

Improving propagation efficiency also requires solving the linked bottlenecks of dormancy release, sanitary control, and field enlargement. In fritillaries, in vitro bulbs enter dormancy and cannot resume normal growth without low-temperature treatment, making dormancy management one of the main limiting steps in rapid multiplication (Marković et al., 2021). For *F. thunbergii*, cold treatment at 5°C for 5 weeks enabled 100% sprouting of bulblets larger than 10 mm, showing that post-culture handling can be standardized to improve transplant success. Sanitary risk is another obstacle, because repeated use of mother bulbs can transmit viral and fungal infection to daughter bulbs, while field blight caused by *Fusarium oxysporum* has already reached 20%~25% incidence in Zhejiang and can rot whole bulbs within days (Xu et al., 2022). Future large-scale supply systems should therefore combine pathogen-free micropropagation, resistant cultivar selection, and agronomic optimization, especially potassium and organic nutrient management, which increase yield, quality, and economic return while supporting more reliable bulb enlargement in the field (Sui et al., 2021; Huang et al., 2024).

6.2 Improving bulb quality evaluation and standardization systems

A major challenge in bulb standardization is that *F. thunbergii* quality varies with geographic origin, cultivation conditions, and post-harvest handling, which makes it difficult to define a single stable quality benchmark (Wang et al., 2023). Current evidence shows that origin authentication remains necessary: Zhejiang samples clustered together in HPLC-ELSD fingerprint analysis, whereas material from Nantong, Jiangsu separated from Zhejiang samples, likely because of different cultivation environments (He et al., 2021). A stronger future standardization system should therefore integrate external morphology with internal chemistry instead of relying on either alone (Zhang et al., 2026). This is feasible because bulb morphology and chemistry are both discriminative: among cultivated *Fritillaria* species, short bulb diameter was the most informative morphological identifier, while alkaloid and saponin contents helped distinguish morphologically similar materials.

Future quality evaluation should also move beyond a small number of marker compounds toward multicomponent and spatially resolved assessment. LC-MS chemometrics differentiated Zhejiang from non-Zhejiang *Fritillariae Thunbergii Bulbus* and identified 11 alkaloids as characteristic markers that correlated significantly with external morphological traits (Zhang et al., 2026). Processing studies further show that quality markers are not fixed across all product forms, because different processing methods altered steroidal alkaloid composition and revealed zhebeininoside and imperialine-3-β-D-glucoside as new control indicators (Shi et al., 2022). Quality standards should also account for within-bulb heterogeneity, since the outer bulb layers are enriched in total alkaloids, peimine, and flavonoids, whereas the inner layers accumulate more sucrose and starch (Wang et al., 2026). The most useful standardization framework is therefore a full-chain system linking morphology, fingerprinting, multicomponent quantification, origin tracing, and process control, consistent with broader herbal-medicine guidance that calls for molecular authentication, real-time monitoring, and shared industry standards across cultivation, harvesting, processing, and quality control (Wang et al., 2023).

6.3 Prospects of digital management and precision production technologies

Digital management and precision production technologies offer a realistic next step for *F. thunbergii* because the crop's quality and yield respond strongly to local variation in nutrients, light, disease pressure, and soil microecology (Huang et al., 2024; Liu et al., 2026). Precision agriculture research shows that IoT and AI can support real-time monitoring and data-driven decision-making, with soil, optical, and stress sensors already being used to optimize irrigation, fertilization, and pest management in crop systems (Miller et al., 2025; Mansoor et al., 2025). For *F. thunbergii*, this approach is especially relevant because potassium status can already be diagnosed dynamically through a potassium nutrition index based on leaf K concentration, providing a clear entry point for sensor-assisted nutrition management. Digital management could also improve ecological cultivation strategies by enabling site-specific regulation of shading and fertilization, which is important because shading raises active ingredient content but reduces biomass, while potassium under shading partly restores yield and improves medicinal performance (Liu et al., 2025).

The main future direction is to connect sensing, modeling, and field operations into integrated production platforms. Remote sensing and UAV-based systems are already widely used in precision agriculture for crop