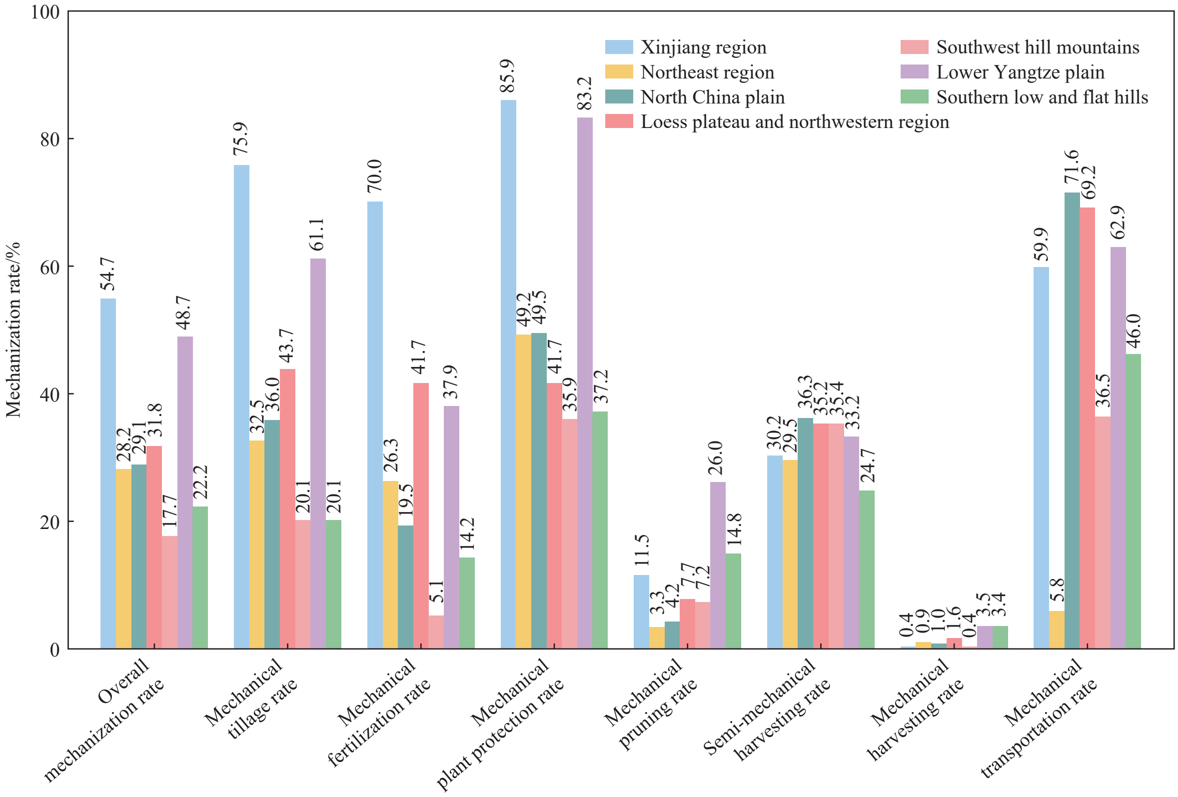


Figure 1 Comparative analysis of orchard mechanization levels across regions in China

According to the data presented in Figure 1, Xinjiang and the Yangtze River Delta Plains serve as representative examples of flatland regions. Supported by favorable agricultural policies and relatively advanced economic development, these areas exhibit well-planned orchard layouts and robust mechanization infrastructure. As a result, their overall levels of orchard mechanization are significantly higher than those observed in other parts of the country. In contrast, mechanization in hilly and mountainous regions remains substantially underdeveloped due to several interrelated constraints. The first challenge lies in the poor mechanization compatibility of existing orchards. Many plantations in these regions are traditional and long-established, characterized by high planting densities and irregular spatial arrangements, which hinder the entry and maneuverability of mechanized equipment. The second issue is the shortage of skilled machine operators, often resulting in improper equipment usage, inefficient operations, and inadequate diagnostic and maintenance capabilities. The third concern pertains to the relatively low technological sophistication of available machinery; many production stages lack appropriate equipment, and the operational quality of key mechanized processes urgently requires improvement. In addition, there is a significant shortage of power platforms suited to the complex terrain of these areas.

Improving orchard mechanization can substantially reduce production costs while enhancing operational efficiency. For instance, in Xinyi, Jiangsu Province, traditional pear orchards with a mechanization rate of approximately 30% report labor costs accounting for 51.2% of total production expenses. By comparison, at the Yejia Pear Orchard in Taixing, where mechanization reaches 80%, labor costs decline to 38.9%, resulting in an annual saving of 11 240 CNY per hectare in labor expenditures.

3 Advanced technologies in orchard mechanization

3.1 Digital orchard scenario reconstruction

A fundamental prerequisite for autonomous orchard operations is enabling machines to effectively perceive and interpret their surrounding environment[5]. Given the narrow aisles, variable lighting conditions, and frequent occlusions that characterize orchards as unstructured environments, exclusive reliance on vision-based simultaneous localization and mapping (SLAM) techniques faces notable limitations. Consequently, Light Detection and Ranging (LiDAR) technology—which provides accurate distance measurements and is largely unaffected by lighting variability—has become the mainstream solution in orchard navigation and mapping.

In the global agricultural robotics community, it is widely recognized that adapting and enhancing open-source SLAM frameworks—such as Gmapping, Hector-SLAM, LOAM, and Cartographer—is essential to addressing the unique challenges of agricultural environments. International research efforts primarily concentrate on algorithmic innovation and multi-sensor integration. For instance, Lepej et al.[6] proposed a novel low-error localization algorithm tailored to the challenges of 2D LiDAR in outdoor environments. Habibie et al.[7] conducted comparative analyses of the Gmapping and Hector-SLAM algorithms within virtual orchard settings using the Gazebo simulation platform, evaluating mapping accuracy. Marden et al.[8] applied the Extended Kalman Filter (EKF)-SLAM framework to vineyard scenarios, achieving improvements in both localization and mapping performance. Meanwhile, the Hector-SLAM method developed by Kohlbrecher et al.[9] demonstrated reduced hardware dependency.

Chinese research teams have also made notable progress in algorithm optimization and environment-specific adaptations. For example, Liu et al.[10] quantitatively evaluated the mapping accuracy of the Cartographer algorithm. Ji et al.[11] employed the 3D LOAM framework and introduced prior maps to enhance localization and mapping stability. Wu et al.[12] proposed a multi-sensor fusion approach that uses fruit targets as landmarks, integrating LiDAR, GNSS, and inertial navigation system (INS) data to enhance perception robustness.

As a complement to ground-based real-time mapping, unmanned aerial vehicles (UAVs) have become an important tool for aerial surveying and 3D reconstruction, offering an effective means of acquiring large-scale digital orchard models. In this domain, international studies have widely adopted deep learning techniques. For example, Ocer et al.[13] utilized the Mask R-CNN model to efficiently extract and count trees from UAV imagery, while Onishi et al.[14] employed convolutional neural networks (CNNs) for high-precision classification of tree species, thereby providing valuable data support for precision orchard management.

The core challenges of orchard environments lie in their repetitive structures and lack of distinctive visual features. To overcome these limitations, researchers have primarily pursued two technical pathways: improving algorithmic robustness and leveraging multi-sensor fusion. By integrating LiDAR's precise ranging capabilities, the attitude estimation of inertial measurement units (IMUs), the absolute positioning of global navigation satellite systems (GNSS), and the rich visual context provided by cameras, it is possible to construct localization systems that are significantly more reliable than those based on any single sensor modality.

3.2 Autonomous navigation technology based on power platforms

Autonomous navigation serves as the foundation for orchard robots to perform all tasks, and its reliability directly determines the success or failure of the automation system.

3.2.1 Power machinery for orchard operations

Orchard tractors, as the primary power platforms, reflect distinct design philosophies shaped by differing market demands and levels of technological maturity[15,16]. International mainstream models are typically highly specialized, engineered for use in well-developed, high-density orchards, and emphasize enhanced maneuverability and increasing electrification. In contrast, Chinese orchard tractors are generally designed with a focus on multifunctionality, durability, and cost-efficiency to accommodate diverse operational needs and varying orchard conditions. Table 1 presents a comparative overview of representative power machinery currently utilized in both domestic and international contexts.

Table 1 Typical power machinery for orchard applications

Category	Brand/Manufacturer	Model name	Functional overview
Traditional mechanical drive	New Holland	T4F/V/N Orchard tractor	Equipped with SuperSteer™ ultra-tight-turn front steering axle for exceptional maneuverability in narrow rows; VisionView™ cab platform offering panoramic visibility; ergonomically designed Command Arc control console; and Blue Cab™ 4 dual-stage air filtration system for operator comfort and safety.
Traditional mechanical drive	CLAAS	NEXOS230	Narrow-track design with an overall width below 1 m for ultra-narrow-row orchards; incorporates Smart Stop automatic clutch engagement and Dynamic Steering technology for enhanced precision and maneuverability.
Traditional mechanical drive	Lovol Heavy Industry	M604	Representative domestically produced orchard tractor featuring a compact chassis for enhanced maneuverability; high-torque engine for robust performance; optimized low fuel consumption; and modular configuration options to accommodate diverse and complex orchard operations.
Intelligent control machinery	Fendt	FendtONE	Features an integrated electrification and intelligent control architecture via the FendtONE digital management platform, providing real-time remote telemetry, mission planning, precision automated steering, and seamless data integration to enhance operational accuracy and flexibility in orchard environments.
New energy machinery	Kubota	X-Tractor	Features a hybrid propulsion system integrating photovoltaic solar panels with plug-in battery charging; employs a triangular tracked undercarriage for superior traction and terrain adaptability; modular architecture supports soil tillage, seeding, fertilization, and harvesting tasks.
New energy machinery	John Deere	Gridcon	Utilizes cable-supplied power for continuous, unattended field operations; incorporates an autonomous navigation system and remote-control interface; specifically engineered for large-scale precision agriculture applications.
New energy machinery	Fendt	e100 vario	The first mass-produced all-electric tractor in the agriculture sector, designed to meet stringent European regulations on low carbon emissions and reduced noise levels, offering zero-emission operation without compromising performance.
New energy machinery	National Agricultural Machinery Equipment Center	ET1004-H	Features an integrated intelligent vehicle control system paired with a hydrogen fuel cell powertrain, enabling fully electronic control of steering, gear shifting, and propulsion.
New energy machinery	Zoomlion	T300	Developed specifically for orchard applications; features a peak power output of 300 kW, delivers power output on par with conventional tractors, and is optimized for high-traction, heavy-load operations.
New energy machinery	Minsk Tractor Works (MTZ)	Belarus-3023	Employs a parallel hybrid drivetrain combining a diesel engine with an electric motor, delivering up to 225 kW of peak power; capable of seamless switching between conventional tractor mode and hybrid operation.
New energy machinery	YANMAR	Solis5015	Engineered for small-scale farm and orchard operations; features a hybrid powertrain with both conventional and electric drive modes, and supports plug-in battery charging.

3.2.2 Single-modal navigation technology

(1) Satellite-based positioning and navigation

The Global Navigation Satellite System (GNSS) determines the absolute position of a device by receiving signals from multiple satellites. When augmented with Real-Time Kinematic (RTK) corrections, GNSS can achieve centimeter-level positioning accuracy in open environments. Han et al.[17] developed an autonomous driving system based on GNSS-RTK, facilitating the implementation of automated operations in agricultural settings. Huang et al.[18] integrated the RTK-based BeiDou Navigation Satellite System (BDS) with an Inertial Navigation System (INS), employing a Kalman filter to effectively fuse the two data sources and compensate for temporary GNSS signal loss. While GNSS provides high-precision, all-weather positioning and performs reliably in open-field scenarios, its signal is highly susceptible to occlusion from orchard canopies. Therefore, GNSS alone is insufficient for robust navigation in orchard environments and must be complemented by other sensing modalities.

(2) Vision-based localization and navigation

Vision-based navigation extracts navigational cues from environmental imagery captured by onboard cameras, using image processing and computer vision algorithms. Opiyo et al.[19] employed precise image segmentation techniques to extract path information, while Radcliffe et al.[20] developed a machine vision system using multispectral cameras to guide autonomous unmanned ground vehicles. Nie et al.[21] applied the HSV color model to mitigate interference from ground-level weeds. The advantages of vision-based navigation include low sensor cost and the ability to extract rich environmental features, particularly object contours. However, its performance is highly sensitive to variations in lighting conditions, which can compromise system reliability.

(3) LiDAR-based localization and navigation

Light Detection and Ranging (LiDAR) technology determines distances to surrounding objects by emitting and receiving laser pulses, generating a point cloud representation of the environment. Mengoli et al.[22] used 3D LiDAR data to extract tree trunk features and applied the Hough transform for orchard row fitting. Jones et al. designed a multi-beam LiDAR navigation system for heavy-duty transport platforms operating in kiwifruit orchards. Xu et al.[23] significantly reduced odometry drift errors by optimizing simultaneous localization and mapping (SLAM) algorithms. The primary strengths of LiDAR-based navigation include high-precision ranging, robustness against environmental interference, and insensitivity to lighting variability. However, its limitations include relatively high cost and reduced performance under adverse weather conditions such as rain, snow, or fog. Additionally, in orchards with dense or irregular canopies, accurate extraction of trunk features may prove challenging.

3.2.3 Multi-sensor fusion localization and navigation

The inherent limitations of single-sensor systems highlight the necessity for multi-sensor fusion technologies. By integrating the complementary advantages of different sensing modalities, more robust and reliable localization and navigation systems can be achieved—a consensus increasingly embraced by both academia and industry. The core principle is to “leverage strengths and compensate for weaknesses”: when GNSS signals are lost, the system can rely on LiDAR and inertial measurement unit (IMU) data; when wheel slip causes odometry drift, IMU inputs can provide corrective stabilization. Velasquez et al.[24] applied an Extended Kalman Filter (EKF) to fuse LiDAR and IMU data, effectively addressing navigation issues in the absence of GNSS signals. Lyu et al.[25] proposed a loosely coupled EKF-based algorithm capable of dynamically assessing and rejecting invalid sensor inputs, thereby enhancing system reliability. Ni Zhikang et al.[26] utilized a factor graph optimization framework to integrate 3D LiDAR with RTK-GNSS, incorporating global positioning constraints to mitigate cumulative errors in simultaneous localization and mapping (SLAM). As multi-sensor fusion technologies continue to mature, they are transitioning from experimental research to real-world deployment. For instance, FarmX’s OrchardPilot autonomous driving suite is specifically designed for orchard environments with limited GPS availability. Its core technology, known as Perceptive Navigation®, claims to enable precise autonomous steering without reliance on GPS, Wi-Fi, or base stations. Instead, it leverages artificial intelligence in combination with multiple onboard sensors—including cameras and LiDAR—to achieve robust perception and control in complex orchard scenarios.

3.3 Mechanized production under orchard canopies

Soil cultivation, nutrient management, and weed control are fundamental operations in orchard production. The level of mechanization and automation in these tasks critically influences production costs as well as the environmental sustainability of orchard systems.

3.3.1 Ditching fertilization and fertigation integration

In the domain of ditching fertilization and fertigation integration, domestic and international research efforts exhibit distinct focal points. In China, studies primarily concentrate on the innovation and refinement of mechanized equipment, aiming to address practical challenges related to operational usability and effectiveness across diverse terrains. For example, to overcome the limitations of conventional fertilization machines, the dual-shaft helical ditcher—recognized for its uniform soil mixing and significant drag reduction—has emerged as an effective alternative. Professor Zhou Bo from Huazhong Agricultural University designed a dual-shaft helical ditcher that effectively resolves torque imbalance and deviation issues commonly encountered in single-shaft systems. Meanwhile, the Nanjing Agricultural Mechanization Research Institute has incorporated ground contour following and intelligent depth control functions into helical fertilization technologies, thereby improving operational stability and precision.

Internationally, fertigation technology has progressed into phases characterized by precision and intelligence, with efforts largely oriented toward the development of data-driven, closed-loop production management systems. In water-scarce countries such as Israel, the adoption rate of fertigation technologies has reached approximately 90%. The Israeli company Eldar-Shany offers several fertigation systems: Fertimix, which utilizes tank mixing and supports flow rates from 6.5 to 55 m^3/h; Fertigal, which employs inline mixing for flow rates between 9 and 225 m^3/h; and Fertijet, which connects to irrigation systems via bypass lines and is compatible with various irrigation scales[27]. Additionally, Netafim’s high-end NetaJet series and solutions from DuPont represent mature fertigation technologies that are widely deployed across farms of varying sizes[28].

In China, systematic research and innovation in fertigation integration are accelerating, leading to the emergence of numerous novel solutions. Luo et al.[29] developed a cost-effective fertigation system based on constant-pressure water supply and remote control, enabling dynamic adjustment of fertilizer ratios according to main pipeline flow. Huang et al.[30] designed a circulating fertigation irrigation system capable of real-time control of electrical conductivity (EC) and pH values, while also incorporating nutrient recovery functions. Zhang et al.[31] proposed an Internet of Things (IoT)-based fertigation system that integrates sensors, data processing, and intelligent control. Zhao et al.[32] developed greenhouse fertigation equipment capable of dynamically regulating water and fertilizer supply based on real-time monitoring of crop growth environments. Furthermore, the Jiangsu Academy of Agricultural Sciences introduced a mobile fertigation supply platform that can quickly interface with orchard irrigation systems, significantly enhancing the delivery efficiency of fertigation resources.

3.3.2 Precision weed control technology

The international market for intelligent weed control robots has reached a relatively mature stage. In response to the diverse turf management needs across orchards, parks, and residential gardens, leading global agricultural equipment manufacturers have actively expanded into this sector, introducing a range of products that feature distinct technological strategies and application-specific functionalities. Table 2 presents a comparative overview of key attributes associated with representative mainstream international weed control robots.

Table 2 Typical intelligent weed control robot products

Brand/ Manufacturer	Model name	Functional overview	Image
Friendly Machines	Robomow RS622[33]	Equipped with flexible differential drive and advanced mulching capabilities; utilizes a boundary wire-based map-matching navigation system tailored for residential horticultural environments.	
Husqvarna	AutoMower[12]	Equipped with an intelligent charging and discharging management system; employs an optimized full-area coverage path planning algorithm, widely utilized for autonomous maintenance of large-scale turfgrass areas.	
Dino Technology	Dino Robot	Designed for large-scale vegetable field operations, featuring fully automated path navigation and multi-row operation capabilities, enabling autonomous weed removal in open fields without human intervention.	
Carbon Robotics	LaserWeeder	Employs laser technology for precise weed eradication, integrating computer vision and deep learning algorithms to autonomously detect and identify field weeds, eliminating the need for chemical herbicides.	
AgXeed	AgBot II[34]	Integrates crop recognition and autonomous path planning systems, suitable for field inspection and weed management; capable of concurrently performing tasks such as identification, pesticide application, and information feedback.	
Honda	Miimo[35]	Features a stable dual omnidirectional wheel design and intelligent functions such as automatic adjustment of mowing height; demonstrates excellent performance across complex terrains.	
Danish scientist	HortiBot	Supports integration of camera systems; equipped with visual-based weed detection and site-specific eradication capabilities, making it well-suited for precision agriculture applications.	

In summary, lawn mowing robots have evolved from simple path-following and mulching functions into integrated, multifunctional platforms that incorporate intelligent navigation, visual recognition, adaptive control, and hybrid power systems.

3.4 Mechanized production technologies targeting fruit trees

Precision is a core direction in the development of fruit tree mechanization technologies, aiming to maximize operational effectiveness while minimizing impact on the trees.

3.4.1 Intelligent spraying technology

The development of intelligent spraying technologies primarily centers on two core aspects: perception and recognition and variable-rate control. International research has consistently pushed the boundaries of sensor precision and intelligent algorithm design. For example, Berk et al.[36] pioneered the use of ultrasonic sensors to measure tree canopy volume, achieving pesticide reductions of up to 70%. Seol et al.[37] improved spray flow accuracy by integrating depth cameras into the system. Air-assisted spraying techniques are also widely adopted to enhance droplet deposition efficiency in deep canopy layers.

On the commercial front, leading global agricultural equipment manufacturers have accelerated the industrialization of intelligent spraying solutions through mergers, acquisitions, and strategic partnerships. John Deere, in collaboration with GUSS Automation, developed a fully autonomous orchard spraying platform capable of precise spot spraying, positioning itself at the forefront of industry innovation. Case New Holland (CNH) has integrated AI-powered visual recognition systems to enable a "spray-on-green" precision application mode. Zhang et al.[38] introduced an intelligent spraying robot that incorporates deep learning algorithms for precise detection and spraying, demonstrating robust performance across various agricultural settings. Oberti et al.[39] developed a selective spraying robot for greenhouse grape disease management, equipped with a six-degree-of-freedom precision spraying end-effector and a multispectral imaging-based disease detection system, significantly reducing pesticide usage. Similarly, Rincón et al.[40] engineered a greenhouse tomato spraying robot capable of targeting internal canopy leaves with high precision, achieving enhanced penetration and coverage.

In China, domestic research closely follows international trends while incorporating adaptive innovations suited to local orchard morphologies. For instance, Ma et al.[41] developed a multi-directional adaptive spraying robot capable of adjusting to various canopy structures. Jiang et al.[42] designed a tracked spraying robot for complex hilly terrains, employing LiDAR to measure canopy volume and facilitate variable-rate application. Xu et al.[43] engineered a flight-capable drone system that generates and disperses ozonated water in-flight, effectively reducing pesticide usage while maintaining pest control efficacy. Lanjiang Technology has integrated high-precision BeiDou satellite navigation with wind-assisted atomization technology to develop an efficient, multifunctional unmanned orchard operation platform (as shown in Figure 2). In terms of commercial deployment, XAG's flagship model—the P150 intelligent spraying robot—is equipped with advanced sensors and laser-based systems, supports a maximum liquid capacity of 10 L, and has been widely adopted in both domestic and international orchards, significantly enhancing the efficiency and precision of plant protection operations.

Figure 2 Lanjiang unmanned plant protection robot

3.4.2 Robotic pruning, flower thinning, and mechanical pollination

Due to the high complexity of perception and operation tasks, robotic pruning technologies for fruit trees remain at the research or small-scale application stage worldwide. For instance, Japan has developed a chainsaw-equipped climbing robot for main trunk pruning, although its effectiveness is limited to orchard systems with highly regular tree structures[44]. Italy's Fa-MA company introduced a "window-type" pruning machine designed for densely planted dwarf orchards, which enables deep canopy penetration for efficient pruning operations. More advanced research is increasingly focused on the use of multi-degree-of-freedom (DoF) robotic manipulators. Botterill et al.[45] developed a six-DoF robotic arm for grapevine pruning, while You[46] and Zahid[47] proposed five-DoF and multi-joint robotic arms for cherry and apple trees, respectively. These robotic solutions share common technical challenges, including complex environmental perception, high-precision path planning, and difficulties in obstacle avoidance and motion control. In China, research efforts have tended to target structured and application-specific scenarios. For example, Xu[48] and Quanzhou Zhiyongda Company developed a pruning robot for power line corridors, capable of autonomous navigation and obstacle removal along overhead transmission routes—demonstrating a scenario-adaptive approach to technological development.

Blossom thinning is a crucial horticultural practice for improving fruit quality, but it is often labor-intensive and inefficient. Among international mechanical solutions, the A-series blossom thinners developed by the German company Assirelli[49] use rotating plastic strips to strike flower clusters, achieving high operational efficiency across large orchard areas. However, these systems have limited adaptability to variable canopy heights. Recent advances in vision-based technology have enabled variable-rate thinning. For instance, Wouters et al.[50] developed a spectral reflectance-based recognition system for blossoms, achieving an identification accuracy of up to 85%. In China, institutions such as the Jiangsu Academy of Agricultural Sciences[51] have designed a modular, three-section airborne thinning device based on canopy profiling principles (as shown in Figure 3). This system features detachable components and adjustable angles, allowing for flexible adaptation to different fruit tree architectures.

Figure 3 Assirelli vehicle-mounted flexible flower thinning

Mechanical pollination is a critical technique for enhancing pollination efficiency and increasing fruit yield. Liquid spray pollination can achieve efficiencies five to ten times greater than natural pollination. Svetlana et al.[52] proposed a biomimetic flying robot coated with ionic gel to facilitate artificial pollination. Shen et al.[53] developed a variable-rate spraying device based on laser sensors, which adjusts spray volume according to leaf density; however, its inability to recognize flowers results in suboptimal pollen utilization. Gianni et al.[54] introduced a wind-assisted atomizing pollination system that enhances droplet uniformity through secondary atomization. Williams et al.[55] created a pollination robot capable of achieving approximately 80% accuracy in flower recognition and spraying, although its targeting precision still requires improvement. In China, research efforts have primarily focused on improving targeting accuracy. For example, Guo et al.[56] developed a spraying actuator that integrates laser and ultrasonic sensors to dynamically adjust spray distance based on target position; however, leaf occlusion remains a limiting factor. Liu[57] designed a vision-based pollination system capable of real-time flower detection and dynamic positioning, achieving a targeting accuracy of 83.3% in "spray-on-flower" precision pollination.

3.4.3 Intelligent harvesting technology

Fruit harvesting constitutes the most labor-intensive, cost-intensive, and technically challenging stage of orchard production. As such, intelligent harvesting robots are often regarded as the "crown jewel" of orchard automation. Globally, this field has become a focal point of intense research and development competition, with diverse technological approaches and business models emerging at a rapid pace.

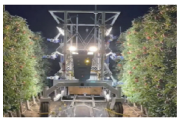
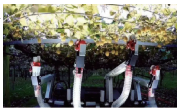
(1) Comparison of harvesting robot architectures: single-arm, multi-arm, and unmanned aerial vehicles

Single-arm robotic systems are commonly employed as foundational platforms for technology validation, with a primary focus on core functionalities such as visual recognition, precise localization, and fruit grasping. For example, an Israeli startup[58] developed a greenhouse sweet pepper harvesting robot that achieved a 61% success rate with an average harvesting cycle of 24 seconds. Similarly, Onishi et al.[59] developed an apple harvesting robot with comparable design principles. However, the overall harvesting efficiency of single-arm systems generally falls short of the throughput required for commercial-scale orchard operations.

As harvesting tasks grow increasingly complex and performance requirements continue to rise, multi-arm robotic systems have emerged as a primary focus in the development and deployment of fruit and vegetable harvesting technologies. To provide a comprehensive overview of current advancements, this paper reviews and summarizes representative multi-arm harvesting robots that demonstrate a high level of technical maturity and engineering feasibility, as detailed in Table 3.

Drone-based harvesting systems represent a disruptive technological innovation that addresses the accessibility limitations of ground-based platforms by employing aerial robotic solutions. One notable example is the system developed by the Israeli company Tevel Aerobotics, which consists of a ground-based mother vehicle and multiple autonomous flying drones. The mother vehicle serves as the central hub, providing power supply and data processing capabilities, while the drones employ onboard AI-driven computer vision algorithms to autonomously navigate to individual fruit trees, identify ripe fruits with high accuracy, and perform harvesting operations using robotic grasping arms. Once harvested, the fruits are transferred to collection containers mounted on the mother vehicle. Tevel Aerobotics has established strategic partnerships with several major international agribusiness firms, including Unifrutti and HMC Farms, and has initiated commercial-scale deployments of its drone harvesting system.

Table 3 Typical multi-arm collaborative harvesting robot products

Model name	Functional overview	Image
CROO robotics strawberry harvesting robot	Equipped with 16 robotic arms, each integrated with vision and radar modules; achieves approximately 2 seconds per strawberry harvest and supports in-field path planning.	
AGROBOT robotics strawberry harvesting robot[60]	Equipped with 24 robotic arms, each with an independent vision sensor, enabling stem-cut harvesting; suitable for high-bed and trellis strawberry cultivation.	
China Agricultural University multi-arm strawberry harvesting robot	Equipped with dual-degree-of-freedom robotic arms; achieves a picking speed of 1.7 seconds per fruit under ideal conditions; designed specifically for strawberry harvesting.	
FFRobotics apple harvesting robot[61]	Equipped with up to 16 robotic arms, capable of harvesting approximately 9,000 apples per hour; end-effectors feature 3-finger anthropomorphic grippers.	
RipeRobotics apple harvesting robot	Uses a vacuum-based end-effector to harvest mature apples.	
Advanced farm apple harvesting robot	Six-arm configuration demonstrated excellent performance during 2024 testing; the six robotic arms can identify and harvest apples at a rate of 2,500 fruits per hour, supporting commercial-scale operations.	
Nanovel citrus harvesting robot	Equipped with multiple robotic arms and flexible grippers, capable of continuous operation for up to 20 hours.	
Robotics plus kiwifruit harvesting robot[62]	A four-arm robotic system designed for kiwifruit harvesting, achieving a picking success rate of 86% with an average cycle time of 2.78 seconds.	
AVL motion white asparagus harvesting robot	Automatically follows planting beds using sensors; capable of harvesting approximately 9,000 white asparagus spears per hour; designed for high-efficiency harvesting.	
Zhongke yuandong power smart agriculture tomato harvesting robot	Utilizes both "single-fruit" and "cluster" end-effectors, achieving a picking success rate of 92%, with an average harvest time of approximately 4 seconds per fruit; exhibits strong adaptability.	

(2) Support operation platform

Orchard elevating platforms offer a safer and more stable working environment compared to traditional ladders and stools, significantly enhancing operational efficiency while mitigating safety risks. International research and development efforts have primarily focused on platforms designed for relatively flat terrains, typically involving large-scale systems suited to standardized orchard layouts. In contrast, domestic designs—particularly those intended for use in hilly and mountainous regions—emphasize adaptability and stability to accommodate variable and challenging topographies.

Domestic research has mainly concentrated on the development of automatic leveling and anti-rollover technologies. Hunan Agricultural University designed a compact, crawler-type self-propelled scissor lift platform specifically tailored for uneven terrain. This platform incorporates a multi-degree-of-freedom contour-following mechanism, enabling it to adapt to complex ground surfaces while maintaining superior traction, thereby effectively addressing the slippage issues commonly observed in wheeled platforms. Wang et al.[63] applied the Load Transfer Ratio (LTR) theory to develop a static anti-rollover control system. When the platform approaches a tipping threshold, the system proactively issues warnings and adjusts the center of gravity, significantly enhancing operational safety.

4 Challenges of mechanized orchard production in China

4.1 Low standardization level of orchard mechanization

Although a wide range of orchard production and management machinery is available on the market, suitable equipment is still lacking for several critical operations, including pollination, fruit bagging, and harvesting. In theory, it is feasible to achieve a mechanization coverage rate of up to 80% across the entire orchard production process. However, according to a 2025 national survey conducted by a fruit cultivation expert panel, the actual mechanization rate remains at approximately 30% nationwide. The primary constraint lies in the low level of mechanization compatibility within existing orchards, which significantly hampers the adoption and integration of relevant equipment.

Gentle-slope orchards are in the process of transitioning from traditional planting models to modern, standardized orchard systems. While large-scale cultivation of high-value fruit varieties has been promoted in major production areas, the implementation of standardized orchard layout and uniform agronomic practices remains insufficient. In hilly and mountainous regions, persistent challenges—such as inadequate construction of machinery-accessible roads, fragmented land parcels, and steep slopes—further constrain mechanization. These issues call for urgent adaptation of machinery systems and the development of renovation strategies focused on improving orchard machinability.

4.2 Significant mechanization shortcomings in orchards of hilly and mountainous regions

Hilly and mountainous orchards are predominantly characterized by steep or gently sloping terrain with highly variable topographic conditions, yet they continue to lack dedicated agricultural machinery tailored for such environments. These regions cultivate a diverse range of fruit crops, many of which differ significantly from those commonly grown in flatland orchards, resulting in distinct and complex equipment requirements. Consequently, machinery designed for flat or regular terrain is often unsuitable for these areas. At present, the market faces a substantial shortage of specialized equipment for mountain-specific planting, transplanting, and harvesting operations. Moreover, the niche nature of certain fruit varieties—such as *Cornus officinalis* and local cultivars like Xi'an peach—further reduces the overall demand for mechanization. High equipment costs and limited market scale have led to insufficient investment and a lack of innovation from agricultural machinery manufacturers, exacerbating the mechanization gap in these regions.

4.3 Insufficient integration of advanced technologies in orchard machinery

Modern orchard management—including intelligent agricultural machinery, protected cultivation systems, and smart control platforms—has yet to fully incorporate advanced technologies such as the Internet of Things (IoT), big data analytics, and next-generation artificial intelligence (AI). In the domain of intelligent orchard machinery, significant gaps remain in machine vision, multi-sensor perception, and autonomous decision-making based on integrated data sources. These deficiencies result in practical challenges, such as imprecise positioning and height control during weeding or mowing, unstable trenching performance, uncontrollable fertilization depth and dosage, coarse pruning quality, low-efficiency fruit transport, and uneven pesticide application. In terms of facility agriculture, limitations include the lack of accurate perception of facility layout and environmental parameters derived from multiple data sources, as well as the absence of data-driven management models tailored to actual production conditions. Consequently, the development of facility agriculture remains fragmented, incomplete, and lacking precision. Smart control systems aim to integrate intelligent machinery data with field and facility crop production information, encompassing data acquisition, analysis, decision-making, and storage. These systems are intended to generate operational prescriptions based on equipment status and crop requirements, guiding intelligent machinery deployment, water-fertilizer system spraying/dripping/irrigation, and environmental regulation in protected cultivation facilities.

4.4 Labor aging and low educational levels

According to national statistics, the current age distribution of agricultural workers is as follows: 10.51% are under 40 years old, 8.77% are between 40 and 45, 16.40% between 46 and 50, 25.84% between 51 and 55, 24.97% between 56 and 60, and 13.52% are over 60. Workers aged over 50 account for 64.33% of the total, indicating a significantly aging agricultural labor force. In addition to aging, the overall level of educational attainment remains low, and the available labor pool is rapidly shrinking. The development of modern orchards is hindered by a shortage of skilled personnel proficient in fruit cultivation, agricultural machinery operation and maintenance, as well as digital technologies such as network systems and new media platforms. To address this gap, national policies are promoting the systematic cultivation of university graduates through targeted training programs, industry guidance, and talent introduction strategies aimed at integrating qualified professionals into the fruit industry.

4.5 Weaknesses in the socially-supported agricultural machinery service system

Due to the unique operational requirements of orchard machinery and its complex working environment, maintenance and support services have become critical factors affecting the long-term reliability and stable operation of equipment. At present, the service infrastructure remains underdeveloped. Although manufacturers provide basic repair guidance, the turnaround time for resolving equipment failures is often prolonged, adversely affecting orchard production. Agricultural machinery cooperatives serve as the primary institutions providing services within the sector. Key personnel are typically experienced operators capable of machine operation, maintenance, and basic repairs. However, these cooperatives are generally small in scale, lack integrated platform support, have limited access to information, and possess weak decision-making capacity. Their inability to provide cross-regional services further constrains their effectiveness, thereby limiting the overall development and service capacity of the orchard machinery industry.

5 Development priorities

5.1 Recommendations for promoting standardized orchard development and integration of machinery with agronomy

First, the establishment of standardized and scientifically designed orchards should be prioritized. The renovation of inefficient and aging orchards must focus on the development of moderately scaled, machine-adapted modern orchard systems. In flat and alluvial regions—such as the former Yellow River floodplain and the plains of Shaanxi and Gansu on the Loess Plateau—uniform tree row and spacing standards should be implemented. Orchard areas should be planned in contiguous blocks with level planting surfaces. A well-designed field road network should be established to ensure interconnectivity among production zones and to enhance machinery traffic efficiency. For gentle slopes under 10°, slope-to-terrace conversion is recommended to enable mechanization-friendly contiguous transformations. On steeper slopes ranging from 10° to 25°, segmented terraced fields should be constructed along contour lines. Terrain modification techniques, such as excavation and backfilling, should be used to smooth sharp corners, crescent-shaped curves, convex ridges, and shallow gullies, thereby reducing the frequency of turning and reversing operations by machinery. Orchard perimeters should include 4 to 6 meters of turning space to facilitate maneuverability. For slopes exceeding 25°, due to the limited area and mechanical constraints, lightweight and simplified equipment is preferable. Transport infrastructure, such as roads or rail tracks, should be constructed to connect mountain tops with foothills. In summary, sloped farmland with inclinations between 10° and 25° should be prioritized as a key target for agricultural machinery R&D in hilly regions.

Second, the configuration of orchard machinery should be tailored to specific fruit cultivation patterns. Crops such as apples, citrus, and pears exhibit distinct agronomic requirements. Some varieties require intensive management and high-precision operations, while others necessitate larger canopy spacing with lower intervention. Even within the same fruit species, variations in planting patterns mean that a single machinery type cannot accommodate all production needs. Therefore, machinery should be classified and configured based on production stages and planting modes.

Finally, research on the integration of agricultural machinery and agronomic practices should be deepened, particularly with respect to intra-species planting characteristics. For instance, in terraced mountain plots with dwarf-dense apple orchards, mid- to small-sized power platforms should be equipped with compatible implements, including fertilizing equipment, weed control machinery, elevating work platforms, and unmanned plant protection devices such as specialized spraying drones (e.g., Jimu). In contrast, traditional mountain apple orchards with dense canopies require specialized configurations to address fertilization, weed management, lifting operations, and spraying challenges. Equipment options may include offset fertilization implements, inter-row or obstacle-avoiding mowers, agricultural tricycles for assisted spraying, and adaptive drone platforms capable of penetrating dense canopies and operating on complex terrain.

5.2 Promoting research and development on key equipment to address weak links in orchard mechanization operations

Specialized power platforms and mechanized equipment for core orchard operations—particularly in harvesting, blossom thinning, pollination, and pruning—remain critical weak links. Among these, fruit harvesting represents the most labor-intensive and technically challenging process. Focusing on major fruit crops such as apples, citrus, and pears, as well as the specific demands of deep-processed fruit production, it is essential to advance research on key technologies related to efficient vibration-based fruit detachment and high-quality integrated collection systems. This includes breakthroughs in rapid gripping based on visual recognition and localization of trunk or branch contours, adaptive pre-tension control mechanisms, real-time adjustment of vibration parameters, automatic following of mobile collection platforms, and flexible fruit receiving technologies, with the overall aim of achieving efficient and high-quality harvesting across diverse fruit varieties.

For fresh-consumption fruits, two parallel approaches should be pursued. On one hand, emerging harvesting methods based on laser cutting and ultrasonic picking—guided by visual or LiDAR sensing—should be explored. This requires addressing key challenges such as precise fruit recognition and localization, understanding the mechanisms through which laser or ultrasonic energy disrupts fruit stems, clarifying the working principles of such harvesting methods, optimizing operational parameters, and developing novel harvesting robots utilizing these techniques. On the other hand, improvements to traditional robotic arms and three-degree-of-freedom Cartesian execution mechanisms are equally important. By integrating machine vision recognition and optimizing control algorithms, it is possible to significantly enhance the performance and efficiency of intelligent fruit-harvesting robots and address existing limitations in picking speed and reliability.

In the context of orchard operations in mountainous terrain, it is critical to overcome persistent obstacles such as poor operational conditions, limited machinery versatility, low equipment transferability, and insufficient levels of automation. Accordingly, research should focus on the development of key technologies and core components including lightweight, low-resistance structural designs, adaptive posture control, autonomous navigation systems, and intelligent operation modules. This effort should be accompanied by the development of highly adaptable universal power chassis, high-efficiency, low-cost, and low-resistance generic implements, integrated control systems, and complete machinery sets. The overarching goal is to realize high-performance mobility in complex orchard environments, real-time adaptive posture adjustment, modular and rapid implement integration, accurate multi-target recognition and localization, and robust intelligent operation capabilities under diverse terrain and crop conditions.

5.3 Emphasizing the intelligent upgrading of equipment for operations in gentle slope orchards

To meet the intelligent production demands of standardized orchards situated on gentle slopes, an integrated model is needed that combines a broadly adaptable universal power platform, multi-stage operational implements, and intelligent control systems. The primary focus is on developing ground-based and near-ground aerial environmental sensing technologies for orchards, enabling rapid acquisition and reconstruction of multi-source, both global and tree-specific, orchard information. Research efforts will aim to advance human-machine collaborative intelligent control technologies tailored to varying orchard terrains and planting structures. This includes the design and implementation of ground-based mobile units, flexible rail-based transport systems, and unmanned aerial vehicle (UAV) carriers to support integrated air-ground intelligent operation platforms. In parallel, predictive modeling and algorithmic research will target the physiological and environmental interactions of fruit crops, thereby enabling improved perception and growth forecasting at critical developmental stages.

In terms of operational functions, specialized intelligent modules will be developed for applications such as precise deep organic fertilizer delivery, target-specific and quantitatively controlled plant protection, assisted pollination, and multidimensional pruning. Using the universal power platform as the foundational carrier, technologies for multimodal sensing, multi-parameter diagnostics, multi-machine coordinated scheduling, and staged intelligent task execution will be integrated to construct a comprehensive intelligent production management and control system tailored to modern gentle-slope orchards. This system is intended to establish an efficient and intelligent operational management framework, ensuring high-quality, high-efficiency control across diverse orchard scenarios. Ultimately, it aims to accelerate the intelligent transformation and high-quality development of apple, citrus, pear, and peach orchards in gently sloped regions.

5.4 Focus on strengthening the integrated promotion and application of intelligent technological equipment in modern standardized orchards

During the 15th five-year plan period, modern standardized orchards will serve as the primary operational scenarios for the large-scale promotion and application of intelligent production technologies and equipment. Support will be directed toward the integrated deployment of intelligent robots for tasks such as weeding, fertilization, plant protection, harvesting, and in-field transportation. These efforts will leverage technological advancements in path planning, autonomous navigation, environmental perception, and intelligent decision-making.

A smart production management and control platform will be developed to harness technical strengths in intelligent task scheduling, multi-machine coordination, and operational decision-making based on multi-source sensor data fusion. The objective is to advance from intelligent control over isolated production stages to comprehensive, end-to-end intelligent applications across the entire orchard management cycle. Demonstration cases will be constructed for key fruit crops—including apples, citrus, pears, and peaches—under both gentle- and steep-slope orchard conditions, thereby providing replicable models for intelligent production. A feedback mechanism will be established to systematically collect and analyze user-reported issues and suggestions during equipment deployment, enabling continuous technical improvement and optimization of machinery performance to better align with real-world production needs. By equipping standardized orchards with intelligent machinery and refining equipment functions through demonstration and iterative promotion, the deep integration of agricultural machinery with agronomic practices will be accelerated. This process will facilitate the substitution of manual labor with mechanized solutions, supporting fruit growers in achieving cost reduction, efficiency enhancement, and yield improvement.

5.5 Attracting and guiding highly qualified professionals for the fruit industry

In response to the pressing societal challenge of employment difficulties—particularly as the number of university graduates peaks and remains largely concentrated in the secondary and tertiary sectors—reforming the development model of the primary industry to attract these graduates back into agriculture represents a promising and effective strategy.

First, employment subsidy policies targeted at university graduates entering the fruit industry, alongside incentive schemes for enterprises, should be introduced. Highly qualified professionals with expertise in the technical and applied aspects of fruit production represent a critical driving force for enhancing industry productivity and innovation. Large-scale fruit producers and leading enterprises are encouraged to actively respond to government initiatives by recruiting skilled personnel. This necessitates strengthened promotional campaigns, the provision of basic material support, and the establishment of equity-based incentive mechanisms to attract and retain talent. In parallel, local governments should offer material security to new hires through housing and living subsidies.

Second, in coordination with the fruit industry, local governments should introduce preferential policies to support university graduates returning to rural areas to pursue entrepreneurial ventures. To reduce the risks associated with agricultural entrepreneurship, these policies should include measures such as rent-free land for a specified period, installment-based acquisition of agricultural machinery and inputs, and zero-interest loans for production and management. These efforts should be further supported by mentorship programs led by experienced industry experts. Importantly, in cases where natural disasters result in significantly reduced yields or complete crop failure, policies should allow for corresponding production cost reductions or exemptions, and repayment obligations should be deferred until production and profitability are restored.

Finally, to create a high-quality working environment that appeals to graduates, the fruit industry should adopt production models characterized by large-scale operations, standardization, intelligent automation, and smart management. Such conditions not only enhance labor efficiency and professional satisfaction but also foster long-term human capital retention and the sustainable development of the sector.

5.6 Strengthening the social service system for agricultural machinery

Under the leadership of the Agricultural Mechanization Management Department of the Ministry of Agriculture and Rural Affairs, and in coordination with institutions such as the Ministry's national fruit production expert panel, local agricultural machinery extension stations, and social organizations such as the China Foundation for Rural Development, a national program will be established to strengthen the social service system for agricultural machinery. This program will leverage existing institutional and technical resources to identify and cultivate a cohort of outstanding young professionals in agricultural mechanization. Upon meeting the necessary qualifications, these individuals will be deployed to township-level regions to establish and operate agricultural machinery cooperatives. These cooperatives will be further strengthened by recruiting professionals with expertise in machinery operation, repair, and maintenance, as well as next-generation fruit growers and technical specialists from surrounding areas. To ensure the long-term stability and sustainability of these cooperatives, a comprehensive, multi-pronged approach will be required.

First, a stable and large-scale service foundation must be established, grounded in orchards collectively owned or managed by cooperative members. On this foundation, an integrated service system—encompassing cultivation, field management, harvesting, and postharvest sales—will be developed to ensure the smooth and efficient operation of member orchards.

Second, an external-facing service platform must be constructed to offer mechanization services to non-member producers. This platform will operate through both offline (local registration) and online channels, enabling service access for smallholders cultivating not only fruit, but also crops such as grains, cotton, and oilseeds. This dual structure—serving both internal member operations and external commercial clients—will support the expansion of cooperative functions and contribute to their long-term sustainability.

Finally, a fair and performance-based compensation mechanism should be implemented. The cooperative will provide a base salary to machinery service personnel, who can earn additional income based on service performance and volume. In addition, the cooperative will distribute annual bonuses to its members based on collective profits.

This multi-functional cooperative service model should be actively replicated and scaled across counties, municipalities, and provinces, with the long-term vision of establishing a nationwide network. Horizontal collaboration among township-level cooperatives will be encouraged to jointly promote the widespread adoption of agricultural mechanization, accelerate the mechanization of orchard production, and advance the high-quality development of China's fruit industry.

6 Conclusions

This paper analyzes the overall level of mechanization in Chinese orchards and regional differences. The overall mechanization level is approximately 30%, with mechanized pruning and harvesting identified as weak points. The lack of standardization in orchards, inadequate mechanized operation skills, unreliable equipment, and the absence of specialized power machinery are key constraints on improving mechanization levels. A comprehensive mechanized production technology framework is proposed, focusing on digital orchard simulation, autonomous navigation, and mechanized management of trees and orchards. The framework highlights a comparative analysis of the application scenarios of power platforms, weeding, plant protection, and harvesting equipment. The study reveals several issues in domestic orchards, including low levels of mechanization standards, significant mechanical shortcomings in hilly and mountainous regions, insufficient integration of high-tech machinery in orchards, aging labor forces with low education levels, and a weak socialized agricultural machinery service system. These issues result in sluggish sales of agricultural machinery, improper use or lack of suitable machinery by farmers, stagnating mechanization levels, and narrowing profit margins for fruit farmers, ultimately hindering the sustainable development of the fruit industry.

During the 15th five-year plan period, five key development priorities are suggested, including standardization, machine suitability, integration of agricultural machinery and agronomy, addressing machinery shortfalls, and upgrading and integrating intelligent equipment for orchard operations in hilly areas. Specific measures include:

(1) Developing standardized and machine-suitable orchards based on planting model requirements, equipping suitable machinery, and promoting mechanized production.

(2) Emphasizing the supplementation of specialized power platforms and machinery for harvesting, thinning, flower thinning, and pruning, with a focus on developing new fruit harvesting robots tailored to different fruit species' raw material needs.

(3) Developing high-adaptability universal power chassis and high-quality machinery, control systems, and complete agricultural machinery equipment for hilly and mountainous orchards.

(4) Upgrading equipment intelligence for orchards on gentle slopes, developing human-machine collaborative intelligent control technologies, and producing intelligent power machinery, rail transport, and multi-functional drone equipment. Meanwhile, developing specialized intelligent components for precise organic fertilizer application, targeted plant protection, auxiliary pollination, and three-dimensional pruning, constructing an intelligent

production management system for modern standard orchards on gentle slopes, and guiding the implementation of smart management for machinery.

(5) Offering subsidies, business incentives, entrepreneurial benefits, and risk management policies to university graduates entering the fruit industry, while balancing the large-scale, standardized, intelligent, and smart management of orchard production to attract talent to the fruit industry.

(6) Government or social organizations should cultivate young agricultural professionals using a distributed development model, starting with concentrated training, decentralizing to grassroots levels, and providing guidance to small groups. This will be supported by operational orchard production, and mechanization service platforms, along with a comprehensive wage payment system to ensure the implementation of the socialized agricultural machinery service system.

In conclusion, these efforts will drive the modernization of the orchard industry, promoting sustainable growth and increasing fruit farmers' economic returns, thereby injecting significant momentum into the process of agricultural modernization.

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[References]

[1] Liu Y, Liu Y Y, Chen J C, Li J B, Lin X W, Lin G Z. Research status and trends of key technologies for multifunctional operation platforms in standardized orchards. Journal of Intelligent Agricultural Equipment, 2024; 5(1): 31–39. (in Chinese)

[2] Fu Z Y, Liu D W, Xie F P, Li X, Xiao X. Research status and prospects of fruit and vegetable transportation equipment in hilly and mountainous areas. Modern Agricultural Equipment, 2023; 44(3): 11–18. (in Chinese)

[3] Wu C Y, Wang J H, Yang Y, Li D Y, Li X. Current situation and mechanization trends of China's cash crop industry. Journal of Chinese Agricultural Mechanization, 2024; 45(1): 1–13.

[4] Liu C X. Discussion on mechanized production technologies for key orchard operations. Hebei Agricultural Machinery, 2021; 7: 10–11.

[5] Hu J T, Gao L, Bai X P, Li T C, Liu X G. Research progress on automatic navigation technologies for agricultural machinery. Transactions of the CSAE, 2015; 31(10): 1–10. (in Chinese)

[6] Lepej P, Rakun J. Simultaneous localisation and mapping in a complex field environment. Biosystems Engineering, 2016; 150: 160–9.

[7] Habibie N, Nugraha A M, Anshori A Z, Ma'sum M A, Jatmiko W. Fruit mapping mobile robot on simulated agricultural area in Gazebo simulator using simultaneous localization and mapping (SLAM). 2017 International Symposium on Micro-Nano Mechatronics and Human Science (MHS), 2017.

[8] Marden S, Whitty M. GPS-free localisation and navigation of an unmanned ground vehicle for yield forecasting in a vineyard. Recent Advances in Agricultural Robotics, International Workshop Collocated with the 13th International Conference on Intelligent Autonomous Systems (IAS-13), 2014.

[9] Kohlbrecher S, Meyer J, Graber T. Hector open source modules for autonomous mapping and navigation with rescue robots. Springer Berlin Heidelberg. Springer Berlin Heidelberg, 2013.

[10] Liu L W, Zhu X K, Li X H, Zhao Z J. Map evaluation study of 2D SLAM algorithms for low-cost mobile robots. Computer Simulation, 2021; 38(4): 291–295.

[11] Ji P. Research and design of an autonomous navigation control system for orchard operation robots. Nanjing: Nanjing University of Science and Technology, 2019. DOI: 10.27241/d.cnki.gnjgu.2019.001445.

[12] Wu C L. Research on autonomous driving system for orchard tractors based on multi-source information fusion. Nanjing: Southeast University, 2019. DOI: 10.27014/d.cnki.gdnau.2019.000405. (in Chinese)

[13] Ocer N E, Kaplan G, Erdem F, Kucuk Matci D, Avdan U. Tree extraction from multi-scale UAV images using Mask R-CNN with FPN. Remote Sensing Letters, 2020; 11(9): 847–856.

[14] Onishi M, Ise T. Explainable identification and mapping of trees using UAV RGB image and deep learning. Scientific Reports, 2021; 11(1): 903.

[15] Liang J M. Development of a self-propelled electric chassis for winter jujube orchard operations. Jinan: Shandong Jiaotong University, 2019. DOI: 10.27864/d.cnki.gsjtd.2019.000002. (in Chinese)

[16] Zeng H. Overall design and experimental study of an electric tractor driven by hub motors. Hangzhou: Zhejiang A&F University, 2020. DOI: 10.27756/d.cnki.gzjlx.2020.000254. (in Chinese)

[17] Han J H, Park C H, Park Y J, Kwon J H. Preliminary results of the development of a single-frequency GNSS RTK-based autonomous driving system for a speed sprayer. Journal of Sensors, 2019; 2019(1): 4687819.

[18] Huang Y, Fu J, Xu S, Han T, Liu Y. Research on integrated navigation system of agricultural machinery based on RTK-BDS/INS. Agriculture, 2022; 12(8): 1169.

[19] Opiyo S, Okinda C, Zhou J, Mwangi E, Makange N. Medial axis-based machine-vision system for orchard robot navigation. Computers and Electronics in Agriculture, 2021; 185: 106153.

[20] Radcliffe J, Cox J, Bulanon D M. Machine vision for orchard navigation. Computers in Industry, 2018; 98: 165–171.

[21] Nie S, Wang B L, Hao H H, Chen J. Research on centerline extraction algorithm for orchard navigation based on machine vision. Journal of Agricultural Mechanization Research, 2016; 12: 86–89.

[22] Mengoli D, Tazzari R, Marconi L. Autonomous robotic platform for precision orchard management: architecture and software perspective. 2020 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor), 2020. DOI: 10.1109/MetroAgriFor50201.2020.9277555

[23] Xu Y W, Yan W X, Wu W. Improvement of laser SLAM front-end algorithm based on local maps under similar scenarios. Robot, 2022; 44(2): 176–185.

[24] Velasquez A E B, Higuti V A H, Gasparino M V, Sivakumar A N V, Becker M, Chowdhary G. Multi-sensor fusion based robust row following for compact agricultural robots. Field robotics, 2022; 2: 1291–1319.

[25] Lv M, Wei H, Fu X, Wang W, Zhou D. A loosely coupled extended Kalman filter algorithm for agricultural scene-based multi-sensor fusion. Frontiers in Plant Science, 2022; 13: 849260.

[26] Ni Z K, Li M H, Lin R, Sun L N, Liu S Q. Research on SLAM based on fusion of 3D LiDAR and RTK. Manufacturing Automation, 2020; 42(7): 51–54.

[27] Dong H, Lou C R, Wang X J. Analysis of material and equipment selection for integrated water and fertilizer systems in protected fruit and vegetable production. Liaoning Agricultural Sciences, 2017; 5: 54–58. (in Chinese)

[28] He Q H, Zheng L, Chu Y H, Dou Q Q, Ci W L, Sun Y T. Research status and prospects of head-end units in water and fertilizer integrated systems. Journal of Chinese Agricultural Mechanization, 2021; 42(1): 122.

[29] Luo H J, Li Y, Xie Q B, Zhong L Y. Design of a cost-effective water and fertilizer integration system. Modern Agricultural Equipment, 2020; 41(6): 41–47. (in Chinese)

[30] Huang Y Y, Wang T, Liu X, Zheng H Y, Wu B Y, Chen Y K. Design and experiment of a circulating irrigation system for water and fertilizer integration. Water Saving Irrigation, 2019; 8: 94–97, 101. (in Chinese)

[31] Zhang B F, Chen X, Zhu J C, Kang J, Pan W, Zhao Y. Design and experiment of a water and fertilizer integrated system based on the Internet of Things. Journal of Intelligent Agricultural Equipment, 2021; 2(1): 57. (in Chinese)

[32] Zhao P F, Wang X F, Hu C, Xu C, Guo W S, He X W, et al. Design and experiment of water and fertilizer integrated equipment for smart greenhouses. Journal of Agricultural Mechanization Research, 2022; 44(9): 224–228.

[33] Zhang X, Cheng C Q, Hao X Y, Li J S, Hu P. A dynamic path planning algorithm for robots considering both global and local characteristics. Journal of Geomatics Science and Technology, 2018; 35(3): 315–320.

[34] Mccool C S, Beattie J, Firn J. Efficacy of mechanical weeding tools: A study into alternative weed management strategies enabled by robotics. IEEE Robotics and Automation Letters, 2018: pp.1184–1190.

[35] Hub A, Schmitz B. Addition of RFID-based initialization and object recognition to the navigation system TANIA. Proceedings of the 24th Annual International Technology and Persons with Disabilities Conference (CSUN), 2009.

[36] Berk P, Stajnko D, Lakota M, Belsak A. Real time fuzzy logic system for continuous control solenoid valve in the process of applying the plant protection product. Agricultural Engineering, 2015; 15(1): 1–9.

[37] Seol J, Kim J, Son H I J P A. Field evaluations of a deep learning-based intelligent spraying robot with flow control for pear orchards. Precision Agriculture, 2022; 23(2): 712–732.

[38] Zhang J, Yin H, Zhou L, Gu C, Qiu W, Lv X, et al. Variable rate airassisted spray based on real-time disease spot identification. Pest Management Science, 2023; 79(1): 402–414.

[39] Oberti R, Marchi M, Tirelli P, Calcante A, Iriti M, Tona E, et al. Selective spraying of grapevines for disease control using a modular agricultural robot. Biosystems Engineering, 2016; 146: 203–215.

[40] Rincón V J, Grella M, Marucco P, Alcatrão L, Sanchez-Hermosilla J, BalsarI P. Spray performance assessment of a remote-controlled vehicle prototype for pesticide application in greenhouse tomato crops. Science of The Total Environment, 2020; 726: 138509.

[41] Ma C, Li G L, Li X D, Huang X Y, Song J, Yang S H. Development of a multi-directional automatic spraying device for citrus orchards in hilly and mountainous areas. Transactions of the CSAE, 2019; 35(3): 31–41. (in Chinese)

[42] Jiang S J, Ma H T, Yang S H, Zhang C, Su D B L G, et al. Target detection and tracking system of orchard spraying robot. Transactions of the CSAE, 2021; 37(9): 31–39. (in Chinese)

[43] Xu H, Yi L, Li C, Sun Y, Hou L, Bai J, et al. Design and experiment of ecological plant protection UAV based on ozonated water spraying. Drones, 2023; 7(5): 291.

[44] Ishigure Y, Hirai K, Kawasaki H. A pruning robot with a power-saving chainsaw drive. 2013 IEEE International Conference on Mechatronics and Automation (ICMA), 2013 . DOI: 10.1109/ICMA.2013.6618088

[45] Botterill T, Paulin S, Green R, Williams S, Lin J, Saxton V, et al. A robot system for pruning grape vines. Journal of field robotics, 2016; 34(6): 1100–1122.

[46] You A, Sukkar F, Fitch R, Karkee M, Davidson J R. An efficient planning and control framework for pruning fruit trees. 2020 IEEE International Conference on Robotics and Automation (ICRA), 2020. DOI: 10.1109/ICRA40945.2020.9197551

[47] Zahid A, Mahmud M S, He L, Choi D, Heinemann P, Schupp J. Development of an integrated 3R end-effector with a cartesian manipulator for pruning apple trees. Computers and Electronics in Agriculture, 2020; 179: 105837.

[48] Xu Z X, Wu G P, Liu X Z. Research on a tree-branch pruning robot for overhead high-voltage transmission line corridors. Mechanical Design and Manufacturing, 2015; 9: 204–207.

[49] Assirelli A, Giovannini D, Cacchi M, Alberto A, Daniela G, Mattia C, et al. Evaluation of a new machine for flower and fruit thinning in stone fruits. Sustainability, 2018; 10(11): 4088.

[50] Wouters N, Ketelaere D B, Deckers T, Baerdemaeker J D, Wouter S. Multispectral detection of floral buds for automated thinning of pear. Computers and Electronics in Agriculture, 2015; 113: 93–103.

[51] Lei X H, Lü X L, Zhang M N. Development and experiment of a three-section arm airborne blossom thinner. Transactions of the CSAE, 2019; 35(24): 31–38. (in Chinese)

[52] Chechetka S A, Yu Y, Tange M, Li X, Chang Y H. Materially engineered artificial pollinators. Chem, 2017; 2(2): 224–239.

[53] Shen Y, Zhu H, Liu H, Chen Y, Ozkan E. Development of a laser-guided, embedded-computer-controlled, air-assisted precision sprayer. Transactions of the ASABE, 2017; 60(6): 1827–1838.

[54] Tacconi G, Michelotti V, Caciopp O, Vittone G. Kiwifruit pollination: the interaction between pollen quality, pollination systems and flowering stage. Journal of berry research, 2016; 6(4): 417–426.

[55] Williams H, Nejati M, Hussein S, Penhall N, Lim Y J, Jones M H, et al. Autonomous pollination of individual kiwifruit flowers: toward a robotic kiwifruit pollinator. Journal of Field Robotics, 2020; 37(2): 246–262.

[56] Guo H M. Development of a spraying-type end-effector for kiwifruit pollination. Yangling: Northwest A&F University, 2016.

[57] Liu S H. Research on target-oriented pollination method and control system design for kiwifruit. Yangling: Northwest A&F University, 2019.

[58] Arad B, Balendonck J, Barth R, Shahar O B, Edan Y, Hellstrom T, et al. Development of a sweet pepper harvesting robot. Journal of Field Robotics, 2020; 37(6): 1027–1039.

[59] Onishi Y, Yoshida T, Kurita H, Fukao T, Rihara H, Wai A. An automated fruit harvesting robot by using deep learning. Robomech Journal, 2019; 6(1): 1–8.

[60] Trinidad J B. Machine for automatically harvesting fruits cultivated in rows. United States patent application: US 15/366, 091, 2018-06-07.

[61] Avigad G, Salomon S, Kahani A, Koster Y. Robotic fruit harvesting machine with fruit-pair picking and hybrid motorized-pneumatic robot arms. United States patent: US 11, 477, 942, 2022-10-25.

[62] Williams H A, Jones M H, Nejati M, Seabright M J, Bell J, Penhall N, et al. Robotic kiwifruit harvesting using machine vision, convolutional neural networks, and robotic arms. Biosystems Engineering, 2019; 181: 140–156.

[63] Wang P F, Liu J F, Qian J, Hao Y J. Design of a static anti-rollover system for orchard operation platforms. Journal of Agricultural Mechanization Research, 2013; 35(3): 137–139.