A Comparative Study on Tools and Methods for Fruit Harvesting of *Pinus armandii*

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Abstract: *Pinus armandii* is an important economic and ecological tree species in China, and its seeds (pine nuts) possess high economic value. However, fruit harvesting of P. armandii faces considerable challenges in terms of operational safety, harvesting efficiency, and ecological protection due to the tall tree stature, the concentrated distribution of cones at the upper canopy, and the complex terrain of mountainous forestlands.
Based on a comprehensive review of published literature and multi–source information surveys, this study systematically analyzes the fruit maturation characteristics, harvesting approaches, and seed extraction methods of P. armandii, and conducts a comparative analysis with harvesting practices of common economic fruit trees such as apple. By comparing the advantages and limitations of different harvesting tools—including manual harvesting, impact–type cone harvesters, and vibration–based harvesting machines—as well as seed extraction methods such as peeling, knocking, and mechanical seed separation, this study identifies existing problems and potential optimization pathways in P. armandii fruit harvesting. The results are expected to provide theoretical references for the improvement of harvesting technologies and the development of specialized equipment for *P. armandii*.

Keywords: *Pinus armandii*; fruit harvesting; harvesting tools; harvesting methods; comparative analysis

0. Introduction

Pinus armandii is characterized by its tall and straight trunk, evergreen needles, attractive crown shape, and relatively rapid growth, making it an excellent species for landscaping and ecological afforestation. It is widely used as an ornamental tree, shade tree, roadside tree, shelterbelt species, and scenic forest species in mountainous areas.
Despite its ecological and ornamental value, fruit harvesting of *P. armandii* has long relied on traditional manual methods, which are associated with high safety risks, intensive labor requirements, and low harvesting efficiency. These limitations have become increasingly incompatible with the demands of modern forestry production for safety, efficiency, and scalability.

With the continuous advancement of agricultural and forestry mechanization, various fruit harvesting technologies have been applied in production. However, due to differences in tree architecture and forestland conditions, many mature harvesting technologies are not directly applicable to *P. armandii*. In recent years, harvesting robots incorporating machine vision techniques have gradually emerged in the market, enabling automatic detection and harvesting of cones and offering potential solutions to labor shortages and rising labor costs.
Therefore, a systematic comparative analysis of harvesting tools and methods for *P. armandii* fruit is of great practical significance for improving harvesting practices and enhancing resource utilization efficiency.

1. Fruit Maturation Characteristics and Harvesting Timing of *Pinus armandii*

Pinus armandii is a tall tree species, typically reaching heights of approximately 35 m. Its cones are predominantly distributed at the upper canopy, with a small number located at the terminal ends of branches. Flowering generally occurs from April to May, while cones mature in September to October of the following year. The species prefers light, cool and humid climates, as well as deep, loose, and well-drained soils.

The onset of fruiting usually occurs at 10–12 years of age, with peak production between 30 and 60 years. On average, each mature tree produces approximately 25–40 cones. Cone maturation exhibits distinct stages: when cones gradually change from green to yellow-green and partial scale cracking occurs, they enter the initial maturity stage; subsequently, scales turn yellow and some cones begin to naturally detach, indicating full maturity.

Given the high economic value of *P. armandii* cones and their tendency to naturally fall after maturity, failure to harvest at the appropriate time can result in significant resource loss. Therefore, accurately determining harvesting timing and adopting safe and efficient harvesting methods are critical components of *P. armandii* production.

2. Comparative Analysis of *Pinus armandii* and Apple Harvesting Practices

2.1 Characteristics of Apple Harvesting

Apple trees are deciduous trees that can reach heights of up to 15 m under natural conditions but are typically maintained at 3–5 m through cultivation practices. Their relatively low stature and concentrated fruit distribution make manual harvesting convenient and safe. With the development of smart agriculture, apple harvesting robots based on color recognition have been successfully applied, as the color contrast between apples and the background facilitates reliable fruit identification.

2.2 Specific Challenges of *Pinus armandii* Fruit Harvesting

In contrast, *P. armandii* trees are significantly taller, with cones concentrated at the top of the canopy. Manual harvesting requires workers to climb to considerable heights, often relying on simple climbing tools with limited safety protection, which poses a high risk of falling accidents. Statistics indicate that multiple high-altitude accidents occur annually in China during the pine nut harvesting season.

Moreover, manual harvesting is time-consuming and often fails to complete harvesting within the concentrated maturity period. Although robotic harvesting based on color recognition has been explored, its applicability is limited due to the similarity between cone color and surrounding foliage, as well as the concealed position of many cones.

3. Comparative Analysis of *Pinus armandii* Fruit Harvesting Tools

3.1 Manual Harvesting

Manual harvesting remains the most widely used method and relies on workers climbing trees to collect cones. This approach requires minimal equipment investment and offers operational flexibility. However, due to the extreme height of *P. armandii* trees and the concentration of cones at upper canopy levels, manual harvesting involves high safety risks, heavy labor intensity, and low efficiency, making it unsuitable for large-scale production.

3.2 Impact-Type Cone Harvesters

Impact-type cone harvesters use hydraulic systems to generate vibrations by striking the tree trunk, causing cones to detach. This method reduces the risks associated with manual climbing and improves harvesting efficiency to some extent. Nevertheless, such equipment is generally large and tractor-mounted, limiting mobility in densely forested mountainous terrain. In addition, trunk vibration may cause bark damage, negatively affecting tree growth and understory vegetation, and its effectiveness is limited for older trees with thick trunks.

3.3 Vibration-Based Cone Harvesters

Vibration-based harvesters determine appropriate vibration parameters by analyzing the natural frequency of trees and transmit mechanical vibrations to induce cone detachment. Compared with impact-type methods, this approach reduces direct physical damage to trees and offers advantages in safety and efficiency. However, these machines still face limitations related to large size, poor adaptability to complex terrain, and potential structural impacts on trees under prolonged vibration.

4. Comparative Analysis of Pine Nut Extraction Methods

4.1 Peeling and Composting Methods

The peeling method involves manually removing the outer layers of cones, followed by composting and sun-drying to promote scale opening and seed release. Composting methods accelerate maturation through piling, watering, and the addition of lime or plant ash. Although these methods are simple, seed extraction is often incomplete, leading to residual seeds and resource loss.

4.2 Knocking Method

The knocking method involves sun-drying cones until scales fully open, followed by physical striking to release seeds. While visually effective, this method is time-consuming and may cause seed damage during the knocking process, reducing seed quality.

4.3 Mechanical Seed Extraction

Mechanical seed extraction is conducted after cones have fully opened, using specialized equipment to remove seeds. This method offers significant efficiency advantages and is suitable for batch processing. However, extracted seeds may contain impurities, requiring additional cleaning and sorting.

5. Conclusions

Based on the comparative analysis of harvesting tools and methods for *Pinus armandii*, the following conclusions can be drawn:

(1) The tall stature of *P. armandii* trees and the unique distribution of cones make harvesting significantly more difficult than that of common economic fruit trees, with pronounced challenges in safety and efficiency;

(2) Manual harvesting is associated with high safety risks and low efficiency and is increasingly unsuitable for modern forestry production, while impact-type and vibration-based harvesting equipment improve efficiency to some extent but remain limited in their adaptability to mountainous terrain and ecological protection;

(3) In the seed extraction stage, traditional manual methods are simple but inefficient in resource utilization, whereas mechanical extraction offers clear advantages in efficiency but requires further optimization in impurity removal and seed integrity preservation.

Overall, there is currently no mature harvesting technology that achieves a comprehensive balance among safety, efficiency, and ecological protection for *P. armandii*. Given its extensive application in urban greening and mountainous ecological restoration, *P. armandii* plays an important role in landscape aesthetics, disaster prevention, and ecosystem stability. Future research should focus on the development of lightweight, highly adaptable, and low-damage harvesting equipment, as well as the optimization of post-harvest processing technologies to enhance resource utilization efficiency and promote sustainable forestry development.

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