

bulb yield, peimine and peiminine content, and net income by 6.4~23.8%, 2.1~26.6%, and 47.7~205.4%, respectively, and both yield and quality were positively correlated with potassium accumulation in underground parts. These findings show that nutrient accumulation indicators should include not only active alkaloid content, but also mineral accumulation and biomass partitioning to bulbs (Sui et al., 2021).

Physiological evaluation should also recognize that bulb quality is spatially heterogeneous within the bulb and dynamically shaped by ecological regulation. Multi-omics analysis showed that the outer scale layers were enriched in total alkaloids, peimine, and flavonoids by about 1.18-fold, 1.28-fold, and 1.24-fold, whereas the inner layers accumulated more sucrose and starch, at 1.37-fold and 2.18-fold of the outer layers (Wang et al., 2026). Shading increased active ingredient content by about 20.71% but reduced biomass by about 17.24%, while potassium under shading improved both medicinal substance accumulation and pharmacological performance, with the K2S treatment giving the best antitussive, expectorant, and anti-inflammatory effects (Liu et al., 2025). Biocontrol-agent application likewise significantly enhanced plant growth and increased steroidal alkaloids, including peimine and peiminine, while metabolomic profiling identified 48 alkaloids in treated and control bulbs (Cheng et al., 2023). Taken together, nutrient and physiological evaluation of *F. thunbergii* bulbs should combine targeted alkaloid quantification, carbohydrate and starch assessment, and responsiveness to cultivation conditions that affect biosynthesis pathways such as ABA signaling, oxidative phosphorylation, and alkaloid-related genes (Huang et al., 2024; Liu et al., 2025).

4.3 Establishment of bulb grading standards and quality control systems

A standardized production system for *F. thunbergii* bulbs should extend from raw-material evaluation to finished-product control, because herbal medicine quality cannot be assured by end-point testing alone. Standardization in herbal medicines is fundamentally the assurance of identification, quality, and purity across the whole life cycle, and current guidance emphasizes pharmacopoeial criteria, WHO-style standardization parameters, and in-process controls rather than isolated appearance checks. For *F. thunbergii*, a practical bulb grading system should therefore combine external grade descriptors with internal quality markers. Morphological descriptors should include bulb diameter, mass, uniformity, integrity, and disease-free status, while chemical grade descriptors should include peimine, peiminine, and broader alkaloid fingerprints (He et al., 2021; Zhang et al., 2026). The concept of quality markers (Q-markers) is particularly useful here, because it provides a basis for linking raw bulbs, processing stages, and final medicinal efficacy in one traceable system.

The quality control system should also specify the methods used at each stage. Raw bulbs should undergo documental, organoleptic, physicochemical, and microbiological evaluation, supported by macroscopic and microscopic examination, chromatographic analysis, and contaminant testing for heavy metals and other hazards. For chemical authentication and consistency control, HPLC-ELSD fingerprinting with multicomponent quantification has already shown that Zhejiang samples cluster together while some Jiangsu materials separate, indicating that fingerprint analysis can discriminate origin-related quality variation (He et al., 2021). LC-MS combined with chemometrics can further differentiate Zhejiang from non-Zhejiang materials and identify 11 alkaloid markers significantly correlated with external morphology, which supports a more rigorous origin-specific grading framework (Zhang et al., 2026). At the production level, standardized protocols should be implemented under propagation and cultivation, with proper documentation, personnel training, hygiene, SOPs, and traceability from bulb propagation to processing, because only this full-chain approach can stabilize the composition, safety, and clinical consistency of *F. thunbergii* products (Wang et al., 2023).

5 Large-scale Production Models and Applications of *Fritillaria thunbergii* Bulbs

5.1 Regionalized bulb propagation production models based on cultivation conditions

Regionalized production models for *Fritillaria thunbergii* bulbs should be built around the species' established cultivation belt in southeastern and central-eastern China, especially Zhejiang, Jiangsu, and Anhui, because production origin and local cultivation environment measurably affect both bulb quality and industrial suitability (He et al., 2021). Zhejiang remains the core region for geo-authentic production, and elite cultivars such as "Zhebei 3" have shown stable characters, higher yield, stronger disease resistance, and suitability for planting in