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Analysis of the Mechanisms by Which Controlled-Environment Regulation Affects Polysaccharide Accumulation in *Dendrobium officinale*

Xinchao Cao
Caonong Herbal Health Food Business Department, Lin'an District, Hangzhou, 311300, Zhejiang, China
Corresponding email: 994954377@qq.com

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Abstract *Dendrobium officinale* is an important medicinal and edible plant, and polysaccharides are its major bioactive constituents and key indicators for evaluating medicinal quality. Their formation and accumulation are jointly influenced by multiple factors, including genetic background, developmental stage, and cultivation environment. This study systematically analyzes the effects of controlled-environment regulation on polysaccharide accumulation in *D. officinale* and the underlying mechanisms, with particular emphasis on the regulatory roles of light, temperature, water, air humidity, mineral nutrition, cultivation substrates, and the rhizosphere microenvironment. The analysis indicates that appropriate light intensity and light quality, suitable day-night temperature differences, and coordinated water and fertilizer supply can improve photosynthetic carbon assimilation, increase the supply of sugar precursors, and promote polysaccharide accumulation by regulating sucrose metabolism, sugar transport, and the expression of polysaccharide biosynthesis-related enzymes and genes. Moderate environmental stresses, such as drought, low temperature, and nutrient limitation, can also enhance soluble sugar and polysaccharide accumulation through stress responses and carbon reallocation, whereas excessive stress suppresses plant growth and photosynthesis. Meanwhile, substrate physicochemical properties, rhizosphere water–air conditions, and beneficial microorganisms can indirectly regulate polysaccharide formation by affecting root vigor, nutrient uptake, and source–sink relationships. Polysaccharide accumulation in *D. officinale* is therefore the integrated outcome of photosynthetic carbon supply, sugar metabolic conversion, source-sink transport, environmental stress responses, and aboveground–belowground environmental interactions. Future studies should further clarify the optimal thresholds and interaction patterns of multiple environmental factors, establish precise controlled-environment regulation systems that balance biomass production and polysaccharide quality, and integrate environmental monitoring, quality prediction, and intelligent control technologies to achieve high-quality, efficient, and standardized production of *D. officinale*.

Keywords *Dendrobium officinale*; Polysaccharide accumulation; Controlled-environment regulation; Sugar metabolism; Carbon allocation

1 Introduction

Dendrobium officinale is an important medicinal and edible orchid that has been used in China for centuries and is now valued as both a traditional medicine and a functional food. Modern studies consistently identify polysaccharides as its principal bioactive constituents and as the core material basis for many of its health-promoting effects (Chen et al., 2024). These polysaccharides exhibit broad biological activities, including immunomodulatory, anti-inflammatory, hypoglycemic, hepatoprotective, gastrointestinal protective, antioxidant, antitumor, and vasoregulatory effects, which explains why *D. officinale* has attracted sustained attention in medicine, food, and health-related industries (He et al., 2022; Xu et al., 2022). Recent work has further expanded the application prospects of *D. officinale* polysaccharides to anti-aging, neuroprotection, skin barrier repair, and biomaterial development, indicating that their medicinal value depends not only on content but also on structural features and downstream mechanisms of action (Okoro et al., 2023; Guo et al., 2025).

Polysaccharides are also central to the quality evaluation of *D. officinale*. Existing studies state directly that polysaccharide content is used as a criterion for quality assessment, and some reports describe polysaccharides as the only selected quality marker in current quality control practice. However, the quality characteristics of *D. officinale* polysaccharides are not captured by content alone. *D. officinale* polysaccharides are mainly composed of mannose and glucose, but their monosaccharide ratios, molecular weights, glycosidic linkages, and

higher-order conformations vary substantially among fractions and preparations, and these structural differences are closely associated with biological activity (He et al., 2022; Guo et al., 2025). This complexity creates a key quality-control challenge: bioactivity differs with source, cultivation condition, extraction process, processing method, and storage condition, because each of these factors can alter polysaccharide yield, composition, and physicochemical properties (Xu et al., 2022). Consistent with this, substantial variation in polysaccharide content has been reported across regions, tissues, developmental stages, and cultivation years, with stems generally richer than leaves and flowers, and with content changing across flowering and seasonal cycles.

Because wild *D. officinale* is scarce, slow-growing, and no longer economically reliable as the main source, artificial cultivation has become the dominant production mode, making environmental regulation a practical route for improving both yield and medicinal quality. Multiple studies show that ecological factors are tightly linked to the accumulation of medicinal components in *D. officinale*, and that light, temperature, humidity, radiation, and nutrient-related variables jointly shape polysaccharide formation (Okoro et al., 2023). In field and semi-artificial systems, maximum and minimum relative humidity, maximum temperature, sunshine duration, soil pH, and soil nitrogen and phosphorus status have been identified as key ecological drivers of medicinal quality, while soil factors overall show significant positive relationships with polysaccharide content. Controlled-environment studies provide more direct mechanistic clues. Light quality regulates growth and polysaccharide synthesis, with red light significantly promoting UGPase expression, and a red:blue ratio of 1:3 enhancing biomass and polysaccharide accumulation through Ca^{2+}-CaM signaling, improved photosynthetic performance, increased sucrose phosphatase and sucrose synthase activities, and greater glucose and fructose precursor supply (Wang et al., 2024). High light also increases polysaccharide accumulation, especially mannose, and activates a DoHY5-dependent regulatory pathway in which DoHY5 directly induces polysaccharide biosynthetic genes such as *DoGMPP2* and *DoPMT28*. Temperature regulation is similarly important: diurnal temperature difference favors polysaccharide accumulation in protocorm-like bodies and changes the expression of sugar-metabolism genes including *SUS, SUT, HKL1, HGL, AMY1*, and *SS3*, while seasonal low temperature and drought are associated with sugar accumulation and stress-responsive hub genes in stems and leaves (Chen et al., 2024). Related evidence from *Dendrobium nobile* further supports the carbohydrate-promoting role of temperature regulation, as short-term 0℃ treatment increased polysaccharide accumulation by 56.18% and upregulated genes in starch and sucrose metabolism (Fan et al., 2024).

This study investigates the mechanisms by which controlled-environment regulation affects polysaccharide accumulation in *Dendrobium officinale*, with particular emphasis on the effects of light, temperature, water availability, humidity, nutrient supply, and the rhizosphere environment on polysaccharide formation and accumulation. The underlying relationships are analyzed from the perspectives of photosynthesis, carbon allocation, sugar precursor formation, regulation of sugar metabolism, stress adaptation, and signal transduction. Existing studies indicate that polysaccharide accumulation in *D. officinale* results from the combined effects of aboveground environmental conditions and the belowground rhizosphere environment, with pronounced synergistic and interactive effects among different environmental factors. However, current findings remain relatively fragmented, and a systematic understanding of how multiple environmental factors jointly regulate polysaccharide formation through physiological and metabolic processes is still lacking. Therefore, this study aims to clarify the regulatory pathways linking environmental signals, physiological metabolism, and polysaccharide accumulation, and identify the key processes through which controlled environments influence quality formation in *D. officinale*. The findings are expected to provide a theoretical basis for optimizing controlled cultivation conditions, enhancing polysaccharide accumulation, and stabilizing medicinal quality, while also providing guidance for the efficient utilization of *D. officinale* resources, standardized production, and the development of medicinal and functional food products.

2 Physiological and Metabolic Basis of Polysaccharide Formation and Accumulation in *Dendrobium officinale*

2.1 Composition, distribution, and accumulation characteristics

Polysaccharides are the principal bioactive constituents of *Dendrobium officinale*, and the medicinal stem is their main storage organ (Lai et al., 2024; Liang et al., 2025). Structurally, *D. officinale* polysaccharides are dominated by mannose and glucose, although galactose, xylose, arabinose, and rhamnose can also occur in different fractions and tissues (Guo et al., 2025). Cytochemical and compositional analyses indicate that the stem polysaccharides are mainly non-starch glucomannans or mannan-rich polymers, with water-soluble polysaccharides reaching about 35% of stem dry weight, whereas starch generally accounts for less than 10% (He et al., 2017). At the fine-structure level, several studies consistently report backbones enriched in 1→4-linked β-D-Manp and β-D-Glcp residues, although fermented or differently processed fractions can also contain α-linked motifs and distinct branching patterns, showing that DOPs are chemically diverse rather than a single uniform product (He et al., 2022; Zhong et al., 2022).

Polysaccharide distribution in *D. officinale* is strongly tissue-and stage-dependent. Histochemical observations show abundant polysaccharide granules in stem parenchyma cells, stored in plastids, which supports the central medicinal role of the stem as a sink tissue (He et al., 2017). Comparative organ analyses further indicate that stems have the highest polysaccharide content, whereas leaves and flowers also contain recoverable polysaccharides and represent underused biomass resources (Zhong et al., 2022; Chen et al., 2025). Accumulation is dynamic rather than static: stem water-soluble polysaccharides increase and then decline across development, peaking before flowering, while seasonal monitoring shows that stem sugars accumulate mainly from October to April, with especially rapid accumulation from October to February (Yang et al., 2025). This developmental and seasonal variation explains why polysaccharide content is widely used as a quality marker in cultivation and harvest management, but it also implies that quality depends on both amount and structure, since molecular weight, monosaccharide ratio, and conformation differ among stem, leaf, fermented, and extraction-derived fractions (Chen et al., 2025).

2.2 Photosynthetic carbon assimilation

Photosynthetic carbon assimilation provides the primary material source for polysaccharide biosynthesis in *D. officinale*. This species is a facultative CAM plant that can exhibit concomitant C3 and CAM photosynthesis under non-stressed conditions, while substrate moisture and light-dark cycle can shift the balance between these pathways. As substrate water declines, *D. officinale* shifts toward a more typical CAM pattern, and rewatering restores mixed C_3/CAM behavior, showing that environmental regulation directly changes the mode of carbon capture and therefore the carbon supply available for downstream sugar synthesis (Zhang et al., 2014). Because CAM and C_3 differ in the timing and efficiency of CO_2 fixation, this photosynthetic plasticity is a key physiological basis by which controlled environments can alter carbohydrate production and ultimately polysaccharide accumulation.

Recent physiological and transcriptomic evidence further shows that photosynthetic performance is tightly coupled to sugar accumulation. Seasonal analyses found that genes associated with sugar metabolism in stems and leaves were enriched not only in starch and sucrose metabolism but also in photosynthesis-related pathways, and identified hub genes that likely maintain sugar metabolism under low-temperature and drought conditions by regulating photosynthetic responses. Temperature-regulation experiments in protocorm-like bodies similarly showed that diurnal temperature difference increases chlorophyll and favors polysaccharide accumulation, while differentially expressed genes include photosystem components such as PSAB and PSBA together with sugar-metabolism genes (Chen et al., 2024). These findings indicate that carbon assimilation is not merely a background source process; rather, regulated photosynthesis determines source strength, precursor availability, and source-sink coordination, thereby setting the upper physiological limit for polysaccharide synthesis in *D. officinale*.

2.3 Sugar metabolic pathways

After photosynthetic fixation, carbon enters the sugar metabolic network that directly supplies precursors for polysaccharide assembly. Current pathway models divide DOP biosynthesis into three major steps: sucrose is first converted into intermediates such as glucose-1-phosphate and fructose-6-phosphate, these are then transformed into nucleotide-diphospho sugars, and finally glycosyltransferases polymerize these activated donors into macromolecular polysaccharides in the Golgi apparatus. Within this framework, sucrose synthase is a central enzyme because it cleaves sucrose with UDP to generate UDP-glucose and fructose, thereby linking source carbohydrate turnover to precursor supply for cell wall and storage polysaccharide synthesis (Chen et al., 2024). Transcriptomic studies support this model by showing that starch and sucrose metabolism is repeatedly enriched during developmental transitions associated with stem polysaccharide change, and that candidate biosynthetic genes co-vary with polysaccharide content (Yang et al., 2025).

The physiological basis of polysaccharide accumulation therefore lies in coordinated regulation of precursor formation, sugar transport, and polymer assembly. Diurnal temperature difference alters the expression of genes involved in polysaccharide metabolism, including *SUS, SUT, HKL1, HGL, AMY1*, and *SS3*, indicating that carbon partitioning among sucrose turnover, hexose generation, and starch-related metabolism is environmentally responsive (Chen et al., 2024). Seasonal transcriptomics likewise shows that sugar accumulation in stems is coordinated with abiotic-stress adaptation, suggesting that low temperature and humidity shifts reshape sugar metabolism rather than simply increasing total soluble sugars passively. At the polymerization step, mannan synthesis depends on CSLA-family mannan synthases, especially DoCSLA6, which is implicated in mannose production and mannan polysaccharide biosynthesis, providing a direct mechanistic link between upstream sugar metabolism and the formation of the mannose-rich polysaccharides that dominate *D. officinale* stems (He et al., 2017).

3 Effects of Light and Temperature Regulation on Polysaccharide Accumulation in *Dendrobium officinale*

3.1 Effects of light intensity and light quality on photosynthesis and polysaccharide formation

Light intensity and light quality directly regulate photosynthesis in *D. officinale*, a facultative CAM species whose carbon-assimilation pattern shifts with environmental conditions (Zhang et al., 2014). Early physiological work showed that leaf CO_2 uptake was highest at 500 μmol·m^{-2}·s^{-1} and 20℃, whereas net photosynthesis approached zero at 35℃, indicating that light response is constrained by temperature and stomatal behavior. The same study found that irradiance above 500 μmol·m^{-2}·s^{-1} induced photoinhibition, and prior high-light exposure reduced apparent quantum yield and CO_2 uptake, showing that stronger light is not universally beneficial. However, light regime also changes pathway use: shortening the light–dark cycle to 4 h/4 h induced a C_3 pattern, and 2 h/2 h or 4 h/4 h cycles improved photosynthetic apparatus status, doubled daily net CO_2 exchange and biomass gain relative to 12 h/12 h, and increased soluble polysaccharide yield, especially under 2 h/2 h aeroponic cultivation (Cheng et al., 2019).

Light quality further affects polysaccharide formation by simultaneously altering photosynthetic performance and precursor metabolism. Under different spectral treatments, red, blue, and yellow light all increased stem polysaccharide content relative to natural light, with the order red>yellow>blue>natural light, and red light showed the strongest promotion of UGPase expression, a key step in UDP-glucose formation for polysaccharide biosynthesis (Wang et al., 2024). In protocorms, a red:blue ratio of 1:3 promoted biomass and polysaccharide accumulation, and this effect depended on Ca^{2+}-CaM signaling, improved photosynthetic apparatus development, higher CaM content and Ca^{2+}-ATPase activity, enhanced sucrose phosphatase and sucrose synthase activity, and greater glucose and fructose precursor supply (Lei et al., 2021). However, within a physiologically tolerable range, relatively high light can also promote quality formation rather than only causing stress: in stems, high light increased polysaccharide accumulation, particularly mannose, activated flavonoid and polysaccharide biosynthesis, and induced DoHY5, which directly activates *DoGMPP2* and *DoPMT28* to enhance polysaccharide synthesis (Li et al., 2023). Related Dendrobium evidence is directionally similar, with intermediate red-blue light intensity around 400 μmol·m^{-2}·s^{-1} supporting chlorophyll accumulation, soluble sugar buildup, antioxidant stability, and

medicinal metabolite accumulation, which supports the broader principle that moderate-to-high but non-photoinhibitory light optimizes source strength and metabolic quality (Xu et al., 2024).

3.2 Effects of temperature and day-night temperature differences on carbon metabolism and polysaccharide accumulation

Temperature regulates polysaccharide accumulation by altering carbon turnover, respiration, and sugar-metabolic gene expression. Within a suitable range, rising temperature increases hydrolase activity, accelerates starch hydrolysis, and raises soluble sugar content, whereas lower temperature weakens respiration and sugar consumption, thereby favoring sugar accumulation (Chen et al., 2024). Seasonal monitoring in *D. officinale* confirms that sugar accumulation is strongly climate-dependent: stem sugars mainly accumulated from October to April, with rapid accumulation from October to February, and related genes were enriched in photosynthesis and starch-sucrose metabolism pathways. Weighted gene co-expression analysis further identified hub genes that appear to maintain sugar metabolism by coordinating photosynthesis-related pathways under low-temperature and drought stress. Developmental transcriptomics also supports this carbon-metabolic basis, because stages with changing stem water-soluble polysaccharide content were enriched in starch and sucrose metabolism, indicating that temperature effects act through a pathway already central to endogenous polysaccharide formation (Figure 1) (Yang et al., 2025).



Figure 1 Phenotypes of *D. officinale* at different developmental stages (Adopted from Yang et al., 2025)
Image caption: S1: 2 months after sprouting; S2: 5 months after sprouting; S3: 11 months after sprouting; S4: 13 months after sprouting; and S5: 15 months after sprouting (Adopted from Yang et al., 2025)

Day–night temperature difference is a particularly important regulatory lever in controlled environments. In protocorm-like bodies, the DIF treatment favored soluble polysaccharide accumulation and produced higher chlorophyll, polysaccharide, and flavonoid contents than constant-temperature treatments. Transcriptome analysis under DIF showed differential expression of genes involved in sugar metabolism, including *SUS, SUT, HKL1, HGL, AMY1,* and *SS3*, together with heat-stress-responsive HSPs and HSFs, indicating that temperature amplitude changes both carbon partitioning and stress adaptation networks (Chen et al., 2024). The response is not simply "larger DIF is better," because plant species differ in how diurnal temperature amplitude balances photosynthesis, respiration, and metabolite allocation: tea showed reduced photosynthesis at excessive DIFs and sorghum showed reduced soluble sugars and biomass when diurnal temperature amplitude narrowed through elevated night

respiration (Sunoj et al., 2020). Taken together, the *D. officinale* evidence supports an intermediate, physiologically coordinated DIF that enhances daytime carbon gain while limiting nighttime carbon loss and redirecting assimilates toward polysaccharide accumulation.

3.3 Integrated regulation of polysaccharide synthesis and quality formation by light-temperature interactions

Light and temperature act jointly because both determine whether *D. officinale* operates closer to CAM, C_3, or an intermediate photosynthetic mode, and this sets the overall carbon supply for polysaccharide synthesis (Zhang et al., 2014). In natural and controlled conditions alike, CO_2 exchange patterns vary across sunny, cloudy, and rainy days, reflecting combined effects of irradiance, humidity, and air temperature rather than any single factor alone. Ecological-factor analysis likewise identified maximum temperature and sunshine duration among the key variables influencing medicinal quality in cultivated *D. officinale*, showing that light and thermal conditions are already coupled at the production scale. Recent reviews reach the same conclusion more broadly, noting that light, temperature, and water significantly affect the synthesis and accumulation of functional components across growth stages.

Mechanistically, light-temperature interactions converge on photosynthesis, sugar metabolism, and quality gene networks. Light quality regulates UGPase expression and Ca^{2+}-CaM-mediated sucrose metabolism, whereas high light activates DoHY5-dependent transcription of polysaccharide biosynthetic genes; temperature and DIF regulate SUS-centered sugar turnover, chlorophyll status, and abiotic-stress pathways (Lei et al., 2021; Chen et al., 2024; Wang et al., 2024). This means polysaccharide accumulation is determined not only by how much carbon is fixed, but also by how efficiently assimilated carbon is retained, transported, and converted into mannose- and glucose-rich polymers that define medicinal quality (Lai et al., 2024). For controlled cultivation, the practical implication is that light and temperature should be co-optimized rather than regulated independently, because suitable spectral composition, moderate effective irradiance, and an appropriate day-night temperature regime together promote biomass, sugar precursor supply, and stable quality formation (Li et al., 2023).

4 Effects of Water, Humidity, and Nutrient Conditions on Polysaccharide Accumulation in *Dendrobium officinale*

4.1 Effects of water supply and air humidity on carbon assimilation and sugar metabolism

Water supply and air humidity regulate carbon assimilation in *D. officinale* largely by altering photosynthetic behavior and internal sugar balance. *D. officinale* is a facultative CAM plant, and decreasing substrate water content shifts it toward a more typical CAM pattern, whereas rewatering restores mixed C_3/CAM behavior. As the substrate dries, nocturnal leaf titratable acidity increases and then declines again after rewatering, indicating that plant water status directly changes nighttime carbon fixation and acid metabolism (Zhang et al., 2014). Seasonal evidence likewise shows that sugar accumulation patterns in stems and leaves are influenced by temperature and humidity variation, with stem sugars accumulating mainly from October to April and especially rapidly from October to February.

Humidity is also an ecological determinant of medicinal quality rather than only a background climate factor. In cultivation-scale analyses, maximum and minimum relative humidity were identified among the key ecological factors influencing the medicinal quality of cultivated *D. officinale* together with maximum temperature, sunshine duration, and soil nutrients. Physiological and transcriptomic results further indicate that humidity-linked seasonal change affects sugar metabolism through pathways involving photosynthesis and starch–sucrose metabolism, while hub genes appear to maintain sugar metabolism under low-temperature and drought conditions. At the transport level, orchid mycorrhizal colonization creates an additional carbon sink in roots, increases allocation of photosynthates belowground, and raises glucose, fructose, and sucrose levels, showing that water- and humidity-sensitive root environments can reshape whole-plant carbon distribution rather than only leaf assimilation.

4.2 Regulatory effects of moderate water stress on polysaccharide synthesis and accumulation

Moderate water stress appears to promote polysaccharide-related carbon reallocation in *D. officinale*, although severe or combined stress impairs growth and quality. Recent work on the Danxia cultivar showed that harsh environments characterized by intense heat and limited rainfall were associated with substantial accumulation of bioactive polysaccharides, and that abiotic stress enhanced soluble sugar accumulation by transcriptionally activating sucrose synthase genes (Liu et al., 2025). Among these genes, *DoSUS2* responded strongly to drought and ABA, and its heterologous expression enhanced drought tolerance, soluble sugar accumulation, and ROS scavenging capacity, supporting a mechanism in which stress-induced sucrose turnover increases osmotic protection and precursor supply for polysaccharide synthesis. Consistent with this, dehydration increased soluble sugar content in leaves, and cold stress increased soluble sugars in both leaves and stems, while acid invertase genes were implicated in stress-responsive sucrose hydrolysis and osmotic homeostasis (Liu et al., 2024).

The beneficial effect is conditional, because genotype and stress intensity matter. Comparative drought analysis showed that the drought-tolerant genotype maintained stronger antioxidant capacity, with higher proline, APX, and CAT under intensifying drought, whereas the drought-sensitive genotype showed more severe repression of photosynthesis-related genes (Huang et al., 2023). Under combined heat–drought stress, *D. officinale* showed marked genotype-dependent differences in morphology, antioxidative capacity, polysaccharide accumulation, and transcriptome response, and dual stress induced glycosyltransferase genes that likely support stress adaptation (Figure 2) (Gao et al., 2026). Additional mechanistic evidence shows that drought-related transcription factors can directly regulate mannan biosynthesis: *DoMYB75* activates *DoCSLA* genes and improves drought tolerance, and *DoDof7* promotes polysaccharide biosynthesis under combined heat-drought stress by activating *DoGMPP2* and increasing mannose content (He et al., 2026; Yang et al., 2026). Together with evidence that droughted strains differ in intracellular water utilization, nutrient transport, and metabolic capacity, these findings indicate that moderate stress promotes accumulation, but excessive stress shifts the balance toward injury and growth suppression (Luo et al., 2024).

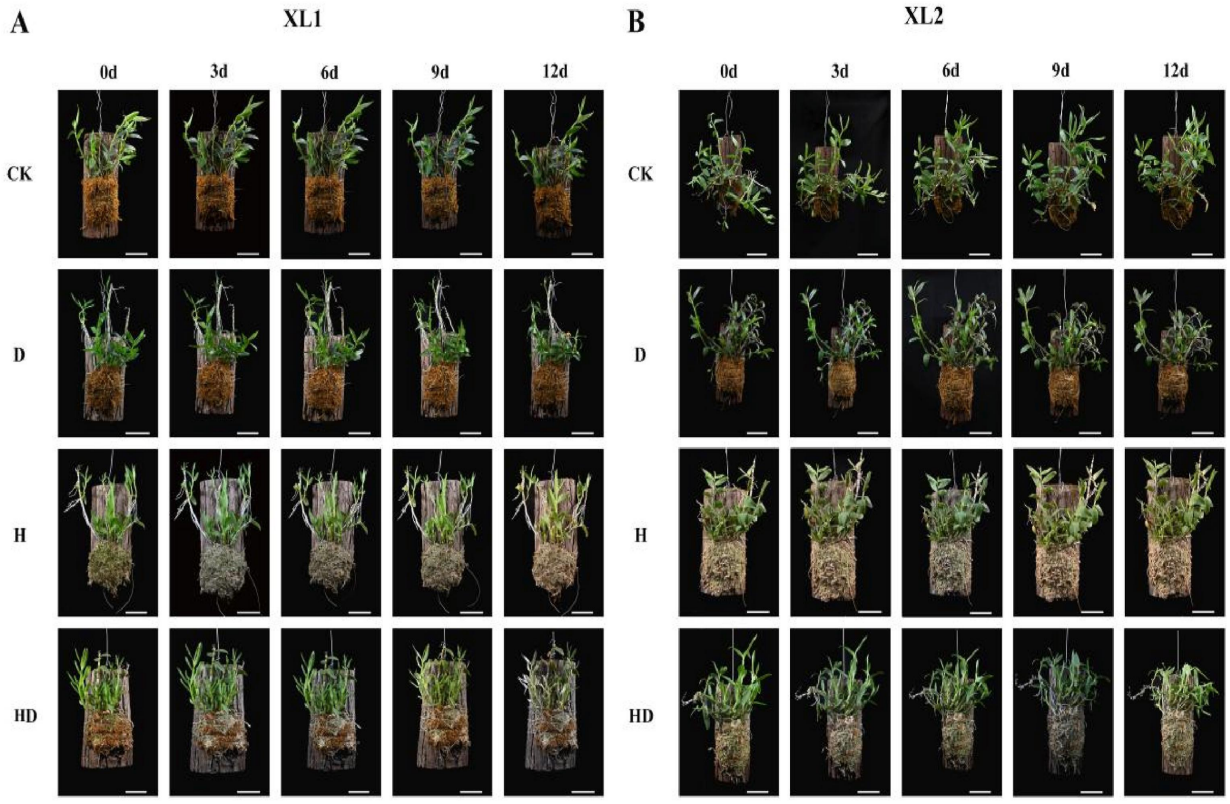


Figure 2 Phenotypic changes of *D. officinale* XL1 (A) and XL2 (B) under different treatments (Adopted from Gao et al., 2026)

Image caption: CK: Control group; D: Drought treatment; H: High temperature treatment; HD: High temperature and drought composite stress; the scale is 5 cm (Adopted from Gao et al., 2026)

4.3 Effects of mineral nutrition and water-fertilizer interactions on polysaccharide formation

Mineral nutrition affects polysaccharide formation by changing both precursor metabolism and the transcription of mannan-biosynthetic genes. Ecological-factor analysis in cultivated *D. officinale* identified soil total nitrogen, total phosphorus, and available phosphorus as important variables affecting medicinal ingredients, indicating that nutrient supply is a major component of quality formation. Nitrogen responses are not linear: under low nitrogen, growth and photosynthesis were inhibited, but polysaccharide and flavonoid contents increased significantly, suggesting that nutrient limitation can redirect carbon away from growth and toward secondary and storage metabolism (Wu et al., 2023). Phosphorus limitation shows a similar pattern. Moderate phosphorus deficiency had little effect on stem height inhibition but promoted polysaccharide accumulation and increased the mannose-to-glucose ratio, while expression of active-ingredient pathway genes including DoCSLA6 increased significantly (Liu et al., 2021).

Mechanistic work now links phosphorus starvation directly to mannan synthesis. Low-phosphorus environments promoted polysaccharide accumulation, and *DoCSLA6*, a CSLA-family gene directly involved in mannose synthesis, was highly positively correlated with that accumulation (Feng et al., 2024). The DoSPX1-DoMYB37-DoCSLA6 pathway explains part of this response: *DoSPX1* and *DoMYB37* reduced phosphate accumulation and increased *DoCSLA6* expression, providing a direct regulatory bridge between phosphate status and polysaccharide biosynthesis. Nutrient interactions can also enhance quality when supply is balanced rather than restrictive. Carbon–nitrogen co-application improved photosynthetic performance and quality, and the 0.4AN/20KG treatment increased stem soluble sugar, micronutrient content, carbon-metabolism enzyme activity, and metabolite accumulation more than single-factor treatments, whereas high nitrogen alone had adverse effects on photosynthetic trends (Yin et al., 2026). Supporting evidence from another *Dendrobium* species showed that optimized N-P-K fertilization increased polysaccharide content by 26.84% and that nitrogen had the strongest overall effect, while rhizosphere bacteria such as *Pandoraea* may further promote polysaccharide production and provide a basis for microbiome-informed fertilizer design (Fan et al., 2023; Zhu et al., 2025).

5 Effects of Cultivation Substrates and the Rhizosphere Environment on Polysaccharide Accumulation in *Dendrobium officinale*

5.1 Effects of substrate physicochemical properties on root growth and nutrient uptake

D. officinale is now cultivated mainly under epiphytic or simulated-natural systems, so the substrate is not just physical support but a primary regulator of water retention, nutrient availability, and root-zone microhabitat (Zhu et al., 2022). Comparative metabolomics showed that different cultivation substrates have distinct physical properties such as water-holding capacity and distinct chemical properties such as nitrogen, phosphorus, and potassium content, and that these differences strongly reshape *D. officinale* metabolism. The same study found clear metabolic separation among substrate groups, indicating that substrate-driven differences are large enough to alter global metabolite profiles rather than only isolated compounds (Zuo et al., 2020). At the cultivation-scale ecological level, soil pH, total nitrogen, total phosphorus, and available phosphorus were identified as key quality-related factors in cultivated *D. officinale*, reinforcing that substrate chemistry is tightly linked to medicinal-component formation.

These substrate effects are expressed first through the root system. Mycorrhizal inoculation increased peloton formation in root cortical cells and produced more flourishing roots than uninoculated plants, showing that a biologically compatible root-zone environment can directly improve root vigor. In field cultivation, the same mycorrhizal treatment ultimately increased plant and stem dry weight to 2.69-fold and 2.87-fold of the control after 19 months, indicating that improved root symbiosis can translate into substantially greater sink capacity for polysaccharide accumulation (Chen et al., 2016). Substrate choice also changes downstream chemical quality: pine bark, coconut coir, and mixed substrates produced similar classes of metabolites but significantly different abundances, and pine bark favored flavonoid accumulation, while stone-epiphytic and greenhouse systems produced higher polysaccharide content than live-tree epiphytic cultivation (Zuo et al., 2020; Yang et al., 2023). Case-based cultivation analyses similarly suggest that pine bark substrate has high potential for improving quality

traits, and that mycorrhizal fungi enhance drought and disease resistance, which would be expected to stabilize root uptake under controlled production (Zhang et al., 2024).

5.2 Regulation of polysaccharide accumulation by rhizosphere water–air conditions and nutrient supply

Rhizosphere water, aeration, and nutrient supply regulate polysaccharide accumulation by controlling root respiration, nutrient flux, and the balance between growth and stress metabolism. Across *Dendrobium*, soil total nitrogen, available phosphorus, ammonium nitrogen, and pH are among the strongest drivers of rhizosphere microbial composition, and soil is considered the dominant factor shaping these microbial communities. In cultivated *Dendrobium* rhizospheres, dominant bacterial groups repeatedly include Proteobacteria, Bacteroidetes, Actinobacteria, and Acidobacteria, indicating a fairly consistent microbial core that still shifts with species and environment (Zuo et al., 2021). Because rhizosphere microbes promote nutrient absorption and can improve medicinal-plant yield and quality, shifts in water and nutrient conditions are likely to affect polysaccharide accumulation partly through microbial mediation rather than only through direct plant physiology (Sarsaiya et al., 2025). This interpretation is supported by recent *D. officinale* data linking polysaccharide accumulation closely to rhizosphere bacteria and identifying *Pandoraea* as a candidate polysaccharide-promoting genus (Zhu et al., 2025).

Water–air status in the rhizosphere is especially important because excess moisture can drive hypoxia and impair aerobic root metabolism. Broader rhizosphere evidence shows that hypoxia caused by waterlogging or compaction inhibits root aerobic respiration, disrupts energy metabolism, and alters rhizosphere microecology, while micro-nano bubble aeration can improve pore structure, continuously release oxygen, regulate microbial communities, and increase aeration in irrigation systems (Zheng et al., 2025). Although this was not tested directly in *D. officinale*, it fits the crop's dependence on an aerated epiphytic root zone and suggests a plausible controlled-environment strategy for avoiding carbon loss belowground (Zhu et al., 2022). Nutrient supply interacts with water status rather than acting independently: in another medicinal plant, the highest biomass and alkaloid accumulation occurred under an intermediate water–nitrogen regime, illustrating that water-fertilizer coordination can optimize rhizosphere physicochemical status and metabolite accumulation better than maximizing either input alone (Huang et al., 2024). In *D. officinale*, recent karst-environment work further showed that high-calcium limestone soils altered both rhizosphere properties and stem metabolism, with long-term calcium-rich conditions promoting calcium accumulation and mannose synthesis in stems, linking root-zone chemistry directly to polysaccharide-related carbon flow (Du et al., 2025).

5.3 Synergistic effects of the rhizosphere microenvironment and aboveground controlled environment

The strongest current model is that polysaccharide formation depends on synergy between the rhizosphere microenvironment and the aboveground controlled environment, rather than on either domain alone. Cultivation mode alters both substrate-associated and plant-associated bacterial and fungal communities, and some of these taxa are positively correlated with the main chemical components of *Dendrobium catenatum*, including stem polysaccharides. The same work showed that pot cultivation differed significantly from living-tree and cliff-epiphytic modes in microbial community structure, indicating that cultivation architecture and aboveground conditions feed back onto the rhizosphere and root microbiome (Zhu et al., 2022). More broadly, rhizosphere microbial communities vary among *Dendrobium* species and rhizocompartments, and the root environment acts as a selective interface for bacteria and fungi that support nutrient cycling, pathogen suppression, and stress resilience (Xie et al., 2024; Sarsaiya et al., 2025). In stressful Danxia habitats, the *D. officinale* microbiome showed diverse taxonomic and metabolic functions, including abundant carbohydrate- and energy-metabolism potential, which likely helps sustain plant growth in nutrient-poor environments.

This belowground support interacts with aboveground regulation through carbon supply and plant signaling. Root exudation dynamics shape microbial interactions, and beneficial rhizosphere bacteria and fungi enhance nutrient uptake, phytohormone status, stress tolerance, and root growth, which together increase the plant's capacity to convert photosynthate into polysaccharides (Sarsaiya et al., 2025). Orchid mycorrhizae likely contribute not only nutrients but also carbon, because photosynthetic orchids can be mixotrophic and recover carbon from root-associated fungi (Chen et al., 2016). Consistent with this, beneficial taxa such as *Sphingomonas paucimobilis*

have been reported to promote growth and active polysaccharide accumulation in *Dendrobium*, while nitrogen-fixing and stress-responsive genera such as *Devosia* are enriched in rhizocompartments and may support adaptation to nutrient-poor or stressful substrates (Xie et al., 2024). The practical implication is that precise greenhouse control of light, temperature, and moisture should be coordinated with substrate selection, root-zone aeration, and microbiome management, because sustainable improvement in *D. officinale* polysaccharide accumulation appears to emerge from this whole-plant environmental network rather than from single-factor optimization.

6 Mechanisms of Controlled-Environment Regulation of Polysaccharide Accumulation in *Dendrobium officinale*

6.1 Regulation of carbon supply for polysaccharide synthesis through photosynthesis

Photosynthesis is the primary upstream source of carbon for polysaccharide synthesis in *Dendrobium officinale*, and controlled environments regulate this source first by altering the plant's photosynthetic mode and then by changing total assimilate supply. *D. officinale* is a facultative CAM plant that can switch between CAM, C_3, and intermediate states depending on substrate moisture and light-dark regime, so environmental regulation changes not only photosynthetic rate but also the timing and pathway of carbon fixation (Zhang et al., 2014). Under natural weather variation, sunny days favor a typical CAM-like pattern, rainy days favor C_3-like daytime uptake, and cloudy days produce an intermediate pattern, indicating that light intensity, humidity, and temperature together determine whole-day CO_2 assimilation behavior. Controlled cultivation can exploit this plasticity: shortening the light-dark cycle to 4 h/4 h or 2 h/2 h improved photosynthetic apparatus status, shifted carbon fixation toward C_3 behavior, doubled daily net CO_2 exchange and biomass increase relative to 12 h/12 h, and increased soluble polysaccharide yield, especially under 2 h/2 h conditions (Cheng et al., 2019).

Carbon supply is further regulated by light and temperature effects on photosynthetic efficiency and by their downstream effects on carbohydrate metabolism. Developmental transcriptomics showed that changes in stem polysaccharide content are tightly associated with genes enriched in starch and sucrose metabolism, indicating that photosynthetic carbon enters a regulated source-to-sink pathway rather than passively accumulating (Yang et al., 2025). Seasonal transcriptomics similarly found that genes associated with sugar accumulation were enriched in photosynthesis and starch-sucrose metabolism, and identified hub genes that appear to stabilize sugar metabolism under low-temperature and drought conditions. Temperature studies show an important source-sink distinction: net photosynthesis and vegetative growth were highest around 30℃, but stem polysaccharide content was highest at 20℃, indicating that maximal carbon fixation does not necessarily produce maximal polysaccharide concentration because carbon partitioning also shifts with temperature. Consistent with this, carbon-nitrogen co-application improved photosynthetic pigments, net photosynthetic rate, carbon-metabolism enzyme activity, soluble sugars, and overall quality, showing that controlled environments increase polysaccharides partly by strengthening the upstream carbon source that feeds downstream biosynthesis (Yin et al., 2026).

6.2 Promotion of polysaccharide formation through sugar transport and metabolic enzyme activity

Once carbon is fixed, controlled-environment regulation promotes polysaccharide formation by controlling sugar transport, sucrose cleavage, precursor interconversion, and polymer assembly. Transcriptome analysis identified 430 glycosyltransferase genes and 89 cellulose synthase-related genes in *D. officinale*, establishing that polysaccharide formation depends on a large enzymatic network rather than a single biosynthetic step (Zhang et al., 2016). Developmental expression profiling further showed that polysaccharide-associated genes change across stem growth stages and that 15 key genes are positively correlated with water-soluble polysaccharide content (Yang et al., 2025). Sugar transporter regulation is now directly implicated in this process: comparative genomics and silencing experiments identified several *DoSWEET* genes as candidate regulators, and silencing six candidates reduced polysaccharide accumulation by 14~22%, with the strongest effects for *DoSWEET1, 8, 13, 17,* and *24*. Because these *SWEET* genes also contain abiotic-stress-responsive cis-elements and show stress-dependent expression, controlled environments likely regulate polysaccharide accumulation partly by changing sugar export, unloading, and redistribution between source and sink tissues.

Sucrose-metabolizing enzymes provide the second major mechanistic layer. Abiotic stress induced the transcriptional activation of *DoSUS* genes, and *DoSUS2* responded strongly to drought and ABA; heterologous expression of *DoSUS2* increased soluble sugar accumulation and stress tolerance, while the DobHLH14-DoSUS2 module was linked to a broader saccharometabolism network involving *DoSUS1, DoGT5, DoUGE2, DoUGE3,* and *DoVIN2* (Liu et al., 2025). Acid invertases act in parallel: cold and dehydration increased soluble sugar content in leaves and stems, and the associated upregulation of *DoAINV* genes likely enhanced sucrose hydrolysis into glucose and fructose, thereby supporting osmotic homeostasis and polysaccharide accumulation (Liu et al., 2024). Diurnal temperature difference further altered expression of *SUS, SUT, HKL1, HGL, AMY1,* and *SS3*, indicating that environmental control acts on transport, sucrose turnover, starch breakdown, and hexose metabolism simultaneously (Chen et al., 2024). Related *Dendrobium* evidence is mechanistically consistent: cell wall invertase activity rises with sink activation and sucrose feeding stimulates hexose accumulation, supporting a general model in which increased sink-side sucrose cleavage promotes downstream carbohydrate deposition.

6.3 Regulation of carbon allocation and polysaccharide accumulation through environmental stress responses and multifactor interactions

Controlled environments also regulate polysaccharide accumulation by redistributing carbon under stress and by integrating multiple environmental signals. In *D. officinale*, seasonal sugar accumulation depends on temperature and humidity variation, and related genes are enriched in abiotic-stress, photosynthesis, and starch-sucrose metabolism pathways, showing that carbon allocation is embedded in a stress-response framework. Drought and cold often increase soluble sugar pools rather than depleting them, because carbon is redirected toward osmotic adjustment and protective metabolism; under dehydration or cold, soluble sugars rose and AINV-related sucrose cleavage increased, while long-term dehydration changed genes involved in stress response, photosynthesis, phytohormone signaling, carbon metabolism, and fructose/mannose pathways (Liu et al., 2024). This stress-buffering role is consistent with the biology of the species: *D. officinale* can survive prolonged water deficit and rapidly resume growth after rehydration, and its thick, polysaccharide-rich organs are part of that drought-adaptive system (Yu et al., 2025). Moderate stress can therefore favor accumulation, but the response is conditional. In *Dendrobium nobile*, 0℃ for 4 d increased polysaccharides by 56.18%, whereas -4℃ caused severe damage, indicating that beneficial accumulation occurs within a stress window rather than under unlimited stress intensity (Fan et al., 2024).

The mechanism becomes more complex under combined stresses, because light, temperature, humidity, and water supply interact rather than acting additively. In *D. officinale*, combined high temperature and drought caused genotype-dependent differences in morphology, antioxidative capacity, polysaccharide accumulation, and gene expression, and dual stress markedly upregulated glycosyltransferase genes, linking multifactor stress directly to polysaccharide-related biosynthetic capacity (Gao et al., 2026). Broader plant evidence supports the same carbon-allocation principle: drought under elevated temperature tends to reduce starch more than soluble sugars, implying that stored carbon is degraded to maintain osmotic regulation and defense demands when current photosynthesis cannot fully meet metabolic need (Wang and Wang, 2023). At the cultivation scale, ecological analyses identified maximum temperature, humidity, sunshine duration, pH, and soil nitrogen and phosphorus as key variables affecting medicinal quality, confirming that polysaccharide accumulation emerges from multifactor coordination rather than single-factor control.

7 Current Challenges and Future Directions

A central challenge is that the environmental determinants of polysaccharide accumulation are clearly multifactorial, but their optimal thresholds and interaction patterns are still not resolved. Ecological analysis identified eight key factors affecting medicinal quality-maximum and minimum relative humidity, maximum temperature, sunshine duration, soil pH, soil total nitrogen, soil total phosphorus, and available phosphorus-showing that polysaccharide formation depends on a coupled environmental network rather than any single variable. Seasonal work further showed that stem sugar accumulation follows a nonlinear annual pattern and is jointly shaped by temperature and humidity, with rapid accumulation from October to February and transcriptomic enrichment in photosynthesis, abiotic stress, and starch-sucrose metabolism pathways. At the

treatment scale, environmental responses are also non-monotonic: red light most strongly promoted UGPase expression under different light qualities, high light induced mannose-rich polysaccharide accumulation through DoHY5-dependent signaling, and a 25/13℃ day-night regime gave higher polysaccharide content than constant temperatures in protocorm-like bodies. Moderate light also appears superior to extremes, because 11 000 lx simultaneously maximized biomass, bioactive compound yield, and sensory quality, whereas extreme high light increased structural carbohydrates but compromised growth-related and edible-quality traits. The main unresolved issue, therefore, is not whether light, temperature, humidity, and nutrients matter, but how their nonlinear interactions, developmental dependence, and cultivation-mode dependence should be parameterized into transferable threshold models for production.

A second challenge is establishing a regulation system that balances biomass production with polysaccharide quality, because maximizing growth does not always maximize medicinal value. Temperature studies showed that photosynthesis and vegetative growth were more favorable at 30℃, whereas stem polysaccharide content was significantly higher at 20℃, directly demonstrating a source–sink tradeoff between biomass expansion and polysaccharide concentration. Different cultivation environments also produce different quality profiles: tree-epiphytic stems had significantly lower polysaccharide content than stone-epiphytic and greenhouse samples, but stone epiphytic cultivation often accumulated more differential metabolites and stronger antioxidant-related quality traits, indicating that equal polysaccharide levels do not imply equal overall quality. This matters because polysaccharides remain the main Pharmacopoeia quality marker, yet regional metabolomics showed that small-molecule profiles can vary inversely with polysaccharide rankings, making polysaccharide-only evaluation incomplete for judging medicinal quality. Future regulation systems should therefore optimize for multiple endpoints at once: biomass yield, polysaccharide content, polysaccharide composition, and broader metabolite quality markers, ideally with cultivation-mode-specific targets for greenhouse, stone-epiphytic, and bionic systems. This is also the practical path for scaling artificial cultivation, since greenhouse production now dominates supply because of stable output and fast growth, yet uncontrolled optimization for yield alone risks weakening the medicinal traits that originally define high-quality *D. officinale.*

A third priority is integrating environmental monitoring, quality prediction, and intelligent control into a true precision-regulation platform. Recent predictive work already shows that this is feasible: machine-learning models outperformed linear models for predicting polysaccharide content across production areas, with XGBoost performing best, and also revealed that facility agriculture shifts the dominant drivers of high-quality production from rainfall and temperature toward altitude and sunlight. Harvest optimization studies similarly achieved high-accuracy prediction of dry matter content and suitable harvest period using chemometrics, and identified November to April, especially December, as the suitable harvest window, with specific daily water and shading recommendations. At the systems level, an IoT edge-computing and hybrid digital-twin platform for *D. officinale* improved prediction accuracy to 92.7%, increased production by 23.6%, and reduced energy use by 42.6%, showing the technical plausibility of closed-loop intelligent cultivation. Broader precision-agriculture evidence indicates that smart sensors for moisture, pH, and plant stress, combined with IoT, AI, and automated control, enable real-time irrigation, fertilization, and predictive analytics, but adoption remains constrained by cost, data-management complexity, technical expertise, and connectivity limitations. Future precision regulation in *D. officinale* should therefore couple sensor networks, transcriptome-and metabolome-informed quality models, and automated environmental control so that quality prediction moves upstream from post-harvest testing to dynamic cultivation management.

Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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Propagation of High-Quality Fingered Citron Seedlings and Application of Standardized Orchard Establishment Techniques

Xudong Kong [1,2]

1 Zhejiang Jinhua Fingered Citron (JFC) Biomedical Technology Co. Ltd., Jinhua, 321000, Zhejiang, China
2 Zhejiang Agronomist College, Hangzhou, 310021, Zhejiang, China
Corresponding email: zhejiangkong@163.com

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Abstract Fingered citron possesses medicinal, edible, ornamental, and aromatic value, and the propagation of high-quality seedlings together with standardized orchard establishment constitutes an important foundation for improving cultivation quality and production stability. This paper focuses on seedling propagation and standardized orchard establishment techniques for fingered citron, systematically analyzing key aspects including the selection of superior mother plants and propagation materials, cutting and grafting propagation, and environmental, water, and nutrient management during the seedling stage. Methods for seedling quality evaluation and grading are also summarized based on morphological traits, growth indicators, root system status, and plant health. For orchard establishment, emphasis is placed on site selection, soil improvement, infrastructure construction, planting density, and standardized planting, followed by discussion of water and nutrient management, root recovery, training and pruning, and pest, disease, and abiotic stress control in young orchards. The analysis indicates that fingered citron production should integrate source material management, seedling propagation, quality grading, standardized orchard establishment, and young orchard management into a coordinated whole-process system. Technical parameters should be optimized according to ecological conditions in different production regions, while demonstration, technical training, and quality traceability should be strengthened to improve the standardized application of these techniques. This paper provides a technical reference for high-quality seedling production, standardized orchard establishment, and large-scale cultivation of fingered citron.

Keywords Fingered citron; High-quality seedlings; Propagation techniques; Standardized orchard establishment; Young orchard management

1 Introduction

Fingered citron (*Citrus medica* L. var. *sarcodactylis*) is a perennial cultivated type of citron (*Citrus medica* L.) in the genus Citrus (Rutaceae). Citron represents an ancestral lineage important to citrus diversity (Denaro et al., 2020). Fingered citron has medicinal, edible, ornamental, and aromatic uses, and its distinctive finger-shaped fruit contributes to its commercial identity (Sun et al., 2024; Li and Fan, 2026). Morphological variability in fruit size, finger number, shape, and tree growth highlights the need to identify and preserve true-to-type propagation materials. Because traits can also respond to environmental conditions, mother-plant evaluation should combine varietal identity, health status, and field performance rather than relying on fruit appearance alone.

The ecological adaptability of fingered citron determines both its production range and its cultivation risk. Current evidence indicates that fingered citron is mainly cultivated in warm regions of southern China, including Guangdong, Fujian, Zhejiang, Sichuan, and Chongqing, while global cultivation also extends to parts of Europe, the United States, and Southeast Asia. At the same time, the species is clearly constrained by climate: it is not resistant to cold or drought, is vulnerable to freezing injury, and shows declining occurrence probability when annual temperature range increases. Habitat suitability studies in citrus identify annual precipitation, temperature annual range, elevation, precipitation seasonality, soil conditions, and human activity as important determinants of adaptation. These broader citrus findings provide comparative support for evaluating fingered citron production environments, but they should not replace species-specific assessment of topography, soil fertility, and management intensity. More broadly in citrus, environmental suitability is shaped by climate, geography, and soil fertility together, and improved orchard performance is associated with evaluating pH, organic matter, and

available nutrients before management optimization (Wu et al., 2022). Human factors are also central, because propagation methods, planting structure adjustment, and regional production decisions directly influence distribution and cultivation success. Under climate change, broader citrus studies also indicate possible shifts in suitable production areas, providing additional support for adapting fingered citron cultivation layout to local conditions and future environmental trends rather than relying on traditional planting experience alone (Yang et al., 2024).

Against this background, high-quality fingered citron seedlings are essential for reliable orchard establishment. Citrus nursery research emphasizes verified varietal identity, vigorous root systems, and freedom from important transmissible pathogens (Budiarto et al., 2024). Studies of the genus Citrus describe cuttings, grafting, and layering as possible vegetative approaches (Gogoi and Basumatary, 2017). Rooting under protected mist, suitable rooting substrates, and auxin treatment have improved cutting propagation in some citrus materials, but quantitative rooting rates are genotype-specific and must not be used as validated benchmarks for fingered citron. Likewise, rootstock choice, graft compatibility, nursery hygiene, and aftercare should be evaluated with locally available fingered citron materials before specific survival or yield benefits are claimed (Vashisth et al., 2020).

This study aims to establish a technical basis for the propagation of high-quality fingered citron seedlings and to provide a reference for the application of standardized orchard establishment techniques suited to its biological and ecological characteristics. This research has strong practical significance for production because, despite the high medicinal, edible, aromatic, and ornamental value of fingered citron, its cultivation still faces problems such as variation in habitat suitability, inconsistent nursery techniques, uneven seedling quality, and insufficient standardization of cultivation management. Even under favorable agro-climatic conditions, stable and healthy tree growth and satisfactory yields are difficult to achieve without standardized nursery practices and true-to-type, reliable-quality planting materials. Integrating climate, soil fertility, topography, propagation quality, and adaptive management into standardized orchard planning can help improve production efficiency and fruit quality while enhancing the adaptability of the production system to environmental and market changes. Therefore, research on the propagation of high-quality fingered citron seedlings and standardized orchard establishment is not only a technical requirement for the development of the fingered citron industry, but also an important approach to conserving germplasm resources, maintaining varietal authenticity, reducing production risks, and promoting the sustainable development of this distinctive citrus crop.

2 Selection of High-Quality Propagation Materials and Mother Plant Management

2.1 Selection of superior mother plants

Superior mother plants should first be identified as true-to-type elite trees that represent the target cultivar stably and can serve as the starting point for healthy propagation material production. Citrus mother tree systems are built around selected source plants that are registered, characterized, and maintained so that the genetic identity of propagated seedlings remains reliable across multiplication cycles. Because rootstock–scion choice strongly affects yield, fruit quality, and stress tolerance, mother plant selection should also consider compatibility and the intended production environment rather than visual vigor alone (Vashisth et al., 2020). Regional disease pressure, soil properties, and climate should be considered during source selection, because the best propagation parent is the one that combines varietal authenticity with adaptation to the pathogen and stress profile of the planting area (Wang et al., 2025).

The second core criterion is sanitary status. Candidate mother plants should be tested for systemic pathogens before they enter propagation programs, because latent infections can reduce productivity and shorten the longevity of all daughter plants (Ventura et al., 2019). Multiple citrus programs screen mother plants for graft-transmissible pathogens and maintain only disease-free source trees, with shoot-tip grafting and indexing used when sanitation is required. Shoot-tip grafting has been standardized to generate true-to-type, virus-free plants and then establish protected foundation blocks that continuously supply clean scion material. This emphasis is justified because certified disease-free planting material improves tree uniformity, early bearing, productive life,

and farm returns, while use of uncertified material increases biological and economic risk (Bhattacharyya et al., 2025).

2.2 Selection of propagation shoots and scions

Propagation shoots and scions should be collected from healthy, vigorous, and genetically verified mother plants, because the quality of the harvested budwood directly determines the quality of grafted seedlings (Wang et al., 2025). In citrus nursery systems, varietal purity must be guaranteed for both scion and rootstock materials, and off-type seedlings or shoots should be identified and discarded during propagation. For seed-propagated citrus rootstocks, the proportion of true-to-type seedlings differs among genotypes, so propagation strategy needs to match the biological behavior of the specific rootstock rather than assume that all citrus materials are equally suitable for seed multiplication (Bisi et al., 2020). Modern citrus rootstock breeding programs further highlight the need for authenticated and selected rootstock germplasm (Bowman et al., 2021). When nucellar seed supply is inadequate or uniform seed propagation is impossible, cuttings or tissue culture can provide genetically identical liners for later grafting (Albrecht et al., 2020). For fingered citron production, these findings should be treated as references for selecting and propagating rootstocks used in grafting, rather than as evidence that fingered citron itself must be propagated through seed-derived rootstocks.

For vegetative propagation, shoot maturity and handling are critical selection criteria. Reviews of citrus cutting propagation indicate that virus-free hard, semi-hard, and softwood cuttings can all be used, but rooting and uniformity depend strongly on cutting maturity, auxin treatment, season, growing medium, and microclimate. Semi-hardwood cuttings often perform best for rooting and survival, and mist-house conditions together with IBA treatment improve propagation success. Single-node cutting systems can propagate diverse citrus genotypes efficiently, with some rootstocks reaching 82~91% establishment of rooted, growing plants, although success still differs sharply by genotype (Bowman and Albrecht, 2017).

2.3 Standardized management of mother plant orchards

Standardized management of mother plant orchards depends on protected production systems, routine inspection, and documented certification procedures. Citrus programs in Brazil and elsewhere show that standardization and frequent nursery inspection are central to assuring the genetic and sanitary quality of mother trees and propagation materials. Protected environments are especially important because plants used in sanitation and mother-stock programs are commonly maintained under vector-exclusion conditions, and screen protection is a defining feature of many certified budwood and nursery tree systems (Zamzami et al., 2021). In certified citrus systems, planting disease-free trees, controlling psyllids, and removing infected trees form key elements of HLB management, while pathogen-free nurseries provide an important barrier against graft- and vector-transmitted diseases (Graham et al., 2024). These HLB-oriented measures are citrus examples; for fingered citron mother-stock management, the transferable principle is to maintain verified clean source plants and prevent the introduction or spread of graft- and vector-transmitted pathogens, rather than assuming an identical disease profile or regulatory system.

Standardized mother orchard management also requires regular renewal, clean handling, and optimized cultural care. Bud-stick multiplication blocks are periodically replanted from higher-order clean sources, and their maintenance under screens enables repeated budwood harvest while preserving sanitary quality and conformity to standards. Clean production further depends on disinfected facilities and tools, pathogen-free substrates and water, secure waste disposal, weed elimination, and routine operational records to reduce introduction and spread of inoculum (Ventura et al., 2019). Nursery and mother block performance is also strengthened by correct rootstock seed sowing, nucellar seedling selection, use of authorized budwood sources, appropriate grafting height, and optimum maintenance throughout production. In addition, improved substrates and nutrition can accelerate seedling growth and raise budding success, so standardized management should integrate sanitation with cultural practices that produce vigorous, field-ready plants efficiently.

3 Key Techniques for High-Quality Fingered Citron Seedling Propagation

3.1 Cutting propagation techniques

Cutting propagation is an important vegetative method for producing true-to-type citrus planting material when seed propagation gives non-uniform offspring or when rapid clonal multiplication is needed. In citrus, rooting success depends strongly on the physiological status and maturity of the cutting, the season of collection, the rooting medium, hormonal treatment, and the surrounding microclimate (Guchhait et al., 2024; Saini et al., 2025). Reviews across citrus species indicate that virus-free hard, semi-hard, and softwood cuttings can all be used, but semi-hardwood materials often show the best rooting and survival performance. Auxin treatment is especially important, and indole-3-butyric acid is repeatedly identified as a key regulator that improves root initiation, root number, root quality, and subsequent shoot growth. Rooting media must simultaneously provide water retention, drainage, aeration, and mineral supply, because these physical properties directly influence rooting percentage and early seedling vigor.

For fingered citron seedling production, evidence from citrus cutting systems suggests using healthy semi-lignified shoots from superior mother plants, retaining physiologically active buds, treating the basal end with appropriate auxin, and placing the cuttings in a porous, moist rooting medium under protected high-humidity conditions. Citrus studies show that mist-house or intermittent-mist systems can improve propagation success, and single-node or single-bud cuttings can root efficiently under nursery conditions. In one citrus rootstock study, 82~91% of single-node cuttings of the best-performing genotype established as rooted, growing plants by eight weeks, although rooting efficiency differed sharply among genotypes. This value is a genotype-specific citrus rootstock result and should not be treated as a target for fingered citron. Cuttings can approach seedling size within a short nursery period, but vegetatively propagated plants tend to have a higher shoot-to-root ratio and a root system dominated by adventitious and lateral roots rather than a clear taproot, so nursery hardening and root-quality assessment are important before field planting (Albrecht et al., 2020). For fingered citron, the specific hormone concentration, humidity regime, rooting period, and acceptance thresholds still require validation with local material and nursery conditions.

3.2 Grafting propagation techniques

Grafting is a core technique in citrus propagation because it combines the genetic identity and fruiting characteristics of the scion with the stress tolerance, disease resistance, and growth-regulating effects of the rootstock (Shivran et al., 2022). Citrus nurseries commonly use bud grafting methods such as chip budding, T-budding, and inverted T-budding, as well as branch grafting methods such as cleft, splice, wedge, whip-and-tongue, and side grafting. Successful grafting depends on rootstock-scion compatibility, proper developmental stage, stem thickness, close cambial contact, operator skill, and favorable temperature and humidity during healing (Hussain et al., 2017). Compatible combinations improve plant growth, water and nutrient uptake, fruit quality, and tolerance to drought, temperature stress, salinity, waterlogging, and major diseases, whereas unsuitable combinations lead to weak growth, delayed bearing, and poor nursery performance (Wang et al., 2025).

For high-quality fingered citron seedlings, grafting should use vigorous, disease-free rootstocks of suitable stem diameter and healthy scions with full buds collected from standardized mother orchards. Comparative studies in other citrus taxa provide useful technical references, but their numerical parameters should not be transferred directly to fingered citron. For example, wedge grafting on six-month-old rootstocks achieved 90.0% graft success and 88.87% plant survival in Khasi mandarin (Deshmukh et al., 2017), while wedge and side grafting performed well in Kinnow mandarin (Hussain et al., 2017). Nursery-scale citrus studies have also evaluated inverted T-budding at 25~30°C and protected minigrafting systems using defined grafting heights or short apical segments (Mendes et al., 2019; Suárez Padrón et al., 2022). These cases show that rootstock age, grafting method, cambial contact, healing environment, and post-grafting care are important control factors. For fingered citron, however, suitable rootstock age, grafting type, temperature and humidity, and healing period should be determined by local validation rather than adopted as fixed values from other citrus species.

3.3 Environmental, water, and nutrient management during the seedling stage

During the seedling stage, propagation success depends not only on the method used but also on precise control of the nursery environment, water supply, and nutrient regime. In cutting propagation, temperature, relative humidity, and light intensity are critical determinants of rooting and survival, while irrigation water and nutritional status also influence early establishment (Suárez Padrón et al., 2022). In grafted seedlings, protected greenhouse or shade-house systems are commonly used to stabilize temperature and moisture and to support rapid healing of the graft union. Citrus management studies also show that generalized irrigation and fertilization schedules are often inefficient because plant demand varies with substrate condition, growth stage, and local environment, making real-time monitoring and precision management preferable to uniform input application (Zhang et al., 2017).

Water and nutrient management should aim to maintain steady seedling growth without causing leaching, salt stress, root hypoxia, or excessively soft vegetative growth. Citrus studies show that heavy rainfall or over-irrigation can increase nutrient leaching, while flooding and waterlogging reduce aeration and damage fine roots. Fertigation and soluble fertilizers can improve nutrient-use efficiency when carefully managed, but excessive inputs are harmful; high fertigation rates may acidify the soil solution and increase ammonium accumulation (Quaggio et al., 2019). Likewise, a citrus pot study showed that very high nitrogen reduced total biomass from 14.24 to 6.95 g per plant, largely through direct and indirect inhibition of root growth (Niu et al., 2024). This result demonstrates the risk of excessive nitrogen in citrus seedlings, but it should not be converted into a direct fertilizer threshold for fingered citron. Practical nursery management should therefore emphasize moderate and split fertilizer application, good drainage, and irrigation scheduling based on substrate moisture rather than fixed routines (Srivastava et al., 2026). Evidence across citrus systems further supports coordinated water, nitrogen, and potassium management to improve resource-use efficiency (Zhang et al., 2026). For fingered citron seedlings, fertilizer rate and irrigation frequency should ultimately be adjusted according to substrate properties, seedling vigor, and local nursery conditions.

4 Seedling Quality Evaluation and Nursery Stock Management

4.1 Morphological and growth indicators of seedlings

Morphological and growth indicators are the most practical basis for routine nursery evaluation because they are rapid, simple, and usually nondestructive, even though they do not capture every aspect of field performance (Wang et al., 2026). Across seedling quality studies, the most commonly used indicators are seedling height, stem or root-collar diameter, height-to-diameter ratio, shoot and root dry mass, total biomass, shoot-to-root ratio, root length, root volume, and lateral root development (De Melo et al., 2018; Robonen et al., 2023). For citrus seedlings specifically, useful shoot indicators include plant height, stem diameter, leaf number, leaf area, branch number, sprout length, and sprout diameter, while root evaluation includes root length, root diameter, root number, fibrous root number, and root dry matter (Cruz et al., 2019; Xu et al., 2020; Kaur et al., 2024). Morphological markers such as leaf form, leaf size, and thorniness can also help distinguish seedling types or identify off-types in citrus breeding and nursery populations, although morphology alone is not always sufficient for definitive identification (Kurt and Koyuncu, 2024).

Among these indicators, stem diameter is consistently one of the strongest single predictors of overall seedling quality because it correlates well with biomass-based indices and later establishment potential (Robonen et al., 2023). Root traits add essential information because aboveground morphology alone does not always predict post-planting performance, whereas large root volume, high root fibrosity, abundant first-order laterals, and greater root system development tend to support better establishment, water uptake, and nutrient absorption (Figure 1) (Cruz et al., 2019; Pecoraro Sanches et al., 2026). Citrus studies also show that stronger shoot growth is positively associated with stronger root growth: seedling height and diameter correlate with root length, root diameter, root number, photosynthetic rate, stomatal conductance, and chlorophyll status, while vigorous rootstocks develop more absorbing roots and greater biomass accumulation (Kaur et al., 2024; Dattola and Gullo, 2026). Accordingly, these indicators can provide a reference framework for fingered citron seedling evaluation, but species-specific grading thresholds should be developed and validated for fingered citron rather than copied directly from other nursery systems (Kamanga et al., 2026).

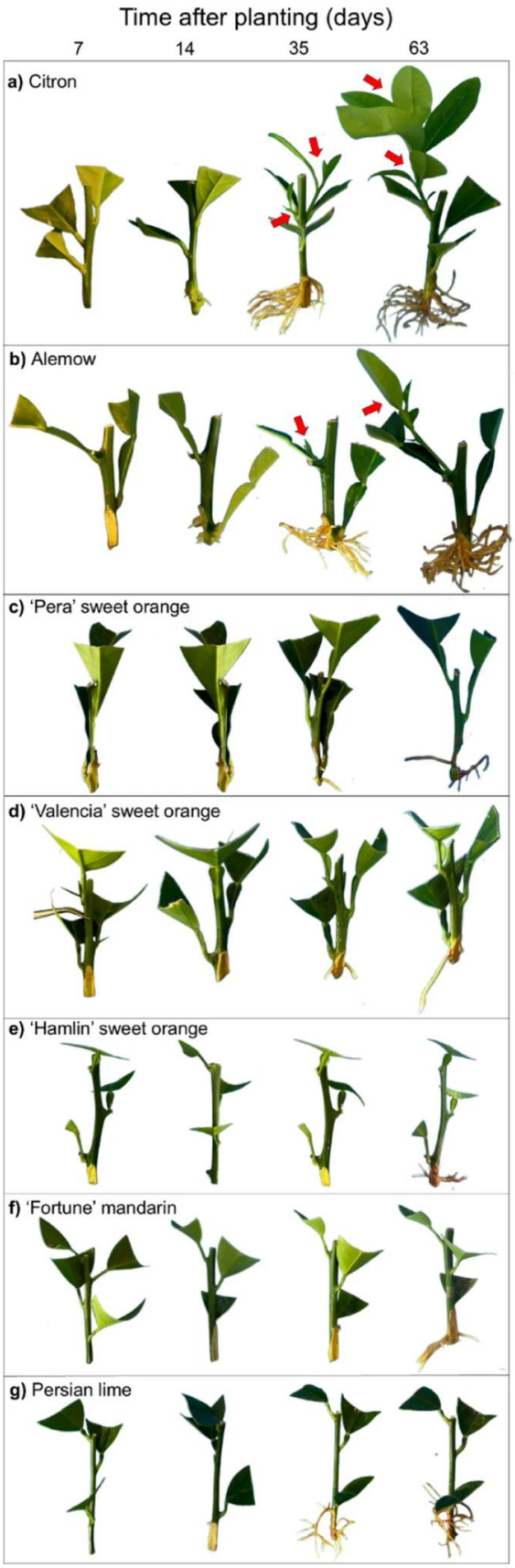


Figure 1 Root development and vegetative flush at 7, 14, 35, and 63 days after planting (Adopted fromPecoraro Sanches et al., 2026)
Image caption: (a) citron (*Citrus medica*); (b) alemow (*C. macrophylla*); (c) Pera, (d) Valencia, and (e) Hamlin sweet oranges (*Citrus*×*sinensis*); (f) Fortune mandarin (*C. reticulata*); and (g) Persian lime (*C. latifolia*). Red arrows indicate new vegetative flushes; All stem cuttings were 6~8 cm long at planting (Adopted fromPecoraro Sanches et al., 2026)

4.2 Seedling quality grading and health assessment

Seedling grading should convert these measurements into operational classes that distinguish plantable from unqualified nursery stock. Citrus grading studies show that classification can be built from a larger measured dataset and then simplified into a few key indicators that are practical in production (Wang et al., 2026). In annual grafted *Citrus aurantium* seedlings, plant height, scion diameter, and branch number were used to establish three quality grades, and seedlings below the third-grade threshold were considered unqualified (Xu et al., 2020). This provides a useful example of how citrus nursery measurements can be translated into operational grades, but the numerical thresholds of *Citrus aurantium* should not be used directly as fingered citron standards. More broadly, plant height, stem or ground-line diameter, and root system condition are commonly used grading indicators, while integrated indices such as sturdiness quotient, shoot:root ratio, and Dickson quality index can reduce error from relying on a single trait (Robonen et al., 2023).

Health assessment should accompany grading because a morphologically large seedling is not necessarily a healthy or field-ready one (Grossnickle and MacDonald, 2018; De Melo et al., 2018). Physiological assessment methods such as root growth potential, cold hardiness, stress resistance, water relations, nutrient status, and root electrolyte leakage provide information on transplant performance that morphology alone can miss, although they are more time-consuming and are used less often operationally. Nursery quality control should therefore screen for root deformities, abnormal shoot-to-root ratios, low photosynthetic competence, cellular stress, and poor hydration status, because these problems can occur even where seedlings appear acceptable externally (Kamanga et al., 2026). A relative water content above about 75% has been associated with better leaf water status and drought tolerance in other seedling-quality studies; this value can serve only as a physiological reference and should not be treated as a fingered citron grading threshold. Nursery assessment is also valuable for preventing disease spread and qualifying plant material in trade, so fingered citron grading should integrate morphology, physiology, and sanitary inspection into one standard evaluation process (Mataruga et al., 2023).

4.3 Hardening, lifting, and transportation of seedlings

Before seedlings leave the nursery, hardening is used to improve tolerance to transplant stress, especially in dry or exposed planting environments. In nursery practice, seedlings are often water stressed and then gradually weaned under shade before transport so they become less vulnerable to drought after planting. Evidence on drought hardening is mixed overall, but field studies show that it tends to improve survival and growth as site aridity increases, while benefits are reduced when a long delay occurs between hardening and transplanting (Puértolas et al., 2024). Hardening therefore needs to be linked closely to the expected field site and planting schedule rather than applied as a fixed routine (Guimarães et al., 2024). In addition, nursery practices such as watering, shading, fertilization, root pruning, suitable growing media, and short-day or storage protocols all influence the final transplant quality of planting stock (Kamanga et al., 2026).

Quality can decline substantially between lifting and planting if seedlings are exposed to desiccation, extreme temperatures, rough handling, root loss, or prolonged storage. These stresses often occur in combination, and the cumulative effects of desiccation and storage appear especially harmful, making careful lifting, packing, and rapid delivery essential. European nursery surveys similarly identify unsuitable transport and handling during shipping and planting as a common cause of declining seedling quality (Mataruga et al., 2023). For fingered citron seedlings, lifting should retain as much of the functional root system as possible, avoid mechanical injury, and keep roots moist and shaded during grading, bundling, loading, and transport, because root morphology and physiological condition are closely tied to successful establishment after transplanting (Grossnickle and MacDonald, 2018).

5 Standardized Orchard Establishment and Planting Techniques for Fingered Citron

5.1 Site selection and soil improvement

Site selection for fingered citron should begin with climatic and topographic suitability, because this species is sensitive to mismatched environments and its current planting problems have been linked directly to inadequate suitability analysis. For fingered citron, the dominant environmental variables identified across habitat modeling

studies are temperature annual range, annual precipitation, elevation, precipitation seasonality, and human activity intensity. The most suitable present habitats are concentrated in eastern Sichuan, western Chongqing, southern Guizhou, western Guangxi, central and southern Yunnan, and parts of southeast Tibet or western Taiwan, which provides a practical regional reference for orchard layout (Figure 2) (Xia et al., 2023). More broadly in citrus, orchard location is a primary planning decision, and land suitability models consistently show that site choice should integrate multiple criteria rather than rely on local experience alone (Tercan and Dereli, 2020).



Figure 2 Field overview of *C. medica* L. var. sarcodactylis planting (Adopted from Xia et al., 2023)
Image caption: a: plant; b: fresh fruit; c: dried fruit slices (Adopted from Xia et al., 2023)

Within citrus suitability assessments, winter temperature, elevation, precipitation, sunshine, land capability, and proximity to irrigation water are repeatedly identified as major filters for productive orchard land (Tercan and Dereli, 2020). Fingered citron studies similarly show that future suitable areas may shift under climate change, so orchard establishment should account for both current fit and likely regional change in hydrothermal conditions. After climatic screening, soil evaluation becomes the next core step. Citrus studies show that soil acidification and deficiencies of available nitrogen and phosphorus can reduce orchard suitability, while poor soil and water conservation on slopes can accelerate nutrient loss. Measures such as decomposed organic fertilizer, green manure, integrated water-fertilizer management, and soil amendments have been used to improve citrus orchard soil conditions. For fingered citron, these measures should be selected according to site-specific soil testing and local production conditions rather than adopted as a uniform amendment prescription.

5.2 Orchard planning and infrastructure construction

Once a suitable site has been chosen, orchard planning should match the terrain, water supply, and intended management intensity, because orchard performance depends not only on planting location but also on how the production space is physically organized. Citrus suitability studies identify climate, geography, and soil fertility as joint dimensions of orchard performance, which means infrastructure planning should coordinate slope, drainage, roads, irrigation access, and fertilization logistics rather than address them separately. In commercial citrus systems, orchards established on long raised beds with drainage swales on each side provide a useful model for improving water movement and reducing waterlogging risk (Hamido and Morgan, 2020). This is especially relevant because excessive waterlogging damages fine roots and limits nutrient uptake, whereas better-controlled irrigation improves water availability, plant nutrition, and tree growth (Atta et al., 2025).

Irrigation infrastructure should be built as a core component of standardized orchard establishment rather than added later. Citrus studies show that irrigation scheduled according to evapotranspiration and soil moisture monitoring can stabilize water supply more effectively than fixed manual schedules (Hamido and Morgan, 2021). Drip and microsprinkler fertigation systems, as well as root-zone-targeted irrigation, have been used in citrus to improve water and nutrient distribution and support early tree establishment. These citrus results provide a practical framework rather than fixed operating parameters for fingered citron. Accordingly, fingered citron orchard infrastructure should prioritize dependable water sources, distribution pipelines, filtration and fertigation capacity, drainage channels, access paths, and slope-conserving measures, with system capacity adjusted to local topography, soil, and water availability (Chhetri and Kandel, 2019).

5.3 Planting density and standardized planting

Planting density is a major management lever in citrus orchard establishment. Citrus studies consistently show that moderately higher density can increase early yield per unit area when it is matched with suitable rootstocks, canopy control, irrigation, and nutrition management (Devite et al., 2025). Studies in sweet orange, grapefruit, and mandarin also demonstrate that the direction and magnitude of density effects vary markedly with cultivar, rootstock, orchard age, and production environment (Lakshmi et al., 2025). These results are useful for understanding the principle of density management, but they do not establish a suitable spacing for fingered citron. Fingered citron planting density should therefore be determined from its own tree vigor, canopy expansion, site fertility, drainage, water availability, and intended management system rather than by directly adopting spacing values reported for other citrus crops.

High-density planting is not universally beneficial because its performance depends on tree vigor, scion-rootstock combination, climate, soil fertility, drainage, water availability, and annual canopy management. Citrus reviews and comparative trials show that spacing often needs to be adjusted as canopies develop and that dwarfing and standard rootstocks require different density strategies. These findings again illustrate the need to match density with canopy vigor rather than use a single fixed number. For fingered citron, standardized planting should use healthy and uniform seedlings, determine row direction and spacing according to light interception and field access, and coordinate density with pruning, fertigation, and irrigation. Any specific spacing recommendation should be validated under local fingered citron production conditions so that early use of space does not lead to later canopy crowding or management difficulty (Atta et al., 2025).

6 Standardized Management Techniques for Young Fingered Citron Orchards

6.1 Water and nutrient management and root recovery

Evidence from young citrus orchards provides useful reference for water management in fingered citron, but irrigation parameters need local validation. Young citrus trees require stable root-zone moisture because vigorous vegetative growth, repeated leaf flushing, and canopy establishment depend on an active root system. Poor irrigation scheduling can reduce efficiency and restrict young-tree growth through either excess water or water deficit. On sandy citrus soils, moderate irrigation improved fibrous-root development, root survival, leaf nutrient status, and overall tree growth. These findings support maintaining a stable but well-aerated root-zone water regime in young fingered citron orchards. Irrigation scheduling tools, weather information, and soil-moisture monitoring can therefore be used to guide management, while the actual irrigation amount and frequency should be adjusted to local soil, weather, and tree condition (Kadyampakeni and Guzmán, 2021)

Root recovery depends on both water management and soil improvement. Disease-specific citrus research has shown that root decline may precede visible canopy symptoms under HLB pressure, illustrating the value of early root-zone monitoring, although this should not be interpreted as the normal root response of fingered citron (Atta et al., 2025). Citrus orchard studies also show that compost can improve soil water status, organic matter, cation exchange capacity, pH, and nutrient availability, especially when combined with weed control to reduce competition (Pokhrel et al., 2025). Mulching and ground-cover management can also support early orchard establishment; studies in sweet orange and other citrus systems report improved canopy growth or foliar nutrient status under suitable ground-cover and irrigation combinations (Giménez-Valero et al., 2025). In sloping or acidic orchards, organic amendments, mulching, liming where appropriate, and regular weeding can further improve soil conditions and reduce competition. For fingered citron, these measures should be selected according to soil testing and local stress conditions rather than applied uniformly.

Targeted water-saving strategies in mature or fruiting citrus provide useful evidence on stage sensitivity, but they should not be converted directly into deficit-irrigation schedules for young fingered citron orchards. Studies in semiarid citrus show that regulated deficit irrigation and partial rootzone drying can reduce irrigation use without necessarily reducing yield when timing and intensity are appropriate. Other citrus research indicates that flowering and fruit growth are particularly sensitive to water stress (Dutta et al., 2023). For young fingered citron orchards, the priority during establishment should therefore remain stable root-zone moisture and avoidance of

prolonged drought or waterlogging. Nutrition should be coordinated with irrigation, because citrus studies show that optimized water and potassium management can improve soil inorganic nitrogen availability, nutrient productivity, and irrigation water productivity. Irrigation-water chemistry alone does not predict plant nutrition well, so fertigation decisions should be based on soil properties and plant response rather than water source alone (Imbernón-Mulero et al., 2026).

6.2 Training and pruning for canopy development

Canopy training in young fingered citron orchards should aim to build a strong, balanced framework early and then maintain light penetration, ventilation, and manageable tree size through repeated light interventions rather than delayed severe cuts. Across perennial fruit crops, canopy management improves light interception, photosynthesis, microclimate, fruit quality, and orchard efficiency, while also helping balance vegetative and reproductive growth. In citrus, poorly maintained trees develop oversized, dense peripheral canopies that limit aeration and inner-canopy light, create unproductive shaded interiors, and make spraying and harvest less efficient. Orchard design and canopy management also interact, because spacing, row orientation, and tree shape together determine how well canopies intercept and distribute light.

For newly established trees, drastic pruning in the first year should be avoided, while unwanted shoots should be removed early and the developing framework should be guided before crowding occurs. Higher-density citrus systems have used central-leader, multiple-leader, and pyramidal canopy forms to improve light distribution, but these are examples from other citrus production systems rather than fixed training forms for fingered citron. The transferable principle is to establish a stable branch hierarchy, retain adequate leaf area, and avoid a dense outer canopy with a shaded interior. Maintenance pruning, cleaning pruning, and water-sprout removal are important after establishment because they remove dead or damaged wood, reduce excessive vegetative growth, and preserve productive canopy space. In young citrus under water-limited conditions, reducing early fruit load can favor vegetative development, and ground-cover management can also influence canopy expansion (Giménez-Valero et al., 2025). Fingered citron training should therefore be adjusted to its own branching habit, vigor, planting density, and local management objectives rather than directly adopting a canopy form developed for another citrus crop.

6.3 Pest, disease, and abiotic stress management

Young fingered citron orchards require integrated pest, disease, and stress management, but the risk profile should be defined from local fingered citron production rather than inferred directly from citrus decline in general. Surveys and reviews of citrus identify insects, diseases, climatic extremes, nutrient deficiency, poor planting material, and weak orchard management as major contributors to tree decline (Kalatippi et al., 2024). These citrus findings provide a broad risk framework for fingered citron orchard management. Drought can weaken tree defenses and interact with disease pressure, while salinity, flooding, nutrient imbalance, high temperature, and other abiotic stresses may also act in combination. However, the relative importance of individual diseases, pests, and abiotic stresses in fingered citron should be determined from local occurrence and monitoring rather than assumed to match other citrus crops. Standardized management should therefore integrate water, nutrition, sanitation, and plant-health monitoring.

Practical control should combine orchard sanitation, canopy hygiene, monitoring, and selective intervention. Citrus IPM programs provide useful examples: pruning diseased or infested branches, using monitoring traps, applying pesticides according to thresholds, removing dead twigs and dropped fruit, and conserving natural enemies can reduce pest and disease pressure and improve production efficiency (Meena et al., 2025). These measures illustrate IPM principles rather than define a fixed pest and disease list for fingered citron. Where viroid or other graft-transmissible pathogen risk is confirmed, clean nursery stock, surveillance, prompt removal of infected plants, and tool disinfection can be used as sanitation measures (Bagherian et al., 2026). Abiotic-stress mitigation may include suitable irrigation, mulching, salinity monitoring, soil amendments where justified, and tolerant rootstocks. For fingered citron, the choice of each measure should follow local diagnosis, because hygiene, water-nutrient management, and healthy propagation materials are transferable principles, whereas specific disease targets and treatment thresholds may differ among citrus crops (Kalatippi et al., 2024).

7 Application of Fingered Citron Seedling Propagation and Orchard Establishment Techniques

7.1 Whole-process quality control of seedling propagation

Whole-process quality control in fingered citron seedling propagation should begin with a clear crop plan and standard operating procedures that monitor each production stage from source material and rootstock preparation to substrate management, grafting, grading, and dispatch. Citrus nursery production likewise treats rootstock propagation, attainment of buddable size, and subsequent grafting as linked quality-control steps rather than independent operations (Vashisth et al., 2020). Where seed-propagated citrus rootstocks are used for fingered citron grafting, seed pretreatment and seed maturity can influence emergence, vigor, and uniformity; studies using GA3 or different fruit-harvest stages illustrate these control points (De Carvalho et al., 2021). These findings should be used to guide quality control of the selected rootstock source, not as direct evidence that fingered citron itself requires the same seed treatment or harvest timing.

Substrate, containers, irrigation, and fertigation determine whether nursery plants reach the desired specification. Citrus studies show that substrate physical and chemical properties can influence seedling development through grafting, and inappropriate formulations may restrict growth (Liberato et al., 2021). Compost-containing potting mixes improved germination, biomass accumulation, and budding success in citrus rootstocks (Vashisth et al., 2020), while moderate N and P fertigation improved several nursery growth and physiological traits (Kaur et al., 2024). These results support the principle of balanced substrate and nutrient management, but study-specific formulations or nutrient rates should not be used directly as fingered citron prescriptions. Container type also affects root architecture, because enclosed containers can induce root circling while root-pruning containers can reduce deformation. Final release should therefore use explicit grading criteria. Citrus grading studies show that plant height, scion diameter, branch number, and root condition can be translated into operational quality classes (Xu et al., 2020), but fingered citron thresholds should be established from its own nursery and field performance.

7.2 Coordination between seedling quality and orchard establishment techniques

Seedling quality and orchard establishment techniques need to be coordinated because nursery traits influence post-planting survival, recovery, and early orchard performance, while field conditions determine which seedling traits are actually valuable. The target-seedling concept captures this relationship by linking nursery production to the conditions of the eventual planting site rather than defining quality only inside the nursery. In citrus, this coordination begins with choosing compatible propagation materials, since high-quality grafted seedlings form the foundation of stable, high-yield production and inappropriate rootstock-scion combinations can weaken stress resistance and delay fruiting (Wang et al., 2025). Rootstock choice is part of orchard establishment strategy because rootstocks affect scion growth, nutrition, fruit quality, and tolerance to biotic and abiotic stress, so the same seedling is not equally suitable for all planting environments (Vashisth et al., 2020).

Coordination also depends on transplant timing, root-system quality, and field readiness. A Cleopatra mandarin study showed that transplant age can influence survival, stem-diameter growth, and branching during the rootstock stage, demonstrating that transplant timing is an important nursery-to-field control point; however, the reported age should not be transferred directly to fingered citron. Root-system quality is central because successful field establishment depends on healthy roots, while containerized nursery systems can restrict root expansion and alter later growth. Propagation method also influences orchard-stage behavior, and citrus studies show that orchard growth depends on the combination of propagation method and rootstock rather than propagation method alone (Albrecht et al., 2020). Nursery certification further supports orchard establishment. In citrus systems, protected-environment production and certified seedling distribution have been used to reduce the spread of diseases such as HLB and CVPD. These are disease-management examples from citrus; for fingered citron, the transferable principle is to use verified healthy planting material and minimize pathogen introduction. Even after delivery, quality can decline through poor handling, transport, or planting, so standardized orchard establishment should include proper seedling handling and timely water support at the receiving site (Mufidah et al., 2021).

7.3 Demonstration and promotion of standardized techniques

Demonstration and promotion are necessary because scientific production techniques are often not adopted automatically, even when they outperform traditional practice (Shah et al., 2022). Evidence from fruit systems shows that both traditional and digital agro-technology promotion significantly increase farmer adoption of improved production technologies, and the two modes can complement each other rather than function as substitutes in all cases (Zhang et al., 2024). Systematic service models appear especially effective when they combine training with diagnosis and follow-up support: in apple, a six-in-one model including soil testing, pest and disease diagnosis, course training, meteorological monitoring, on-site guidance, and experimental demonstration raised adoption of integrated management technologies to 84.4% and stabilized yields over time (Duan et al., 2023). These results are directly relevant to fingered citron because standardized propagation and orchard establishment also require coordinated action across soils, weather, plant protection, and management skills.

Field demonstration remains one of the strongest extension tools. In fruit production extension, practical demonstrations were the most preferred communication method for adopting technical knowledge, and training raised impact levels markedly while full adoption varied by practice. Frontline demonstrations in banana increased yield by 30.77% and improved gross return, net return, and benefit-cost ratio relative to farmer practice, showing that on-farm demonstration can accelerate both adoption and economic gains (Desai et al., 2025). In citrus-specific training systems, each additional training event increased the probability of adopting multiple green production technologies, and enterprise-led training showed the strongest promotion effect, although a diversified extension system remained the recommended model. Certified seedling distribution programs likewise show the value of pairing material supply with farmer empowerment, because seedling mortality remained relatively low at 12%, but continued constraints in water availability, weather forecasting, and grower support limited outcomes (Mufidah et al., 2021).

8 Summary and Future Prospects

The future high-quality fingered citron seedling system should shift from experience-based nursery work to whole-process quality control built around crop plans, standard operating procedures, verified mother stock, propagation-material sanitation, nursery environment management, and final seedling grading. Citrus rootstock studies show that seed quality, pretreatment, substrate, nutrition, container type, and transplant timing can all influence nursery performance, but these results should be used as comparative references rather than direct production parameters for fingered citron. For fingered citron itself, the priority is to establish a traceable mother-stock system, optimize cutting and grafting protocols with local material, strengthen root-system and health assessment, and reject substandard seedlings before orchard use. Future work should therefore focus on developing fingered citron-specific technical thresholds for propagation success, seedling vigor, root quality, and field readiness, so that nursery standards are based on its own biological characteristics and production performance.

Standardized orchard establishment for fingered citron should be optimized around site-specific suitability and the coordination between seedling quality and field conditions. Citrus research demonstrates that rootstock choice, rootstock-scion compatibility, soil condition, drainage, irrigation, canopy vigor, and planting density can interact strongly with orchard performance. These findings provide a useful framework, but exact rootstock combinations, spacing values, irrigation schedules, and disease-management measures should not be transferred directly from sweet orange, mandarin, grapefruit, or other citrus crops to fingered citron. Fingered citron orchard standards should therefore emphasize verified healthy seedlings, suitable sites, sound drainage and irrigation infrastructure, careful transplant handling, root-system integrity, and density matched to local tree vigor and management capacity. Long-term field validation across major production regions is needed to convert these general citrus principles into fingered citron-specific orchard-establishment parameters.

The future industrialization of fingered citron should emphasize standardized production bases, technical training, and integrated service systems so that nursery quality can be translated into stable orchard performance. Extension studies in fruit and citrus production show that field demonstration, repeated training, digital and traditional

communication, diagnostic support, and follow-up services can improve the adoption of standardized technologies. These results are most useful as extension-method references rather than as direct evidence of fingered citron yield responses. Accordingly, industrialized fingered citron production should connect certified or verified propagation material, standardized nursery procedures, orchard establishment adapted to local conditions, young-orchard management, and follow-up technical services. Region-specific demonstration bases and traceable production records should be used to refine technical standards continuously, so that high-quality seedlings, appropriate orchard design, and standardized management form one coordinated production chain.

Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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Construction of a Quality Traceability System for Green Production Bases of Hangzhou White Chrysanthemum

Weiying Gao [1,2]

1 Tongxiang Lukang Chrysanthemum Industry Co. Ltd., Tongxiang, 314501, Zhejiang, China
2 Zhejiang Agronomist College, Hangzhou, 310021, Zhejiang, China
Corresponding email: 1304837229@qq.com

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Abstract The quality of Hangzhou White Chrysanthemum is jointly affected by multiple factors, including production environment, seedling source, water and fertilizer management, pest and disease control, harvest timing, processing methods, and storage conditions. Therefore, end-product testing alone cannot fully reflect the process of quality formation. Based on the production characteristics and quality management requirements of green production bases, this paper proposes a whole-process quality traceability framework covering cultivation, harvesting, processing, storage, circulation, and supervision. Taking production batches as the main traceability line, the system links information on production-base environment, seedlings and field management, water and fertilizer inputs, pest and disease control, harvest maturity, processing parameters, packaging and storage, and quality testing, while unified coding, QR codes, the Internet of Things, and blockchain technologies are introduced to support information collection, storage, and inquiry. For quality evaluation, appearance traits, basic physicochemical indicators, functional components such as chlorogenic acid, luteolin-7-O-glucoside, and 3,5-O-dicaffeoylquinic acid, as well as safety indicators are incorporated into the key quality control system. The proposed evaluation scheme further integrates geographical-origin authenticity, fingerprint profiles, and batch consistency. The proposed framework could improve information continuity throughout Hangzhou White Chrysanthemum production and enhance the ability to identify the sources of quality problems, while also providing support for product grading, green certification, brand protection, and market supervision. In the future, intelligent sensing, molecular identification, and digital evaluation technologies can be further integrated to improve the authenticity, real-time performance, and practical value of traceability data, thereby promoting the development of Hangzhou White Chrysanthemum production toward standardization, digitalization, and whole-process quality management.

Keywords Hangzhou white Chrysanthemum; Green cultivation; Quality traceability; Quality control; Digital management

1 Introduction

Hangzhou White Chrysanthemum is a well-known medicinal chrysanthemum and one of the “Zhejiang eight flavors,” with distinct production rhythms and quality traits that make source-oriented quality control especially important. Its cultivation is strongly shaped by seasonal and biological characteristics: branch pressing is commonly carried out from April to May, terminal buds are removed around late August, and the transition from vegetative to reproductive growth accelerates as temperature declines and daylength shortens (Zhang et al., 2023). Because it is usually planted in open-air environments rather than highly controlled ornamental systems, its growth, flowering, and final product quality are especially sensitive to external ecological conditions and field management. Existing studies show that quality formation in chrysanthemum is a combined result of genotype, environment, and cultivation measures. Variety selection matters because different genotypes express different growth, flowering, yield, and post-harvest traits under particular environments. Water and fertilizer regulation also directly affect floral traits and output: optimized irrigation and fertigation improved flower yield and quality in chrysanthemum, while excessive fertilizer concentration inhibited plant growth (Lu et al., 2024). Production system differences further influence quality-related compounds, since hydroponic cultivation increased flower yield, total flavonoids, and chlorogenic acid relative to soil culture in tea chrysanthemum. At the physiological level, flowering and floral organ development are co-regulated by photoperiod, temperature, and endogenous hormones, and gene-expression evidence in Hangzhou White Chrysanthemum confirms differential responses to

temperature and hormone stressors (Pan et al., 2023). Agronomic interventions can therefore alter both yield and quality: increasing branch number is crucial because flowers are borne on branch tops, but traditional manual decapitation is labor-intensive and raises disease risk, while growth-regulator treatments have increased yield and maintained medicinal quality above Pharmacopoeia standards. Virus-free rapid propagation and polyploid breeding technologies also reduce production cost and improve the prospects for standardized commercial cultivation.

Against this background, green production bases for Hangzhou White Chrysanthemum face stringent quality management requirements because product quality and safety are determined at the source and can be compromised by inappropriate input use and weak process control. Evidence from Chinese agriculture shows that excessive fertilizer and pesticide use may raise short-term output but creates long-term problems including resource-use decline, environmental pollution, and hidden risks to agricultural product quality and safety. This is why green production transition has become imperative, yet actual implementation remains incomplete, and compliance problems persist in practice, including failure to follow standard production requirements and illegal marketing of substandard products. Quality certification has emerged as an important governance tool because it strengthens quality monitoring, raises market access thresholds, and can create price premiums that encourage greener production behavior. Empirical evidence across multiple sectors shows that certification participation improves green or low-carbon production, increasing low-carbon production levels among rice farmers and raising eco-efficiency among vegetable farms, with stronger effects generally found for green and especially organic certification (Kang et al., 2023). At the same time, certification is not self-executing. Supervision can be imperfect, some producers may misuse the label while increasing chemical inputs, and many smallholders face financial, technical, and market barriers to obtaining and maintaining certification. Cooperative membership and technical training therefore matter because they improve certification adoption, support compliant production, and enhance the performance of certified farmers (Du et al., 2023). More broadly, certification standards establish key sustainability principles, but compliance remains uneven and under-studied in many value chains, reinforcing the need for operational management systems that convert standards into verifiable field records (Oppong and Bannor, 2022).

A quality traceability system is therefore a necessary extension of green base management for Hangzhou White Chrysanthemum, because traceability provides the information infrastructure needed to connect production behavior, quality formation, circulation, and accountability. Research on agri-food traceability consistently shows that reliable systems should record the whole chain, including production, processing, warehousing, transportation, sale, and supervision, so that specific batches can be tracked and problem sources rapidly identified. Traditional centralized systems are limited by data invisibility, tampering risk, fragmented information, and difficulty for downstream users or consumers to access complete origin data. For that reason, blockchain and IoT have become prominent technical routes because IoT devices can reduce manual recording and continuously collect environmental and process data, while blockchain can preserve data integrity, transparency, and cross-actor trust. Studies have proposed layered architectures that combine physical objects, IoT sensing, and blockchain nodes, and have shown that production, processing, distribution, sale, and supervision nodes can form a complete traceability chain. Consortium or alliance chains appear especially suitable for agricultural traceability because they offer faster transactions, stronger privacy control, and coordinated internal supervision among participating organizations. Recent digital traceability work also emphasizes parsimony and practicality: only key data linked to quality requirements, data certification, and product identification should be captured, including farming diaries, input records, environmental conditions, and certification documents for each batch (Lukács et al., 2025).

Accordingly, the objective of this study is to construct a quality traceability system for green production bases of Hangzhou White Chrysanthemum that starts from the characteristics of its field production and quality formation, identifies the key control points affecting product safety and medicinal quality, and establishes a verifiable information chain covering production and related downstream links. The system should integrate core elements of green base management, such as seedling or propagation source, variety information, field environment, water and fertilizer management, pest control, harvest timing, certification status, and batch identity, while using digital

tools to reduce human error and improve data credibility. Its significance lies not only in improving internal quality management and rapid responsibility tracing, but also in supporting green certification implementation, enhancing consumer trust, and increasing the market competitiveness of high-quality regional agricultural products. At the industry level, such a system can help transform scattered production records into standardized, shareable, and auditable data assets, support the modernization of chrysanthemum production bases, and provide a reference model for other medicinal and edible agricultural products pursuing green development and digital governance.

2 Overall Framework of the Quality Traceability System for Green Production Bases of Hangzhou White Chrysanthemum

2.1 Principles for constructing the quality traceability system

The overall framework of a quality traceability system for green production bases of Hangzhou White Chrysanthemum should be built around the full-chain objectives of quality assurance, safety control, and provenance reconstruction. Traceability systems are designed to let stakeholders reconstruct the entire flow of activities and transactions related to a product from origin to final sale, while supporting quality control, regulatory compliance, and consumer access to product history. More generally, traceability is now treated as a core mechanism for food quality and safety management and for improving supply-chain performance, transparency, and recall efficiency (Tagarakis et al., 2021). For Hangzhou White Chrysanthemum, this means that the framework should not stop at simple origin labeling, but should connect pre-harvest management in the base with post-harvest circulation data, because sustainability and quality claims increasingly depend on what happens before harvest as much as after it.

In terms of construction principles, the system should follow four basic requirements: clear identification, accurate recording, effective integration, and accessible sharing (Islam and Cullen, 2021). At the technical level, the stored information should be secure, reliable, transparent, and resistant to tampering, while still remaining scalable and adaptable to changing regulatory requirements Research on agri-food traceability further shows that effective systems depend on common standards for data formats, labeling, exchange protocols, and interoperability, especially where many actors must collaborate across organizational boundaries (Moysiadis et al., 2023). Accordingly, the Hangzhou White Chrysanthemum traceability framework should adopt standardized batch coding, unified key data elements, and open interfaces that allow data from production bases, processors, distributors, retailers, and regulators to be linked into one consistent chain (Latino et al., 2022).

2.2 Traceability participants and allocation of responsibilities

The allocation of traceability responsibilities should begin with the identification of traceability information providers at each critical traceability event. Studies of agri-food systems emphasize that information providers must be clearly identified before data collection, that each provider is responsible for the accuracy of the information it enters, and that the required information should be defined as key data elements linked to known physical events in the chain. In the case of Hangzhou White Chrysanthemum, the main participants should include agricultural input suppliers, green production bases, processing enterprises, logistics and distribution organizations, sales terminals, and regulatory or certification bodies, which is consistent with the actor structures proposed in broader agri-food traceability research (Ehsan et al., 2022). Because successful implementation depends on multiple stakeholder perspectives, the framework should assign rights and duties in a way that matches each actor’s operational role and data-generation capacity.

At the production-base stage, growers or base managers should record the source of seedlings and inputs, cultivation plots, irrigation and fertilization measures, pest-control actions, environmental conditions, and harvest information, because pre-harvest activities and sustainability practices are crucial to downstream quality claims (Prashar et al., 2020). This is especially important for Hangzhou White Chrysanthemum, whose quality formation is sensitive to flowering regulation, cultivation measures, water and nutrient management, and harvest-stage decisions (Zhang et al., 2023). Processing organizations should record processing conditions, batch transformation relations, storage, packaging, operators, and finished-product labels. Distribution and sales organizations should

record logistics information, storage and transfer events, retailer identity, sales time, quantities, and prices, while supervision bodies should record inspection, testing, certification, and enforcement information and validate whether products meet the relevant standards before and during market circulation.

2.3 Design of the whole-process quality traceability procedure

The whole-process quality traceability procedure for Hangzhou White Chrysanthemum should be designed as an end-to-end chain that covers input supply, field production, harvesting, processing, storage, distribution, sales, and supervision. Existing research suggests that an effective procedure should first map the supply-chain process and identify where data are generated, in what format, and by which actor; it should then specify the technologies used for data capture and analysis; and finally ensure that useful traceability information can be communicated to downstream users and consumers (Latino et al., 2022). For green production bases, the front end of the procedure must begin before harvest rather than at harvest, because field operations such as pesticide, fertilizer, and water management are part of the quality and sustainability record that downstream actors and consumers increasingly expect to access (Moysiadis et al., 2023).

Operationally, each production batch of Hangzhou White Chrysanthemum should be assigned a unique identification code that accompanies the product through all subsequent links, so that incoming, transformed, and outgoing batches remain associated across the chain. Data collection should combine manual confirmation with IoT-assisted acquisition, such as sensors, scanners, QR codes, RFID, cameras, or mobile terminals, because these tools support real-time monitoring, reduce recording errors, and improve continuity of information flow (Lin et al., 2020). At the storage and computing level, a permissioned or alliance-chain architecture is well suited to this application because agri-food traceability usually involves a defined set of organizations that need secure sharing, internal supervision, and immutable transaction records without relying on a single centralized database (Prashar et al., 2020). After data from each link are uploaded and associated with the batch code, retailers should disclose the relevant traceability information to consumers, while regulators and certification bodies retain authority to inspect records, verify authenticity, locate problematic batches rapidly, and initiate accountability or recall actions when necessary.

3 Quality Traceability in the Green Cultivation Process of Hangzhou White Chrysanthemum

3.1 Production base environment and seedling source information

Traceability in Hangzhou White Chrysanthemum cultivation should begin with production-base environmental information, because chrysanthemum quality varies significantly with geographical origin and growing environment (Figure 1) (Li and Wang, 2026). Studies of Hangbaiju show that key pharmacodynamic compounds, including rutin and chlorogenic acid, were most abundant in samples from Tongxiang, and soil mineral elements were positively correlated with several differential metabolites, indicating that origin and soil conditions directly shape medicinal quality (Long et al., 2023). More broadly, chrysanthemum origin can be authenticated with high accuracy using mineral-element, stable-isotope, or fused NIR-ICP-MS signatures, which shows that environmental and edaphic differences leave measurable chemical fingerprints that are suitable for traceability verification (Yao et al., 2023). Accordingly, the traceability record for each production base should include location, plot identity, altitude if relevant, soil type, pH, organic matter, available nitrogen, phosphorus, and potassium, irrigation-water source, and surrounding ecological conditions, because these variables are repeatedly treated as foundational to chrysanthemum yield and quality formation (Zhang et al., 2023).

Environmental traceability should also include the source and health status of seedlings, because seedling origin is the first biological node in the production chain and directly affects the uniformity and reliability of later quality records (He and Shi, 2021). Hangzhou White Chrysanthemum can be propagated through virus-free rapid propagation, in which infected buds are detoxified and cultured to obtain virus-free callus and clustered buds, and this technology reduces production cost while accelerating propagation, making it highly suitable for standardized base management. Related chrysanthemum studies also specify that healthy, disease-free cuttings and equally sized seedlings are used for uniform field establishment, while self-cultivated seedling cuttings and owned stock plants provide clear provenance for planting materials. Therefore, traceability files should record cultivar name,

propagation method, nursery or mother-stock source, virus-free certification, seedling age and specification, transplanting date, and receiving plot, so that any later difference in growth, flowering, or quality can be traced back to the original planting material (Pan et al., 2023).



Figure 1 Geographical regions for representative chrysanthemum samples (Adopted from Li and Wang, 2026)

3.2 Water and fertilizer management and green pest and disease control

Water and fertilizer management is the core control link in green cultivation traceability, because chrysanthemum growth, flowering, yield, and quality respond strongly to irrigation level, nutrient supply, and their timing. In field chrysanthemum, irrigation at 0.75 Epan repeatedly produced the best balance of yield and water-use efficiency, while 100% of the recommended fertilizer dose improved flowering, yield, quality parameters, and economic returns. Split NPK application through drip fertigation also improved bud diameter, inflorescence traits, chlorophyll content, and soil nutrient status, showing that fertilization records should capture not only total input but also stage-specific application (Choudhary et al., 2022). At the same time, fertilizer concentration cannot simply be increased without limit, because chrysanthemum growth improved with appropriate increases but declined when concentration was too high, and recent work on nitrogen management shows that fertilization beyond optimal demand induces luxury uptake and lowers nitrogen-use efficiency.

For that reason, the traceability system should record irrigation mode, irrigation frequency, water quantity, fertigation concentration, fertilizer formula, application stage, operator, and any sensor-based monitoring data, so that input behavior can be matched to plant performance and audited against green standards (He and Shi, 2021). Green pest and disease control should be traced with the same rigor, because excessive chemical dependence remains a known risk in medicinal-material production, while sustainable alternatives can support quality and soil health. For complementary soil biological management, PGPR such as *Bacillus subtilis* produced outcomes comparable to conventional fertilization while enriching beneficial soil microorganisms, and organic manures, bio-fertilizers, and bio-stimulants improved soil microbial activity and nutrient availability (Sarkar et al., 2024). Bio-enhancer systems such as Jeevamrit also increased rhizosphere microbial counts and enzymatic activity, and studies of planting dates and fertilizer modules have highlighted further links between cultivation practices, chrysanthemum yield, and soil health, so pesticide and disease-control records should include both chemical and ecological measures, their dosages, dates, targets, and residue-risk controls (Pathania et al., 2024).

3.3 Agricultural operations and production process records

Traceability in the cultivation process finally depends on complete agricultural operation records, because standardized production of Chinese herbal medicines requires quality control across planting, processing, purchasing, and selling, and separate planting by many operators makes quality harder to supervise without detailed records (He and Shi, 2021). For medicinal materials in China, policy has explicitly called for complete quality traceability across the whole supply chain and for technical standards covering collection, origin processing, ecological cultivation, and standardized cultivation. In Hangzhou White Chrysanthemum, these records should begin with branch pressing from April to May, transplanting, spacing arrangement, gap filling, topping or terminal-bud removal, and other key field operations, because these operations determine reproductive

transition, branch number, and subsequent flower yield (Pan et al., 2023). This is especially important because manual decapitation has traditionally been used to increase branching but is labor-intensive and can increase disease occurrence, which makes operation timing and method critical traceability points (Zhang et al., 2023).

Process records should also cover flowering regulation, foliar treatments, weed control, harvesting decisions, and batch coding, so that each product lot can be linked to its exact cultivation history. This need is strengthened by evidence that exogenous hormones alter flowering-related gene expression in Hangzhou White Chrysanthemum, and that 6-BA combined with Pro-Ca can increase branch number, yield, and nutritional quality while slightly shifting medicinal-component profiles, all of which means that growth-regulator use must be fully documented in traceability archives (Zhang et al., 2023). Harvest records are equally important because the bud stage has the highest commercial value and the optimal harvest window is short, so traceability should record harvest period, bud maturity, picker or machine identity, batch number, and transfer destination (Wu et al., 2026). With IoT sensors and digital numbering of planting, processing, purchasing, and selling links, whole-process records can improve supervision efficiency, reduce circulation cost, and strengthen confidence in medicinal chrysanthemum quality, which is exactly the operational goal of a green production-base traceability system for Hangzhou White Chrysanthemum (He and Shi, 2021).

4 Quality Traceability in the Harvesting and Processing of Hangzhou White Chrysanthemum

4.1 Harvest timing and production batch management

Harvest timing is the first key control point after field cultivation, because the commercial and medicinal value of chrysanthemum changes with flower developmental stage. Hangzhou White Chrysanthemum has its highest commercial value at the bud stage, but the optimal harvesting window is short, so delayed or non-uniform harvesting can quickly reduce product consistency (Figure 2) (Wu et al., 2026). More broadly, medicinal chrysanthemum studies show that chemical profiles vary significantly across bud, initial flowering, full bloom, and eventual stages, and most active constituents are highest or relatively high at the initial or full-bloom stages rather than at late stages. In cultivated Hangbaiju, fresh flowers harvested at 70% tubiform-flower flowering were used as the defined sampling stage for yield and quality analysis, which indicates that harvest maturity should be operationally standardized in traceability rules rather than left to subjective judgment (Zhang et al., 2023). These two maturity criteria are not interchangeable and should be specified according to product type and quality targets.

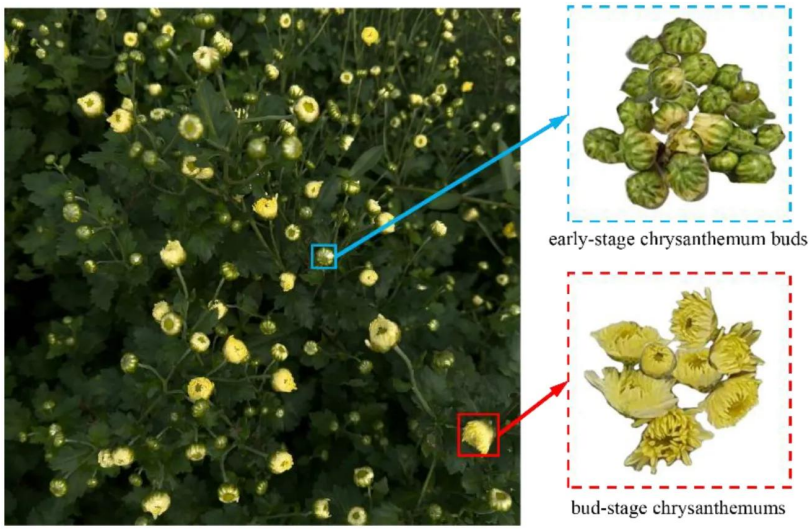


Figure 2 Data augmentation of the bud-stage chrysanthemum images (Adopted from Wu et al., 2026)

Because flowering and harvest timing are influenced by cultivation schedule and plant regulation, batch management should preserve the production history that explains why one lot matures earlier or differs in quality from another. Hangzhou White Chrysanthemum enters rapid reproductive growth after terminal-bud removal around 20 August as temperature declines and daylength shortens, and flowering regulation is also responsive to exogenous hormones, temperature, and photoperiod (Pan et al., 2023). Chrysanthemum studies further show that

planting time and pinching schedule affect days to first bud initiation, 50% flowering, and first harvest, while robotic or AI-based recognition can support standardized selective harvest under labor constraints (Khandre et al., 2025). Therefore, each harvested lot should be assigned a unique batch code linked to plot number, cultivar, seedling source, planting date, pinching or topping record, harvest date, harvest maturity, picker or device identity, and inspection result, so that later quality differences can be traced back to the biological and operational causes of the batch.

4.2 Processing procedures and recording of key parameters

Processing is the second major quality-control node, because post-harvest treatment directly affects storability, color, aroma, active compounds, and safety. Drying is consistently identified as a crucial post-harvest step for medicinal chrysanthemum, and different drying methods produce different outcomes in phenolics, flavonoids, amino acids, volatiles, shrinkage, and microstructure (Sun et al., 2022). Evidence across drying studies shows that process choice matters: infrared-assisted hot-air drying improved volatile retention and increased chlorogenic acid, luteolin, total phenolics, and flavonoids; tempering combined with infrared-assisted hot-air drying reduced drying time and energy use while increasing chlorogenic acid, luteolin, total phenolics, total flavonoids, antioxidant capacity, and volatile number; and pulsed vacuum drying preserved phenolics and flavonoids while yielding high chlorogenic acid and 3,5-dicaffeoylquinic acid under specific settings. These findings show that traceability records must capture not only whether drying occurred, but also the exact method, equipment, temperature, duration, tempering time, pulsed ratio where relevant, and endpoint moisture.

The kill-green step should be treated as a separate traceability item, because it is a critical determinant of downstream drying behavior and product quality. Kill-green increased water mobility and shortened subsequent drying time by up to 46.15%, and high-humidity air impingement kill-green for 60 s gave better PPO and POD inactivation, color, phenolic retention, amino acids, volatiles, and sensory acceptance than steam kill-green for the same duration (Xu et al., 2025). Earlier work similarly found method-specific optima, including microwave power of about 680~850 W for 8~13 min, steam kill-enzyme time of 2~4 min, kill-enzyme time of 0.5~1 min, and oven temperature of about 55~65℃, while another Hangbaiju study dried flowers at 50℃ to constant weight for later analysis. Processing traceability should therefore record the name and order of each process, start and end time, operator, equipment, environmental conditions, moisture measurements, and key quality indicators such as color, relative density, pH, extraction ratio, transfer rate, or fingerprint where applicable, since standardized process parameters are the basis for consistent evaluation of chrysanthemum products.

4.3 Packaging, storage, and batch information linkage

After processing, packaging and storage determine whether earlier quality control is maintained through circulation. In Chinese herbal medicine supply chains, storage errors and poor standardization in storage, transportation, and retail management remain recognized sources of quality risk, alongside problems from harvesting, processing, and packaging (Ngai and Shaw, 2025). Storage enterprises are expected to upload warehousing time, storage methods, and pest- and mold-prevention records, while warehouse humidity should be monitored in real time so that environmental conditions can be adjusted when materials fall outside the standard moisture range. Recent TCM traceability designs also treat warehousing as an independent sub-chain that records temperature, humidity, storage duration, and inventory level, and logistics records should include transport time, mode, and environmental monitoring during transit (Chen et al., 2026). For dried chrysanthemum specifically, final moisture content is a practical control target, and one community-scale processing model required moisture below 8% and vacuum-sealed packaging before distribution (Leelapattana and Assawarachan, 2025).

Batch linkage across packaging, storage, transport, and sales should preserve one continuous identity code from harvested raw material to final commercial unit. Existing herbal-medicine traceability systems number the planting, processing, purchasing, and selling links, upload package QR codes or barcodes with product name, specification, and manufacturer, and use blockchain or multi-chain architectures to connect stage-specific records while preventing tampering (He and Shi, 2021). Circulation systems based on blockchain, cloud platforms, and NB-IoT also support real-time collection, review, and third-party validation of source information, forming an

information loop that enables whole-process supervision and consumer participation in traceability (Shi et al., 2020).

5 Quality Evaluation and Key Control Indicators of Hangzhou White Chrysanthemum

5.1 Appearance traits and basic quality indicators

The quality evaluation of Hangzhou White Chrysanthemum should begin with appearance traits and basic physicochemical indicators, because market grading and authenticity judgment still rely first on visible morphology and then on measurable quality parameters. In chrysanthemum, inflorescence diameter is an important classification factor, and smaller flower heads can contain higher chlorogenic acid and 3,5-O-dicaffeoylquinic acid, which means appearance is not only a commercial trait but also linked to medicinal quality. The same study showed that first-grade material had smaller diameters and higher polyphenol content, confirming that flower-head size can serve as a practical grading index when combined with chemistry rather than used alone (Yang et al., 2025). Chrysanthemum evaluation studies more broadly show that objective phenotyping can extract traits such as color coverage, saturation, visual uniformity, flowering efficiency, and plant morphology, and that these visible traits explain much of varietal differentiation (Sun et al., 2025). For production-base traceability, this means the recorded appearance indices of Hangzhou White Chrysanthemum should include flower-head diameter, uniformity, color, integrity, cleanliness, and batch consistency at harvest and after drying.

Basic quality indicators should then verify whether the external appearance corresponds to acceptable internal quality. For Hangzhou white chrysanthemum standard decoction, useful evaluation indices include traits, relative density, pH, extraction ratio, transfer rate, and fingerprint similarity, and these parameters showed good precision, stability, and repeatability in standardized testing. In that study, the standard decoction was a clear yellow-brown solution with relative density of 1.007~1.011, pH of 5.37~5.56, and an average extraction ratio of 23.6%, which illustrates how decoction-specific physicochemical values may inform operational acceptance ranges; these values should not be used directly as quality limits for dried flower heads. Tea-oriented chrysanthemum quality work also uses moisture, water extract, total ash, water-soluble ash, acid-insoluble ash, crude fiber, and microbial counts as routine indicators, and one snow-white chrysanthemum product met packaged dry-tea standards on these measures (Keliat et al., 2026). Because harvest time, origin, and nutrition affect inflorescence diameter and other visible traits, appearance records should always be linked with batch-based analytical results instead of being treated as independent evidence of quality (Yuan et al., 2022).

5.2 Functional components and safety quality indicators

The core functional quality of Hangzhou White Chrysanthemum is determined by its flavonoids, phenolic acids, and related secondary metabolites, which are repeatedly identified as the main active constituents of *Chrysanthemum morifolium* (Miao et al., 2026). The Chinese Pharmacopoeia specifies chlorogenic acid, luteolin-7-O-glucoside, and 3,5-O-dicaffeoylquinic acid as key components for Chrysanthemi Flos, and these compounds are also the main ingredients used in recent grading and Q-marker studies. Chromatogram-effect and spectrum-effect approaches further show that quality evaluation should not depend only on origin or processing reputation, because bioactive ingredients and their antioxidant associations provide a more direct basis for quality control (Yuan et al., 2022). Across chrysanthemum materials, chlorogenic acid, 3,5-dicaffeoylquinic acid, and luteolin-7-O-glucoside are strongly associated with antioxidant or protective activity, supporting their use as key functional indicators in Hangzhou White Chrysanthemum traceability files.

Functional quality also varies with origin, cultivation conditions, and process choices, so the traceability system should capture these sources of variation together with the analytical results. Hangbaiju from Tongxiang contained higher levels of rutin, chlorogenic acid, and apigenin-7-O-glucoside, and soil mineral elements were positively correlated with some of these differential metabolites, showing that geographical environment directly shapes medicinal quality (Long et al., 2023). Stable isotope, mineral-element, and fused NIR-ICP-MS models classified chrysanthemum origin with very high accuracy, making origin authentication itself a safety and authenticity indicator for premium regional material (Yao et al., 2023; Li and Wang, 2026). Cultivation and processing further alter bioactive profiles: hydroponic culture increased total flavonoids and chlorogenic acid,

while drying conditions can degrade heat-sensitive antioxidants or, when optimized, improve retention of chlorogenic acid, luteolin, total phenolics, total flavonoids, and volatiles. Safety quality indicators should therefore include heavy metals, microbial contamination, and other routine safety tests in addition to active components, because chrysanthemum tea evaluation commonly measures cadmium, lead, tin, mercury, arsenic, total plate count, coliforms, and molds (Keliat et al., 2026).

5.3 Identification of critical quality control points

Critical quality control points for Hangzhou White Chrysanthemum should be identified by following the chain from origin and seedlings to harvest, drying, storage, and final authentication, because chrysanthemum quality is formed cumulatively rather than at a single stage (Yao et al., 2023). The first control point is origin and seedling consistency, since growth environment affects quality and sale price, soil mineral signatures influence active compounds, and reasonable seedling classification standards improve subsequent plant quality (Long et al., 2023; Jing et al., 2024). The second control point is cultivation-input regulation, since agronomic measures can change both nutritional and medicinal indices, sometimes increasing yield while slightly reducing some medicinal constituents, though remaining above Pharmacopoeia standards (Zhang et al., 2023). The third control point is harvest stage, because harvest time affects inflorescence diameter and active-ingredient accumulation, and chlorogenic acid can peak in late-bud or early bloom before declining during fuller flowering and senescence (Neatpatiparn et al., 2025).

The fourth and fifth control points are processing and post-processing management, because drying, kill-green treatment, packaging, and storage all alter quality and safety. Drying is a crucial post-harvest step, and optimized drying or pretreatment can improve retention of phenolics, flavonoids, volatiles, and antioxidant capacity, whereas prolonged or poorly controlled heating can degrade heat-sensitive compounds (Yang et al., 2025; Keliat et al., 2026). Fingerprint similarity, batch similarity analysis, and Q-marker quantification are suitable tools for judging whether processed batches remain within an acceptable quality range, since commercial chrysanthemum batches can vary substantially even within the same accession. The final control point is traceability-enabled authenticity verification, because origin misidentification and fragmented supply chains weaken quality assurance, while IoT-based numbering and whole-process traceability improve supervision from planting through processing and sale (He and Shi, 2021). Accordingly, the key control indicator set for Hangzhou White Chrysanthemum should integrate appearance grading, basic physicochemical indices, marker compounds, safety tests, fingerprint consistency, and full-batch provenance, so that quality evaluation can support both green production management and reliable traceability in the market.

6 Information Management and Application of the Quality Traceability System for Hangzhou White Chrysanthemum

6.1 Traceability coding and QR code-based information management

The traceability coding system for Hangzhou White Chrysanthemum should use a unique batch identity that follows the product from cultivation through packaging and sale (He and Shi, 2021). Existing agricultural systems commonly encode product ID, batch number, harvest date, processing date, supplier identity, storage conditions, and a blockchain record link, which provides the core data structure for reliable lifecycle tracking. A hierarchical coding structure is also practical, because upstream material, planting, harvest, storage, and packaging nodes can be split into subcodes that preserve process detail without breaking batch continuity.

QR codes are suitable as the consumer-facing carrier of this coding system, because they allow direct inquiry of traceability information from raw material to finished product (Jing and Li, 2024; Sonawane, 2025). In herbal systems, QR codes can carry not only identity data but also quality data, including chemical-fingerprint information that can be read by smartphone applications and compared across batches. Dynamic QR codes further improve communication because the displayed information can be updated, shared, and integrated into social platforms, making the code part of both supervision and brand sales.

6.2 Traceability data recording and abnormality early warning

Traceability data recording should cover the whole cultivation and circulation chain, because agricultural and herbal quality control depends on linked records from production, processing, warehousing, logistics, sales, and inspection (Jing and Li, 2024). In practice, growers should enter cultivation records, inspectors should enter testing and warehousing records, and processing or packaging operators should enter processing and package-identity records. For medicinal plants, species identity and lab quality indicators should also be anchored to the same batch, because DNA barcoding and laboratory results strengthen authenticity and whole-process supervision.

Abnormality early warning should be built on real-time sensor data and rule-based or predictive analytics rather than end-point inspection alone. IoT systems already monitor temperature, humidity, location, and other environmental factors during storage and transport, send these data to databases or dashboards, and compare them against preset safety limits (Gupta and Jain, 2026). When abnormalities are detected or forecast, systems can issue early warnings, record the event immutably, and support decisions such as holding, reinspection, or blocking circulation of compromised products.

6.3 Application of quality traceability in product grading and brand development

Quality traceability can be used directly in product grading, because quantified detection indices and batch-linked quality data allow agricultural products to be classified by measurable standards rather than appearance alone (Jing and Li, 2024). For Hangzhou White Chrysanthemum, this means linking each batch code to appearance grade, functional components, safety-test results, and origin or process records, so that higher-grade lots have verifiable evidence behind the label. Q-marker frameworks are especially useful here because they connect process control with final herbal quality from raw material to finished product.

The same traceability system can support brand development and premium pricing by turning verified production data into differentiated quality claims. Studies of agricultural branding report that traceability data can be mined into quantitative labels, cultural narratives, and provenance stories that improve repurchase, trust, and price premium (Chen and Lu, 2025). This function is especially relevant for regional products, because geographical indication and origin-authentication tools can protect brand value, distinguish authentic high-quality goods, and reinforce the market identity of traditional production areas.

7 Summary and Prospects

The quality traceability system for green production bases of Hangzhou White Chrysanthemum should consist of a whole-process information chain covering cultivation, processing, storage, transportation, sales, and supervision, because medicinal-material traceability is effective only when information is continuous from planting to circulation. At the data level, the system should integrate environmental information, seedling and cultivation records, processing parameters, logistics records, transaction data, and quality inspection results, with IoT devices used to capture temperature, humidity, location, and other key variables in real time. At the architecture level, a practical framework combines business activities, IoT sensing, blockchain storage, and application services, so that traceability information can be uploaded, stored, queried, and displayed to regulators, enterprises, and consumers. For product quality evaluation, the traceability system should be linked with measurable indicators such as appearance traits, polyphenol content, standard-decoction parameters, and fingerprint similarity, because these indices provide an operational basis for batch assessment and grading. Since *Chrysanthemum morifolium* is both medicinal and edible, its traceability system should also preserve evidence on flavonoids, phenolic acids, and other bioactive constituents that underlie its therapeutic and functional-food value.

Current application problems mainly arise from fragmented production, uneven standards, and limited data credibility. Chinese herbal medicines are often planted separately by many operators, which makes production quality and standardization difficult to control, and existing traceability systems remain incomplete enough that off-site cultivation, counterfeit origin claims, and fake or inferior products can still enter the traceability chain. Traditional traceability platforms also rely heavily on centralized databases, which create information islands and make records more vulnerable to opacity, tampering, and weak cross-link sharing. Even when blockchain is

introduced, the authenticity of the original uploaded data is still a major constraint, because immutability protects stored records but does not itself guarantee that the source data were correct at entry. Research on agricultural blockchain systems further notes that many proposals remain too general or are still at an early application stage, so real-world deployment, interoperability, and integration across technologies are not yet mature. On the product side, quality variation between batches remains substantial, as shown by unqualified chrysanthemum batches in marker-compound testing and by significant variation in common-peak contents even within the same accession, which means that traceability without synchronized quality standards cannot fully solve market inconsistency.

Future development should move toward smarter, more accurate, and more biologically grounded traceability. IoT, embedded sensing, and machine learning can improve automatic data capture, reduce manual entry errors, and screen abnormal source data, with reported blockchain-IoT-ML systems reaching high verification accuracy for on-chain information. For Hangzhou White Chrysanthemum, this creates a path toward early warning of abnormal cultivation, storage, or circulation conditions, while supporting auditable correction procedures, tamper resistance, and efficient queries. At the source-authentication level, future systems are likely to combine blockchain with DNA barcoding, molecular identification, high-precision localization, and even individual-plant tracking to address counterfeit origin, misreported planting years, and authenticity disputes. Product evaluation should also advance from simple origin or appearance judgment toward Q-marker-based and bioactivity-linked quality control, because current chrysanthemum research shows that chromatogram-effect and spectrum-effect approaches can identify more informative markers for authentication and quality assessment. In addition, objective phenotyping, remote sensing, and digital grading tools can modernize visual evaluation, while alternative cultivation systems such as hydroponics may support greener production with higher yield and higher flavonoid and chlorogenic acid contents. Looking ahead, the most promising direction is a traceability system that not only records the full history of Hangzhou White Chrysanthemum, but also supports brand protection, counterfeit control, quality grading, and the development of higher-value medicinal and functional products.

Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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Meta Analysis Open Access

Optimization of Primary Processing and Commercial Grade Classification System for *Polygonatum*

Jiakai Ma [1,2]
1 Jiande Zhangliang Forestry Co. Ltd., Jiande, 311601, Zhejiang, China
2 Zhejiang Agronomist College, Hangzhou, 310021, Zhejiang, China
Corresponding email: 1250620285@qq.com
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Abstract *Polygonatum* is an important medicinal and edible resource, and its commercial quality is influenced by multiple factors, including botanical origin, production environment, cultivation years, harvest time, and primary processing methods. To improve the stability of primary processing quality and the scientific basis of commercial specification grading, this paper systematically analyzes the raw material basis of *Polygonatum* quality formation, as well as the effects of key processing steps, including cleaning and sorting, steaming or boiling, drying, shaping, and storage, on rhizome morphology, color, texture, and internal chemical composition. Existing studies indicate that different botanical sources and raw material specifications show marked morphological and chemical variation, while repeated steaming and drying can continuously alter polysaccharides, fructans, saponins, and other constituents; excessive processing may result in the loss of certain bioactive components. Traditional commercial grading mainly relies on external characteristics such as size, integrity, color, and origin, but it remains limited by insufficient quantification, inconsistent standards among production areas, and incomplete correspondence between appearance grade and internal quality. Accordingly, this paper proposes a multi-indicator commercial grading system based on botanical origin and raw material specifications, integrating external traits, processing quality, moisture content, internal quality indicators such as polysaccharides and saponins, and rapid detection technologies. The proposed system follows a hierarchical framework of "basic qualification–external specification–processing quality–internal quality" and can be further standardized through graded processing, control of key processing parameters, batch documentation, and quality traceability. This framework may provide a reference for standardizing the primary processing of *Polygonatum*, stabilizing commercial quality, promoting classified utilization, and improving market circulation standards.
Keywords Polygonatum; Primary processing; Commercial specification; Quality grading; Quality control

1 Introduction

Polygonatum is an important medicinal-and-edible resource whose rhizomes have been used for more than two millennia in China and other parts of Asia, and the genus is broadly distributed across the temperate Northern Hemisphere (Shu et al., 2026). Current official medicinal materials are mainly derived from the dried rhizomes of *Polygonatum cyrtonema*, *P. sibiricum*, and *P. kingianum*, which are recognized in the Chinese Pharmacopoeia as major botanical sources of Polygonati Rhizoma (Liao et al., 2023). As a homologous food and medicine resource, *Polygonatum* is rich in polysaccharides, saponins, flavonoids, amino acids, fructans, and other nutritional or functional constituents, which support reported activities such as hypoglycemic, hypolipidemic, antioxidant, immunomodulatory, anti-fatigue, and anti-aging effects (Xiao et al., 2024). In addition to medicinal use, its rhizomes have historically served as a famine-relief food and are now developed into wines, teas, beverages, yogurt, powders, biscuits, snacks, and other functional products, reflecting a strong commodity production basis and expanding industrial value (Cheng et al., 2026). Recent agronomic and germplasm studies further show that *Polygonatum* resources exhibit substantial variation in yield, morphology, and chemical composition across species, provenances, cultivation environments, and growth years, which creates both opportunities for quality-oriented production and challenges for standardization.

From the perspective of commodity production, the resource endowment of *Polygonatum* is accompanied by rising market demand, but also by constraints related to wild resource depletion, mixed germplasm, unstable quality, and incomplete domestication. Wild *Polygonatum* resources are decreasing because of overharvesting and

environmental pressure, while artificial cultivation has become an important route for securing raw materials for the medicinal, food, and health-product industries. Annual demand in China has been estimated at 3.5×10^6~4.0×10^6 kg, and cultivated production can generate considerable economic returns, indicating that *Polygonatum* has already become a characteristic understory economic crop with significant social and industrial benefits (Cheng et al., 2026). At the same time, origin, climate, species, variety, and growth year all influence metabolite accumulation and nutritional quality, and elite materials differ markedly in polysaccharide content, fiber, mineral composition, and broader metabolomic profiles. This heterogeneity means that establishing a stable commodity production basis for *Polygonatum* cannot rely only on botanical identification or yield, but must also integrate resource evaluation, raw-material selection, and quality-linked grading criteria (Liao et al., 2023).

Primary processing is a decisive link connecting fresh rhizome resources with commercial products, because raw *Polygonatum* contains irritating substances such as calcium oxalate raphides and therefore usually requires postharvest treatment to reduce throat irritation, improve edibility, facilitate storage, and enhance tonic efficacy (Guo et al., 2026). Traditional methods are diverse, including single steaming, repeated steaming, nine steaming and nine basking, wine-processing, and processing with auxiliary materials, but modern production still lacks precise control of processing parameters, leading to uneven product quality (Bi et al., 2025). Existing studies show that different processing methods and processing intensities significantly alter appearance, color, sweetness, viscosity, polysaccharides, saponins, low-molecular-weight fructans, volatiles, and antioxidant-related traits (Mei et al., 2025). Several studies even suggest that the traditional nine-cycle process may involve over-processing, because key saccharides or fructans tend to stabilize or decline substantially after four to six cycles, whereas some simplified methods or wine-assisted processing can yield better comprehensive quality (Zhu et al., 2022). Despite this progress, commercial grading research remains comparatively weak: current practice often depends on empirical judgment of shape, size, and color, while multidimensional, quantitative systems linking external traits with intrinsic metabolites are only beginning to emerge. Recent work indicates that appearance traits, chromatic values, and multi-index chemical markers can be combined through chemometrics to classify samples and evaluate quality objectively, providing a methodological basis for commercial grade classification.

Against this background, the purpose of this review is to synthesize evidence on primary processing optimization and propose a scientifically grounded commercial grade classification framework for Polygonati Rhizoma that coordinates sensory characteristics, processing degree, and intrinsic quality indicators. Such a study is necessary because current research has emphasized either compositional transformation during processing or germplasm-level quality differences, but has not sufficiently connected processing-induced changes, quality control, and commodity specification in a unified framework. By integrating external morphology, color or slice characteristics, and representative bioactive constituents such as polysaccharides, saponins, and related markers, it becomes possible to move from experience-based judgment toward standardized, reproducible, and industry-applicable evaluation of *Polygonatum* raw and processed products. The establishment of an optimized primary processing route and commercial grading system would help preserve effective components while avoiding unnecessary over-processing, improve batch consistency, support raw-material procurement and market circulation, and provide a technical basis for the standardized, high-value, and sustainable development of the *Polygonatum* industry. In this sense, optimizing primary processing and commercial classification is not only a quality-control issue, but also a key step for transforming *Polygonatum*'s rich biological resources into stable, high-quality, and competitive commodities.

2 Raw Material Basis for the Formation of *Polygonatum* Commodity Quality

2.1 Effects of botanical origin and production area conditions on raw material quality

The three official botanical sources of Polygonati Rhizoma, *Polygonatum cyrtonema*, *P. sibiricum*, and *P. kingianum*, differ significantly in agronomic traits, yield, and chemical composition, establishing species identity as a primary determinant of raw material quality (Cheng et al., 2026). A common garden experiment across five species confirmed that saponin and polysaccharide contents, stem diameter, and inflorescence length vary substantially by species, with *P. cyrtonema* demonstrating high-yield potential up to 7.5 tons per hectare in Zhejiang (Liao et al., 2023). Within *P. cyrtonema* and *P. sibiricum*, five distinct rhizome types-"Jitou-type",

atypical “Jitou-type”, “Jiang-type”, “Cylinder-type,” and “Baiji-type”, exhibit different mucilage cell densities and comprehensive nutritional and medicinal values, with Baiji-type and Jitou-type showing superior quality (Hu et al., 2022). For *P. kingianum*, the improved variety ‘Linyun 1’ accumulates higher levels of amino acids, alkaloids, and phenolic acids than traditional germplasm, demonstrating the additional influence of intraspecific genetic variation on metabolite profiles (Xiao et al., 2024).

Beyond species and variety, geographical origin and local environmental conditions exert significant but sometimes inconsistent effects on quality. Provenance trials of 11 *P. cyrtonema* accessions across three heterogeneous garden sites revealed highly significant differences in growth and medicinal components, with saponin content increasing with altitude and temperature while flavonoid accumulation was promoted in drier conditions (Cheng et al., 2026). A multi-origin comparison of 40 germplasm resources from ten provinces found that *P. cyrtonema* from Huaihua, Lu’an, Hezhou, and Lishui, along with *P. kingianum* from Baoshan, exhibited the highest overall nutritional quality, with polysaccharide content exceeding 20% (Li et al., 2025). However, HPLC fingerprinting of 25 *P. cyrtonema* batches from six provinces showed that chemical composition specificity lacked obvious regularity with longitude, latitude, or altitude, suggesting that local environmental variation may override broad geographic patterns (Zhou et al., 2021). For *P. kingianum*, rhizosphere microbial communities and soil variables such as hydrolysable nitrogen and available potassium further influence active ingredient content, indicating that soil ecology is an additional quality driver. Cultivation mode also matters: intercropping *P. cyrtonema* with *Paris polyphylla* increased polysaccharide content by 12.1% compared with monoculture.

2.2 Effects of cultivation years and harvest time on rhizome quality

Cultivation years significantly influence the accumulation of bioactive components in *Polygonatum* rhizomes, though the optimal harvest age varies by species and target constituent. In *P. cyrtonema*, functional components increased significantly during the one- to four-year growth period, with the most active accumulation occurring between years three and four, followed by a significant decline from years four to five (Pu et al., 2024). A separate temporal study of *P. cyrtonema* found that polysaccharide and alcohol-soluble extractive contents peaked at the two-year age section and then decreased with age, while provenance and harvesting season also affected quality significantly (Su et al., 2019). Transcriptomic and metabolomic profiling of biennial and triennial *P. cyrtonema* identified 1 721 differentially expressed genes and 150 differential metabolites, with the phenylpropanoid biosynthetic pathway being the most crucial enrichment pathway, confirming that growth years are a critical factor affecting active substance accumulation. For *P. kingianum*, metabolomic analysis showed that differential compounds were mainly enriched in traditional germplasm at year one, while the improved ‘Linyun 1’ variety showed greater variety and higher content of differential compounds at year three. Studies on *P. kingianum* polysaccharide content across different growth years identified the fourth year after planting as the best harvest time for polysaccharide accumulation (Xiao et al., 2024).

Seasonal and harvest timing effects are equally consequential, as rhizome quality fluctuates dramatically from spring to autumn. In *P. cyrtonema*, spring-harvested rhizomes contained more flavonoids, alkaloids, and phenolic acids, while autumn-harvested rhizomes comprised more steroids, yielding unequal quality depending on the target application. For *P. odoratum*, polysaccharide content peaked in spring at 13.3% before declining through summer and fall, driven by a “source-sink” conversion mechanism in which overwintering starch reserves are mobilized into polysaccharides via upregulated α-amylase and invertase (Zhu et al., 2026). However, another *P. odoratum* study found that autumn-harvested rhizomes were highest in polysaccharides and saponins and thus more suitable for medicinal use, while summer-harvested rhizomes were richer in soluble sugars and free amino acids with better taste for food applications (Yuan et al., 2023). A separate study recommended late August to early September as the optimum harvest window for *P. odoratum* in northeast China based on drying rate and polysaccharide content. For *P. cyrtonema*, phenological data indicated that rhizomes should be harvested when aboveground parts have just withered, as neither the traditional February/August collection nor strict spring/autumn harvesting yielded the highest polysaccharide and extractive contents (Su et al., 2019).

2.3 Differences in raw material characteristics and criteria for preliminary grading

The substantial variation in raw material characteristics across species, origins, growth years, and harvest seasons creates a clear need for systematic preliminary grading criteria. Agronomic and quality traits of five *Polygonatum* species showed coefficients of variation ranging from 14.57% for leaf width to 42.93% for total inflorescence diameter, with polysaccharide and saponin contents varying by 27.55% and 24.63%, respectively. Stem diameter has been proposed as a practical indicator for variety screening and harvest assessment, providing a morphological marker that correlates with yield and quality (Liao et al., 2023). Among 40 cultivated germplasm resources, multivariate analyses including PCA, membership function scoring, and hierarchical clustering were applied to comprehensively rank nutritional quality, demonstrating that statistical methods can effectively differentiate accessions for grading purposes (Li et al., 2025). The five rhizome types of *P. cyrtonema* and *P. sibiricum* also differ in mucilage cell area ratio, with Baiji-type reaching 6.14% and Cylinder-type as low as 1.17%, providing a microscopic basis for quality differentiation.

Recent studies have begun integrating external appearance traits with multi-index metabolite quantification to establish objective grading frameworks. A quality evaluation of 16 batches of *P. sibiricum* slices from different regions quantified eight appearance traits and six functional metabolites, using PCA and OPLS-DA to cluster samples into three categories by origin and identify differential quality-affecting markers. A weighted TOPSIS-GRA fusion model combining appearance traits and metabolite contents confirmed significant quality differences among slices from different regions, providing a scientifically reliable method for quality control and standardization (Wang et al., 2025). Near-infrared spectroscopy combined with chemometrics has also been validated for rapid polysaccharide and saponin quantitation in *P. cyrtonema*, offering a non-destructive tool for preliminary grading (Liao et al., 2023). For the distinct medicinal commodity *P. odoratum* (Yuzhu), comparisons of round-leaf and long-leaf strains across two-and three-year growth periods found that long-leaf strains consistently outperformed round-leaf strains and that three-year rhizomes surpassed two-year rhizomes in drying rate, water extract, and polysaccharide content, suggesting that strain type and age can serve as preliminary grading criteria. Together, these findings indicate that a multidimensional grading system integrating botanical type, morphological traits, growth year, harvest season, and key chemical markers is both feasible and necessary for standardizing *Polygonatum* commodity quality.

3 Major Steps in Primary Processing of *Polygonatum* and Their Effects on Quality

3.1 Postharvest cleaning, sorting, and pretreatment

Fresh *Polygonatum* rhizomes contain 75~85% moisture and irritant components such as saponins that induce tongue numbness, making postharvest pretreatment essential for dehydration, enzyme inactivation, and component transformation (Wang, 2026). Raw rhizomes are irritating and can cause allergic reactions in their unprocessed form, necessitating thorough cleaning and sorting before further processing (Zhu et al., 2025). Initial preparation typically involves removing fibrous roots, washing with water to remove soil and impurities, and sorting rhizomes by size and quality to ensure uniform processing. Only fresh and undamaged rhizomes within a similar weight range and size are selected for optimal processing outcomes (Sabier et al., 2026).

Pretreatment practices also include preliminary grading based on morphological characteristics, which significantly influences final product quality. Among different lengths of *Polygonatum cyrtonema*, short-length rhizomes with younger tissues showed better performance after processing, indicating that raw material sorting by size and maturity serves as an effective pretreatment strategy. Fresh rhizomes may be stored at 4℃ for short periods prior to thermal processing, or sliced and quick-frozen in liquid nitrogen for laboratory sample preparation (not routine commercial primary processing) (Figure 1) (Shen et al., 2024). The selection of the appropriate raw material state-whether whole rhizomes or slices-further affects drying kinetics and component retention, with sliced samples requiring different processing parameters than whole rhizomes (Wang, 2026).

3.2 Steaming, boiling, and other thermal processing treatments

Thermal processing is the most critical step in *Polygonatum* primary processing, with steaming being the predominant method that considerably influences rhizome quality. Traditional methods include atmospheric

steaming and drying, simmering, and the well-known "nine-steam-nine-bask" process, while innovative approaches such as constant temperature and humidity steaming combined with vacuum-steam pulsed steaming have shown superior outcomes. The constant temperature and humidity combined with vacuum-steam pulsed steaming and drying method yielded the highest antioxidant capacity, better preservation of polysaccharides, and lower levels of 5-hydroxymethylfurfural compared to traditional atmospheric steaming. This innovative method also reduced production time by 66.7% while achieving a comparable color profile to conventional technology (Ren et al., 2025).



Figure 1 The *P. cyrtonema* rhizome samples during nine processing cycles of steaming and drying (Adopted from Shen et al., 2024)
Image caption: CP represents the crude rhizome samples and SD3, SD6, and SD9 represent the processed samples subjected to three, six, and nine processing cycles, respectively (Adopted from Shen et al., 2024)

Processing methods and cycle numbers profoundly affect chemical composition, with strong consensus that excessive steaming leads to over-processing. Total polysaccharide content decreases progressively with increasing processing cycles, stabilizing at approximately 5.2 g/100 g after four cycles, a 45.81% reduction from raw rhizomes (Yao et al., 2022). In *Polygonatum sibiricum*, polysaccharide content decreased by 47.38% after nine cycles, with the most significant decline occurring in the first three cycles. Low molecular weight fructans underwent significant degradation within the first three processing cycles, with complete degradation by the seventh cycle, suggesting that the traditional nine-cycle method may be excessive (Mei et al., 2025). Total saccharides in *P. cyrtonema* increased from one to four cycles but decreased from four to nine cycles, indicating that four cycles of steam-heated air drying represents the ideal processing method for optimal saccharide, fructose, and phospholipid retention (Zhu et al., 2022).

Different thermal processing methods, steaming, wine-processing, and processing with auxiliary materials such as black beans, produce distinct chemical transformations. Wine-processed *P. cyrtonema* exhibited the best comprehensive quality, with surface colors gradually deepening, sweetness increasing, viscosity strengthening, and tongue-numbing sensation disappearing after processing. Steaming *Polygonatum kingianum* with black beans promoted a dual metabolic enhancement, incorporating isoflavones and triterpenoid saponins from black beans while most active components peaked after three steaming cycles. Multiple steaming and roasting methods increased sugars, nucleotides, esters, and flavonoids but reduced amino acid content significantly, with sugars predominantly being monosaccharides from polysaccharide depolymerization (Xu et al., 2023). Processing-induced chemical mechanisms include hydrolysis, oxidative decomposition, dehydration, Maillard reaction, and polymerization, with Maillard reactions between amino acids and reducing sugars being the primary driver of browning (Jiang et al., 2022).

3.3 Drying, shaping, and storage management

Drying methods significantly affect the final quality of processed *Polygonatum*, with different techniques offering distinct advantages and limitations. Among five drying methods-hot-air drying, infrared drying, microwave drying, freeze-drying, and vacuum drying, vacuum drying achieved an optimal balance between energy consumption and product quality, demonstrating significant advantages in maintaining antioxidant activity, active ingredients, and flavor. Microwave drying achieved the highest drying rate with a drying time only 1/83 that of freeze-drying, yet demonstrated a relatively low retention rate of total polysaccharides. Freeze-drying maintained antioxidant activity and active ingredients effectively but required extended duration of 1 080 minutes, leading to high energy

consumption that restricts large-scale industrial application (Wang, 2026). Heated-air drying and infrared drying were not suitable replacements for traditional steam-sun drying, as hierarchical cluster analysis showed these methods produced samples far in distance from steamed ones (Zhu et al., 2022).

Drying parameters, including temperature, time, and steaming cycles, must be carefully controlled to optimize quality and minimize harmful byproduct formation. Response surface methodology and back-propagation neural network optimization of wine-processed *P. sibiricum* identified optimal conditions of 3.6 hours steaming time, 75℃ drying temperature, 11.4 hours drying time, and eight steaming cycles, which improved taste and bioactivity while reducing 5-hydroxymethylfurfural to 0.18 mg/g. Polysaccharides undergo hydrolysis under moist heat during drying, resulting in continuous accumulation of reducing sugars that promotes 5-HMF formation, making drying temperature and time critical control points (Li et al., 2026). For laboratory analysis, processed samples were ground and passed through a 40-mesh sieve and the resulting powder stored in a desiccator; these are analytical preparation procedures rather than general commercial storage specifications (Mei et al., 2025). The lack of precise control of processing parameters has led to uneven quality of processed *Polygonatum*, underscoring the need for standardized drying and storage protocols to ensure consistent product quality (Bi et al., 2025).

4 Effects of Primary Processing on the Formation of Commercial Specifications of *Polygonatum*

4.1 Changes in rhizome size, integrity, and external morphology

Thermal processing induces significant structural degradation in *Polygonatum* rhizomes, disrupting the microscopic pore wall structure and facilitating the release of intracellular components. Repeated steaming and drying cycles cause the rhizome surface to become wrinkled and shriveled as moisture is lost and cellular matrices collapse. Initial processing effectively disrupts cell wall structure, leading to a slight increase in extracted crude polysaccharide yields, though yields stabilize with further processing cycles as the enhancement effect reaches its limit (Mei et al., 2025). The disintegration of calcium oxalate raphides, which cause throat irritation, is a primary morphological goal of processing, with the change rate of needle crystals exceeding 90% by the fifth processing cycle (Cheng et al., 2022).

Raw material dimensions significantly influence post-processing morphology and final product integrity. Among different lengths of *Polygonatum cyrtonema*, short-length rhizomes with younger tissues demonstrated better performance after processing, indicating that preliminary sorting by size and maturity preserves structural integrity. Slice thickness dictates drying kinetics, as moisture diffuses from the interior to the exterior during hot-blast air drying, with steamed samples of less than 6 mm thickness exhibiting faster water loss and superior quality retention (Liu et al., 2022). The physical breakdown of rhizome tissue during steaming also enhances the solubility and dissolution rates of chemical components, which subsequently increases extract yields in the processed material.

4.2 Changes in color, texture, and processing yield

Color transformation is a primary visual indicator of processing adequacy and commercial quality in *Polygonatum*. The inner transverse section of processed rhizomes gradually turns moist black with a specular luster, matching the traditional identification standard of "brightness like oil and color like black lacquer". Quantitative colorimetric analysis using the CIE L*a*b* color space demonstrates that L* values significantly decrease while ΔE*ab values increase from crude to steamed to wine-processed products, reflecting the progressive darkening of the rhizome surface (Figure 2) (Cheng et al., 2022). In *Polygonatum sibiricum*, optimal quality corresponds to an L* value ranging from 21.0 to 22.0 and an a* value between 2.0 and 5.0, establishing specific chromatic thresholds for commercial grading. The browning mechanism is primarily driven by non-enzymatic Maillard reactions between amino acids and reducing sugars, alongside caramelization and the oxidative polymerization of phenolic substances (Ren et al., 2025).

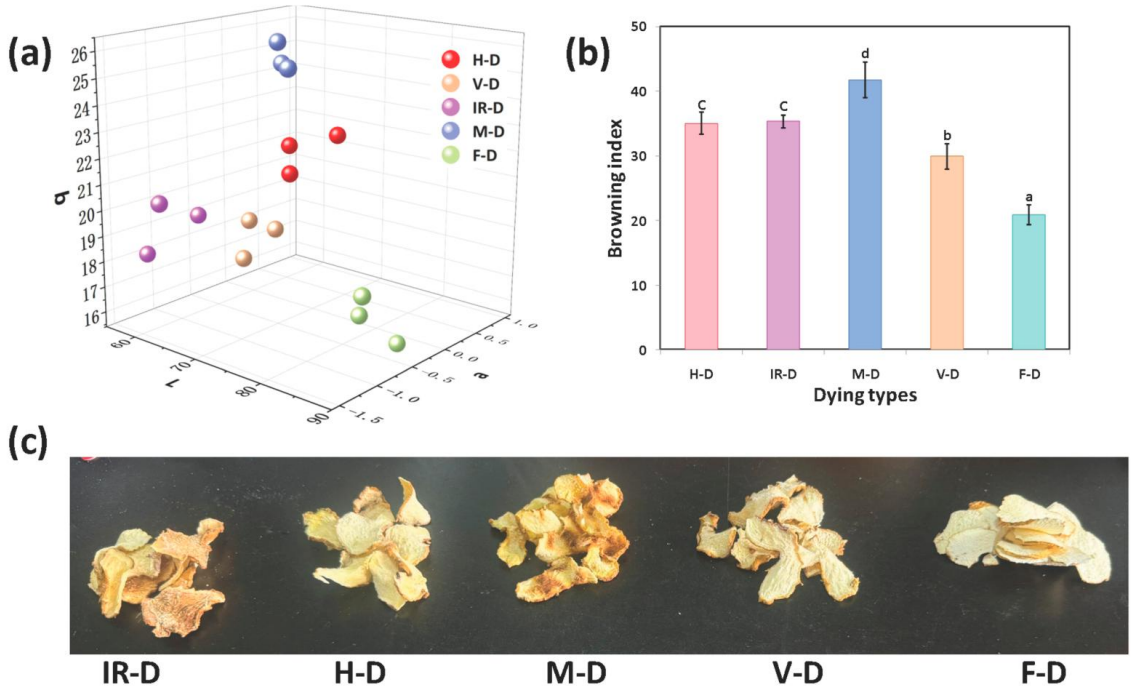


Figure 2 (a) Three-dimensional projection of L*, a*, and b* values; (b) Comparison of browning index of different drying methods. Different lowercase letters indicate significant differences at $p < 0.05$ as determined by the LSD test; (c) Samples of PCH dried by five drying methods (Adopted from Wang, 2026)

Texture modifications accompany color changes, with processed rhizomes exhibiting increased sweetness, strengthened viscosity, and the complete disappearance of tongue-numbing sensations. Wine-processing accelerates these textural transformations, allowing the product to reach the endpoint of "color resembling black lacquer, sweetness akin to syrup" earlier than standard steaming methods. Processing yield and extractable matter content vary significantly by method; water extract and alcohol extract contents gradually increase from crude to steamed to wine-processed products due to enhanced solubility from thermal disruption. However, excessive steaming and drying cycles intensify bitter and sour flavors, causing overall quality to deteriorate and reducing the commercial value of the final product.

4.3 Effects of primary processing on internal quality and commercial grade

Primary processing fundamentally alters the internal chemical composition of *Polygonatum*, dictating its medicinal efficacy and commercial grade classification. Total polysaccharide content decreases progressively with increasing processing cycles, stabilizing at approximately 5.2 g/100 g after four cycles, representing a 45.81% reduction from raw rhizomes. In *Polygonatum sibiricum*, polysaccharide content decreased by 47.38% after nine cycles, with the most significant decline occurring within the first three cycles. Low molecular weight fructans undergo significant degradation within the first three processing cycles, with complete degradation by the seventh cycle, suggesting that the traditional nine-cycle method causes excessive glycan depletion (Mei et al., 2025). Conversely, total saponins, phenols, and flavonoids exhibit an increasing trend during processing, with antioxidant activity peaking after three to four cycles before stabilizing (Yao et al., 2022). Processing with black bean juice significantly increases saccharide and saponin content while enhancing DPPH and ABTS radical scavenging capacities compared to raw samples.

The correlation between external chromatic values and internal chemical composition provides a scientific basis for commercial grade classification. *L. values* are significantly correlated with *Polygonatum cyrtonema* polysaccharide (PCP) content, suggesting that L can objectively characterize the extent of processing and serve as a rapid grading parameter. Multivariate statistical analyses, including PCA and OPLS-DA, successfully cluster processed samples into distinct quality categories based on secondary metabolite and carbohydrate profiles, confirming that chemical composition shifts predictably across processing stages (Shen et al., 2024). The first six

processing cycles induce drastic changes in functional component accumulation, while subsequent cycles yield diminishing returns, suggesting that four to six cycles may provide a favorable balance under the processing conditions investigated between enhanced medicinal effects and preserved bioactive components. Establishing a commercial grade classification system that integrates these processing-induced chemical variations with morphological and chromatic criteria is essential for standardizing *Polygonatum* commodity quality and ensuring consistent industrial efficacy (Bi et al., 2025).

5 Analysis of Existing Commercial Specifications and Grading Criteria for *Polygonatum*

5.1 Traditional methods for commercial specification classification

Traditional commercial classification relies primarily on morphological characteristics and geographical origin. As a related methodological example, *Polygonatum odoratum* (PO; Yuzhu), which is a distinct medicinal commodity rather than one of the three official botanical sources of Polygonati Rhizoma (Huangjing), is divided into two main commercial specifications: Xiangyuzhu (XPO) and Guanyuzhu (GPO), which are distinguished by their appearance, origin, and price. According to the "Standard compilation of authentic medicinal materials," XPO is characterized by a thick, long, translucent, and light yellow appearance, with products from Hunan considered authentic and occupying the majority of the Chinese market. GPO, in contrast, is a wild product from Northeast China, Inner Mongolia, and Hebei, and its cost is lower than that of XPO. These traditional specifications also dictate end-use applications; XPO is more frequently used as the raw material for dietary supplements, while GPO is more inclined toward medicinal use (Nan et al., 2023).

Beyond the *P. odoratum* market, *Polygonatum* species used for Huangjing (*P. sibiricum*, *P. kingianum*, and *P. cyrtonema*) exhibit extensive morphological diversity that historically guided classification. However, these morphological characteristics are seasonal, rendering it difficult for taxonomists to identify plants in the wild and complicating consistent commercial sorting. To evaluate germplasm resources systematically, agronomic traits such as stem length, stem diameter, leaf dimensions, and inflorescence characteristics are measured as direct representations of plant growth and quality. Among these traits, stem diameter has been identified as a practical indicator for variety screening and harvest assessment, providing a morphological marker that correlates with yield (Liao et al., 2023).

5.2 Differences in grading standards among production areas and markets

Grading standards and quality traits differ significantly among *Polygonatum* production areas, reflecting both genetic and environmental influences. A common garden experiment cultivating five *Polygonatum* species revealed that the plants mainly differed in yield, saponin and polysaccharide contents, stem diameter, leaf width, and inflorescence length. *P. cyrtonema* (PC) demonstrated high-quality yield when planted in Zhejiang, with output reaching 7.5 tons per hectare, making it particularly suitable for cultivation in Zhejiang and similar surrounding areas. Further analysis of 43 PC provenances from six geographical provinces showed that the specific relationship pattern between PC quality and its provenance was unclear, with most components not significantly correlating with longitude, latitude, or altitude. This suggests that short-term changes in the growth environment do not override long-term genetic variations acquired from original adaptive environments (Liao et al., 2023).

Market grading also reflects chemical composition differences that vary by species and region. In the *P. odoratum* market, current quality control focuses solely on polysaccharide content, yet studies indicate that the polysaccharide content of GPO is actually higher than that of XPO. A comprehensive qualitative analysis identified 62 compounds in PO, from which 13 robust chemical markers-including 6 flavonoids and 7 steroidal saponins-were screened to differentiate the two commercial specifications. The ratio of timosaponin H1 to polygodoraside G was proposed as a promising indicator to distinguish the specifications, with samples having a ratio<2 considered XPO and>5 considered GPO (Nan et al., 2023). For Huangjing species, saponin content varied significantly, with *P. kingianum* reaching 10.54%, significantly higher than PC, PS, and PF, while polysaccharide content ranged from 25.30% to 6.24% across species (Liao et al., 2023).

5.3 Problems in the existing commercial grading system

The existing commercial grading system for *Polygonatum* faces significant challenges due to germplasm confusion, lack of good varieties, and the indiscriminate introduction of seedlings across regions (Liao et al., 2023). These issues impede the development of the industry and lead to inconsistent product quality in the market . A major limitation is that traditional classification methods based on appearance and origin lack systematic chemical validation. For instance, no comparison had been made between the small molecule chemicals of the two main PO commercial specifications prior to recent instrumental analysis, making it difficult to objectively distinguish XPO and GPO based solely on traditional criteria. Furthermore, the quality of different batches within the same specification varies greatly; the total content of three marker compounds in XPO ranged from 137.70 to 1 005.55 μg/g, while GPO quality was comparatively stable between 349.19 and 859.64 μg/g (Nan et al., 2023).

Current quality evaluation methods are also insufficient for comprehensive commercial grading. The traditional colorimetric method for determining polysaccharide and saponin contents is time-consuming and labor-intensive, rendering it unsuitable for determining the contents of large quantities of samples needed for market grading. While near-infrared spectroscopy (NIRS) combined with chemometrics has been established for the rapid determination of saponin content in Huangjing, with a residual prediction deviation (RPD) of 2.25 indicating potential for quantitative grading-the model for polysaccharide content achieved an RPD of only 1.15, restricting its use to preliminary screening rather than precise commercial classification. The lack of precise control over processing parameters further exacerbates grading inconsistencies, leading to uneven quality of processed *Polygonatum* products (Nan et al., 2023). These shortcomings highlight the need for a multidimensional grading system that integrates morphological traits, chemical markers, and rapid detection technologies to standardize *Polygonatum* commodity quality.

6 Optimization of the Commercial Grade Classification System for *Polygonatum*

6.1 Establishment of quantitative indicators for raw materials and external specifications

Traditional commercial grading of medicinal materials relies heavily on external morphological features such as size, weight, and color, but modern research indicates these criteria do not always correspond to actual chemical quality. In the case of Polygoni Multiflori Radix (PMR), an unrelated medicinal material considered here only as a methodological comparison, wholesalers grade material into three classes based strictly on weight, yet quantitative analysis of twelve major bioactive components revealed no significant chemical differences across these size-based grades. This shows that size alone was insufficient to distinguish internal quality in PMR, suggesting a hypothesis that should be evaluated directly in Polygonati Rhizoma with quantitative chemical testing (Liang et al., 2018). For *Polygonatum odoratum* (PO), the market is divided into two commercial specifications, Xiangyuzhu (XPO) and Guanyuzhu (GPO), based on appearance and origin, but these distinctions also lacked systematic chemical validation until recently (Nan et al., 2023).

To establish reliable quantitative indicators, researchers have turned to advanced analytical techniques to differentiate commercial specifications. Ultra-high-performance liquid chromatography coupled with charged aerosol detection (UHPLC-CAD) was successfully validated for the absolute determination of three key saponins-polygodoraside G, polygonatumoside F, and timosaponin H1, across 27 batches of PO, providing a precise chemical basis for specification differentiation. The ratio of timosaponin H1 to polygodoraside G emerged as a robust quantitative indicator, with ratios below 2 identifying XPO and ratios above 5 identifying GPO. Furthermore, multivariate statistical analyses, including principal component analysis (PCA) and orthogonal partial least squares discriminant analysis (OPLS-DA), successfully screened 13 chemical markers, comprising six flavonoids and seven steroidal saponins-that reliably distinguish the two commercial specifications. These findings provide a methodological example of quantitative indicator development, although the specific ratios were established for *P. odoratum* (Yuzhu) and cannot be directly applied to Huangjing, moving beyond subjective appearance-based grading to objective chemical marker evaluation (Nan et al., 2023).

6.2 Improvement of processing quality and internal quality evaluation indicators

While external specifications provide initial sorting criteria, internal quality evaluation must account for the significant chemical transformations that occur during primary processing. Tissue-specific analysis has emerged as a powerful tool for linking internal morphology with bioactive component distribution, as demonstrated in PMR where laser microdissection combined with UPLC-QqQ-MS/MS mapped the accumulation patterns of twelve secondary metabolites across six distinct tissue types. This approach revealed that stilbene glucosides, combined anthraquinones, and polyphenols predominantly accumulated in the cork tissue, while free anthraquinones concentrated in the phloem, establishing that transverse section features directly correlate with medicinal quality. Such tissue-specific profiling provided a morphological grading criterion in the material studied; an analogous approach in *Polygonatum* would require direct histological and chemical validation rather than extrapolation from PMR (Liang et al., 2018).

The improvement of internal quality indicators also requires addressing the significant variation in chemical composition that occurs across processing methods and cycles. In PO, the average content of polygonatumoside F, a furostanol saponin serving as a key quality control marker, differed significantly between commercial specifications, with GPO containing 329.35 μg/g compared to 195.49 μg/g in XPO, indicating that saponin profiles must be evaluated as processing-sensitive indicators. Additionally, the total content of three marker compounds varied dramatically across batches within the same specification, ranging from 137.70 to 1 005.55 μg/g in XPO, highlighting the need for processing standardization to reduce batch-to-batch variability. The application of UHPLC-Q-TOF/MS for comprehensive qualitative analysis enabled the identification of 62 compounds in PO, including 43 steroidal saponins, 11 flavonoids, and 8 alkaloids, establishing a full chemical profile that can serve as a reference for monitoring processing-induced changes in *Polygonatum*. These methods demonstrate that internal quality evaluation must move beyond single-marker assays to multi-component quantitative profiling that captures the full spectrum of processing-induced chemical transformations (Nan et al., 2023).

6.3 Construction of a multi-indicator comprehensive commercial grading system

The construction of a comprehensive grading system requires integrating external morphological features, tissue-specific chemical distribution, and multi-component quantitative analysis into a unified evaluation framework. The PMR study demonstrated that tissue-specific analysis of secondary metabolites can create new morphological criteria-such as broader cork and phloem regions in transverse sections-that reliably predict quality better than traditional size and weight measurements (Liang et al., 2018). This methodological principle could be tested in Polygonati Rhizoma by examining external appearance, internal histology, and chemical markers jointly; the PMR results alone do not validate those criteria for Huangjing. The successful application of OPLS-DA models with 99% explained variation and 97% predictive ability in differentiating PO specifications confirms that multivariate statistical approaches can robustly classify commercial grades when appropriate chemical markers are selected (Nan et al., 2023).

A multi-indicator system must also account for the fact that different commercial specifications may serve different end-use applications, requiring tailored quality criteria. In PO, XPO is more frequently used as a raw material for dietary supplements while GPO is more inclined toward medicinal use, meaning that grading systems should incorporate use-case-specific indicators rather than applying a universal standard. The identification of specific chemical markers unique to each specification, such as isomers of hydroxylwattinoside C and 3β-hydroxy-25S-spirost derivatives found only in GPO, provides the chemical basis for application-specific grading. Furthermore, the timosaponin H1-to-polygodoraside G ratio provides a published example of specification-specific grading for *P. odoratum*, but it has not been validated as a grading threshold for Huangjing . By integrating these quantitative chemical markers with traditional morphological features and tissue-specific distribution patterns, a comprehensive commercial grading system for *Polygonatum* can be constructed that ensures accurate quality assessment, supports appropriate end-use allocation, and provides a scientific foundation for industry standardization.

7 Standardized Application of Primary Processing and Specification Grading of *Polygonatum*

7.1 Promotion of graded processing and control of key processing parameters

Optimizing traditional processing methods requires precise control over key parameters to prevent over-processing and preserve bioactive components. The traditional nine-steaming and nine-drying method induces significant chemical transformations, but the first six processing cycles account for the most drastic changes in functional component accumulation, while subsequent cycles yield no further benefits and may even reverse enhancing effects. Most functional components are significantly enhanced after the first three cycles and stabilize after six, indicating that the full nine cycles are often excessive (Shen et al., 2024). Response surface methodology (RSM) has been successfully applied to optimize specific processing parameters, such as the solid-to-liquid ratio, decocting temperature, and time, achieving a highly reliable model with significant predictability for standardized processing protocols. Parameters established under particular experimental conditions should be validated for the botanical source, processing scale, and target indicators before being adopted as industrial operating standards.

Graded processing must also account for species-specific chemical reactivity and volatile compound transformations. Different *Polygonatum* species exhibit distinct aroma trajectories during processing, with early-stage losses of green aldehydes reflecting suppressed lipid-oxidation pathways and later-stage increases in roasted notes consistent with Maillard reactions and Strecker degradation. Species-specific differences in ester, ketone, and phenolic formation suggest variations in precursor pools and thermal reactivity that necessitate tailored processing parameters rather than a universal protocol (Sabier et al., 2026). Processing with auxiliary materials such as black bean juice significantly alters chemical fingerprints, increasing lower-polarity compounds and generating six new compounds while degrading medium-polarity constituents. This processing method significantly increases polysaccharide content from an average of 12.19% in raw samples to 32.28% in processed samples, alongside enhanced antioxidant and antidiabetic activities (Zhang et al., 2023). These findings underscore the necessity of controlling key processing parameters to maximize therapeutic outcomes and standardize commercial quality.

7.2 Improvement of processing records and quality traceability systems

Establishing comprehensive quality traceability systems requires integrating macroscopic, microscopic, and chemical characterization data into processing records. Color quantization based on the CIE L*a*b* system provides objective metrics for tracking processing levels, with parameters h, L, and ΔE demonstrating significant differentiation ability across *Polygonatum sibiricum* samples. The inner transverse section of processed rhizomes gradually turns moist black with specular luster, consistent with the traditional identification standard of "brightness like oil and color like black lacquer," providing a reliable visual marker for processing records. Microscopic characterization of calcium oxalate needle crystals offers an additional traceability marker, as the change rate of needle crystal morphology increases with processing level and exceeds 90% by the fifth cycle. High correlations between color parameters and needle-like crystals confirm the potential applicability of these features for classifying samples from different processing levels, enabling processors to document and verify processing adequacy (Cheng et al., 2022).

Advanced analytical technologies further strengthen traceability by linking processing records to chemical fingerprints and volatile profiles. Flash GC-E-nose profiling of volatile transitions across ten processing stages tentatively identified 71 compounds, providing foundational knowledge for aroma-based authentication tools that can verify processing consistency. Multivariate analyses, including PCA and hierarchical cluster analysis, clearly discriminate both species and steaming stages, revealing consistent chemical transformation patterns that can serve as reference standards in traceability databases (Sabier et al., 2026).

Untargeted GC-MS and FT-NIR spectroscopy identified 333 metabolites across 14 processing methods, with FT-NIR-based PLS-DA models reporting recognition rates of 71.43%–96.43% under the conditions studied (Xu

et al., 2023). Electronic eye technology combined with chemometrics offers a rapid, environment-friendly method for determining whether samples have reached sufficient processing time, with specific color parameter ranges serving as quantitative thresholds for quality acceptance. These tools collectively enable the construction of digitized processing records that link raw material origin to final product quality.

7.3 Coordination between commercial grading and market circulation requirements

Aligning commercial grading with market circulation requires multidimensional evaluation models that integrate external appearance traits with internal metabolite profiles. A weighted TOPSIS-GRA fusion model combining eight appearance traits and six functional metabolite contents successfully differentiated *Polygonatum sibiricum* slices from different regions, with PCA clustering 16 batches into three distinct quality categories. The correlation coefficients from gray relation analysis ranged from 0.3895 to 0.8094 for the optimal reference sequence, effectively distinguishing superior-quality samples from inferior ones. OPLS-DA identified differential quality-affecting markers, providing a scientific basis for categorizing commercial grades that correspond to actual market quality variation. The established multi-index content determination method demonstrated accuracy and reliability with recovery rates between 98.54% and 103.07%, supporting analytical repeatability under the conditions investigated (Wang et al., 2025); wider interlaboratory reproducibility would require further validation.

Effective coordination between grading and market circulation also demands rapid assessment tools and standardized variety selection to meet diverse consumer and industrial demands. Near-infrared spectroscopy combined with chemometrics enables rapid quantitation of polysaccharide and saponin contents, providing a practical tool for preliminary quality screening during market transactions. Stem diameter has been identified as a practical agronomic indicator for variety screening and harvest assessment, offering a morphological marker that correlates with yield and facilitates preliminary grading at the cultivation stage (Liao et al., 2023). The *Polygonatum* industry currently faces challenges including germplasm confusion, unclear functional composition, and decentralized small-scale processing, all of which undermine consistent market quality. Addressing these issues requires accelerating the selection of improved varieties, ensuring high-quality seedling supply, and eliminating unauthentic species to stabilize the raw material basis for commercial grading. Future market growth depends on technological innovation, brand strategy, and internet-based traceability platforms that integrate processing standards with commercial grading to ensure sustainable industry development (Su et al., 2018).

8 Summary and Prospects

Standardizing primary processing requires precise control of key parameters to prevent over-processing and preserve bioactive components. The traditional nine-steaming and nine-drying method induces significant chemical transformations, but some studies suggest that four processing cycles can provide favorable results for selected constituents under specified conditions; this cannot establish a universally optimal cycle number for all species and processing routes. Low molecular weight fructans undergo significant degradation within the first three processing cycles, with complete degradation by the seventh cycle, suggesting the traditional technique is often excessive. Polysaccharide content decreases progressively with increasing cycles, stabilizing at approximately 5.2 g/100 g after four cycles, a 45.81% reduction from raw rhizomes, while saponins, phenols, and flavonoids exhibit an increasing trend with slight fluctuations after the fourth cycle. The first six processing cycles account for the most drastic changes in functional component accumulation, while subsequent cycles yield no further benefits and may even reverse enhancing effects. The lack of precise control over processing parameters has led to uneven quality of processed *Polygonatum*, underscoring the need for quantitative prediction models that correlate processing methods, component contents, and biological activity. A CRITIC-based prediction model has been developed to optimize processing by correlating method, component contents, and biological activity, ensuring consistent quality and efficacy. Establishing standard operating procedures also requires elucidating the toxicity-reducing and efficacy-enhancing mechanisms of processing. Calcium oxalate raphides are among the irritating components of raw *Polygonatum*, and processing disintegrates these raphide bundles, particularly at their tips, reducing throat irritation. Processing-induced chemical mechanisms include hydrolysis, oxidative decomposition, dehydration, Maillard reaction, and polymerization, with processing stages divisible into raw (0 h), middle (1–6 h), and late (8–18 h) phases. Polysaccharides partially degrade into oligosaccharides during

processing, with molecular weight gradually decreasing and neutral sugars converting into uronic acids, while saponins partially degrade into sapogenins or undergo modification. Processing with black bean juice significantly alters chemical fingerprints, increasing lower-polarity compounds and generating six new compounds while degrading medium-polarity constituents. In the cited *P. cyrtonema* experiment, black-bean-juice processing increased measured polysaccharide and saponin contents and enhanced in vitro antioxidant and antidiabetic activities (Zhang et al., 2023). These mechanistic insights provide a scientific basis for establishing standardized processing protocols that balance detoxification with bioactive retention.

Improving the commercial grade classification system requires moving beyond traditional appearance-based grading to integrate multidimensional quality indicators. Traditional Chinese medicine quality control faces challenges lacking multidimensionality and reliable quantitative evidence, and comprehensive evaluation models based on external characteristics and multiple indicator metabolites represent the future research direction. Color quantization based on the CIE L*a*b* system provides objective metrics for tracking processing levels, with parameters h, L, and ΔE demonstrating significant differentiation ability across *Polygonatum sibiricum* samples. The inner transverse section of processed rhizomes gradually turns moist black with specular luster, consistent with the traditional identification standard of "brightness like oil and color like black lacquer," providing a reliable visual marker for processing records. Microscopic characterization of calcium oxalate needle crystals offers an additional traceability marker, as the change rate of needle crystal morphology increases with processing level and exceeds 90% by the fifth cycle. High correlations between color parameters and needle-like crystals confirm the potential applicability of macroscopic and microscopic features for classifying samples from different processing levels. Advanced identification methods are essential for standardizing *Polygonatum* products and preventing adulteration with morphologically similar congeneric species. A multidimensional approach integrating phenological, morphological, anatomical, and molecular characteristics has been developed to distinguish eight *Polygonatum* species, addressing the limitations of single-method identification. Significant interspecific differences were observed in phenological and morphological traits, with coefficients of variation reaching 135.92% for floret number and 117.82% for fruit number (Sun et al., 2025). Molecularly, optimized SCoT-PCR identified 12 polymorphic primers showing 96.56% polymorphism in the studied *Polygonatum* species (Sun et al., 2025), providing a robust basis for species identification and classification. These integrated approaches support botanical species identification; their value for chemical-quality grading requires independent validation.

Coordinating primary processing with industrial standards demands accelerating the selection of improved varieties, ensuring high-quality seedling supply, and eliminating unauthentic species to stabilize the raw material basis. The *Polygonatum* industry currently faces resource depletion, low-tech cultivation, and unclear functional composition, all of which undermine consistent industrial standardization. Strengthening the conservation and rational use of wild resources, alongside breakthroughs in high-quality artificial cultivation technologies for light regulation, site control, density control, and precision harvesting, are essential measures for sustainable development. Future market growth depends on technological innovation, cultural creativity, integration of three industries, brand strategy, and internet-based techniques that integrate processing standards with commercial grading. Despite promising pharmacological properties, underlying mechanisms remain insufficiently elucidated, and clinical evidence supporting therapeutic efficacy is still lacking, necessitating further research to clarify links between chemical constituents and pharmacological activities. Achieving industrial scale requires transitioning laboratory-scale extraction and purification technologies to green, efficient methods suitable for large-scale production. Most current methods for separating dietary polysaccharides from *Polygonatum sibiricum* are suitable only for small-scale laboratory processing and cannot meet the requirements of large-scale production. There is an urgent need for safe, harmless methods of purifying polysaccharides in green and environmentally friendly food industry production to meet consumer demand. Extraction methodologies for flavonoids remain at the laboratory stage with relatively low yields, and no definitive conclusions have been reached regarding optimal parameters for their application. Future investigations should focus on optimizing these methods and developing green, highly efficient extraction technology applicable on an industrial production scale. Exploring the potential applications of *Polygonatum* in functional foods and pharmaceutical formulations is recommended to advance the development

of industries focused on healthy aging. The relative lack of mechanistic studies on functional components and the absence of correlation between processing-induced compositional changes, pharmacological efficacy, and quality control remain critical research gaps that must be addressed to establish scientific evidence-based quality standards.

Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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Feature Review Open Access

Optimization of Perennial Cultivation Models and Continuous Production Management Strategies for *Paeonia lactiflora*

Chuchu Liu [1,2]
Institute of Life Science, Jiyang College of Zhejiang A&F University, Zhuji, 311800, Zhejiang, China
Corresponding email: chuchu.liu@jicat.org

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Abstract *Paeonia lactiflora* Pall. is an important perennial medicinal and ornamental plant. However, its industrial development is constrained by a long propagation cycle, continuous cropping obstacles, limited ecological adaptability, and insufficient standardization of production management. This review systematically synthesizes the growth characteristics, cultivation models, and key management technologies of perennial *P. lactiflora*, and explores strategies for optimizing continuous production systems. The reviewed literature indicates that traditional open-field cultivation has advantages of strong adaptability and low production costs but is vulnerable to environmental fluctuations and soil-related problems. Large-scale standardized cultivation improves production stability through tissue culture, elite seedling propagation, and precision management, whereas ecological and green cultivation enhances quality improvement through soil health maintenance, rhizosphere microbiome regulation, and biological control. Future production should focus on establishing a collaborative optimization model integrating cultivar selection, environmental adaptation, and cultivation management, while developing continuous production systems covering seedling propagation, soil regulation, growth-stage management, and post-harvest processing. Furthermore, the integration of digital agricultural technologies will promote precision and intelligent management, providing technical support for the sustainable development of the *P. lactiflora* industry.

Keywords *Paeonia lactiflora*; Perennial cultivation; Continuous production management; Continuous cropping obstacles; Precision cultivation

1 Introduction

Paeonia lactiflora Pall., a perennial herbaceous species in the family Paeoniaceae, has been used medicinally for over two millennia, with its processed root products-Paeoniae Radix Alba and Paeoniae Radix Rubra-occupying a central role in traditional Chinese medicine (Cai et al., 2026). The species is also globally renowned as an ornamental, cherished for its large, colorful, and fragrant flowers, and is widely cultivated as a landscape, potted, and cut-flower plant across European, North American, and Asian countries (Li et al., 2023). Over 200 bioactive compounds have been identified from *P. lactiflora*, including monoterpene glycosides, flavonoids, and polysaccharides, with paeoniflorin as the principal pharmacologically active constituent underpinning its anti-inflammatory, antioxidant, hepatoprotective, and neuroprotective effects. Given its dual medicinal and ornamental value, *P. lactiflora* serves as both an agricultural cash crop and a traditional famous flower, and market demand for high-quality seedlings and cut flowers has increased considerably in recent years.

In Japan alone, annual peony root consumption reached approximately 1 712 tons in fiscal year 2020, with roughly 98% of supply imported from China, underscoring strong international demand. China possesses rich germplasm resources across five main producing areas-Anhui, Zhejiang, Sichuan, Shandong, and Hunan-where 12 medicinal cultivars have been documented, including eight monopetalous red-flower types. Since 1900, over 2 200 new horticultural *Paeonia* cultivars have been created worldwide through the discovery and breeding of wild species, reflecting rapid industrialization (Yang et al., 2020).

However, the species is naturally distributed in temperate regions (hardiness zones 3~7), and expanding cultivation into lower-latitude subtropical and tropical zones remains a significant horticultural objective constrained by hot-humid climates (Zhang et al., 2019a). Climate modeling projects a 25~45% expansion of total suitable habitat under future warming scenarios, accompanied by a northeastward centroid shift, suggesting both

opportunities in emerging northern regions and risks of degradation in traditional production areas. As a high-value crop with temperature-dependent growth, *P. lactiflora* requires worldwide production to satisfy year-round demand, motivating the development of perennial cultivation systems that can sustain productivity across diverse environments (Lewis et al., 2023).

Despite its economic importance, perennial cultivation of *P. lactiflora* faces multiple interconnected challenges. The species exhibits a characteristic double dormancy of both the hypocotyl and epicotyl, requiring a two-phase stratification-warm conditions for radicle elongation followed by cold conditions for shoot growth-that spans a prolonged winter period, resulting in an extended propagation cycle and low seedling emergence rates (Mu et al., 2026). Traditional seed reproduction entails a long cycle with a low reproduction coefficient, and plants grown from seed require four to five years before normal flowering, and their offspring may not retain the maternal cultivar's traits. Division propagation, the predominant method, is similarly constrained by a long cultivation period and low propagation rate, requiring more than three years from rhizomes and more than six years from seeds, making it difficult to propagate large numbers of plants within a short period (Yamamoto et al., 2025). A particularly severe problem is the replanting disease that occurs when ramet seedlings are planted at the original site: growth and flowering rates decline, quality deteriorates, and pests and diseases aggravate, eventually resulting in plant mortality (Li et al., 2023). Long-term replanting reduces soil pH, nutrient contents, enzyme activities, and the diversity and richness of fungal and bacterial communities, while increasing the relative abundance of harmful microorganisms such as *Gibberella* and reducing beneficial genera such as *Bacillus* (Li et al., 2023). This soil microecological imbalance damages normal growth and restricts the sustainable development of the industry. Additionally, insufficient chilling accumulation in warm-winter climates, exacerbated by global warming, severely hinders bud dormancy release and flowering, limiting cultivation at low latitudes (Wang et al., 2020). High temperatures and humidity in subtropical regions impede the "Southward Planting of Herbaceous Peony," and the lack of an efficient and stable regeneration system further restricts rapid propagation and large-scale production. Production planning for perennial crops also presents logistical challenges, as large variations in yield and demand across multiple growth cycles can lead to costly shortages or excess in seed stock (Van Der Kruk et al., 2024).

Given these multifaceted challenges, optimizing perennial cultivation models and continuous production management strategies for *P. lactiflora* is essential for sustaining industry growth. Recent advances offer promising directions. Tissue culture systems have been developed for efficient regeneration, with optimized media achieving germination rates up to 91.11% and shoot induction rates of 96.67%, providing a foundation for rapid propagation and germplasm conservation. Bio-nursery systems using diurnal temperature treatments and elevated calcium concentrations during root induction have improved acclimation success, contributing to a more stable seedling supply. For season extension, high-tunnel production has advanced initial harvest by 21~34 days compared with natural field conditions, and staggered planting across high-tunnel and field environments extended harvest duration up to 38 days. Multi-criteria decision-making models incorporating adaptability, ornamental features, and growth habits have been established to screen elite cultivars for low-latitude cultivation, identifying 'Hang Baishao' and 'Meiju' as strongly adaptive germplasms. The Utah model has been validated as optimal for evaluating chilling requirements, enabling cultivar selection tailored to specific climatic conditions. Wild-like cultivation environments have demonstrated that paeoniflorin content and product traits increase year by year, offering an alternative production approach. Optimal harvest timing-late September of the fourth growing year-and shade drying have been identified as the most suitable post-harvest strategy for maximizing bioactive compound yield. Integrated production-inventory planning using model predictive control has been proposed for perennial crop seeds, balancing inventory levels and anticipating future deliveries to reduce both shortages and surpluses. This article synthesizes these advances to provide a comprehensive framework for optimizing perennial cultivation models and continuous production management, aiming to address the propagation bottlenecks, soil health deterioration, climatic constraints, and logistical challenges that currently limit the sustainable development of the *P. lactiflora* industry.

2 Growth Characteristics and Cultivation Basis of Perennial *Paeonia lactiflora*

2.1 Growth and development patterns and stage characteristics of perennial *Paeonia lactiflora*

Paeonia lactiflora is a perennial geophyte with a clear annual cycle built around overwintering bud dormancy, spring sprouting, vegetative and reproductive growth, summer senescence, and renewed underground persistence. Long-running observations in low-latitude introductions show that annual growth cycle traits, dormancy duration, and resistance performance differ substantially among cultivars, which makes stage-based cultivar evaluation essential for perennial production planning (Wang et al., 2022). In the low-chilling cultivar 'Meiju', sprouting can exceed 50% in March, leaves unfold 1~2 weeks later, and aboveground parts usually wither by early August, illustrating a compressed aboveground season followed by underground dormancy. Reproductively, mature clumps can support annual cut-flower harvest after establishment, and healthy plants may remain productive for about 10 years under suitable management (Li et al., 2023).

The earliest developmental bottleneck occurs at seed germination because *P. lactiflora* seeds exhibit double dormancy of the hypocotyl and epicotyl. Dormancy release requires warm stratification first to promote radicle growth, followed by cold stratification to trigger epicotyl elongation and seedling emergence, and this prolonged sequence lengthens the propagation cycle and lowers field emergence. Physiological evidence indicates that the warm phase mainly drives root growth, whereas the cold phase intensifies reserve degradation, hydrolytic enzyme activity, and hormonal rebalancing needed for shoot emergence; in transcriptome-metabolome profiling, the 28-day warm-stratification stage was the key transition period (Mu et al., 2026). Because conventional propagation from rhizomes or seeds is slow, in vitro embryo culture and rooted shoot systems now provide a practical basis for compressing early developmental stages and stabilizing seedling supply (Xin et al., 2025; Zhu et al., 2026).

2.2 Root development and formation characteristics of medicinal quality in *Paeonia lactiflora*

As a perennial root medicinal crop, the underground organ of *P. lactiflora* is both the main harvested product and the principal site of bioactive compound accumulation, so root development directly determines yield and medicinal quality (Guo et al., 2026). Reviews of its phytochemistry show that more than 200 compounds have been identified, including terpenoids, flavonoids, polyphenols, and organic acids, with paeoniflorin recognized as the major indicator compound and a major focus of quality evaluation. Root secondary metabolism is not autonomous: metabolomic and microbiome studies show that root metabolite accumulation is closely linked to rhizosphere microbial communities, and varietal comparisons further indicate that differences in paeoniflorin, total phenols, flavonoids, and antioxidant capacity track biological variation among germplasms (Wu et al., 2025). Environmental-response analysis similarly found that root secondary metabolites are jointly shaped by soil water content, mean annual precipitation, pH, and specific biotic factors such as *Alternaria*, indicating that medicinal quality is an outcome of genotype-environment-microbiome interaction rather than age alone (Sun et al., 2022).

Root medicinal quality also changes markedly with plant age, harvest season, and post-harvest processing (Guo et al., 2026). Across cultivation studies, active components tend to reach comparatively high levels in 4-year-old roots, while further extension to older ages yields limited chemical gain and greater structural or pathological risk; 5-year-old plants often show more disease, and 6-year-old roots can become hollow and lignified, which lowers medicinal quality. In the Tongliao study, comprehensive evaluation ranked late September of the fourth growing year as the optimal harvest period, and paeoniflorin content was positively correlated with root dry weight. Wild-like cultivation work further showed that root traits and paeoniflorin content increased year by year under simulated natural conditions, suggesting that ecological cultivation patterns can improve medicinal attributes when matched to developmental timing

2.3 Ecological requirements and cultivation conditions for optimal growth of *Paeonia lactiflora*

The optimal growth of *P. lactiflora* depends on a temperate ecological niche characterized by cool winters, moderate thermal seasonality, adequate summer moisture, and sufficient light, which explains why the species is concentrated in temperate regions and is difficult to maintain in hot, humid low latitudes (Cai et al., 2026). Distribution modeling identified precipitation of the warmest quarter, mean temperature of the coldest quarter,

temperature seasonality, and November solar radiation as the dominant environmental drivers, highlighting that active-season water supply and an appropriate winter cold period are both indispensable. Low-latitude cultivation is constrained because hot-humid spring weather can induce stem bending, bud abortion, and severe disease, extreme summer heat can hasten withering, and warm autumn-winter conditions can leave chilling requirements unmet (Wang et al., 2022). This pattern is consistent across observational, physiological, and modeling studies showing that winter warmth is a major barrier to southward expansion (Wang et al., 2020).

Cultivation practice therefore needs to align site selection, cultivar choice, chilling management, and soil regulation with the species' perennial biology. Chilling studies show that lower temperatures and longer durations improve sprouting and flowering, with 0℃ for 6 weeks or 5℃ for 9 weeks sufficient to break dormancy in Korean cultivars, while low-CR cultivars such as 'Hang Baishao' and 'Meiju' are better suited to warm-winter regions (Rhie et al., 2012). Practical regulation can also be effective: chilling at 0~4℃ for four weeks plus humic-acid irrigation improved forcing performance in 'Hang Baishao', and high-tunnel cultivation advanced harvest by 21~34 days, although excessive heating and humidity reduced quality and increased pest and disease pressure (Zhang et al., 2019b). Belowground management is equally important because long-term replanting lowers pH, nutrients, enzyme activities, and microbial diversity while increasing harmful taxa, whereas rhizosphere studies indicate that cation exchange capacity, soil water, and cooperative microbial networks are closely tied to growth and metabolite accumulation (Sun et al., 2022; Li et al., 2023).

3 Cultivation Models and Application Characteristics of Perennial *Paeonia lactiflora*

3.1 Traditional open-field perennial cultivation model and production characteristics

The traditional open-field perennial cultivation model remains the basic production form for medicinal and ornamental *P. lactiflora* because the crop is widely grown in temperate regions and performs as a cool-season, field-based perennial with strong dependence on local seasonal temperature patterns (Qi et al., 2020). In this model, establishment is slow: medicinal production generally requires more than three years from rhizomes and more than six years from seed, and conventional seed propagation also suffers from long cycles, season-dependent germination, and delayed flowering after 4~5 years (Yamamoto et al., 2025). Seed-based open-field expansion is further constrained by double dormancy, because radicle growth requires warm stratification and shoot emergence then requires cold stratification, which prolongs winter propagation and lowers emergence (Mu et al., 2026). Even so, open-field cultivation remains attractive because it is simple, broadly adaptable in temperate zones, and can support multiple product types including medicinal roots, cut flowers, and even seed oil production, although fertility traits vary markedly among genotypes (Sun et al., 2022).

Its production characteristics are defined by strong environmental exposure and by tradeoffs among yield, flower timing, and medicinal quality. In field production of 'Coral Charm', natural field systems yielded about 16.1~20.8 stems/m², and combining field with protected production extended harvest duration up to 38 days, showing the value of open-field plots for staggered supply. Open-field cultivation can also outperform forcing systems in yield: in 'Taebaek', greenhouse forcing shortened time from sprouting to flowering by about 26 days, but yield was lower than under open-field cultivation and early forcing increased susceptibility to powdery mildew and gray mold (Bae et al., 2008). For medicinal roots, open-field management strongly affects both biomass and chemistry: late September of the fourth year produced the best combined yield-quality score in Inner Mongolia, and root dry weight declined with later harvest dates (Guo et al., 2026). Field weed and tillage regimes also matter, because inter-tillage substantially reduced weed biomass, while grass management tended to increase paeoniflorin content and sometimes yield, indicating that conventional open-field systems involve a real balance between cleaner fields and stress-linked quality formation (Seki et al., 2021).

3.2 Large-scale standardized cultivation model and technical advantages

Large-scale standardized cultivation models are designed to overcome the main bottlenecks of perennial *P. lactiflora* production: slow multiplication, unstable seedling supply, and inconsistent field performance (Yamamoto et al., 2025). The strongest technical basis for this model is tissue culture. Mature embryo systems achieved germination rates up to 91.11%, direct seedling formation up to 67.78%, multiple-shoot induction of

96.67%, shoot proliferation coefficients of 3.48, and rooting rates of 73.33%, showing that standardized in vitro protocols can sharply compress the early propagation phase (Xin et al., 2025). Complementary regeneration studies show that tissue culture is not only useful for multiplication but also for germplasm conservation, cultivar improvement, and later genetic engineering (Duan et al., 2022). Standardization also now extends to rooting and acclimation: embryo-derived shoots rooted best after 7 days of darkness followed by 28 days of light, and modified half-strength medium with double calcium, putrescine, indole-3-butyric acid, and coumarin produced 75% rooting with 8.3 roots per shoot.

The technical advantage of this model is that it converts a long, variable perennial crop into a more controllable production chain spanning propagation, nursery management, protected cultivation, and harvest standardization. In a bio-nursery system, a 15/5℃ day-night regime increased shoot proliferation relative to constant 15℃, 6 mmol/L calcium during root induction improved post-transplant vigor, and acclimation was suitable in a closed greenhouse at 20℃ after cold treatment, all of which support stable commercial seedling supply. Standardized protected production can also regulate market timing: high tunnels advanced initial harvest by 21~34 days while maintaining 15.7~19.4 stems/m², although extra soil heating under low tunnels reduced quality under excessive temperature and humidity. Standardization is also supported by harvest-year optimization, because both chemical profiling and bioactivity testing indicate that a 4-year growth period is sufficient for desired root quality, avoiding unnecessary extension of the production cycle (Jin et al., 2026).

3.3 Ecological and green cultivation model and development potential

Ecological and green cultivation models focus less on maximal input intensity and more on matching perennial biology with soil health, rhizosphere function, and environmentally safer disease control. This direction is well supported because *P. lactiflora* root secondary metabolism is closely linked to rhizosphere microorganisms, and current evidence shows that root metabolites respond jointly to abiotic conditions such as soil water, precipitation, and pH and to biotic factors such as *Alternaria* (Wu et al., 2025). Rhizosphere studies further show that the rhizosphere contains enriched carbohydrates and organic acids, more complex and stable microbial co-occurrence networks, and more cooperative microbial relationships than bulk soil, making it a practical target for ecological regulation. In ornamental cultivars, pH and alkaline phosphatase significantly affected rhizosphere bacterial communities, while some cultivars enriched more stress-tolerant growth-promoting bacteria, indicating that green cultivation can combine soil management with cultivar choice (Zu et al., 2022). More broadly, rhizosphere engineering research supports two complementary routes for sustainable agriculture: precise agronomic management of environment-dominated microbiomes and breeding for plant genetic-dominated microbiome assembly (Mahmud et al., 2021; Xun et al., 2024).

Its development potential is especially strong because ecological practices can improve both sustainability and product quality while reducing chemical dependence. In medicinal peony fields, grass management increased paeoniflorin content relative to inter-tillage, suggesting that moderated competition and less intensive soil disturbance can sometimes favor medicinal quality even when weed pressure rises (Seki et al., 2021). Disease management can also shift toward biological control: *Bacillus subtilis* SY8 suppressed four major fungal pathogens, reduced black spot incidence, increased defense-related enzyme activities, and restructured microbial communities toward greater bacterial diversity and fewer pathogenic fungi. Varietal evidence likewise suggests that long-domesticated local lines can maintain stable phenotypes for decades and differ in paeoniflorin, phenolics, flavonoids, and antioxidant capacity, which creates room for ecological model selection around both adaptation and quality (Wu et al., 2025). The ecological green model appears best suited for the next stage of perennial *P. lactiflora* development because it integrates quality formation, soil-microbiome management, and biological disease suppression into a lower-input cultivation framework while retaining clear commercial potential.

4 Key Management Technologies for Continuous Perennial Production of *Paeonia lactiflora*

4.1 Elite germplasm selection and standardized seedling propagation technology

Elite germplasm selection for continuous perennial production should prioritize regional adaptability, especially chilling requirement, heat-humidity tolerance, flowering stability, and division-propagation potential. In

low-latitude evaluation systems, 'Meiju', 'Hang Baishao', 'Hongpan Tuojin', and 'Bo Baishao' consistently ranked as top-performing materials, with 'Hang Baishao' standing out as a local low-chilling germplasm with strong warm-winter adaptation and long cultivation history in subtropical China. Regional mismatch matters: cultivars can perform very differently across sites, so large-scale introduction should follow local multi-criteria evaluation rather than name-based transfer, and traits such as bud number, flowering earliness, upright stem habit, and cross-breeding value can all be used as practical screening indices for commercial deployment and breeding parent choice (Zhang et al., 2019a).

Standardized seedling propagation is needed because conventional breeding and division are slowed by double seed dormancy, long juvenile periods, and low multiplication efficiency (Mu et al., 2026). Mature-embryo and zygotic-embryo tissue culture now provide workable large-scale routes: optimized media achieved 91.11% embryo germination, 67.78% direct seedling formation, 96.67% multiple-shoot induction, 3.48 shoot proliferation, and 73.33% rooting, while an improved rooting system using 7 days dark plus 28 days light, doubled calcium, IBA, putrescine, coumarin, and porous perlite-vermiculite substrate raised rooting to 75% with 8.3 roots per shoot (Xin et al., 2025). For low-chilling 'Hang Baishao', embryo culture on half-strength MS with 6-BA, GA3, and PVP was effective, and transplant survival depended strongly on vascular bundle development; bio-nursery work further showed that 15/5℃ diurnal culture, 6 mmol/L calcium during rooting, and 20 ℃ acclimation after cold treatment improved post-transplant vigor and seedling supply stability (Figure 1) (Xin et al., 2025).

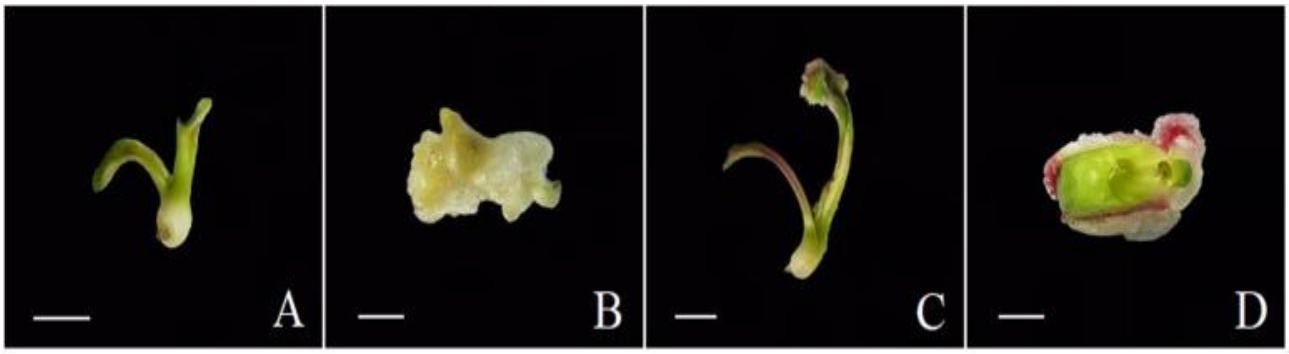


Figure 1 Effects of GA_3, NAA and 6-BA on embryo germination status of *P. lactiflora* (Adopted from Xin et al., 2025)
Image caption: The germination status of embryo in different medium: (A) 1.0 mg/L GA_3, (B) 1.0 mg/L NAA, (C) 1.0 mg/L GA_3+0.5 mg/L 6-BA, (D) 1.0 mg/L NAA+0.5 mg/L 6-BA. MS: Murashige and Skoog; GA3: gibberellin 3; NAA: 1-naphthaleneacetic acid; 6-BA: 6-benzyleaminopurine. Scale bars=0.5 cm (Adopted from Xin et al., 2025)

4.2 Soil quality maintenance and control technologies for continuous cropping obstacles

Soil quality maintenance in continuous perennial *P. lactiflora* production should focus on preventing replanting obstacles rather than assuming all long-term cultivation is equally harmful. In peony, replanting at original sites reduced growth and flowering, worsened quality, increased pests and diseases, and eventually caused plant death, while sequencing studies showed that five years of replanting lowered pH, available nutrients, enzyme activities, and bacterial and fungal diversity, and increased harmful microorganisms such as *Gibberella* while reducing beneficial *Bacillus* (Li et al., 2023). Root-soil studies refine that picture: seven years of continuous planting did not produce obvious adverse soil factors, but four years of replanting shifted soil from a bacterial high-fertility state to a fungal low-fertility state, decreased pH, organic matter, nutrients, enzymes, and bacterial abundance, and increased benzoic acid, which is a plausible autotoxin contributor.

Control technologies therefore need to combine soil improvement, microbial regulation, and system-level cropping design. Broader medicinal-plant reviews agree that continuous-cropping obstacles are mainly driven by altered microbial communities, nutrient imbalance, and allelopathic effects, and that effective mitigation includes soil amendments, crop rotation, intercropping, and management aimed at rebuilding beneficial microbiota and soil fertility (Haq et al., 2023; Liao and Xia, 2024). This systems view also matters because not all continuous-cropping systems develop obstacles; some can enrich beneficial microorganisms and become disease-suppressive, so management should target microbial food-web structure and plant-soil-organism

interactions instead of treating years of continuous cultivation alone as the decisive risk factor. For *P. lactiflora*, that implies practical use of organic matter enhancement, pH and nutrient correction, avoidance of repeated hole replanting, and introduction of beneficial microbes such as *Bacillus*, which are biologically aligned with the mechanisms identified in replant soils (Xie et al., 2023).

4.3 Growth-stage precision management and quality improvement technologies

Growth-stage precision management should match perennial peony's temperature-dependent developmental stages, from dormancy release and sprouting to flowering, harvest, and post-harvest handling. Bud dormancy release is a major control point in warm-winter regions: high winter temperatures hinder flowering, while 'Hang Baishao' succeeds because of its lower chilling requirement, and chilling at 0~4℃ for four weeks plus 300 mg/L humic acid improved flowering advancement and quality under forcing conditions (Zhang et al., 2019b). Protected cultivation can then regulate harvest windows: high tunnels advanced first harvest by 21-34 days with yields of 15.7~19.4 stems/m², field plots yielded 16.1~20.8 stems/m², and combining both systems extended harvest duration to 38 days, although low tunnels with soil heating sometimes reduced quality because excessive temperature and humidity damaged buds and increased pest and disease pressure (Lewis et al., 2023).

Quality improvement also depends on stage-specific regulation of plant architecture, harvest age, and post-harvest processing. Paclobutrazol reduced plant height and crown width but increased stem diameter, leaf thickness, chlorophyll, water status, soluble sugar, and antioxidant enzyme activity, and improved flower diameter and fresh weight when applied at the flower-bud stage, although it also reduced anthocyanin content and total aroma compounds under some other application timings. For medicinal root production, the best combined yield-quality outcome was region-specific but clear in Tongliao: 4-year-old plants performed best, late September of the fourth year was the optimal harvest window, shade drying gave the highest quality, and paeoniflorin correlated positively with root dry weight (Guo et al., 2026). Wild-like cultivation adds a useful ecological option, because paeoniflorin content and product traits increased year by year under simulated natural conditions, while varietal metabolomics showed that root quality traits such as paeoniflorin, total phenols, flavonoids, and antioxidant capacity differ systematically among cultivars and are linked to rhizosphere microbial composition (Wu et al., 2025).

5 Optimization Strategies for Perennial Cultivation Models of *Paeonia lactiflora*

5.1 Establishment of a collaborative optimization model integrating cultivar selection, environmental adaptation, and cultivation management

A collaborative optimization model for perennial *P. lactiflora* should begin with cultivar stratification by adaptation traits, because low-latitude expansion is constrained by warming, humidity, and insufficient winter chilling. Multi-criteria screening identified 'Meiju', 'Hang Baishao', 'Hongpan Tuojin', and 'Bo Baishao' as Level I germplasm with strong adaptability and ornamental value under hot-humid conditions (Figure 2) (Wang et al., 2022). Chilling-requirement studies further showed that 'Hang Baishao' and 'Qihua Lushuang' are representative low-CR cultivars, and the Utah model was the most dependable framework for evaluating cultivar chilling demand across winters. This supports a coordinated introduction pathway in which germplasm is screened first for stress adaptation, then matched to target production zones and management schedules (Wang et al., 2020).

The second layer of collaboration is linking adaptive cultivars with standardized propagation systems and downstream quality goals. China's medicinal peony industry already contains rich cultivar resources across five main producing areas and 12 documented medicinal cultivars, which provides a broad germplasm base for differentiated deployment. Because conventional propagation is slow and breeding remains limited by fragmented germplasm knowledge and low efficiency, optimized embryo and tissue-culture systems are critical for rapidly multiplying selected materials (Xin et al., 2025). Mature-embryo culture reached 91.11% germination, 96.67% shoot induction, and 73.33% rooting, while low-chilling 'Hang Baishao' also now has a workable embryo-propagation and transplanting protocol. At the breeding end, large fertility differences among genotypes and the need for marker-assisted, trait-directed parent selection argue for using propagation, adaptation testing, and breeding as one continuous optimization chain rather than separate tasks (Qi et al., 2020).



Figure 2 Challenges encountered in the cultivation and application of the herbaceous peony at low latitudes (Adopted from Wang et al., 2022)

Image caption: (A-H) High spring temperatures and high humidity caused stem bending, flower bud abortion and severe diseases; (I-K) High summer temperatures induced heat damage and premature withering of aboveground parts; (L, M) High autumn and winter temperatures caused insufficient chilling requirement and induced subsequent abnormal flowering and vegetative growth (Adopted from Wang et al., 2022)

5.2 Development of a green and efficient long-term continuous production system

A green and efficient long-term continuous production system should center on stable seedling supply, lower-input establishment, and rhizosphere-mediated quality regulation. Tissue culture and bio-nursery work directly address the chronic bottleneck of slow multiplication, which is especially important because medicinal peony production takes more than three years from rhizomes and more than six years from seed (Song et al., 2023). In the bio-nursery system, a 15/5℃ diurnal regime increased shoot proliferation, 6 mmol/L calcium improved post-transplant vigor, and 20℃ greenhouse acclimation after cold treatment improved plantlet establishment. Rooting can be further strengthened by 7 days dark plus 28 days light and by a modified half-strength medium with doubled calcium, IBA, putrescine, and coumarin, which produced 75% rooting and 8.3 roots per shoot (Zhu et al., 2026). These propagation advances make green long-cycle production more feasible by reducing loss rates at the nursery stage.

Long-term efficiency also depends on soil ecological stability, because replanting obstacles in *P. lactiflora* are strongly linked to declining pH, nutrients, enzyme activities, and beneficial microbes, alongside increases in harmful fungi and possible autotoxins such as benzoic acid (Xie et al., 2023). Rhizosphere studies show that root secondary metabolism is closely tied to microbial communities, and cultivar differences in paeoniflorin, phenolics, flavonoids, and antioxidant capacity track microbial differences as well (Wu et al., 2025). Green production should therefore combine organic matter and pH management with microbial optimization, especially because pH and alkaline phosphatase significantly shape rhizosphere communities and some cultivars enrich stress-tolerant growth-promoting bacteria (Zu et al., 2022). Quality-oriented green systems can also incorporate optimized harvest and processing: 4-year roots performed best overall, late September was the best harvest window in Tongliao, shade drying gave the highest quality, and low-temperature storage followed by washing, boiling, and 30℃ machine drying improved main active components in processed roots (Komatsu, 2024; Guo et al., 2026).

5.3 Promotion of precision cultivation management through digital agricultural technologies

Digital agricultural technologies can convert perennial peony management from calendar-based practice to data-driven precision cultivation. More broadly, digital agriculture integrates sensors, drones, satellites, and analytics to collect crop, soil, weather, and phytosanitary data and use them for more precise decisions on irrigation, fertilization, and pest control. Remote sensing and UAVs are particularly useful for non-destructive, near real-time monitoring of growth and field heterogeneity, while AI and big-data tools improve pattern detection and operational decision-making (Fuentes-Peñailillo et al., 2024). For perennial *P. lactiflora*, this framework is well matched to key control points that already show strong environmental sensitivity, including chilling fulfillment, dormancy release, stem emergence, flowering timing, soil moisture, and disease pressure (Wang et al., 2020).

In practice, precision management should prioritize cultivar-specific models that combine climatic suitability, stage regulation, and harvest optimization. Protected-cultivation experiments already show that high tunnels advance initial harvest by 21~34 days, low tunnels with soil heating can further advance harvest, and excessive heat-humidity lowers stem quality and increases disease pressure. Those results are directly translatable into digital control rules, where real-time sensing could regulate tunnel temperature and humidity against cultivar-specific thresholds rather than relying on fixed schedules. Precision systems should also integrate biochemical quality targets, because 4-year roots already match 5-year roots in major active constituents and antidepressant-related bioactivity, making prolonged cultivation unnecessary when monitored quality indices are achieved (Jin et al., 2026). The main limitation is implementation: scalable AI-IoT systems still need better dataset integration, user-friendly interfaces, and adaptation to diverse farm conditions, so digitalization in peony should advance in parallel with standardized field data collection and model validation.

6 Current Research Problems and Future Development Directions

6.1 Insufficient research on perennial cultivation cycles and optimal harvesting strategies

Research on perennial cultivation cycles and optimal harvesting strategies for *P. lactiflora* is still insufficient because most available studies identify useful local harvest windows but do not yet establish a broadly validated, multi-region production calendar. Recent work in Tongliao compared 3-, 4-, and 5-year-old plants on the same plot and found that 4-year-old plants gave the best combined yield-quality score, with late September outperforming earlier and later harvest dates, but the authors explicitly noted that these results are region-specific rather than universal (Guo et al., 2026). Independent chemical-bioactivity integration reached a similar conclusion that 4-year roots were comparable to 5-year roots in key active constituents and antidepressant-related effects, supporting a shorter production cycle, yet this line of evidence is still based on limited cultivation-year contrasts rather than long-term multilocation validation (Jin et al., 2026). At the same time, the long juvenile period and double seed dormancy of *P. lactiflora* continue to slow cycle optimization research itself, because warm-cold stratification, prolonged establishment, and difficult rooting make full-cycle experiments expensive and slow to repeat across environments (Mu et al., 2026).

Future work should therefore move from single-point harvest screening to a full life-cycle optimization framework integrating cultivar, site, developmental stage, and end-use quality. Existing studies already show that flowering, sprouting, and dormancy release are highly climate-sensitive, especially in low-latitude regions where winter warmth disrupts chilling fulfillment and spring-summer heat damages growth. Long-running observation and multi-criteria evaluation have proven useful for comparing cultivar performance across years, and low-chilling materials such as ‘Hang Baishao’, ‘Meiju’, and ‘Qihua Lushuang’ offer a practical basis for region-specific cycle design. Future studies should combine multilocation age-by-harvest experiments with metabolomics, bioactivity assessment, and controlled environment trials so that cultivation years, harvest dates, and post-harvest methods can be optimized for both medicinal roots and ornamental stems rather than inferred from isolated local trials (Sun et al., 2022).

6.2 Incomplete understanding of continuous cropping obstacle mechanisms and green control technologies

The mechanism of continuous-cropping obstacles in *P. lactiflora* remains incomplete because current evidence clearly identifies soil deterioration and microbial imbalance, but does not yet resolve how autotoxins, root

exudates, nutrient shifts, enzyme changes, and pathogen enrichment interact over time in perennial peony systems. In replanted peony, growth and flowering decline progressively, while soil pH, nutrients, enzyme activities, and microbial diversity decrease and harmful genera rise as beneficial taxa such as *Bacillus* fall (Li et al., 2023). Broader medicinal-plant syntheses point to the same three main drivers-microbial community change, nutrient imbalance, and allelopathic effects-and emphasize that rhizosphere plant-soil-microbe interactions are the core system where obstacles develop (Liao and Xia, 2024). Yet a key complication is that not all continuous cropping systems inevitably deteriorate; some long-term systems can become more suppressive or self-repairing, which means years of continuous planting alone do not explain obstacle formation.

Future development should focus on green control technologies grounded in mechanism rather than blanket soil replacement or chemical intervention. Reviews across medicinal plants support soil amendments, crop rotation, and intercropping as effective directions because they can increase beneficial microorganisms and improve fertility and nutrient availability. In *P. lactiflora*, rhizosphere studies show that secondary metabolite accumulation is linked to microbial communities and is shaped by soil water, precipitation, pH, and biotic factors such as *Alternaria*, while microbial networks in the rhizosphere are more complex and cooperative than in bulk soil (Wu et al., 2025). This supports future strategies based on microbiome screening, synthetic beneficial communities, and soil ecological regulation, especially since recent long-term monoculture work in another crop showed that suppressive microbiomes can be rebuilt and even mimicked through designed inoculation. For peony, the next step is to connect replant years, root exudate chemistry, microbial food-web structure, and quality outcomes in long-term field experiments so that green prevention targets can be defined precisely rather than descriptively (Liao and Xia, 2024).

6.3 Need for establishment of intelligent production systems and standardized management models for *Paeonia lactiflora*

There is also a clear need to establish intelligent production systems and standardized management models for *P. lactiflora*, because current production still depends heavily on local experience, fragmented propagation methods, and inconsistent environmental control. Standardized regeneration systems have advanced rapidly: mature embryo culture achieved high germination, shoot induction, and rooting rates, and optimized rooting protocols improved root architecture and survival of embryo-derived shoots (Zhu et al., 2026). These advances solve part of the seedling bottleneck, but they do not yet constitute a farm-scale standardized management model that links germplasm screening, nursery propagation, field deployment, environmental monitoring, and harvest timing across production regions (Wang et al., 2022). The need is especially urgent because *P. lactiflora* is temperature-sensitive, and protected cultivation studies show that changes in soil and air temperature can shift harvest timing substantially while also affecting quality and disease pressure.

Future development should therefore promote a digital, standardized perennial management platform that combines cultivar-specific thresholds with real-time sensing and decision support. Precision-agriculture research shows that AI, IoT, remote sensing, and automated systems can collect real-time soil, crop, and environmental data, support irrigation and input decisions, and reduce labor and environmental costs. Integrated smart systems have already reached high predictive accuracy for crop selection and yield forecasting and can save substantial irrigation water through sensor-driven fuzzy control, which indicates that similar architectures are feasible for peony production zones (Saha et al., 2025). The main constraints are dataset integration, scale-up cost, connectivity, and farmer training, so future peony research should pair digital trials with unified phenological indicators, soil-health standards, and operational protocols to build a truly standardized intelligent production model.

7 Conclusions and Perspectives

Optimization of cultivation models is essential for improving the production efficiency of *Paeonia lactiflora*, as its growth is highly influenced by temperature, winter chilling requirements, and regional climatic conditions. Multi-criteria evaluation studies in low-latitude regions have identified ‘Qihua Lushuang’, ‘Hang Baishao’, ‘Meiju’, ‘Hongpan Tuojin’, and ‘Bo Baishao’ as highly adaptable germplasm resources, highlighting the importance of elite cultivar selection as the foundation for cultivation model optimization. Among them, ‘Hang

Baishao' exhibits strong heat-humidity tolerance and low chilling requirements, making it suitable for warm-winter regions. In addition, the integration of open-field and protected cultivation systems can effectively improve production efficiency by extending harvest periods and regulating flowering time, although precise environmental control remains necessary to maintain quality.

Continuous production management is critical for maintaining stable yield and medicinal quality in perennial *P. lactiflora* cultivation. Advances in embryo culture and tissue culture have significantly improved propagation efficiency, providing technical support for standardized seedling production. However, sustainable production still requires effective control of replanting obstacles, as long-term cultivation can disrupt soil microbial communities, reduce nutrient availability, and increase harmful microorganisms. Therefore, integrated management involving standardized propagation, soil health maintenance, optimized cultivation duration, and appropriate post-harvest processing is necessary. Regional studies suggest that four-year-old roots and late September harvesting can provide favorable yield-quality performance, while ecological cultivation approaches may further enhance paeoniflorin accumulation and medicinal quality.

Future development of the *P. lactiflora* industry should focus on green, standardized, and intelligent production systems integrating breeding, propagation, environmental regulation, and digital management. Standardized regeneration technologies, including optimized embryo culture and tissue culture systems, provide a foundation for rapid propagation and germplasm improvement. Meanwhile, the application of AI, IoT, remote sensing, and data-driven decision systems can enable real-time monitoring of environmental conditions, plant growth, irrigation, nutrition, and disease risks. Establishing standardized field datasets and intelligent management platforms will facilitate precision cultivation, improve resource utilization efficiency, and promote the sustainable development of the *P. lactiflora* industry.

Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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