

2.3 Main factors affecting bulb quality formation in *Fritillaria thunbergii*

Bulb quality formation in *F. thunbergii* depends on the interaction of genotype, cultivation year, nutrient supply, light environment, and rhizosphere ecology, and quality must be understood as both biomass performance and accumulation of steroidal alkaloids such as peimine and peiminine (Nile et al., 2021). Genotypic differences are already evident in elite materials: “Zhebei 3” had a bulb proliferation rate of 261.2%, a propagation coefficient of about 1:2.6, higher yield, higher combined peimine and peiminine content, and better resistance to bulb stem soft rot than controls (Jiang et al., 2019). Cultivation duration also changes bulb output, because yield increased by 88% at two years and 189% at three years relative to one year, although the proportion of bulbs heavier than 5 g declined from 89% at one year to 77% at three years, indicating a trade-off between cumulative yield and size structure. Quality control studies further show that production origin and cultivation environment can shift chemical profiles, since Zhejiang samples clustered together whereas Nantong, Jiangsu material separated from them in HPLC fingerprinting analyses (He et al., 2021).

Nutrient and ecological management have especially strong effects on medicinal quality formation. Fertilization influences both yield and quality, and organic fertilizer gave the best combined performance in one recent study, with peimine and peiminine contents of 0.060 3% and 0.050 2% and a yield of 2.70 kg/m² (Huang et al., 2024). Potassium is particularly important: bulb quality met Pharmacopoeia standards above 40 kg K₂O/hm², yield rose to a plateau above about 120 kg K₂O/hm², and the optimal K range for yield was 108.4~128.0 kg K₂O/hm². Shading increased active ingredient accumulation by about 11.7~20.71% but reduced bulb biomass by about 11.3~17.24%, whereas combining shading with potassium partly offset the biomass penalty and enhanced steroidal alkaloid accumulation and pharmacological activity (Liu et al., 2025). Soil-centered strategies also matter: compost and manure increased yield and marketable proportion in older fertilizer trials, while recent understory work showed that biochar plus organic fertilizer improved yield, total alkaloids, soil nutrients, beneficial microbes, and overall rhizosphere function (Liu et al., 2026). At the mechanistic level, bulb quality formation appears to involve both plant metabolic regulation and microecological mediation, including ABA signaling, FtFPS-linked steroidal alkaloid biosynthesis, and rhizosphere microbial groups positively associated with medicinal component accumulation (Huang et al., 2024).

3 Key Technologies for Bulb Propagation of *Fritillaria thunbergii*

3.1 Conventional bulb division propagation technology and its application characteristics

Conventional bulb division propagation of *Fritillaria thunbergii* is based on the natural renewal pattern of mother bulbs producing daughter bulbs, and this has long been the principal domestication and commercial reproduction route for the species (Li et al., 2019). In *Fritillaria* more broadly, vegetative multiplication through bulb splitting remains standard because seed propagation is slow and of limited practical value for production, with seedlings requiring many years to develop usable bulbs. Evidence from the related medicinal species *F. cirrhosa* provides a comparative example of in vitro bulblet regeneration (Figure 1) (Chang et al., 2020; Marković et al., 2021; Thakur et al., 2024). The main advantage of this method is that it is simple, field-adapted, and does not require specialized facilities, so it remains suitable for traditional production bases and routine nursery multiplication of locally adapted germplasm (Hasnain et al., 2022; Bhardwaj et al., 2025). Its practical application also depends strongly on varietal traits, because elite cultivars differ in multiplication coefficient, bulb vigor, and disease resistance, as shown by “Zhebei 3,” which had a bulb proliferation rate of 261.2%, a propagation coefficient of about 1:2.6, and better resistance to bulb stem soft rot than the controls.

The main limitation of conventional division is its inherently low propagation rate, since only a few daughter bulbs are produced from each mother bulb annually, making it difficult to meet the demand for rapid expansion of standardized planting materials (Chang et al., 2020). This method also carries a sanitary risk, because repeated use of mother bulbs can transfer viral and fungal infections to daughter bulbs and gradually reduce population health. In addition, conventional vegetative propagation in bulbous crops is often economically inefficient because development is slow and commercial profitability may require several years (Marković et al., 2021). For that reason, conventional division in *F. thunbergii* is best understood as a reliable but slow baseline technology, most