

explants (Hamdeni et al., 2022; Mehbub et al., 2022; Thakur et al., 2024). More generally, high-quality planting material for horticultural production should be genetically uniform, physiologically vigorous, and pathogen-free, and tissue culture is valued precisely because it can reduce disease transmission while accelerating multiplication (Bhardwaj et al., 2025). In *F. thunbergii*, micropropagation systems have been established from bulblet scales, stems, node-buds, and shoot tips, and explant age strongly affects response. Node-bud and young stem tissues can outperform bulb-scale segments, with young tissues below 3 cm shoot length showing stronger regeneration and a maximum multiplication rate of about 20-fold. Organogenic routes are also explant-specific, because many bulbs in culture are formed directly from axillary buds, and favorable kinetin concentrations for bulblet induction vary by source tissue from 1.0 to 5.0 mg/L.

The industrialization of tissue-culture propagation depends not only on multiplication, but also on stable dormancy release, acclimatization, genetic fidelity, and cost control (Hamdeni et al., 2022; Bhardwaj et al., 2025). In fritillary bulbs, dormancy is a major bottleneck, and low-temperature pretreatment is often essential for sprouting; in *F. thunbergii*, bulblets chilled at 5°C for 5 weeks and larger than 10 mm achieved 100% sprouting after transplantation. Broader fritillary evidence shows that short cold treatments can markedly improve sprouting, whereas prolonged chilling may reduce sprouting percentage, underscoring the need for calibrated dormancy-breaking protocols (Marković et al., 2021). For large-scale production of high-quality seed bulbs, current research also emphasizes species-specific protocol optimization rather than uniform historical recipes, along with early monitoring of somaclonal variation and the use of improved systems such as low-cost media strategies, molecular diagnostics, and bioreactor-supported propagation (Pasternak and Steinmacher, 2024).

4 Bulb Quality Evaluation and Standardized Production System of *Fritillaria thunbergii*

4.1 Evaluation of bulb morphological characteristics and external quality

The external quality evaluation of *Fritillaria thunbergii* bulbs should begin with macroscopic observation, because raw-material assessment in herbal medicines routinely starts from organoleptic and visual inspection of identity, appearance, and abnormalities (Wang et al., 2023). For *Fritillaria* bulbs specifically, morphological traits differ significantly among cultivated species, and these differences are useful for source identification and medication safety control. Among measured external traits, the short diameter of the bulb was identified as the most important indicator for distinguishing species, indicating that bulb size and shape should be core descriptors in *F. thunbergii* grading. Recent work on *Fritillariae thunbergii* Bulbus further argues that traditional morphological assessment should not be discarded, but integrated with chemical profiling because external traits can correlate with intrinsic quality parameters (Zhang et al., 2026).

In practice, morphological evaluation of *F. thunbergii* bulbs should include size uniformity, transverse and longitudinal diameter, fullness, surface integrity, color, and freedom from visible rot or blight lesions. This is especially important because bulb diseases can rapidly destroy commercial quality: in Zhejiang fields, blight incidence reached 20~25%, with early browning of the stalk followed by complete bulb rot within days (Xu et al., 2022). External morphology also reflects internal structural differences in storage materials, since *Fritillaria* starch granules vary in size and shape across species, and *F. thunbergii* starch granules ranged from 5 to 30 µm, supporting the view that bulb appearance is linked to underlying compositional traits. Because production origin affects quality, morphological assessment should also be interpreted together with provenance information, as Zhejiang and non-Zhejiang materials can differ enough to require origin authentication in market standardization (Zhang et al., 2026).

4.2 Evaluation of nutrient accumulation and physiological indicators of bulbs

The internal quality of *F. thunbergii* bulbs is determined primarily by the accumulation of alkaloids, carbohydrates, amino acids, nucleosides, and related metabolites, with steroidal alkaloids remaining the most important medicinal components (Nile et al., 2021; Cheng et al., 2023). Quantitative analysis of peimine and peiminine is therefore central to bulb evaluation, and cultivation studies show that these compounds respond strongly to management conditions. Organic fertilizer produced bulbs with peimine and peiminine contents of 0.060 3% and 0.050 2%, together with a yield of 2.70 kg/m² (Huang et al., 2024). Potassium fertilization increased