

monitoring, nutrient management, disease detection, and yield prediction, although performance still depends on image resolution, growth stage, and environmental conditions (Sishodia et al., 2020). These tools could support *F. thunbergii* by enabling earlier disease detection, more reproducible field diagnosis, and simpler decision workflows for bulb fields, where current disease losses can be rapid and severe (Xu et al., 2022). Broader IoT work suggests that future systems will likely include digital twins, 5G or LPWAN-enabled connectivity, scalable sensor platforms, and AI-assisted prediction, but adoption will depend on lowering costs, improving usability, and addressing data ownership and cybersecurity concerns (Mansoor et al., 2025). In *F. thunbergii*, the long-term goal should be a precision production system that links propagation batches, storage conditions, nutrient diagnosis, disease warning, and quality fingerprint data, so that high-quality bulbs can be produced with greater consistency, lower waste, and stronger traceability across the full industrial chain (Wang et al., 2023; Liu et al., 2026; Zhang et al., 2026).

7 Conclusion

Bulb propagation remains the fundamental production pathway for *F. thunbergii*, because bulb reproduction has historically been the main domestication method in *Fritillaria*, has been commercially practiced in China for centuries, and is much faster than seed-based reproduction, which generally requires more than five years. At the same time, conventional vegetative propagation alone cannot meet modern industrial demand, because only a few daughter bulbs are produced annually from each mother bulb, conventional propagation is economically slow, and infected mother bulbs can transmit viral or fungal problems to progeny. The practical solution supported across studies is to combine field bulb propagation with rapid in vitro multiplication, since bulb-scale culture in *F. thunbergii* can produce an optimum of 13.7 bulblets per explant within 12 weeks, while young stem or node-bud explants can reach about 20-fold multiplication under suitable kinetin conditions. Stable production also depends on cultivar improvement and physiological regulation, as “Zhebei 3” showed higher yield, a bulb proliferation rate of 261.2%, a propagation coefficient of about 1:2.6, and stronger soft-rot resistance, while mechanistic work indicates that genes such as *FtGGPS* and ABA- and GA-related regulation are involved in bulb development and yield formation.

A standardized propagation system is necessary because *F. thunbergii* quality is highly sensitive to cultivation conditions, nutrient supply, geographic origin, and bulb developmental status. Fertilization studies show that standardization can improve both output and medicinal quality: organic fertilizer increased yield to 2.70 kg/m² while producing high peimine and peiminine contents, potassium fertilization increased bulb yield, quality, and net income, and an optimal K range of about 108.4–128.0 kg K₂ O/hm² or a practical target of 120 kg K₂ O/hm² was repeatedly supported. Standardization must also extend to quality evaluation, because HPLC-ELSD fingerprinting distinguished *F. thunbergii* from related species and showed clustering among Zhejiang samples, while LC-MS chemometric analysis identified 11 alkaloid markers and linked external morphology with internal chemical quality. Together, these findings support a propagation standardization framework that integrates elite cultivar selection, seed-bulb grading, nutrient diagnosis through leaf K-based indices, and coordinated morphological and chemical assessment so that propagation materials and medicinal bulbs can be managed under the same quality logic.

Future development of the *F. thunbergii* industry will depend on technological innovation that simultaneously expands bulb supply, protects wild resources, and improves ecological and economic sustainability. Tissue culture and morphogenesis technologies are central to this transition because they enable year-round multiplication from small explants, can use bulb scales as highly effective starting material, and are suitable for large-scale propagation when hormone balance, explant type, and dormancy management are optimized. Dormancy release remains a key technical bottleneck, but cold treatment at 5°C for 5 weeks enabled 100% sprouting of *F. thunbergii* bulblets larger than 10 mm, showing that propagation, storage, and transplant establishment can be linked into a controllable production chain. Sustainability-oriented innovations are also expanding beyond classical propagation, because biochar plus organic fertilizer improved understory yield, total alkaloids, soil nutrients, and rhizosphere microbial structure, shading plus potassium increased active ingredient accumulation while mitigating