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Research progress on picking/harvesting techniques, and equipment of tea shoots

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Abstract

The research and development of tea shoots picking/harvesting techniques is the core link in the tea industry's mechanized upgrading, with technological breakthroughs critical to improving tea production efficiency and quality. This paper reviews relevant research progress and analyzes the technical characteristics and application scenarios of different types of equipment combined with agronomic requirements. Studies show that bulk tea picking/harvesting equipment mainly adopts reciprocating cutting machines, which enable large-scale operations but are associated with a relatively high tea shoot damage rate and impurity content, as well as moderately poor quality. For premium tea, handheld picking/harvesting equipment has significantly improved the integrity of tea shoots by optimizing picking/harvesting structure effector and operating parameters. However, it still relies on manual visual recognition and positioning, and the level of intelligence urgently needs enhancement. Intelligent picking/harvesting technology focuses on tea shoot recognition, picking point positioning, and biomimetic end-effector design. Although breakthroughs have been made in tea shoot recognition capabilities, three key bottlenecks remain: relatively low equipment integration, moderately high failure rates, and comparatively lower efficiency than manual picking, which hinder industrial promotion. Future efforts should prioritize the research and development of intelligent, lightweight, and modular equipment, integrate agricultural machinery with agronomy, and establish a unified standard system covering equipment, agronomic measures, and operation processes. This will promote the practical application of picking/harvesting equipment, providing technical support and a theoretical basis for the tea industry's mechanized and intelligent transformation.

Keywords: Tea, Tea shoots picking/harvesting, Harvesting machinery, Intelligent picking, Integration of agricultural machinery and Agronomy

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Introduction

As one of the world's three major beverages, tea, with its unique cultural connotations and health value, is regarded as an important beverage that covers more than 160 countries worldwide and benefits three billion people[1−3]. As the birthplace of tea culture and a core area of the tea industry, China's output of dried crude tea reached 3.49 million tons in 2024, with an output value exceeding 320 billion yuan, ranking first in the world for ten consecutive years[4]. The tea industry is not only a carrier of cultural inheritance but also plays a key role in rural revitalization. However, the technological differentiation in the tea shoots picking/harvesting link significantly restricts the industrial upgrading: bulk tea production relies on mechanized harvesting to improve efficiency, but traditional reciprocating cutting machine has the problem of relatively low integrity rate of harvested tea shoots, which can only meet the raw material demand of crude tea; premium tea, due to strict requirements on picking/harvesting standards, still highly depends on manual picking/harvesting, facing the dual challenges of labor shortage and quality fluctuation. In batch harvesting technology, the term "harvesting" is adopted, while in selective harvesting technology, the term "picking" is used. For the sake of conciseness, this paper uniformly employs the term "picking".

With the global population aging and the transformation of agricultural labor structure, realizing "machine replacement of labor" has become an inevitable choice for the sustainable development of the tea industry[5]. At present, picking technology presents a three-pronged development path: in the field of bulk tea, mechanized equipment represented by reciprocating cutting type (such as single-person backpack-type, two-person hand-carried tea harvesters, and ride-on tea harvesters) reduces costs through efficiency improvement. These devices are widely used in flat and gentle-slope tea gardens, while single-person backpack-type harvesters are also applicable to hilly and mountainous tea gardens; however, constrained by the principle of "undifferentiated picking", they fail to meet the quality requirements of premium tea[6−11]. In the field of premium tea, technological evolution has formed a "handheld-intelligent" gradient. Handheld picking equipment—manually held small- and medium-sized picking machines that are portable, flexible, and structure-optimized for premium tea, and suitable for scattered hilly/mountainous tea gardens—requires manual holding and operation, which has a certain improvement in efficiency compared with traditional manual work and has become a transitional solution for hilly tea gardens[12−17]. Intelligent picking technology (comprehensive technology integrating AI and bionic design: "perception-decision-execution" system for automated, precise, low-damage tea shoots picking) based on visual recognition attempts to break through the bottleneck of "selective picking". However, it has not been widely applied due to two practical constraints. First, its supporting walking chassis is difficult to accommodate the complex terrain of hilly and mountainous tea gardens, limiting the coverage of core application scenarios. Second, the balance between operational efficiency

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and equipment cost has not met the requirements of industrial practicality, which further restricts the large-scale promotion of the technology[18−44].

Against this backdrop, this paper systematically sorts out the technological evolution of tea shoots picking technology and divides the discussion into three sections based on application scenarios: first, it analyzes the mechanization progress of bulk tea picking technology, including the principles and applicability of single-person portable equipment, two-person collaborative equipment, and ride-on equipment; second, it discusses how handheld picking technology for premium tea realizes the efficiency improvement and quality maintenance of manual picking and reduces the dependence on skilled labor; finally, it focuses on the core breakthroughs of intelligent picking technology for premium tea, including tea shoot recognition, picking point positioning and biomimetic end-effector design. This study aims to reveal the technical logic of balancing "efficiency–quality" and provide theoretical reference and innovative paths for solving the industrial pain points in the picking link.

Requirements for tea shoots picking

Picking is a critical link in tea processing. Bud, leaves, and tender stems picked from tea plant are collectively referred to as fresh tea leaves, which serve as the raw material for processing various types of tea. Fresh tea leaves are generally graded based on the differences in picking positions. Currently, mainstream tea types can be categorized into three major classes—premium tea, bulk tea, and specialty tea—according to picking standards[6].

Specifically, the production of premium tea focuses on the tender tea shoots at the top of the tea plant, requiring the picking of the initial unfolding of one bud with one leaf or a single bud. Such fresh tea leaves must maintain intact morphology and no mechanical damage to ensure the uniform appearance and endoplasmic activity of the finished tea. Therefore, premium tea production still highly relies on manual precision picking. In contrast, bulk tea production tends to adopt large-scale picking, mainly targeting one bud with two to three leaves. Its raw materials allow moderate mixing of old leaves, and this standard has high compatibility with mechanized cutting-based picking, making bulk tea the main breakthrough area for mechanization in tea production. For specialty teas such as Oolong tea, tea shoots need to develop to a specific maturity stage before picking. Typically, two to four leaves are picked when the tea shoot grows to three to five leaves, and the top leaves reach 60%–70% unfolding. At this stage, the tea leaves have accumulated sufficient intrinsic substances, exhibiting unique flavor and aroma. The picking standard for specialty teas requires balancing leaf unfolding degree and toughness. The classification standard for mainstream tea types is shown in Fig. 1[6]. The differences in picking standards among various tea types essentially reflect the dual industrial trade-off between "quality control and production efficiency". The strict requirement of premium tea for tea shoots' integrity stands in sharp contrast to the efficiency advantage of mechanized picking for bulk tea. This standard gradient is precisely the core contradiction restricting the development of tea shoots picking technology.

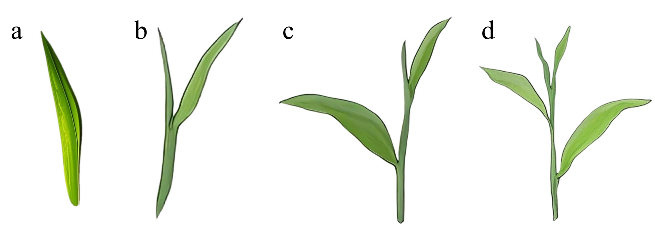

Fig. 1 Schematic diagram of tea shoot classification.

Picking technology and equipment for bulk tea

As the key equipment for picking fresh tea leaves, tea shoots picking equipment can be categorized into two major types based on working principles: breaking type and cutting type. The breaking type has been gradually phased out due to its low picking completeness rate and high tendency to damage the tea plant. In contrast, the cutting type has become the mainstream technology for bulk tea picking due to its high operational efficiency, mainly including reciprocating cutting type, spiral hob type, and disc knife type. Among these, the reciprocating cutting type is most widely applied in tea gardens. Reciprocating cutting harvesters serve as the core equipment for bulk tea production. Their core working principle is based on the high-frequency reciprocating motion of dual moving blade groups: the power-driven blade groups cut into the base of tea shoots, and cooperate with centrifugal fans or leaves-collecting devices to complete the integrated "cutting-collecting" operation.

Single-person tea harvesters (Fig. 2a) are classified into hand-held and backpack types based on power sources. The hand-held type is powered by an electric motor and consists of an eccentric mechanism, cutting blades, and a collection box[7]. It achieves cutting through the relative movement of blades driven by upper and lower eccentric wheels arranged 180° out of phase. This type features a lightweight structure and flexible operation, making it suitable for small-scale tea gardens or mountainous tea gardens. However, it is limited by its picking width and battery life, resulting in limited efficiency improvement. The backpack type (e.g., Model NV60H) is driven by a gasoline engine[7]. Power is transmitted to the eccentric mechanism and fan via a flexible shaft. After cutting, tea shoots are blown into the collection bag by the fan. It has a picking width of up to 60 cm and a daily operation area of 0.25 hm^2 per unit. Nevertheless, its heavy body increases manual load; additionally, it requires auxiliary personnel to handle the collection bags, leading to insufficient operational convenience. Both types are based on the reciprocating cutting principle and are suitable for hilly tea gardens with neat tree canopies.

Two-person tea harvesters (Fig. 2b) improve operational efficiency through dual-person collaboration. A typical model (e.g., Model SV-100) adopts a hand-carried structure, equipped with a gasoline engine-driven reciprocating cutting blade and a fan-based leaves collection system[8]. It has an expanded picking width of 100 cm and a daily operation area of 0.6 hm^2 per unit, making it suitable for terraced and gentle-slope tea gardens. Its working principle is as follows: the main and auxiliary operators jointly control the cutting angle and traveling direction, the gasoline engine power drives the blades for high-frequency reciprocating motion through a reduction mechanism. Meanwhile, the fan generates airflow to convey fresh tea leaves into the collection bag. This type of equipment enhances efficiency by increasing the cutting width, but it requires additional personnel to assist in the collection of fresh tea leaves. Moreover, its heavy body easily causes operational fatigue, limiting the capability of long-term continuous operation.

Ride-on tea harvesters (Fig. 2c, d) achieve autonomous travel through a power-driven chassis and integrate cutting, leaves

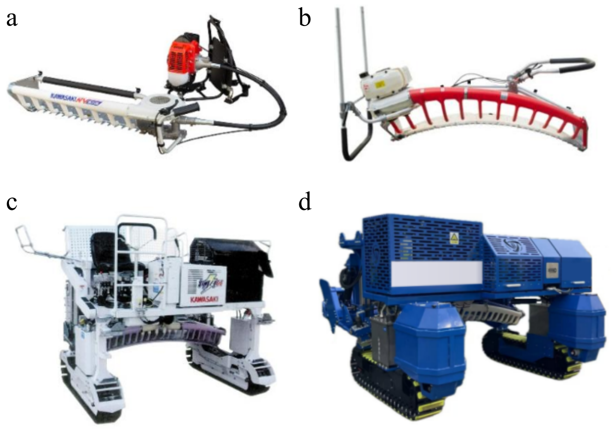

Fig. 2 Bulk tea picking equipment.

collection, and terrain adaptation functions, representing the high-efficiency direction of bulk tea picking. A typical model is the KJ4N crawler-type tea harvester, which is diesel-driven (weight: 1,370 kg) and has an operational capacity of 0.1 hm^2/h[9]. It can realize both picking and light pruning functions by replacing blades, making it suitable for standardized tea gardens with a slope of less than 15° and row spacing ≥ 1.8 m. Its technical features include a full hydraulic drive steering system and a profile-following cutting device (blade holder height adjustment range: 30–80 cm). However, it has strict requirements on the flatness of tea plant canopies and is only applicable to standardized tea gardens. In contrast, tea gardens in hilly and mountainous areas of China have large slopes, uneven furrows between tea rows, variable row spacing, and irregular canopies, making it difficult for ride-on equipment to adapt.

To further improve picking efficiency, a type of lightweight self-propelled equipment is designed with a multi-module quick-hitch mechanism, enabling rapid assembly and disassembly of modules for picking, pruning, and tillage[9]. This design reduces the comprehensive use cost. Another type of equipment is equipped with an ultrasonic ranging and profiling system, which detects the height of the tea canopy and drives a lead screw slide to adjust the cutting height, thereby achieving profiling picking[10,11]. However, acoustic interference in natural environments easily causes detection errors, requiring the integration of visual sensors to further improve recognition accuracy. From the perspectives of multi-functional integration and high-precision picking, these two types of equipment have further enhanced the competitiveness of ride-on picking machinery, providing new ideas and directions for the design and development of large-scale bulk tea picking equipment.

Currently, the bulk tea picking technology has established a "portable-collaborative-self-propelled" technical gradient, meeting the mechanization needs of tea gardens of different scales. Specifically, hand-held and backpack-type equipment are suitable for scattered tea gardens; two-person tea harvesters balance efficiency and cost; ride-on models achieve breakthroughs in large-scale operations. However, the existing equipment, dominated by reciprocating cutting type, features "undifferentiated picking", which leads to a relatively high impurity content rate of fresh tea leaves and comparatively poor quality. This significantly affects the color and taste of finished tea. Furthermore, the fixed cutting height cannot adapt to the differences in tea shoots maturity, resulting in the mixing of old leaves and branches. Thus, the picked fresh tea leaves can only meet the standards of crude tea raw materials.

The "efficiency-quality" contradiction caused by such technical characteristics means that although existing equipment can meet the production efficiency requirements of bulk tea, it fails to meet the quality standards for premium tea. In industrial practice, the hybrid model of "mechanized picking for bulk tea + manual picking for premium tea" still cannot effectively solve the dependence on labor in high-grade tea production. Future efforts in bulk tea picking technology should focus on the research and development of intelligent profiling, low-damage picking, and lightweight materials. It is imperative to overcome the challenge of precise cutting control under complex canopies, so as to balance efficiency improvement and quality assurance, and adapt to the diverse tea garden environments and planting patterns worldwide.

Handheld picking technology and equipment for premium tea

As a high-grade product in the tea industry, premium tea occupies an important market position due to its unique quality and cultural value. Its strict requirements for raw materials—for example, West Lake Longjing requires the "initial unfolding of one bud with one leaf"—make traditional manual picking the mainstream method. However, manual picking is faced with multiple challenges: labor shortage leads to high costs for tea pickers, and quality fluctuation also exists. In contrast, although bulk tea picking has basically realized mechanization with advantages of high efficiency and low cost, such equipment has obvious defects: the reciprocating cutting blade not only easily produces broken leaves but also severely damages cells on the cutting surface, accelerating the oxidation of fresh tea leaves. Furthermore, it cannot grade the picked fresh tea leaves, making it difficult to meet the production needs of premium tea. Against this background, as a transitional technical solution to replace manual picking, handheld picking equipment (Fig. 3), with its portability, flexibility, and relatively low cost, has become a key research direction to solve the picking problems of premium tea, improve picking efficiency, and maximize the integrity and quality stability of tea shoots.

Some scholars have attempted to apply a reciprocating cutting machine to the premium tea picking by optimizing cutter parameters. Du designed a reciprocating cutter with double moving blades based on the terrain of tea gardens and the application status of machinery in China[12]. Through Adams motion simulation and response surface method, the influence of parameters such as blade tooth pitch, blade tooth height, and cutting speed index on picking performance was systematically analyzed. The study determined the optimal parameter combination: 20 mm blade tooth pitch, 19 mm blade tooth height, and 1.05 cutting speed index. Corresponding performance indicators included 76.45% primary cutting rate, 21.34% re-cutting rate, and 2.50% missed cutting rate. Field tests verified that the errors between simulated values and measured values were less than 6% (for primary cutting rate), and 2% (for missed cutting rate), respectively. This provides a theoretical basis for parameter optimization of portable cutters. Wang aimed at the tea picking demand in hilly and mountainous areas, took 'Maolu' tea plant as the research object, guided the design of a portable electric tea picking device by measuring the mechanical properties of the stem, and optimized the parameters of the double moving-blade cutter[13]. The bench test showed that when the cutting speed index. was 1.05, and the cutting angle was 0, the missed cutting rate was lower than 3%, and the tea shoots' integrity rate was higher than 80%, effectively balancing efficiency and quality. The above studies have significantly improved the operational accuracy and the integrity of tea shoots of handheld picking equipment through

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structural parameter optimization and mechanical property analysis of tea stems, providing a key theoretical basis and parameter optimization paths for cutter design.

In the field of bionic structure design, inspired by the manual "pinch-pick" action, Wang et al. developed a flexible picking mechanism (Fig. 3c) that utilizes friction on the upper and lower surfaces, based on the differences in physical properties (such as growth height and breaking strength) between fresh tea leaves and old leaves[14]. The flexible materials were screened through dynamic simulation, and a prototype was built to verify the performance: under a 3.0 N picking force, the fresh tea leaves picking completeness rate was approximately 40%, the old leaves false picking rate was 7%, the damage rate was 5%, and the picking efficiency was 1.44 kg/h. Moreover, the breaking position of fresh tea leaves was consistent with that of manual picking. The application of flexible materials effectively reduced mechanical damage, demonstrating potential for protecting the picking quality of premium tea. However, this technology is highly dependent on working condition parameters such as picking force, and its adaptability in complex canopy environments needs further verification. Jia et al. designed a handheld manipulator (Fig. 3b) for picking tea shoots of premium tea, which simulates manual tea picking actions and consists of a feeding mechanism, a picking mechanism, and a steering gear[15]. The key influencing factors are determined through motion analysis, and the Box-Behnken response surface method is used to model. After optimization, the combination of parameters, such as magnetic steel distance, is obtained. Tests verified that its picking success rate reached 74.3%, the average speed was 25.2 shoots per minute, and the error was less than 5%, providing a new solution for low-damage picking of premium tea in hilly and mountainous areas. Nevertheless, the complexity of its mechanical structure and control algorithm is relatively high, placing higher requirements on the lightweight design and energy consumption control of the equipment. The above two studies, starting from the perspectives of material flexibility and mechanical control, respectively, have made progress in low-damage picking and adaptability. However, there is still room for optimization in picking efficiency and adaptability to complex environments, providing differentiated technical references for the refined design of subsequent handheld equipment.

In the direction of structural innovation, Liu et al.[16] designed a stepped transportation tea picking and grading integrated machine (Fig. 3a) based on the differences in the length of tea shoots of the 'Longjing 43' variety. This machine uses reciprocating cutting blades to complete picking and realizes tea shoots transportation and grading through multiple groups of belts. Through parameter optimization via Box-Behnken experiments, the tea shoots' integrity rate reached 77.9%, and the grading success rate reached 88.7%, achieving the connection between picking and primary processing links. Its multi-belt grading structure has the ability to deal with the difference in tea shoots' length, demonstrating advantages in process simplification and efficiency improvement. However, the reciprocating cutting blades and belt conveyor require high coordination accuracy, and the complex structure may increase equipment maintenance difficulty and manufacturing costs. Furthermore, aiming at the high missed picking rate of breaking-type harvesters, Jiang optimized the tooth profile structure of the breaking rod and designed a 3-degrees-of-freedom (3-DOF) test bench[17]. The optimal parameters (forward speed 0.2 m/s, rotational speed 350.0 r/min) were determined by orthogonal test, which reduced the missing rate to 3.6%, effectively improving the reliability of the picking process. Nevertheless, the breaking-type picking method is highly dependent on the growth angle of tea shoots and the mechanical properties of stems, and its universality in different tea varieties or complex canopies needs further verification. The above studies have promoted functional integration innovation from the perspectives of process integration and reliability improvement, respectively, reflecting the technical exploration direction of handheld picking equipment in multi-link collaboration and working condition adaptability.

From the perspective of current research progress, although handheld picking equipment for premium tea has achieved significant results in structural optimization and performance improvement, there are still multiple technical bottlenecks preventing large-scale replacement of manual picking. At the intelligence level, equipment generally lacks the ability to automatically identify the maturity and position of tea shoots, and over-reliance on manual operation limits efficiency improvement. At the mechanical design level, problems such as fatigue caused by long-term holding and operational stability in complex terrain seriously affect the practicality and promotion of the equipment. In addition, most existing studies focus on the improvement of a single performance index, lacking systematic optimization of the entire picking chain (from recognition and picking to collection). Future research should strengthen the development of multi-sensor fusion technology, ergonomic design, and intelligent control systems, promoting handheld picking equipment for premium tea to develop in the direction of high efficiency, precision, and comfort, and truly realizing the leap from "usable" to "easy to use".

Intelligent picking technology for premium tea

Intelligent picking technology for premium tea is regarded as the core direction of the future tea industry upgrading. Its key lies in constructing an intelligent operation system featuring "perception-judgment-execution". Among these, perception, recognition, and

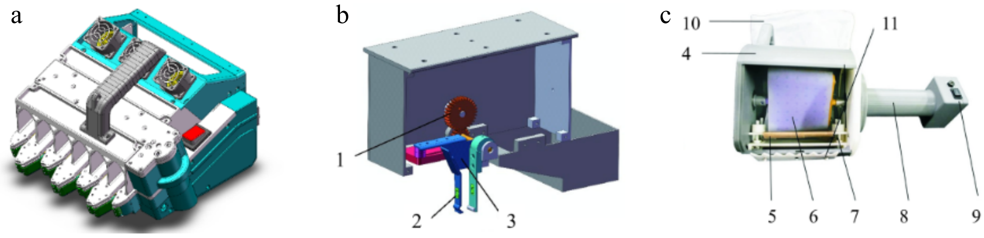

Fig. 3 Handheld picking technology for premium tea: 1. Feeding mechanism. 2. Photoswitch. 3. Picking mechanism. 4. Frame. 5. Moving plate. 6. Rolling element. 7. Pulling force adjustment mechanism. 8. DC motor (including a handle). 9. Power cabinet and controller. 10. Fresh tea leaves collection bag. 11. Old tea leaves isolation teeth.

positioning are the prerequisites and foundation for achieving precise picking. Through multi-sensor fusion, machine vision, and other technologies, it is necessary to accurately identify the growth status of tea shoot, tea shoot grade, and spatial position. The picking end-effector, on the other hand, is the key execution unit for realizing precise picking actions. It needs to be designed in combination with the physical characteristics of tea shoot and picking process requirements, forming an execution mechanism with functions such as flexible grasping, precision cutting, and non-destructive collection. This ensures the integrity of tea shoot and the stability of quality during the picking process. Current research mainly focuses on multiple aspects: improving indicators such as the accuracy, robustness, multi-variety adaptability, and lightweight design of recognition algorithms; and enhancing the success rate and efficiency of picking end-effector while reducing the tea shoot damage rate.

Intelligent recognition technology for premium tea

In the research on intelligent recognition technology of premium tea, researchers focus on the core issues of tea shoot detection accuracy, recognition robustness, positioning accuracy, and model practicability, and carry out multi-dimensional exploration based on deep learning and computer vision technology, forming a technical path with model optimization, multi-modal fusion and accurate positioning as the core.

Aiming at the demand of tea shoot detection in complex tea garden environments, the researchers made targeted improvements on the YOLO series models (V3, V4, V5, V8, V11), and achieved the balance between detection performance and engineering practicability through lightweight design, feature enhancement, and loss function optimization. Chen et al. constructed a computer vision system based on YOLOv3, integrating semantic segmentation and skeleton extraction algorithms to realize tea shoot recognition and picking point positioning[18]. The average recognition accuracy reached 71.96%, and the picking point extraction precision was 83%, providing a technical path for mechanized picking. However, the model lacks robustness under complex lighting and background conditions, and its cross-scenario adaptability needs to be improved. Li et al. improved YOLOv4 to construct the Tea-YOLO model (Fig. 4), replacing the backbone network with GhostNet and introducing the CBAM (Convolutional Block Attention Module)[19]. Verification on the 'Yinghong 9' dataset showed that the detection accuracy for "one bud with one leaf" and "one bud with two leaves" reached 85.15%. Compared with the original model, the GFLOPS (Giga Floating-Point Operations Per Second) and parameters were reduced by 89.11% and 82.36%, respectively, demonstrating significant lightweight advantages. Nevertheless, the single-variety dataset limits its generalization ability, and the robustness under extreme occlusion scenarios needs to be enhanced. Gui et al. improved the YOLOv5 model by introducing the Ghost_conv module and BAM (Bottleneck Attention Module) mechanism, combining the multi-scale feature fusion strategy and CIoU (Complete Intersection over Union) loss function[20]. This improved model increased the mAP (mean average precision) by 9.66% compared with the original YOLOv5, reduced FLOPs (Floating-Point Operations) by 52.402 G, and decreased parameters by 22.71 M, achieving a balance between precision and lightweight design.

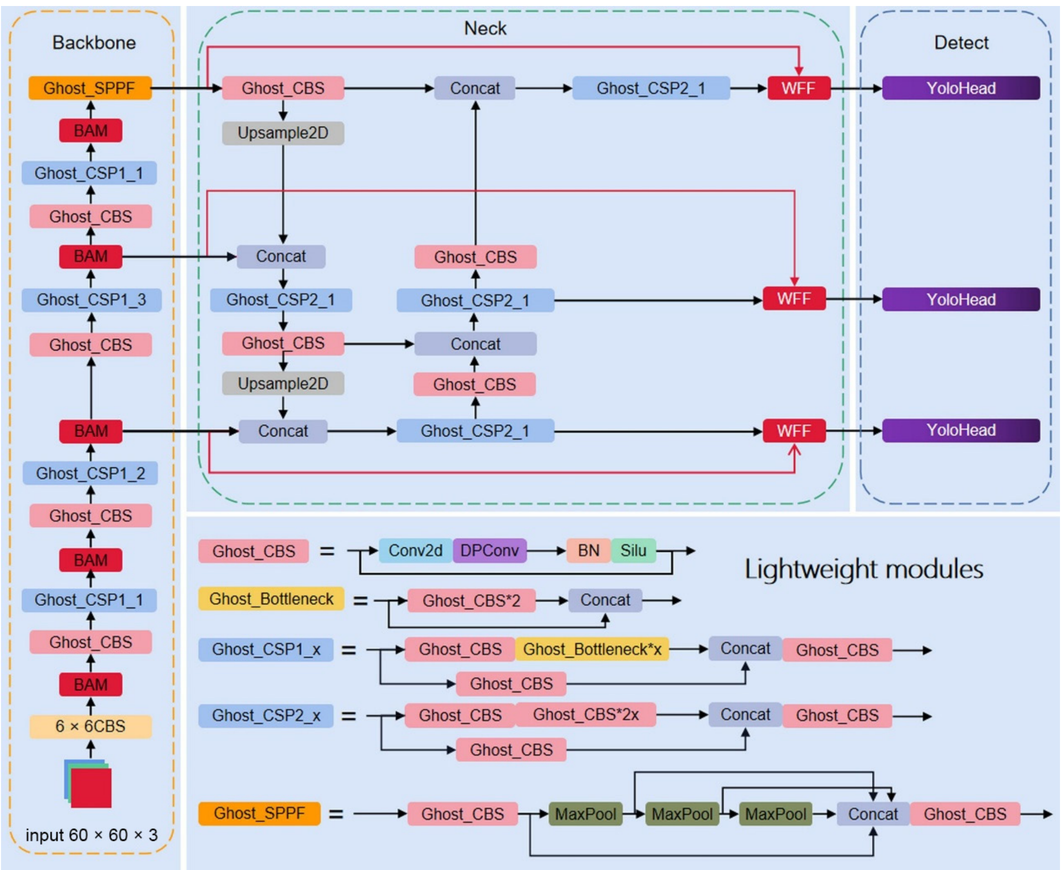

Fig. 4 Lightweight tea shoot detection model based on YOLOv5[19].

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However, its detection speed is slightly inferior to that of some single-stage algorithms, and its adaptability to complex occlusion scenarios needs optimization. Cao et al. integrated GhostNet and YOLOv5 to build the GhostNet-YOLOv5 model, introducing the coordinate attention mechanism and BiFPN (Bidirectional Feature Pyramid Network) feature fusion[21]. The detection accuracy reached 76.31%, which was 4.83% higher than that of YOLOv5, and it showed obvious advantages in F1-score under different lighting conditions. Wang et al. improved YOLOv5 for white tea varieties, integrating the coordinate attention and SPPF (spatial pyramid pooling fast) modules[22]. The precision, recall, and mAP reached 93.38%, 89.68%, and 95.73%, respectively, with parameters reduced by 0.319 M and computational complexity decreased by 1.343 G. It exhibited excellent small-target detection performance, but the missed detection rate under extreme lighting and dense occlusion still has room for optimization. Xie & Sun improved YOLOv8 to construct the Tea-YOLOv8s model, combining data augmentation and multi-module optimization to enhance detection performance under different lighting and angle scenarios[23]. The mAP@0.5 reached 88.27%, and the inference time was 37.1 ms, showing strong adaptability to scenarios with different angles. However, the increase in parameters and computational complexity poses challenges for edge device deployment, and its adaptability to cross-regional tea varieties needs verification. Liu et al. developed the TBD-Y model based on YOLOv11 improvements, adopting the co-attention mechanism and GAGFF feature fusion[24]. The mAP of TBD-Y-L reached 87.89% (2.18% higher than that of YOLOv11-L), and the TBD-Y-S model achieved better precision while reducing parameters by 44%, demonstrating strong feature discrimination ability in complex backgrounds. However, its adaptability to extreme occlusion scenarios and the variety of coverage of the dataset need to be improved.

For these improved technologies of the YOLO series model, the overall light-weight design (such as the introduction of ghost module, replacing the backbone network), feature enhancement (such as attention mechanism, multi-scale fusion strategy) and loss function optimization have effectively improved the tea shoot detection accuracy, reduced the model calculation load and parameter scale, enhanced the adaptability in different lighting, angles and other scenes, achieved a better balance between detection performance and engineering practicability, and provided diversified technical solutions for tea shoot recognition in complex tea garden environment. However, on the whole, such technologies still have common limitations: Most models have verified adaptability to a single tea variety, but their generalization ability across varieties and regions is comparatively insufficient, with limited dataset coverage. Under non-ideal environments such as extreme occlusion and complex lighting, detection robustness still needs to be enhanced, and recognition deviations are prone to occur. Some models face difficulties in balancing precision and real-time performance, or the increase in parameters and computational complexity poses challenges to edge device deployment. These issues collectively reflect that in complex tea garden environments, how to further improve the models' scene universality, stability under extreme conditions, and convenience of engineering deployment remains a direction that requires continuous breakthroughs for such technologies.

To achieve accurate positioning of picking points, the technical path based on segmentation and end-to-end positioning has further broken through the limitations of complex scenarios, improving accuracy through the integration of pixel-level segmentation and positioning. For example, Yan et al. proposed the MR3P-TS model (Fig. 5), an improved version of Mask R-CNN, which uses Res2Net as the backbone network[25]. It identifies the main body of the tea shoot and locates picking points through pixel-level segmentation. The model achieved a mAP of 0.449 for tea shoot recognition, an F_2-score of 0.313, a picking point positioning precision of 0.949, and a recall rate of 0.910. Its performance in segmenting overlapping tea shoots outperforms that of YOLOv3 and Faster R-CNN. However, there is still room for improvement in its recognition indicators, and the real-time detection speed needs optimization. Future improvements can be made by introducing attention modules or adopting a lightweight design. Chen & Chen proposed a method integrating Faster R-CNN and FCN (Fully Convolutional Network), which realizes an end-to-end solution from tea shoot region detection to picking point positioning[26]. The Faster R-CNN achieved a detection accuracy of 79% and a recall rate of 90%, while the FCN achieved an average positioning precision of 84.91% and an IoU (intersection over union) of 70.72%. For untrained varieties ('Chin Shin Oolong', 'Shy Jin Chuen'), the detection accuracy reached 77.27% and 79.66%, respectively, showing good cross-variety adaptability. Nevertheless, positioning deviations occur under extreme occlusion and complex lighting conditions, and there is still room to improve detection accuracy to meet actual picking requirements. Wang et al. constructed a detection and positioning method based on Mask R-CNN[27]. It extracts multi-scale features through ResNet50 and FPN (Feature Pyramid Network), and realizes pixel-level segmentation by combining RoIAlign (Region of Interest Align) and FCN, which improves detection adaptability under different scenarios. The average detection accuracy reached 93.95%, and the recall rate was 92.48%, showing a significant precision improvement compared with traditional methods. However, the integrity of stem segmentation under complex occlusion and computational efficiency needs optimization, and the variety of coverage of the dataset is limited.

This type of technology, based on segmentation and end-to-end positioning, has significantly improved the accuracy of picking point recognition for premium tea through in-depth integration of pixel-level segmentation and positioning, providing key technical support for automated picking in complex canopy environments. Relying on the fine recognition of tea shoot main bodies by segmentation technology, it can effectively distinguish overlapping tea shoots and enhance adaptability to complex growth forms; some methods realize an integrated process from region detection to positioning through end-to-end design, showing certain generalization potential in cross-variety recognition; the application of multi-scale feature extraction and fusion strategies also improves adaptability

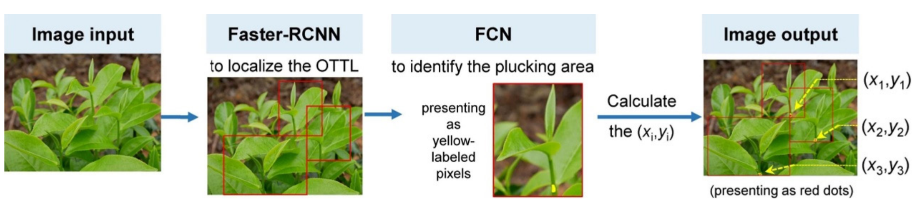

Fig. 5 Location method of tea shoots picking point based on deep learning[25].

to different scenarios, with detection precision achieving obvious breakthroughs compared with traditional methods. However, such technologies still have common limitations: there is room for improvement in the recognition indicators of some methods; the challenge of balancing real-time performance and model complexity has not been fully resolved, making it difficult to meet the high-efficiency requirements of field operations; under non-ideal environments, such as extreme occlusion and complex lighting, positioning robustness is comparatively insufficient, prone to incomplete segmentation or positioning deviations; in addition, the dataset coverage of most methods is limited, and the universality for diverse tea varieties and complex tea garden scenarios needs further verification. These issues collectively reflect that, in complex natural environments, balancing recognition precision, real-time performance, and scenario adaptability, remains a core challenge that requires continuous breakthroughs in this technical path.

To address the limitations of 2D positioning, 3D positioning technology that integrates depth information and point cloud processing has emerged as a new direction, enhancing adaptability to complex scenarios through multi-modal data fusion. For instance, Luo et al. proposed a continuous and accurate picking solution based on 2D vision, constructing a tea shoot tip recognition model for multi-interference environments[28]. Combined with a skeleton algorithm to determine the coordinates of picking points, the model achieved a recognition accuracy of 99.9% on the validation set and a mAP (0.5:0.95) of 0.97, simplifying the recognition process and reducing costs. However, its robustness in complex natural environments requires verification. Li et al. proposed a robotic system integrating deep learning and point cloud processing[29,30]. It detects tea shoot using a compressed YOLOv3 and realizes 3D positioning through point cloud processing (Fig. 6), achieving an 85.16% detection success rate and a 78.90% positioning success rate, thus enabling full-process automation. However, the system's positioning robustness in complex environments still needs improvement; some links (e.g., point cloud extraction) are significantly affected by occlusion, and future research can further explore the optimized design of occlusion-resistant positioning algorithms. In another study by Yatao Li, based on an RGB-D camera, YOLOv3 was used to detect tea shoot, and depth images were fused to generate point clouds, solving the positioning problem in occluded scenarios. The detection accuracy reached 93.1% and the recall rate 89.3%, effectively addressing the occlusion positioning issue. Nevertheless, fluctuations in depth accuracy under high-intensity lighting and errors in point cloud extraction need optimization. Chen et al. proposed a tea shoot detection and pose estimation algorithm based on a depth camera and improved YOLOv5[31]. The algorithm optimizes detection performance through a coordinate attention mechanism and BiFPN, and realizes tea shoot 3D pose estimation by combining the OPVSM (optimal pose-vertices search method) algorithm. It achieved an 85.2% detection mAP, an inference speed of 87.71 FPS, a 90% 3D pose estimation accuracy, and parameter compression to 29.25 M, achieving a good balance between real-time performance and positioning accuracy. However, its adaptability to a single variety ('Longjing 43') and the integrity of point clouds in extreme scenarios need improvement. Yang et al. proposed an RGB-D information fusion positioning method, improving the T-YOLOv8n model and designing a hierarchical visual servoing strategy to enhance the 3D positioning accuracy of picking points[32]. The detection accuracy of long-range views reached 80.8%, the $mAP_{0.5}$ for tea stem bounding boxes and masks in close-range views were 93.6% and 93.7%, respectively, the 3D positioning success rate was 86.4%, and the average depth error was 1.43 mm. This effectively improved the detection and positioning accuracy of picking points in complex scenarios, but the missed detection rate was relatively high under severe tea stem occlusion, and the dataset did not cover more tea varieties or extreme environmental scenarios. Xu et al. fused YOLOv3 and DenseNet201, and improved tea shoot detection and classification accuracy by comparing side-view and top-view perspectives[33]. The side-view detection accuracy reached 95.71% (10.60% higher than the top-view), and the classification F1-score was 96.84%, achieving accuracy improvement through perspective optimization. However, the model has high computational complexity, and its real-time performance and adaptability to dynamic field scenarios require verification.

The 3D positioning technology that integrates depth information and point cloud processing has effectively broken through the limitations of 2D positioning through multi-modal data fusion (e.g., combination of RGB and depth information, collaboration between

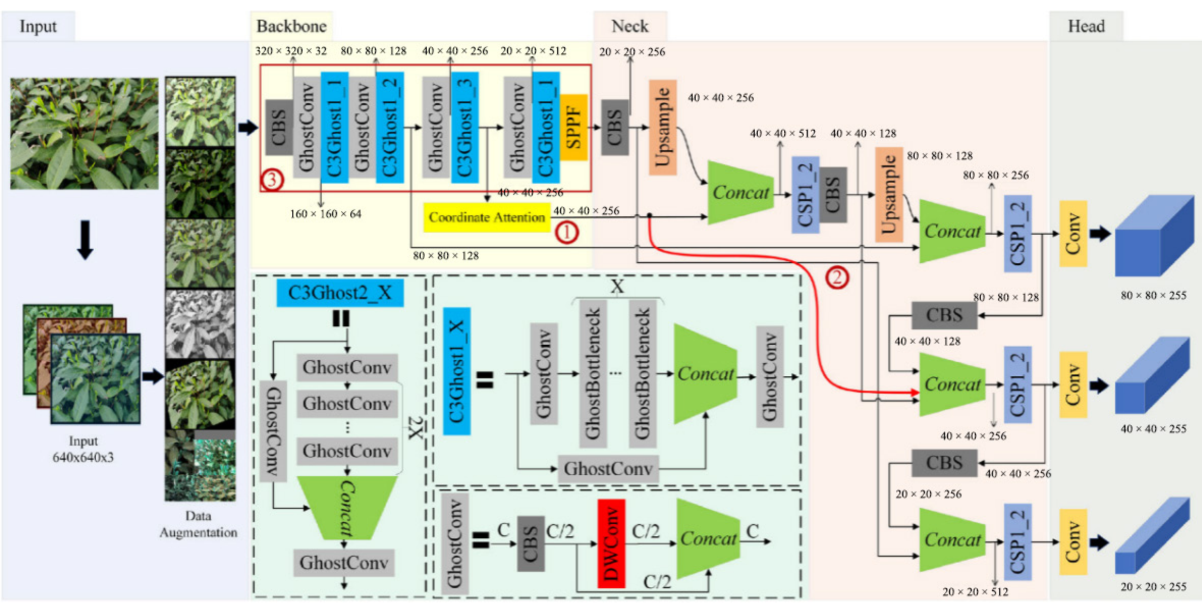

Fig. 6 Tea shoot detection and pose estimation algorithm based on depth camera and improved yolov5[30].

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point cloud processing and deep learning). It has demonstrated significant advantages in improving the positioning accuracy and adaptability of tea shoot in complex scenarios. Some technologies have reduced system costs by simplifying the recognition process, or realized full-process automation from detection to positioning, enhancing engineering practicality; the application of perspective optimization and multi-scale feature fusion strategies has strengthened the ability to recognize tea shoot with different growth forms; some methods have achieved a good balance between real-time performance and positioning accuracy through algorithm optimization, providing technical support for automated picking in complex canopy environments. However, such technologies still have common limitations. In complex natural environments, factors such as occlusion (especially severe occlusion by stems) and high-intensity lighting can easily lead to missed detections, point cloud extraction errors, or fluctuations in depth accuracy, resulting in relatively insufficient robustness in localization; most technologies have verified their adaptability to a single tea variety, but their generalization ability across varieties and regions is limited by dataset coverage, and their universality needs to be improved; some models have high computational load due to complex structures, and the adaptability between real-time performance and dynamic field scenarios still needs optimization. These issues collectively reflect that, in complex tea garden environments, balancing positioning accuracy, environmental robustness, and engineering practicality remains a core direction requiring continuous breakthroughs for this technical path.

In summary, current research has achieved significant progress in tea shoot detection accuracy, positioning accuracy, and adaptability to complex environments through model lightweight design, feature enhancement, integration of segmentation and positioning, and multi-modal information fusion, providing key support for the automation of intelligent picking. Notably, these technical advancements are reflected in three typical technical paths, namely YOLO series improvement, segmentation & end-to-end localization, and 3D point cloud fusion, and mainstream models under these paths exhibit distinct differences in performance metrics and applicable scenarios. To systematically present these characteristics for intuitive comparison, Table 1 summarizes the core information of representative improved models. However, intelligent recognition technology still faces common challenges such as relatively weak cross-variety generalization ability, comparatively insufficient robustness in extreme environments, and a certain gap between real-time performance and engineering deployment, which need to be focused on breaking through in subsequent research.

Intelligent picking end-effector for premium tea

As the core executive component to realize the "machine replacement of labor" in tea shoot picking for premium tea, the research and development of intelligent picking end-effector (Figs 7, 8) focuses on overcoming the challenges of tender tea shoot vulnerability and high picking precision requirements, aiming to achieve accurate positioning and low-damage picking. Although significant progress has been made in current related research, the technology as a whole is still in the experimental testing phase, and faces challenges in terms of picking efficiency, stability, and cost control.

Traditional mechanical picking causes high damage rates to tea shoots due to rigid contact, which seriously affects the quality of premium tea. The introduction of flexible materials and bionic technology can significantly improve picking quality. Motokura et al. proposed the 'Oritsumi' bionic picking system, which adopts a 6-degree-of-freedom Jaco^2 robotic arm from Kinova Robotics, and its end three fingers are covered with flexible materials[34]. Through machine learning of manual picking actions, the system established a database containing parameters such as tea plant branch diameter, hardness, and growth angle, and could dynamically adjust the grasping strategy according to tea branch stiffness. In practical tests, the actions generated by this method showed high similarity to human demonstration actions, achieving the highest success rate and lowest failure rate in actual picking experiments, and could effectively pick high-quality tea leaves. This provides new ideas and methods for the design of an intelligent picking end-effector for premium tea. However, the complex structure of the multi-DOF robotic arm may increase equipment costs and control difficulty, and its universality for different tea varieties needs verification. Luo et al. established a mechanical model of tea stems based on the flexible contact principle of manual picking, and systematically analyzed the relationship between tea stem diameter, tissue maturity, and pulling force[35]. The study found that the pulling force of terminal tea stems was significantly lower, and the flexural strength of tea stems was positively correlated with the degree of lignification. Based on this, the research team determined the optimal combination of mechanical parameters: clamping pressure of 340 kPa, bending force of 0.134 N, and pulling force of 5.1 N. This

Table 1. Comparison of experimental results of different models.

Technical approach	Model/method	Key performance metrics	Application scenarios
YOLO series improvements	YOLOv3-based[18]	mAP 71.96%; Picking point precision 83%	Resource-constrained tea gardens (lightweight deployment on embedded end-effector)
	GhostNet-YOLOv5[19]	Accuracy 76.31% (↑4.83%); F1 ↑under varying lighting	Dynamic lighting tea garden (early morning/late afternoon picking with frequent light adjustments)
	TBD-Y[24]	mAP 87.89% (↑2.18%); Parameters ↓44% (TBD-Y-S)	Complex canopy tea gardens (Mature tea plantations with dense foliage requiring strong feature discrimination)
Segmentation & end-to-end localization	MR3P-TS[25]	Bud mAP 0.449; Picking point precision 0.949	High-precision premium tea picking (e.g., Longjing requiring sub-millimeter accuracy)
	Faster R-CNN + FCN[26]	Localization mAP 84.91%; cross-variety accuracy 77.27%–79.66%	Mixed-variety tea gardens (fields with multiple tea Varieties)
3D point cloud fusion	Tea-YOLOv8s + Point Cloud[29]	Detection success 85.16%; localization success 78.90%; depth error 1.43 mm	Fully automated picking robots (robotic arms requiring 3D spatial positioning)
	TBD-Y + OPVSM[31]	mAP 85.2%; inference 87.71 FPS; 3D pose accuracy 90%; parameters 29.25 M	High-speed real-time picking (balance of precision and speed)
	T-YOLOv8n + Hierarchical Servo[32]	Close-up $mAP_{0.5}$ = 93.7%; depth error 1.43 mm; 3D localization success 86.4%	High-precision servo control: (e.g., Longjing requiring sub-millimeter accuracy)

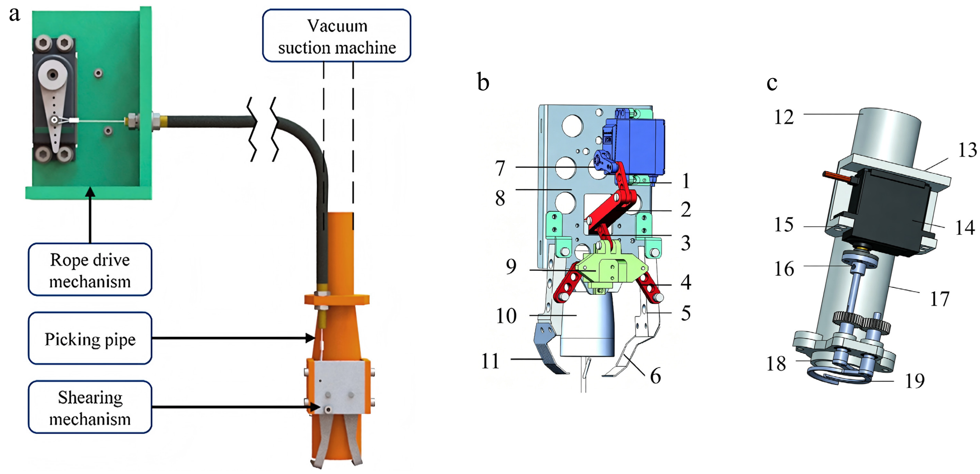

Fig. 7 Intelligent picking end-effector of premium tea: 1. Connecting rod. 2–4. Connecting rod. 5. Blade mounting plate. 6. Integrated cutter. 7. Steering gear 8. Fixed plate. 9. Slide rail. 10. Negative pressure pipe. 11. Split cutter. 12. Upper nozzle of end pipe. 13. Connecting platform. 14. Steering gear. 15. Steering gear bracket. 16. Connecting flange. 17. End pipe. 18. Lower nozzle of end pipe. 19. Annular cutter.

study provides a quantitative basis for the design of a low-damage picking end-effector, effectively reducing quality deterioration caused by tea polyphenol oxidation. Based on this, Luo et al. designed a combined pinch and cut picker, which adopts a dual-function structure of "flexible clamping + precise cutting"[36]. Field tests showed that the single operation time of this end-effector was stably within 0.6 seconds, and the actual picking success rate reached 100%. The combination of stainless steel cutters and high-density sponge achieved low-vibration and accurate picking, effectively controlling surface indentation on tea shoot while ensuring clamping force. However, the dual-function structure requires highly coordinated control precision and may face adaptability challenges for tea shoots with different growth angles in complex canopies. Hao et al. designed a bionic picking finger targeting the mechanical properties of 'Longjing 43' tea shoots, and optimized the parameters of the four-bar linkage using a genetic algorithm, improving the driving force transmission efficiency by 26.6%[37]. Preliminary indoor tests showed that the picking success rate for "one bud with one leaf" was nearly 70%. However, the problem of gripper closing misalignment caused by mechanical processing errors exposed the contradiction between structural stability and assembly precision, which affected the reliability of actual operations. Xue et al. proposed a "rotational lifting" picking method, innovatively embedding PVDF piezoelectric film sensors into the picking fingers[38]. These sensors can real-time monitor the pressure changes on tea shoot during picking; combined with the SMC-PID control algorithm, the system can dynamically adjust the robotic arm's movement trajectory according to feedback signals, effectively avoiding damage to tea shoot caused by action delay. Nevertheless, the integration of sensors may increase the structural complexity and manufacturing cost of the end-effector. The above studies have advanced through paths of bionic picking, flexible materials, mechanical optimization, intelligent feedback, and structural combination, all achieving key breakthroughs in low-damage picking and precise control. This reflects the multi-dimensional technical innovation direction of the intelligent picking end-effector for premium tea.

Aiming at the problems of single-function and poor adaptability of traditional picking end-effector, researchers have carried out innovations from the perspectives of structural reconstruction and function integration. Zhu et al. proposed a negative pressure-guided picking end-effector (Fig. 7a), which realizes real-time posture correction of tea shoot through a negative pressure field of 0.6–0.9 kPa[39,40]. Its unique design of "conical picking tube + vortex adsorption" forms a spiral airflow inside the tube, which can increase the capture success rate to 97.36% within a 10 mm deviationrange.CFD(ComputationalFluidDynamics)simulationbasedonthe 'Y-shaped' tea shoot physical model shows that when the leaf spacing is ≤ 30 mm and the horizontal deviation is ≤ 10 mm, the negative pressure guidance success rate can reach the theoretical maximum of 100%. To verify this theory, the research team conducted tests in an experimental tea garden. The results showed that under complex canopy environments, the high consistency between CFD simulation and field tests verified the theoretical reliability, providing theoretical support and practical verification for efficient picking under complex canopies. However, this technology has high threshold requirements for leaf spacing and spatial deviation, and its adaptability may be limited in canopies with extremely dense or disordered growth. The split-cutter end-effector (Fig. 7b) developed by Chen et al. adopts a deformable split-cutter tooth structure to address the problem of variable growth angles of the lateral shoot[41]. Combined with a visual recognition system, this end-effector can accurately locate lateral shoot, achieving picking success rates of 93% for terminal shoot and 63% for lateral shoot respectively. The differentiated picking success rates between terminal and lateral shoot reflect its targeted design for tea plant morphology; nevertheless, the gap in success rates between lateral and terminal shoot indicates that there is still room to improve the technology's adaptability to complex growth angles. The threaded tube adsorption picking end-effector[42] innovatively combines negative pressure with threaded flow guidance, and optimizes the internal flow field distribution through Fluent simulation, increasing tea collection efficiency from 72% to 98% (Fig. 7c). However, the complex structure optimized by flow field simulation may increase equipment manufacturing and maintenance costs. The rotating two-workstation integrated effector (Fig. 8a) for premium tea picking and collection[43] realizes seamless switching between picking and temporary storage functions through a 180° forward and reverse rotation cycle of the picking end. This end-effector adopts a dual-motor independent drive system, resulting in a short switching time between picking and collection actions. Meanwhile, it uses silica gel material with a Shore hardness of 30HS, and a convex structure is designed on the surface, which effectively reduces the friction damage rate on the tea shoot surface. Through the

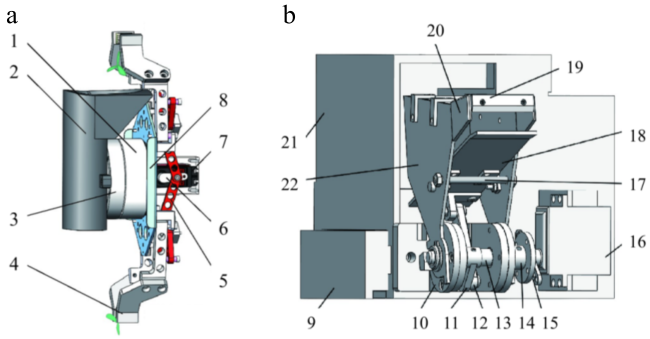

Fig. 8 Intelligent picking end-effector of premium tea. 1. Motor. 2. Temporary storage box. 3. Connecting piece. 4. Picking fingers. 5. Transmission connecting rod. 6. Steering gear arm. 7. Steering gear. 8. Mounting plate. 9. Collection drawer. 10. Stop block. 11. Crank. 12. Connecting rod. 13. Step shaft. 14. Flange. 15. Steering gear arm. 16. Steering gear. 17. Gear lever. 18. Jaw. 19. Customized blade. 20. Blade seat. 21. Leak proof fixing box. 22. Tool rest.

application of dual-function switching and flexible materials, it achieves a balance between picking efficiency and damage control; its short switching time and low-friction design demonstrate engineering application potential. However, the energy consumption control of its dual-motor drive system and the durability of the convex structure still need further verification in long-term field operations. Lin et al.'s optimized design of the under-actuated end-effector (Fig. 8b) is more breakthrough: through topology optimization, the total rod length is shortened by 25.33%, and combined with an adaptive clamping algorithm, the operation success rate remains stable at 93.30%–95.00% under working conditions of clamping positions of 4–8 mm and growth angles of 70–90°, with an average picking time of only 0.64 s, approaching the level of skilled manual picking[44]. Its lightweight design and rapid operation capability are outstanding; however, its adaptability to a wider range of clamping positions and growth angles still needs further verification through more field tests. The above studies have promoted innovation through paths of aerodynamics, morphological adaptability, flow field optimization, and function integration, collectively driving an intelligent picking end-effector for premium tea toward precision and low damage. At the same time, it also exposes the technical balance challenge between equipment reliability and working condition adaptability in complex tea garden environments.

Although the aforementioned studies have made breakthroughs in structural innovation, mechanical optimization, and function integration, the intelligent picking end-effector for premium tea still faces multiple challenges: Some end-effectors have an increase in the number of components due to multi-degree-of-freedom robotic arms, complex sensor integration, or dual-function composite structures. The resulting requirements for assembly precision lead to a significant increase in equipment failure rates. Additionally, accumulated delays in the perception-decision-execution process within the mechanical picking action chain result in a significant efficiency gap between the single operation cycle and skilled manual picking. Furthermore, in natural environments, sudden changes in light intensity, variations in canopy density, and randomness in the growth angles of tea shoots are likely to cause misjudgments in visual recognition and action delays of the end-effector, leading to insufficient picking stability under complex working conditions. Future research should further deepen the application of flexible materials, optimize the design of bionic structures, and strengthen the research and development of multi-sensor fusion technology. This will promote intelligent picking end-effector toward the direction of industrialization, featuring high efficiency, low damage, and reliability.

Existing problems

Although phased progress has been made in tea shoots picking machinery technology, and new equipment and technologies have been gradually promoted, the industrial development still faces structural and technical bottlenecks.

For bulk tea picking equipment, there is insufficient structural innovation and intelligence. Although the reciprocating cutter is the main force of bulk tea picking, its picking quality is poor (with the tea shoots' integrity rate generally below 80%[9]), which can easily cause secondary damage to tea shoots. Links such as fresh tea leaves grading and maturity judgment during the picking process still rely on manual operations, leading to insufficient levels of mechanical automation and intelligence.

In the field of handheld picking equipment, although structural optimization has improved the integrity rate of tea shoots picked (approaching 90%[45]), the level of intelligence remains significantly lagging. Most equipment relies on manual identification of tea shoots' maturity and position, which limits the actual operational efficiency. From the perspective of mechanical design, handheld equipment has certain defects in ergonomics (generally weighing over 1.5 kg), making operators prone to fatigue after long-term work. In addition, existing studies mostly optimize cutting efficiency or collection functions in isolation, lacking collaborative design for the entire "recognition-picking-collection" process. This leads to connection losses between links and a reduction in overall efficiency. At the same time, there is a disconnection in alignment between the agronomic requirements for tea shoots picking and the design of handheld picking equipment, resulting in a low level of integration of agricultural machinery and agronomy.

Although intelligent picking technology has made breakthroughs in intelligent recognition, bionic structure of picking end-effector, and function integration, there is still a gap from industrial application (the cost of a single machine is more than 300,000 yuan, which can only replace one to two personnel[46]). Some end-effectors have a high failure rate due to structural complexity (the success rate of picking is less than 80%), and the time consumed for a single picking operation does not show a significant efficiency improvement compared with manual picking (the time for a single skilled worker to manually pick a shoot is about 1 s, and the time for the existing mainstream equipment to pick is generally more than 2 s). In complex environments, factors such as changes in light intensity and leaf overlap expand the error of visual positioning, leading to a decline in picking success rate. Furthermore, most existing technologies focus on performance verification in laboratories, with low coverage of field adaptability tests, making it difficult to meet the needs of actual production.

The integration degree of agricultural machinery and agronomy is low in some regions. Tea-producing countries such as Japan have basically achieved mechanization, while in some tea gardens in China, there is an obvious conflict between the row spacing range and the adaptive row spacing of existing self-propelled picking equipment, making it difficult for the equipment to carry out large-scale operations smoothly; the cultivation method commonly adopted in the planting of premium tea results in a complex canopy structure of tea plants, which makes existing batch picking equipment difficult to adapt, further restricting the promotion and application of mechanized equipment.

Development trends and recommendations

To meet the demand for high-quality development of the tea industry, tea shoots picking technologies and equipment need to undergo systematic innovation around directions such as intelligent upgrading, lightweight, and modular improvement, standard system construction, and interdisciplinary integration. Specifically, progress can be made from the following dimensions:

Strengthen the research and development of intelligent picking technology. Relying on artificial intelligence and deep learning technologies, construct an integrated "perception-decision-execution" intelligent picking system. Through the development of highly adaptable recognition algorithms and a lightweight picking end-effector, realize intelligent recognition of fresh tea leaves and selective picking. To address the problems of low picking efficiency, poor picking quality and high end-effector failure rate, design a low-degree-of-freedom, lightweight, flexible end-effector to shorten the single-arm picking time to within 1.5 s; optimize the end-effector using multi-modal sensors and bionic flexible materials to reduce the tea shoots damage rate; simplify the structure of the end-effector, select high reliability and lightweight parts to improve stability, and explore multi-robotic-arm collaboration modes to improve overall picking efficiency through spatial layout optimization and motion trajectory planning. To solve the insufficient intelligence of handheld picking equipment and the poor connection of the whole process, use multi-sensor fusion technology to obtain real-time tea canopy data, realize automatic identification of tea shoots maturity and position, dynamically adjust cutting parameters, and improve the picking quality and efficiency of handheld equipment; strengthen the collaborative design of the whole process of "identification picking collection". To address the problems of insufficient intelligence and poor picking quality of bulk tea picking equipment, upgrade the bionic cutting edge of reciprocating cutters to reduce secondary damage, and integrate machine vision to achieve tea leaf maturity assessment and automatic grading. For the issues of large positioning errors and poor field adaptability in complex environments, develop multi-modal fusion recognition algorithms to enhance anti-interference capability and improve picking success rates; expand the scope of field tests covering different terrains, climates, and tea varieties, and conduct iterative optimization of equipment and algorithms.

Promote lightweight and modular improvement of equipment. Integrate ergonomic concepts into the design of handheld picking equipment, optimize the overall weight and distribution to achieve a lightweight design, reduce fatigue during long-term operations, and improve equipment operational stability. In response to the characteristics of complex terrain and scattered plots of tea gardens in hilly and mountainous areas, develop narrow-width and portable self-propelled picking machines. Through adjustable chassis, adaptive profiling frames, and quick-connection interfaces, realize modular integration of multiple operational functions such as picking, pruning, and fertilization.

Improve the standard system and industrial collaboration. Conduct research on the integration of picking equipment and cultivation measures, accelerate the formulation of unified standards for picking machinery, planting agronomy, and operation processes, and establish "demonstration zones for the integration of agricultural machinery and agronomy". Standardize mechanization-friendly parameters, such as tea plant pruning and canopy shape, to provide standardized scenarios for equipment promotion.

Through the above measures, tea shoots picking technology will achieve breakthroughs in intelligence, lightweight design, and adaptability, helping the tea industry to achieve an overall improvement in mechanization levels across tea gardens of different scales and under different picking standards.

Conclusions

The research and development of tea shoots picking technology is the core driving force for promoting the mechanized upgrading of the tea industry. Currently, the bulk tea picking technology has formed a mature technical system, and the reciprocating cutting machine has been widely adopted with high-efficiency operation ability. However, there are still some problems, such as relatively poor tea shoots quality, moderately high reliance on labor, and vibration and noise pollution. Additionally, the adaptability of the reciprocating cutting machine in tea gardens with complex terrain is relatively insufficient, and the equipment reliability and operational stability need to be further improved. Due to the strict quality standards and complex canopy environment of premium tea, its mechanization process is still in the technical breakthrough stage. Constrained by the requirements for tea shoots integrity and complex canopy environment, although the existing handheld picking equipment has improved the tea shoots integrity rate through parameter optimization, it still relies on manual recognition and positioning, resulting in an insufficient intelligence level.

As the core direction of tea industry upgrading, intelligent mechanized picking currently faces dual challenges of technical bottlenecks and industrial application. On the one hand, most integrated intelligent equipment remains in the prototype development stage and has not yet formed mass production capabilities. On the other hand, although intelligent recognition technology has made progress in tea shoot detection and positioning, and has shown potential in improving detection accuracy and adaptability to complex scenarios through feature enhancement, lightweight design, and multi-modal data fusion, it still generally faces problems such as relatively weak cross-variety generalization ability, moderately insufficient robustness in extreme environments (high-intensity lighting, dense occlusion), and pending optimization of real-time performance and engineering adaptability. A stable and reliable industrial application solution has not yet been established. Moreover, the intelligent picking end-effector, as the core executive component, has made technical breakthroughs in bionic structure design, but its complex structure leads to relatively high failure rates and comparatively long time consumption per picking operation, resulting in a certain gap in efficiency compared with manual picking. These problems are intertwined, which not only restrict the operational efficiency of the equipment, but also make it difficult for the picking quality to meet the production requirements of premium tea, becoming the main obstacles to industrial promotion.

Differences among various tea shoots picking technologies in core indicators such as operating efficiency, tea shoots integrity rate, applicable scenarios, core advantages, and main disadvantages can be clearly presented in Tables 2 and 3, providing an intuitive reference for comparing the advantages and disadvantages of various technologies and selecting applicable scenarios.

In the future, the innovation of picking technology should prioritize two key directions: firstly, focus on equipment research and development, and achieve breakthroughs in intelligence, lightweight design, and modularization of picking equipment by improving the accuracy and adaptability of recognition algorithms,

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Table 2. Operation efficiency, shoots integrity and applicable scenarios of different technologies/equipment.

Technology/equipment type	Operating efficiency	Tea shoots integrity rate	Applicable scenario
Manual picking	About 0.003 hm^2/h	> 85%	Any type of tea garden; premium tea picking
Bulk tea picking equipment (single-person type)	About 0.031 hm^2/h	60%–80%	Small-scale tea gardens; tea gardens with complex terrain, hilly and mountainous areas; bulk tea picking
Bulk tea picking equipment (two-person type)	About 0.075 hm^2/h	60%–80%	Medium-scale tea gardens; flatland, gentle slope, and terrace tea gardens; bulk tea picking
Bulk tea picking equipment (ride-on type)	About 0.1 hm^2/h	75%–85%	Large-scale continuous tea gardens; flatland and gentle slope tea gardens; bulk tea picking
Handheld premium tea picking equipment	About 0.016 hm^2/h	80%–90%	Small-scale tea gardens; any terrain tea gardens; premium tea picking
Intelligent picking technology	About 0.005 hm^2/h	> 85%	Large-scale continuous tea gardens; flatland and gentle slope tea gardens; standardized tea gardens; premium tea picking

Table 3. Core advantages and main disadvantages of different technologies/equipment.

Technology/equipment type	Core advantages	Main disadvantages
Manual picking	High picking quality, capable of precise selective picking; extremely strong terrain adaptability	High labor cost; extremely low efficiency, difficult for large-scale operations; quality stability is affected by labor
Bulk tea picking equipment (single-person type)	Low equipment cost, small initial investment; flexible and mobile; simple operation and maintenance; quick return on investment	Poor picking quality; easy to damage tea plants; requires manual sorting, increasing costs; high work intensity
Bulk tea picking equipment (two-person type)	Excellent balance between efficiency and cost; low work intensity; stable equipment and low maintenance cost	Poor picking quality; limited adaptability; relies on two-person cooperation, efficiency affected by coordination
Bulk tea picking equipment (ride-on type)	Extremely high large-scale operation efficiency; significantly reduces labor and management costs; short harvesting cycle	High equipment and maintenance costs; poor terrain adaptability; slightly improved picking quality, but still only applicable to bulk tea
Handheld premium tea picking equipment	Quality close to manual picking, suitable for premium tea; portable and flexible; low maintenance cost	Low intelligence, relies on manual positioning; limited efficiency improvement; poor ergonomics; insufficient integration of agricultural machinery and agronomy
Intelligent picking technology	Intelligent and precise selective picking, stable quality; capable of 24-h continuous operation; convenient for digital management	Extremely high equipment cost; poor adaptability to complex environments; low picking success rate; insufficient industrial application adaptability; high maintenance requirements

integrating and improving picking end-effector, incorporating ergonomic concepts, and integrating multiple operational functions; secondly, promote research on the integration of agricultural machinery and agronomy, deepen the research into the adaptability between picking equipment and tea garden cultivation measures, and construct a unified standard system covering the technical parameters of picking machinery, the agronomic standards for tea garden management, and operation processes. Through continuous technological innovation and application verification, tea shoots picking technology will promote the transformation of picking equipment from prototype development to engineering application, providing technical support and theoretical basis for the mechanized and intelligent transformation of the tea industry.

Author contributions

The authors confirm their contributions to the paper as follows: the presented paper was conducted in collaboration of all authors; draft manuscript writing and revision: Liu H, Yao Y; article collection and collation: Jiang H, Zhou X, Gan N, Li Z, Zhang L; manuscript review: Gan N, Lv L, Dong C, Li X, Li Y. All authors reviewed the results and approved the final version of the manuscript.

Data availability

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

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Conflict of interest

The authors declare that they have no conflict of interest.

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