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Review

Research Progress and Trend Analysis of Picking Technology for Korla Fragrant Pear

Yanwu Jiang [1,2], Jun Chen [1,*], Zhiwei Wang [1] and Guangrui Hu [3]

[1] College of Mechanical and Electronic Engineering, Northwest A&F University, Yangling 712100, China; jywxnd@nwsuaf.edu.cn (Y.J.); zhiweiwang@nwsuaf.edu.cn (Z.W.)
[2] College of Mechanical and Electrical Engineering, Xinjiang Agricultural University, Urumqi 830052, China
[3] School of Design, Xi'an Technological University, Xi'an 710021, China; 2017050952@nwsuaf.edu.cn
* Correspondence: chenjun_jdxy@nwsuaf.edu.cn; Tel.: +86-29-8709-1867

Abstract: This article provides a comprehensive review of the current results of pear-picking technology, delving into the development process, classification, application status, and development trends of picking machinery, picking robots, and intelligent technology. By analyzing the key technologies in pear fruit harvesting, this paper explores the working principles of harvesting machinery, the technical characteristics of harvesting robots, and the potential applications of intelligent technology. Furthermore, a bibliometric analysis was employed to examine two decades of the research literature on Korla fragrant pear, spanning from January 2004 to June 2024, utilizing the core collection of the Web of Science and the China National Knowledge Infrastructure database as the retrieval platforms. The visualization of the analysis results indicates that the focal points of research in this field are predominantly aspects such as the quality and storage conditions of fragrant pears, with a scarcity of studies directed toward mechanized harvesting. Additionally, this study addresses the existing challenges and issues within pear-picking technology and delineates potential avenues for future development, with the objective of providing a foundation for subsequent research on Korla fragrant pear-harvesting technology.

Keywords: pear-picking technology; harvesting machinery; intelligent; bibliometric analysis; Korla fragrant pear

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1. Introduction

Pears, native to Central Asia, are widely distributed across numerous Chinese provinces, such as Hebei, Shandong, Shaanxi, and Gansu. They are also cultivated in Italy, the United States, Spain, and France. Pears exhibit several tolerance traits, such as cold, drought, waterlogging, and salt tolerance, and they possess well-developed root systems. They thrive in conditions with sufficient light and appropriate temperatures. Ideal planting locations are gently sloping mountains with deep, well-draining soil, particularly sandy loam. The primary propagation method for pears is grafting. The main varieties of pears include Snow pear, Ya pear, Korla fragrant pear, Apple pear, Golden pear, and Crown pear [1]. Recognized as one of the major fruits worldwide, pears exhibit high adaptability to various climates and soils, which contributes to their widespread distribution. They are grown and produced in 88 countries and regions worldwide, with China standing out as a significant center of origin for pear plants. With a cultivation history of over 3000 years, China leads in both cultivation area and output. In China, pears are regarded as the most important fruit [2]. Figure 1 presents a comparison chart of pear production over the past 10 years.

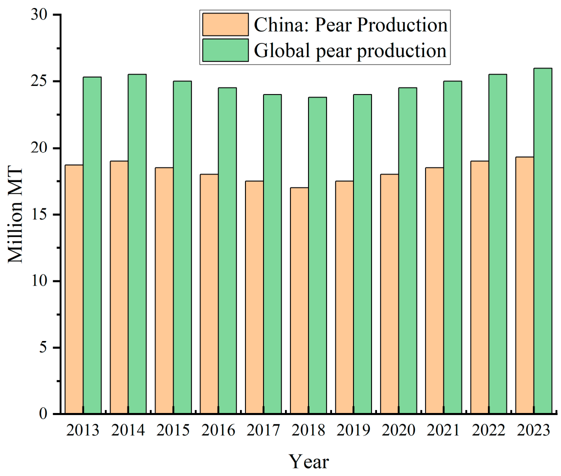


Figure 1. Comparison of pear production in China and the world.

The Korla fragrant pear, a representative of pear fruits, possesses substantial economic value in both domestic and international markets due to its rich nutritional content and unique flavor [3,4]. Traditionally, the harvesting of fragrant pears has primarily relied on manual labor, which is associated with challenges such as high labor intensity, low efficiency, high costs, and susceptibility to seasonal and climatic constraints. These limitations have significantly hindered the sustainable development of the pear industry [5]. As the pear industry continues to develop, addressing key issues such as improving harvesting efficiency, reducing picking costs, and enhancing fruit quality has become increasingly critical in agricultural production [6–8]. Research into pear-harvesting technologies, particularly the integration of mechanization and intelligent approaches, to enhance both efficiency and quality has emerged as a central focus in modern agricultural technology research [9,10].

Fruit-picking technology has evolved gradually from manual picking to mechanized picking [11]. Manual picking relies on experience to judge fruit maturity, enabling maximum protection of the fruit. However, in large-scale production, its limitations, such as high labor intensity, low efficiency, and costs, have become increasingly apparent, making it difficult to meet the demands for efficient and large-scale harvesting [12,13]. To address these challenges, mechanized picking technology has emerged. By introducing specialized machinery and equipment, mechanized picking significantly reduces labor costs and improves production efficiency [14–16]. However, existing mechanized equipment still faces numerous challenges in practice. These include the irregular shape of fruits, the complex distribution of tree branches, and the difficulty of adapting to different fruit and tree types. Additionally, the picking process often causes fruit damage [17–19]. Furthermore, high operating costs limit the widespread adoption of mechanized equipment across growing regions.

Against this backdrop, the rapid advancement of robotics and artificial intelligence has opened up new opportunities for innovation in pear-picking technology [20]. As a novel form of automated and intelligent picking equipment, picking robots have become a research hotspot in orchard management. Utilizing intelligent perception technologies, picking robots can assess factors such as fruit maturity and location to make informed decisions, enabling precise picking operations. This not only significantly enhances picking efficiency but also minimizes fruit damage [21–23]. However, fruit-picking robots are still in the research and development stage. The key challenges for current research include how to further enhance the performance of picking robots and reduce their application costs, which remain critical barriers to widespread implementation [24].

The fruit of the Korla fragrant pear has a delicate, thin skin that is highly susceptible to damage. Harvesting is a meticulous process involving several critical stages, such as assessing fruit ripeness, protecting the peel, determining the optimal harvest timing, and selecting appropriate handling tools. During the harvesting process, it is imperative to avoid damage to the fruit's epidermis to preserve its visual appeal and edible value [25]. Although manual harvesting ensures better fruit quality, the rising labor costs and increasing difficulty in securing a sufficient workforce have made this method inefficient and expensive. This highlights the pressing need to adopt advanced mechanization technologies to improve harvesting efficiency and reduce fruit damage, which has become a key focus in the harvesting of Korla fragrant pears [26]. In recent years, the introduction of automated fruit-harvesting robots, robotic arms, and intelligent control systems has provided fresh perspectives for innovation in harvesting methods and technologies for fragrant pears.

This paper provides a comprehensive review and analysis of advancements in fruit-harvesting technologies, with a systematic examination of the current state of pear production in China. It evaluates the application outcomes and challenges of typical harvesting methods, tracing the evolution from traditional manual techniques to modern mechanical and automated solutions. The study highlights the current application status of fruit-harvesting technologies, emphasizing the development of advanced equipment and insights from practical case studies [27]. Focusing on the specific harvesting requirements of Korla fragrant pears, this paper identifies key technological bottlenecks and challenges and outlines prospective research directions. The aim is to offer theoretical foundations and practical guidance to advance the development of efficient harvesting technologies for Korla fragrant pears.

2. Pear Production in China

2.1. Production Scale

The expanse of land devoted to pear cultivation in China has demonstrated notable stability over the past decade, characterized by decreasing fluctuations since 2015. According to data from the National Bureau of Statistics, the pear-planting area in China reached 9216.59 km^2 in 2021, signifying a contraction of 451.49 km^2 from the 9668.08 km^2 recorded in 2020, which corresponds to a decrease of approximately 4.67%. In comparison, the area in 2012 was 9697.68 km^2, indicating a decline of approximately 486.62 km^2 over the past ten years, or roughly 5.02%. This stabilization, despite the reduction, has been influenced by several factors, including strategic adjustments in the national agricultural industry structure and the implementation of the staple food policy. In 2022, the pear planting area is approximately 9133.79 km^2. Notably, despite the reduction in area, the yield has exhibited a rising trajectory, attributable to advancements in science and technology, optimization of varieties, and improvements in management practices. In 2022, China's pear production soared to 19.2653 million tons, marking a year-on-year increase of 2.06%. Compared to 15.4441 million tons in 2013, this represents an increase of approximately 3.8212 million tons over the past decade, or about 24.74%, with an average annual compound growth rate of 2.24% [1,2,11]. Figure 2 illustrates a comparison of the changes in the planting area and growth rate of pear fruit in China over recent years.

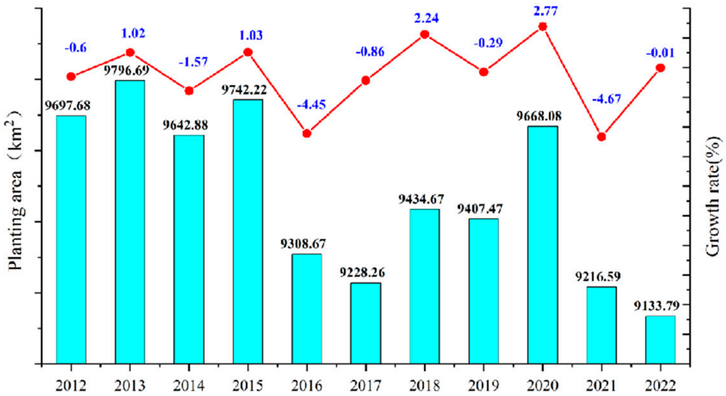


Figure 2. Change in China's pear-planting area and growth rate.

2.2. Pear Production Distribution

According to statistics from the Food and Agriculture Organization of the United Nations (FAO), China's per capita consumption of fresh pears in 2020 was 12.6 kg, significantly exceeding the global average. Together, the top six provinces in pear production—Hebei, Xinjiang, Henan, Liaoning, Anhui, and Shandong—accounted for over 50% of the nation's total pear yield. The development of the pear industry plays a vital role in agricultural advancement in China, directly influencing farmers' income and the operational efficiency of enterprises. In terms of foreign trade, China holds a prominent position as a leading exporter of fresh pears. Data from Chinese customs reveal that in 2020, the export volume of fresh pears reached 539,400 tons, surpassing the import volume of 10,400 tons by a substantial margin of 529,000 tons. Additionally, the export value amounted to USD 667.737 million, exceeding the import value of USD 18.298 million by USD 649.439 million. Major export markets include Indonesia, Vietnam, Thailand, and Malaysia. Figure 3 shows the main export markets for Chinese pears [2,11].

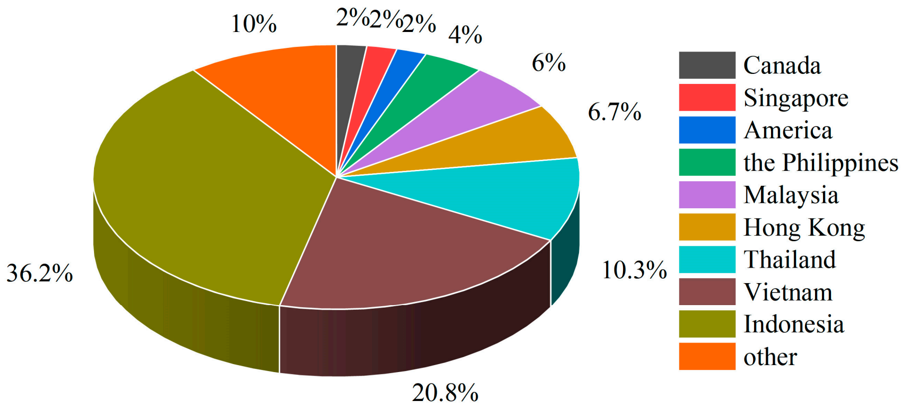


Figure 3. China pear export destination distribution.

2.3. Overview of Korla Pear

The Korla fragrant pear is a unique variety indigenous to the Korla region of Xinjiang, with a cultivation history of over 1300 years. Renowned for its distinctive fragrance, sweetness, and crispness, it is called the "treasure of pears" and the "prince of fruits." Due to the unique climate and soil of the production area, Korla pears have characteristics unmatched by other varieties. They are recognized for their high brand value and are actively exported internationally. According to 2022 statistics, the total area for Korla fragrant pears is 366.49 km^2, with a fruit-bearing area of 288.28 km^2. The total output of Korla fragrant pears reached 590,200 tons, with an output value of USD 325.8 million. The fragrant pear industry has become a cornerstone of local rural economic development, significantly promoting agricultural growth, increasing farmers' income, and boosting regional economic growth [2,6,11–13].

3. *Overview of* Pear-Picking Technology

3.1. Pear-Picking Technology and Classification of Picking Machinery and Equipment

Pear-picking technology is mainly categorized into three types: manual picking, mechanical picking, and robot picking [28]. In terms of traditional manual picking, despite escalating labor costs, manual picking is still the main picking method in some areas, especially for individual farmers and small-scale orchards. Manual picking excels in preserving the integrity and quality of pears but is characterized by inefficiency and labor intensity [29]. The advancement of mechanized harvesting technology has the potential to lessen dependence on manual labor; however, it is associated with an increased incidence of fruit damage. Additionally, it necessitates specific cultivation patterns and row spacing for fruit trees. Recently, intelligent harvesting technology has emerged as a significant trend in pear harvesting, combining mechanical automation with artificial intelligence. Intelligent harvesting robots can identify ripe pears using a visual system and accurately pick them, thereby minimizing fruit damage during the harvesting process. This technology not only enhances harvesting efficiency but also maintains the quality of pears, although it remains in the research and promotion phase. Theoretically, the mechanization and automation of harvesting technologies could greatly enhance operational efficiency; however, practical implementation and commercial adoption face several challenges, including technological maturity, cost–benefit considerations, and adaptation to the diverse agricultural environment [26–29].

The classification of pear fruit-picking machinery and equipment is primarily segmented into three categories: manual picking tools, semi-automatic picking machinery, and intelligent picking machinery. Hand-picking tools include fruit clippers, fruit baskets, etc. These tools rely on manual operation and are suitable for small orchards or selective picking. Semi-automatic picking machinery uses vibrating trunks or branches to separate the fruit, and the other uses auxiliary picking platforms, which are suitable for use in factories and large orchards. Fully automated picking machinery, which incorporates intelligent picking technology, mainly uses computer vision technology to identify and position the fruit. It then feeds back the acquired fruit position information to the picking robot, which ultimately uses an end effector to separate the fruit, thereby completing the picking task. It integrates high-tech technologies such as automation control, sensor technology, and image recognition, which can realize the unmanned picking process [20,21].

3.2. Working Principle of Pear-Picking Machinery

The Korla pear, distinguished by its particular economic attributes within its geographical domain, has yet to see the development of a sophisticated mechanized harvesting technique. The academic literature available on this matter is notably sparse. In response to this deficiency, the current study extrapolates from the established mechanical harvesting methodologies applied to comparable fruit varieties. It provides an extensive analysis of these pivotal technologies and examines their viability for integration into the Korla pear-harvesting process.

The core working principle of pear-harvesting machinery encompasses several critical technical components, including the precise localization and identification of fruit, the design of robotic arms, the development of flexible end-effector grasping mechanisms, and the integration of intelligent control systems [30,31]. Compared to harvesting technologies for other fruits, pear-harvesting machinery must account for the unique physical characteristics and fragility of pears, placing special emphasis on the gentleness and precision of fruit-grasping operations during the design phase [32]. Accurate localization and identification are typically achieved using advanced vision systems and sensor technologies, which analyze features such as fruit shape, size, and color to determine the specific location and maturity state of the fruit [33].

To adapt to varying canopy structures and accurately reach the fruit for harvesting, the robotic arm must be designed with a high degree of flexibility and adaptability. The critical aspect of the end-effector design is its ability to minimize fruit damage, which is particularly crucial for the delicate and easily damaged pear fruit. The intelligent control system plays a pivotal role by processing sensor data in real time, accurately evaluating the fruit's maturity, determining the optimal harvesting time, and guiding the robotic arm to execute precise picking actions [33–35].

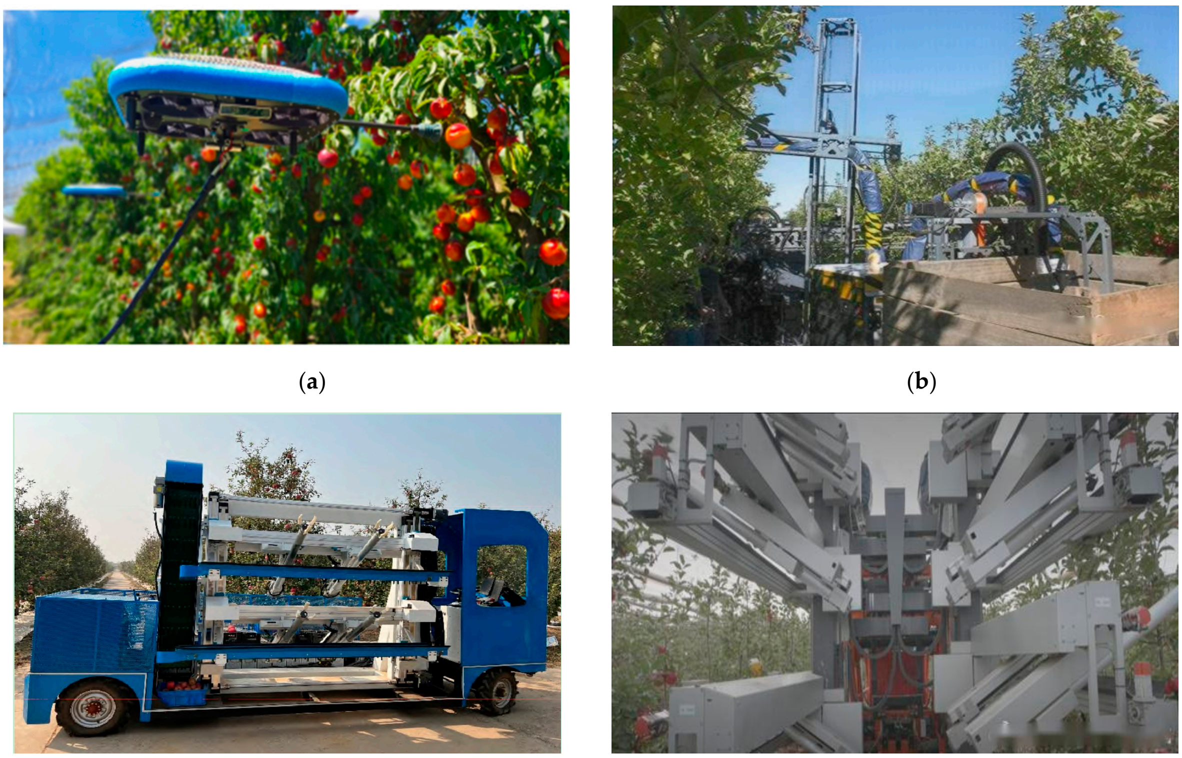
Compared to harvesting technologies for fruits such as apples and citrus, pear-harvesting machinery faces unique technical challenges due to the distinctive characteristics of pears and their canopy structure [36]. These challenges include the fruit's delicate texture and the structural complexity of the canopy. At present, the robot harvesting technology for other fruits such as apples and citrus is still immature and has not been widely promoted and applied [37,38]. Therefore, when developing pear-harvesting machinery, optimizing existing technologies to address the specific characteristics of pears remains a critical issue.

In real-world application scenarios, the design of pear fruit-harvesting machinery must fully consider the complexity and variability of environmental factors [39,40]. Specifically, fluctuations in weather, the diversity of orchard terrain, and the differences in fruit size and shape all present challenges to the performance of the machinery. Given this, the harvesting machinery must possess outstanding adaptability and reliability to ensure efficient and stable operation across various environments.

3.3. Orchard-Picking Robot Technology

The robot technology for pear fruit picking amalgamates advancements in robotics, image recognition, and artificial intelligence to achieve automation and intelligence in the pear-harvesting process. Equipped with sensors and cameras installed on the robot arm, the robot can accurately identify the location, size, and maturity of pear fruits, and then utilize a precise control system to facilitate the grasping and picking of the fruit [41].

Currently, orchard-picking robots are classified into several types based on their picking methods. The Unmanned Aerial Vehicle (UAV) aerial harvesting system, exemplified by the FAR developed by the Israeli company Tevel Aerobotics for orchard harvesting, represents a pinnacle of aerial robotic harvesting technology (as shown in Figure 4a). This UAV is outfitted with a state-of-the-art onboard camera and visual recognition system, enabling it to accurately identify fruits and evaluate their size and ripeness. Furthermore, it autonomously plans the most efficient flight path and performs the harvesting operation with the assistance of an integrated robotic arm and an advanced stabilization system. Ripe Robotics, an Australian company, has made significant advancements in agricultural robotic harvesting with its EVE series of fruit-picking robots, which exemplify the industry (as illustrated in Figure 4b). The EVE robots employ articulated robotic arms in conjunction with a negative pressure adsorption method for effective harvesting. Equipped with machine vision technology, these robots can accurately locate fruits and evaluate their ripeness. The end-effectors are designed in a suction-cup configuration, facilitating the encapsulation, adhesion, and rotational detachment of the targeted fruit. This design is particularly effective for harvesting hard fruits such as apples, plums, and peaches, regardless of whether they are cultivated on 2D planar or V-trellis systems. The EVE robots have undergone five generations of development, culminating in a commercially viable product. Ripe Robotics has implemented a distinctive business model; rather than selling or leasing the robots, the company charges per bin of harvested fruit, similar to the payment structure for human pickers. This strategy lowers the barriers for fruit farmers to adopt new technologies. The Auto Picker, a pioneering integrated orchard robotic harvesting system in China, is specifically designed for dwarf and high-density planting orchards (as illustrated in Figure 4c). This robot incorporates multiple advanced technologies, including stereo vision technology based on multi-task deep learning and heuristic task planning algorithms. Equipped with a four-arm parallel harvesting execution module, it performs efficient harvesting operations, achieving a workspace coverage rate of up to 85%, a successful collection rate of 82%, and a comprehensive harvesting efficiency that exceeds 500 fruits per hour. The fourth type of robotic system features multiple mechanical arms equipped with gripping and twisting mechanisms, developed by the Israeli company FF Robotics (as illustrated in Figure 4d). This robotic platform employs several arms, each fitted with three-finger grippers specifically designed for apple harvesting. The harvested apples are subsequently placed on a conveyor belt for sorting into bins. This advanced system is capable of harvesting thousands of apples per hour, achieving a yield rate between 85% and 96%.



(**a**) (**b**) (**c**) (**d**)

Figure 4. Orchard-picking robot. (**a**) Tevel Aerobotics FAR [41]. (**b**) Ripe Robotics [42]. (**c**) Auto Picker [43]. (**d**) FF Robotics [44].

Despite the rapidly increasing global demand for agricultural products, labor shortages have emerged as a significant constraint on agricultural production. Automated agriculture offers a promising solution to these challenges. The selective harvesting of high-value crops, which is currently performed predominantly by hand, remains one of the most labor-intensive and costly tasks in the agricultural sector. Although there is substantial interest in and research on automated harvesting technologies, their practical application has been limited thus far. While mechanization and automated harvesting technologies theoretically hold the potential for enhanced efficiency, considerable progress is still required in terms of practical implementation and commercialization. The development of robots for pear and fruit picking not only improves harvesting efficiency and reduces labor costs but also ensures the quality of the produce while minimizing damage during the picking process. As technology continues to advance, pear- and fruit-picking robots are evolving towards greater multifunctionality and intelligence, positioning themselves as essential tools for modern orchard management.

4. Korla Pear-Picking Technology Research

4.1. Agronomic Overview of Korla Fragrant Pear Planting

The trees cultivated in the standardized orchard of Korla fragrant pear exhibit a spindle-shaped structure. The formation of the tree is characterized by a height ranging from 3 to 3.5 m, with a trunk height of 70 cm. The trunk's thickness is notably greater than that of the fruiting branches, exceeding three times their width. The main trunk supports approximately 26 to 30 bearing branches, which extend uniaxially. The base angle of these branches ranges from 70° to 80°, while the waist angle varies between 80°and 90°. The length of the middle and lower bearing branches are maintained at no more than 1.6 m, whereas the upper bearing branches progressively decrease in length, measuring less than 1.2 m. The fruiting branches are distributed on the main trunk in a pattern characterized by a smaller upper section and a large lower section, with a consistent spacing of 50 cm between the upper and lower fruiting branches in the same direction [45].

The Korla pear is a petite fruit variety, averaging 110 g per fruit. Its shape is irregular, typically resembling a spindle or an oval. The sepals can be either abscission or persistent, and the calyx may present as concave or convex. The stem is characterized by being semi-fleshy, succulent, or lignified, with an average length of 3.7 cm. When ripe, the fruit skin exhibits a range of colors, from green to yellow-green, or features a striped red halo. The surface of the fruit is smooth, waxy, and thick, with small, dense, reddish-brown dots. The skin is thin, while the flesh is white, juicy, delicate, and crisp, possessing a sweet and fragrant quality. The fruit's pit is slightly acidic and edible, containing stone cells. The natural maturity period occurs in mid-September, and the fruit is known for its durability, and the storage period can reach 6 months to 8 months [46].

4.2. Requirements for Picking Korla Fragrant Pear

Currently, the primary method of harvesting Korla fragrant pears is manual picking, which involves climbing tree trunks and using aerial auxiliary tools to collect the fruit. The optimal harvest period occurs from early to mid-September, lasting approximately two weeks. The main tools used in the process are fruit baskets and fruit ladders. The fruit baskets should be equipped with a harness and hook, and lined with soft materials on the interior walls to prevent damage to the fruit. Fruit ladders need to be sturdy yet portable. Harvesters are recommended to wear woven gloves during the picking process. When detaching the fruit from the branches, a gentle twisting or lifting motion should be employed to avoid damaging the fruit, ensuring careful and delicate handling. The picking sequence should proceed from the lower parts of the tree to the upper parts, and from the outer branches towards the interior [47,48]. Pear picking is a labor-intensive operation, with the labor required for harvesting constituting over 50% of the total labor in fruit production. The harvesting period for fragrant pears is brief, and the picking process is labor-intensive. Mature fruits often drop from the trees naturally due to the limited time available for harvesting. Additionally, the use of props during picking frequently leads to fruit collisions and further loss of fruit. The fragrant pear has a brief harvest period coupled with high picking intensity, which means that ripe fruits tend to fall off naturally if not harvested promptly. The use of prop-assisted picking often results in additional fruit loss. The industrial cultivation of fragrant pears faces significant challenges, including low harvesting efficiency and difficulties in ensuring fruit quality. Consequently, the adoption of intelligent mechanical picking as a replacement for manual labor has emerged as an unavoidable trend.

4.3. Statistics of Korla Fragrant Pear Research and Analysis of the Current Status of Mechanized Harvesting

(1) Data source

The research data were sourced from two databases: the Chinese literature collection database (China National Knowledge Infrastructure, CNKI) and the foreign literature collection database (Web of Science, WoS). In the CNKI database, the search condition was set to 'subject (precise)', with 'Korla fragrant pear' as the search term. The dataset index was selected from the Science Citation Index (SCI), Engineering Index (EI), Peking University Core, and Chinese Science Citation Database (CSCD), resulting in a total retrieval of 466 Chinese literature entries. In the Web of Science database, the 'Web of Science Core Collection' was selected. The search parameters were configured to encompass 'all fields,' and the search terms included 'Korla fragrant pear' or 'Pyrus sinkiangensis', which yielded a total of 114 English documents. According to the inclusion criteria, which restricted the Chinese literature to academic journals and dissertations while limiting English literature to articles and review articles, specific exclusion criteria were applied to identify the relevant literature. The Cite Space 6.3. R1 software was employed to de-duplicate the data, resulting in the selection of 454 valid Chinese literature sources and 112 valid English literature sources. The literature search was conducted from 1 January 2004 to 31 May 2024. Figure 5 illustrates the literature analysis retrieval database [49–51].

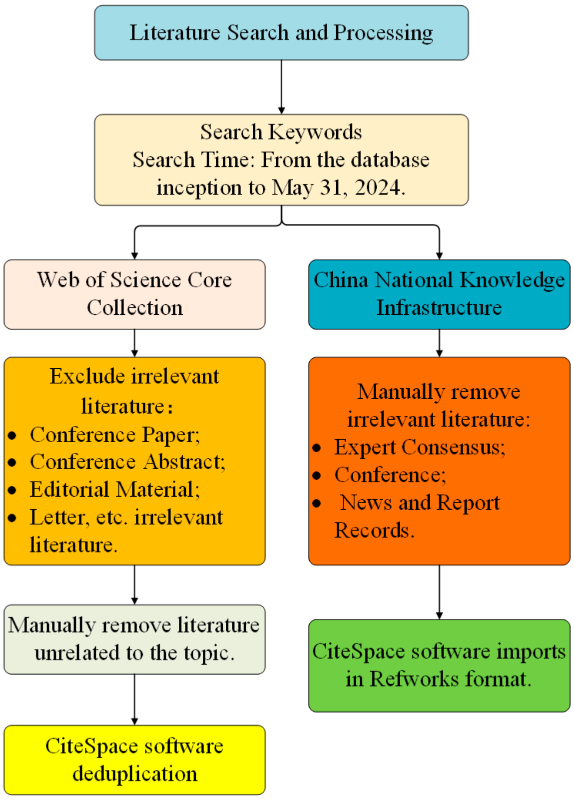


Figure 5. Literature analysis search database.

(2) Analytical methods

This paper focuses on the literature pertaining to Korla fragrant pear-picking technology as its analysis object. The literature metrology method is applied, utilizing the metrology analysis tools available in the Web of Science and China National Knowledge Infrastructure databases. Additionally, CiteSpace 6.3.R1 visualization software is employed for the quantitative analysis of the related literature and the visualization of knowledge graphs. Building on this foundation, the paper systematically summarizes and discusses the hot fields and development trends in Korla fragrant pear research. Given that this study focuses on the latest developments in the fragrant pear-picking technology industry, a detailed analysis of the literature publication trends, key authors, and institutions is not conducted [52].

(3) Analysis of the current status of mechanized harvesting of fragrant pears

The keywords of the paper serve as a highly concise and summarizing representation of the research purpose, object, and method. Figure 6 illustrates the results of the keyword cluster analysis conducted in the Web of Science, which is crucial for identifying the distribution and emerging trends within the related research on Korla fragrant pear. In this study, the Log Likelihood Ratio test was employed to conduct a cluster analysis of keywords, focusing primarily on the content labels associated with the research categories of horticulture and food technology. The emergence of keywords is characterized by a notable increase in their frequency of occurrence over a brief period, signifying a heightened level of attention during that time. This phenomenon facilitates the assessment of research trends and frontiers within the field. The emerging keywords related to Korla pear in the Web of Science are illustrated in Figure 7. The results indicate that English literature predominantly emphasizes composition analysis of Korla pear. However, in recent years, there has been an increase in studies focusing on pear quality, storage conditions, gene transcription, and expression analysis, among other topics.

In the literature on Korla fragrant pears retrieved from the Web of Science, Hu H et al. have developed a non-destructive method using hyperspectral imaging, which can be utilized to differentiate pears without causing damage and meets packaging standards [53,54]. Wang Z et al. conducted research on the morphology and quality indicators of Korla fragrant pears to optimize the harvesting process, thereby providing a foundation for the quality control and processing of these fruits [55]. Yu S et al. developed a portable non-destructive device for measuring soluble solids content in Korla fragrant pears, utilizing near-infrared diffuse reflectance spectroscopy. The precision of the spectral measurements was enhanced through the optimization of preprocessing procedures and the selection of key wavelengths [56]. Liu Y et al. employed a deep learning framework to predict the post-harvest hardness and soluble solids content of fruits. By integrating this method with hyperspectral imaging technology, they have provided an effective means for rapid and non-destructive quality assessment of Korla fragrant pears [57]. Yu S et al. studied the effects of harvest maturity and refrigeration time of Korla fragrant pear on fruit quality indicators (soluble solids and Vc content). By analyzing the changing patterns of maturity in Korla fragrant pear, the authors developed a quantitative evaluation model that accurately quantifies the pear's maturity. This model provides a scientific basis for determining the optimal harvest period and assessing maturity [58].

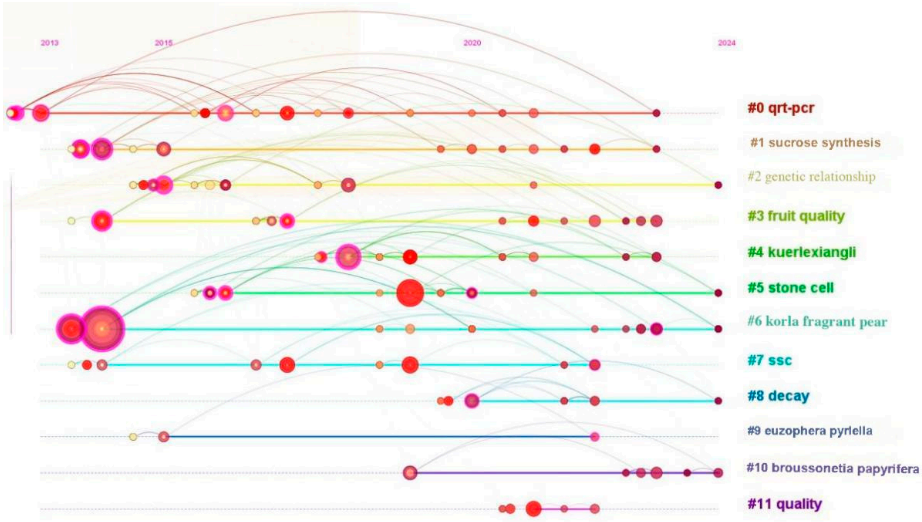
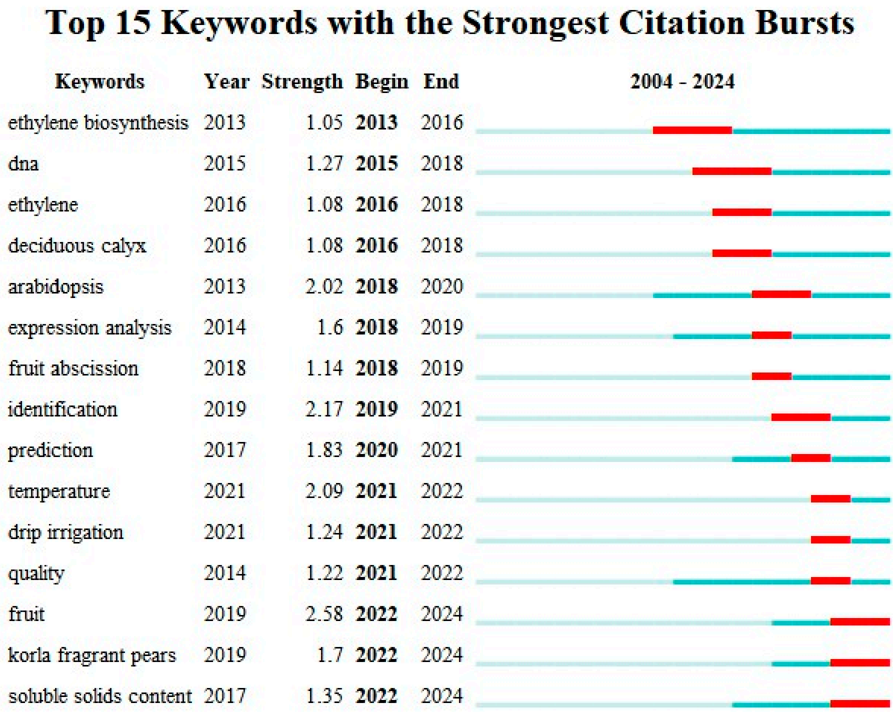


Figure 6. Keyword cluster analysis of Korla fragrant pear literature in WoS database.



Top 15 Keywords with the Strongest Citation Bursts

Keywords	Year	Strength	Begin	End	2004 - 2024
ethylene biosynthesis	2013	1.05	**2013**	2016	
dna	2015	1.27	**2015**	2018	
ethylene	2016	1.08	**2016**	2018	
deciduous calyx	2016	1.08	**2016**	2018	
arabidopsis	2013	2.02	**2018**	2020	
expression analysis	2014	1.6	**2018**	2019	
fruit abscission	2018	1.14	**2018**	2019	
identification	2019	2.17	**2019**	2021	
prediction	2017	1.83	**2020**	2021	
temperature	2021	2.09	**2021**	2022	
drip irrigation	2021	1.24	**2021**	2022	
quality	2014	1.22	**2021**	2022	
fruit	2019	2.58	**2022**	2024	
korla fragrant pears	2019	1.7	**2022**	2024	
soluble solids content	2017	1.35	**2022**	2024	

Figure 7. Keywords of Kuerle fragrant pear in WoS database's Top 15 Keywords (emergent gamma value γ[0, 1] = 0.02).

A search for 'Korla fragrant pear' on CNKI revealed that the retrieved literature predominantly focused on the distribution of subjects related to horticulture, basic agricultural science, agronomy, and plant protection (as illustrated in Figure 8). The primary research theme centered on the development of new pear varieties, with keyword cluster analysis highlighting aspects such as fruit quality, yield, nutrients, light, and other characteristics. However, there is a notable scarcity of research addressing the mechanization of Korla fragrant pear, and investigations into intelligent picking methods are still in their infancy, with a relatively limited number of related investigations. This area warrants further in-depth exploration and research.

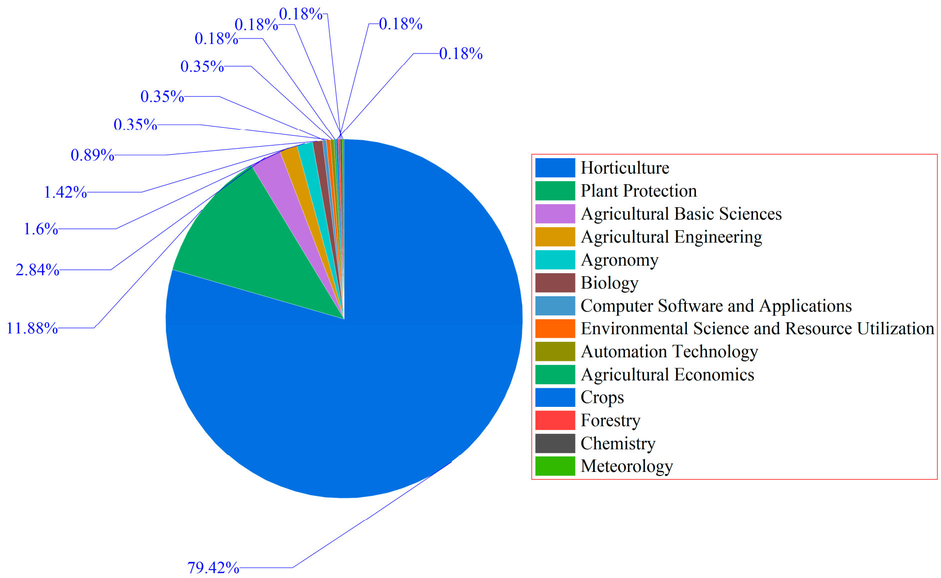


Figure 8. Research on subject distribution of CNKI retrieval.

The crisp texture of the Korla pear presents a significant challenge for mechanized harvesting. To minimize mechanical damage to the fruit and facilitate automated picking, several domestic researchers have undertaken relevant foundational studies. Guo H et al. analyzed the geometric and physical properties of Korla fragrant pears and explored the factors influencing picking and squeezing, providing a theoretical basis for the design of robotic arm parameters. Based on the principle of underactuation, a "Y"-shaped pear-picking robot arm was designed to mimic manual picking actions. It consists of the following three components: the transmission system, the grasping device, and the finger differential system. Driven by a single motor, the robotic arm can grasp the fruit and complete the picking and separation actions with the help of auxiliary devices. Bench test results show that the robotic arm achieves a 96% success rate in grasping and completes a single picking operation in approximately 2.6 s [59]. An J et al. studied the damage to the Korla fragrant pear in the peduncle area caused by different harvesting methods. Based on the principles of statics, a mechanical model was developed to analyze the effects of different harvesting methods on the contact position between the peduncle and the pear body, and this model was experimentally validated according to actual harvesting requirements. The results indicated that pulling is the optimal harvesting method for fragrant pears [60]. Liu Y et al. developed an end-effector for fragrant pear harvesting based on the analysis of physical properties and mechanical models, featuring a controllable clamping force. The end-effector primarily consists of a clamping component, a rotating component, a pressure feedback unit, and a control unit, working in a coordinated clamping-and-twisting manner. The harvesting test results indicate that when the clamping force threshold and twisting angle are set to 7 N and 60°, respectively, the clamping-and-twisting time ranges from 1.01 to 1.75 s, the fruit release time ranges from 0.43 to 0.91 s, and the harvesting success rate is approximately 94.6% [61]. Yu S et al. developed an impact damage model for Korla fragrant pear based on its electrical characteristics. At a consistent impact height, the extent of damage to the fragrant pear correlates positively with its maturity [62].

5. Challenges, Problems, and Trends

5.1. Current Status and Challenges of Intelligent Fruit-Harvesting Technology

Currently, pear harvesting primarily relies on manual labor and is significantly affected by seasonal changes and climate variability, especially in traditional orchards. With the advancement of agricultural mechanization, various harvesting machines have been developed and applied. However, these machines face challenges such as limited adaptability, high fruit damage rates, and excessive costs. In recent years, the rapid development of robotics, artificial intelligence, and Internet of Things technologies has brought pear-harvesting robots into the research spotlight [63–66]. These robots are typically equipped with visual recognition systems, manipulator units, and intelligent decision-making systems, enabling precise fruit identification and harvesting in complex orchard environments, thereby significantly improving harvesting efficiency and fruit quality. Nevertheless, existing research mainly focuses on harvesting robots for fruits like apples and oranges, while robotic harvesting technology for pears remains in the exploratory stage [67]. Compared to apples and oranges, the delicate nature of pears presents additional challenges for intelligent harvesting [68]. Therefore, this study proposes an intelligent harvesting approach tailored to the characteristics of Korla fragrant pears. Future research should focus on enhancing robot adaptability in complex environments, reducing fruit damage rates, and optimizing costs to promote the industrial development of fragrant pears.

5.2. Trends and Gaps in the Research Field of Korla Fragrant Pear

This paper provides a comprehensive review and in-depth analysis of the key hotspots and development trends in Korla fragrant pear research. Keyword cluster analysis in the Web of Science database reveals that studies predominantly focus on horticulture and food technology. In contrast, research in the CNKI database continues to concentrate on new pear variety development, fruit quality, and yield. Notably, there is a significant lack of studies on mechanization and intelligent harvesting technologies for Korla fragrant pears. Research indicates that the mechanization and automation levels in pear harvesting are considerably lower than those for fruit trees like apples and oranges [69–71]. By focusing on the growth and fruit characteristics of Korla fragrant pears, the potential of intelligent harvesting technology to enhance yield and fruit quality, while simultaneously reducing labor costs, is highlighted [72,73]. Future research should prioritize advancements in visual recognition, grasping precision, environmental adaptability, and system integration to promote the mechanization and intelligent development of the Korla fragrant pear industry.

5.3. Research on Key Technologies for Intelligent Harvesting of Korla Fragrant Pears

The primary objective of this study is to establish a scientific foundation for the development of intelligent harvesting technologies by thoroughly analyzing the growth characteristics, harvesting requirements, and limitations of existing harvesting techniques for Korla fragrant pears, and to propose specific technical solutions [70,74]. This study comprehensively evaluates current pear-harvesting technologies and identifies critical factors that influence the efficiency and fruit quality of intelligent harvesting, such as the morphological characteristics of the fruit and challenges related to environmental adaptability [75–77]. Based on these findings, a design framework for an intelligent harvesting system tailored to Korla fragrant pears is proposed. This framework includes a precise visual recognition system, a flexible robotic arm design, research on soft and adaptive end-effectors, and an efficient intelligent decision-making system [78].

Future intelligent harvesting systems for fragrant pears should prioritize enhancing the adaptability and flexibility of robotic arms in complex environments to handle variations in canopy structures and fruit positions [78–80]. Furthermore, the visual recognition system must be capable of accurately identifying fruit, even under highly variable lighting conditions, to ensure reliable fruit detection. The design of the grasping mechanism should specifically account for the delicate nature of pear fruits, aiming to achieve an efficient, non-destructive harvesting process [81]. Cost control is another critical factor in the application of intelligent harvesting technology. Given the current state of technological development, it is essential to optimize the integrated design of intelligent machinery to reduce costs and improve the system's cost-effectiveness [82]. The findings of this study provide a clear scientific basis for the future development of intelligent harvesting technologies for Korla fragrant pears and offer specific technical guidance for their practical application. It is expected that these advancements will accelerate the modernization of the Korla fragrant pear industry and enhance its competitiveness in domestic and international markets.

5.4. Existing Problems and Challenges

Although intelligent harvesting technology demonstrates tremendous potential in pear harvesting, several technical challenges remain unresolved. These challenges are particularly evident in improving harvesting precision, accommodating the diversity of fruit shapes, enhancing environmental adaptability, and ensuring equipment stability. Current mechanical and robotic technologies are still unable to achieve fully automated harvesting in complex orchard environments. Specifically, the precision required to handle pears with varying levels of maturity, shapes, and sizes leaves considerable room for improvement [83,84].

For Korla fragrant pears, the diversity in fruit morphology (including variations in size, shape, and maturity) increases the difficulty of precise recognition and operation by intelligent harvesting equipment. The performance of existing visual recognition and mechanical grasping technologies in complex orchard environments has not yet met expectations [85]. The climatic conditions of orchards, such as changes in lighting, impose higher demands on the environmental adaptability of the equipment. In particular, the intelligent harvesting system relies on big data support and complex algorithm processing. However, the current standardization of data collection is insufficient, resulting in a lack of comprehensive training data for machine learning models, which has become a major obstacle to the promotion of this technology. Additionally, the high cost of existing harvesting machinery, combined with the technical requirements for high precision and low damage, presents challenges for equipment development. Only by overcoming these technical bottlenecks and enhancing the equipment's environmental adaptability and harvesting precision can the automation and intelligent harvesting of Korla fragrant pears be realized, thereby promoting the sustainable development of its industry.

Future advancements will require interdisciplinary collaboration to address these technical bottlenecks. Efforts should focus on optimizing the precision of harvesting equipment, enhancing environmental adaptability, and improving techno-economic feasibility to provide comprehensive support for the intelligent harvesting of Korla fragrant pears.

6. Conclusions and Prospects

6.1. Conclusions

This study systematically reviews the latest advancements in pear-harvesting technologies, with a particular emphasis on intelligent non-destructive harvesting techniques for Korla fragrant pears. Through an in-depth analysis of existing pear-harvesting machinery, robotic technologies, and intelligent systems, we have clarified the operational principles of current harvesting machinery, identified the key features of robotic technologies, and evaluated the application prospects of intelligent decision-making systems. Our findings indicate that, while significant progress has been achieved in the harvesting of fruits such as apples, research specific to Korla fragrant pears remains insufficient. In particular, there is a notable lack of targeted technical solutions and practical operational experience for intelligent non-destructive harvesting of this unique variety.

In response to the current deficiencies in technological research, this study proposes several innovative directions for the intelligent non-destructive harvesting of Korla fragrant pears. Firstly, an in-depth exploration of the growth patterns, fruit maturity determination indicators, and mechanical properties of Korla fragrant pears is undertaken to provide theoretical support for the design of harvesting equipment. Secondly, the development of a fruit recognition and localization system based on image recognition and machine learning is proposed to address the challenges of detecting fruits in complex environments and to enhance the accuracy of recognition and localization. Additionally, the design of a flexible harvesting manipulator that can adapt to the shape and structural characteristics of pear fruits is suggested, with optimized grasping actions to ensure minimal damage to the fruits during the harvesting process. Finally, the construction of an intelligent harvesting environment perception and real-time decision-making system is advocated. This system would utilize multi-source sensor data fusion, real-time dynamic planning, and adaptive control algorithms to improve the operational stability and intelligence level of the equipment in complex orchard conditions.

Through the application of these technological innovations, it is anticipated that practical technical support will be provided for the mechanization and intelligent harvesting of Korla fragrant pears, thereby promoting the modernization of its industry.

6.2. Future Development Trends

In light of the prevailing industrial landscape, recent advancements, and inherent obstacles, pear fruit-picking technology is poised to enter a transformative phase of development. Fueled by scientific and technological innovations, future pear fruit-picking technologies will emphasize the integration of automation and intelligence. By employing advanced sensor technology, machine vision, motion planning, nonlinear control, and artificial intelligence algorithms, picking robots will be equipped to more accurately identify and harvest mature pear fruits. In the context of sustainable development, there is a heightened emphasis on environmental protection and energy conservation. Picking equipment is evolving towards multifunctionality and modularization, integrating functions such as fruit picking, grading, and packaging. Through modular design, the equipment can be customized to accommodate the diverse needs of various pear varieties and sizes. Utilizing big data analytics, the Internet of Things, and cloud computing, precision agriculture technologies can facilitate accurate monitoring of the growth environment for pear fruits and enhance the intelligent management of picking operations. Concurrently, advancements in pear-picking technology will improve the user-friendliness of human–machine interactions, ensuring increased efficiency while guaranteeing the safety and comfort of operational personnel. The shift from labor-intensive to technology-intensive pear-picking processes will facilitate the modernization and intelligent development of agriculture.

In summary, the development of Korla fragrant pear-harvesting technology, driven by precision, intelligence, and sustainability, will continue to provide technical support for improving orchard management efficiency, reducing production costs, and promoting the modernization of the fruit tree industry. Furthermore, it will offer valuable insights for global research on fruit tree harvesting technologies.

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