

excessive pursuit of biomass or yield can reduce the accumulation of active ingredients and lower the proportion of bulbs meeting commercial standards, showing that productive performance and medicinal quality must be coordinated rather than treated separately (Liu et al., 2025). Recent cultivation studies further show that bulb yield and alkaloid quality are highly sensitive to agronomic conditions: organic fertilizer increased peimine and peiminine contents to 0.060 3% and 0.050 2%, respectively, while producing a yield of 2.70 kg/m², and potassium supply above 40 kg K₂O/hm² allowed bulb quality to meet Pharmacopoeia standards while 108.4~128.0 kg K₂O/hm² optimized yield. Shading likewise increased active ingredient accumulation by about 11.7% to 20.71%, but reduced bulb biomass by about 11.3% to 17.24%, whereas combined shading and potassium application partly alleviated the biomass penalty while improving medicinal constituent accumulation and pharmacological activity. These findings indicate that bulb quality is not merely a matter of size; it reflects a complex integration of physiological vigor, nutrient status, environmental adaptation, and secondary metabolite biosynthesis, including key pathways linked to ABA signaling and steroidal alkaloid accumulation. Consistent with this, variety differences also translate into propagation and production differences: the cultivar “Zhebei 3” showed a bulb proliferation rate of 261.2%, a propagation coefficient of about 1:2.6, higher yield, higher peimine plus peiminine content, and better resistance to bulb stem soft rot than controls (Jiang et al., 2019).

For *F. thunbergii*, securing high-quality propagation materials is especially important because conventional reproduction is inherently slow and faces biological and sanitary constraints. Across *Fritillaria*, bulb reproduction is the main domestication method and usually requires about 100 days to 3 years, whereas sexual reproduction by seed often takes more than five years, making rapid multiplication of elite materials difficult. In bulbous plants, natural propagation rates are generally low, only a few daughter bulbs are produced annually, and using limited mother-bulb material can increase the risk of transmitting viral and fungal infections to progeny bulbs (Marković et al., 2021). This has driven the development of rapid propagation and micropropagation technologies in *Fritillaria*, which are important not only for commercial multiplication but also for germplasm conservation and the production of healthy starting materials. For *F. thunbergii* specifically, high-frequency in vitro bulblet regeneration has already been achieved from bulb-scale explants, with an optimum of 13.7 bulblets per scale section on MS medium containing 1.62 µmol/L NAA and 4.65 µmol/L KN, leaf and root formation within 12 weeks, and 100% sprouting after transplanting when bulblets exceeded 10 mm following 5 weeks of cold treatment. Established tissue-culture systems for *F. thunbergii* and other medicinal *Fritillaria* species show that hormone composition, light, temperature, and dormancy release are key technical nodes, while regenerated bulbs may even accumulate more alkaloids than wild bulbs, though consistency in morphology and phytochemical profile remains a barrier to marketization (Qu et al., 2022).

Against this background, research on bulb propagation techniques of *F. thunbergii* should aim to integrate germplasm selection, healthy seed-bulb production, rapid multiplication, dormancy regulation, and quality-oriented cultivation into a scalable technical system for industrial application. Such research is significant because it can shorten propagation cycles, improve the multiplication coefficient of elite lines, stabilize field performance, and coordinate yield with medicinal quality, thereby addressing current bottlenecks in large-scale cultivation. It can also support sexual propagation and early seedling-bulb utilization, since seedling bulbs have been shown to reach the total alkaloid standard required by the Chinese Pharmacopoeia, providing a basis for expanding propagation pathways beyond traditional bulb splitting alone. In parallel, modern quality-evaluation tools, including HPLC fingerprinting and multicomponent quantification as well as hyperspectral imaging with deep learning, provide practical means for discriminating varieties, monitoring consistency, and strengthening standardized quality control of propagation materials and commercial bulbs. Therefore, systematic study of bulb propagation techniques and their large-scale production application is not only a technical need for improving the productivity and quality stability of *F. thunbergii*, but also a strategic requirement for safeguarding geo-authentic medicinal resources, enhancing industrial competitiveness, and promoting the sustainable development of the *F. thunbergii* industry.