

Storage and post-propagation handling are equally important because dormancy is a major bottleneck in bulb multiplication systems. Bulbs produced in vitro enter dormancy and must undergo controlled low-temperature treatment before uniform sprouting in the next vegetation cycle (Marković et al., 2021). For *F. thunbergii*, bulblets chilled at 5°C for 5 weeks and larger than 10 mm achieved 100% sprouting after transplantation, showing that storage protocols can be standardized around bulb size and chilling duration. Related *Fritillaria* studies also show that bulbs are often stored at 4°C before regeneration or acclimatization to improve regeneration capacity and dormancy breaking, while successful bulblet systems depend on low-temperature pretreatment, rooting, and ex vitro enlargement (Muraseva and Novikova, 2018; Marković et al., 2023). Direct evidence for mechanized production in *F. thunbergii* is limited in the supplied literature, but the available studies consistently support the technological logic of integrating standardized propagules, cold-chain dormancy management, uniform field planting, and scalable acclimatization, which are the biological prerequisites for later mechanized transplanting, harvesting, grading, and handling (Sharma et al., 2023).

5.3 Promoting the development of the *Fritillaria thunbergii* industry through the application of high-quality bulbs

Applying high-quality bulbs can directly strengthen the *F. thunbergii* industry because the crop faces high market demand but persistent production bottlenecks related to unstable yield, reduced medicinal quality under yield-oriented cultivation, and inefficient expansion systems (Sui et al., 2021; Liu et al., 2025). High-quality bulbs should be understood as bulbs that combine strong propagation performance, disease resistance, and high alkaloid accumulation, as exemplified by “Zhebei 3,” whose average yield reached 5 095.5 kg/hm², bulb proliferation rate 261.2%, propagation coefficient about 1:2.6, and peimine plus peiminine content 0.172 2% (Jiang et al., 2019). High-quality starting bulbs also support varietal upgrading and molecular breeding, because bulb development differs among cultivars and is associated with genes such as *FtGGPS*, which regulates bulb development through GA and ABA dynamics (Xu et al., 2026). At the germplasm level, breeding methods that shorten selection cycles and improve heat resistance, propagation coefficient, and absolute yield can further expand the supply base for industrial seed bulbs.

Industrial promotion also depends on proving and preserving product quality from bulb to market. *F. thunbergii* bulbs have broad pharmacological value and are used medicinally for cough, inflammation, bronchitis, and related disorders, so stable alkaloid quality is central to industry credibility and market expansion (Nile et al., 2021; Liu et al., 2025). Quality control systems based on HPLC-ELSD fingerprinting and multicomponent analysis can distinguish production origins and support standardized evaluation of commercial bulbs and propagation materials (He et al., 2021). Artificial cultivation and in vitro propagation also have strategic value beyond productivity, because they reduce pressure on wild *Fritillaria* resources, improve supply security, and fit the broader trend toward sustainable domestication of medicinal bulb crops (Qu et al., 2022). Therefore, the large-scale application of high-quality bulbs is not only a technical measure for raising yield and quality, but also a core pathway for strengthening regional brands, stabilizing medicinal standards, and promoting the sustainable modernization of the *F. thunbergii* industry.

6 Current Challenges and Future Development Directions

6.1 Improving bulb propagation efficiency and large-scale supply capacity

A central constraint on the large-scale supply of *Fritillaria thunbergii* bulbs is that conventional vegetative propagation remains inherently slow, while seed reproduction takes several years and therefore cannot rapidly expand elite planting material. This supply problem is economically important because market demand for dried *F. thunbergii* bulbs is high, yet production systems still struggle to deliver stable yield and quality at industrial scale (Sui et al., 2021; Cheng et al., 2023; Liu et al., 2025). The most immediate development direction is therefore to integrate conventional seed-bulb propagation with rapid multiplication systems based on bulb scales and tissue culture, which can greatly raise multiplication efficiency from limited source material (Marković et al., 2021). In *F. thunbergii*, bulb-scale culture already supports this transition, because scale sections on optimized MS medium produced 13.7 bulblets per explant and formed leaves and roots within 12 weeks.