

cultivation environment, yield formation, and peimine accumulation in *F. thunbergii*, providing theoretical references for ecological suitability zoning, standardized cultivation, optimization of high-quality and high-yield cultivation techniques, and construction of a coordinated yield-quality evaluation system. It also offers practical insights for the green, standardized, and sustainable development of the *F. thunbergii* industry.

2 Growth and Development Characteristics of *Fritillaria thunbergii* and Features of Peimine Accumulation

2.1 Biological characteristics and growth cycle of *Fritillaria thunbergii*

Fritillaria thunbergii Miq. is a perennial geophyte of the genus *Fritillaria* in the family Liliaceae. Its underground bulb is used medicinally, serving not only as a storage organ for nutrients but also as the main site for the accumulation of steroidal alkaloids such as peimine and peiminine (Nile et al., 2021; Huang et al., 2024a). The plant usually develops aboveground stems and leaves from sprouting bulbs. The leaves perform photosynthesis, and the photosynthetic products are gradually allocated to the underground bulbs through assimilate transport, thereby supporting bulb enlargement and the accumulation of medicinal constituents. *F. thunbergii* is suitable for growth in mild, humid, cool, well-ventilated environments with loose soil and good drainage. It is relatively sensitive to high temperature, waterlogging, and soil compaction. At present, commercial production mainly relies on artificial cultivation systems, and some cultivation patterns regulate light and microclimate through field shading facilities to simulate its native shaded mountain habitats, thereby improving the plant growth environment and the conditions for bulb quality formation (Liu et al., 2025a).

In terms of growth cycle, *F. thunbergii* generally undergoes several stages, including bulb dormancy, dormancy release, sprouting and emergence, leaf expansion and vegetative growth, bulb enlargement, and aboveground withering. During dormancy, the bulb mainly undergoes physiological regulation and nutrient storage, laying the foundation for sprouting in the following growing season. Studies have shown that storing *F. thunbergii* bulbs at low temperatures of 4°C~10°C for several weeks can reduce the content of phenolic compounds and alter the activities of phenylalanine ammonia-lyase (PAL) and polyphenol oxidase (PPO), changes that are closely associated with dormancy release. In vitro and ex situ studies on *Fritillaria* bulbs have also shown that appropriate temperature regimes and gibberellin (GA) signaling contribute to fresh weight increase and sprouting, whereas unsuitable conditions may delay growth and prolong dormancy (Marković et al., 2020; Marković et al., 2021). In addition, micropropagation systems established using bulb scale sections can regenerate numerous bulblets within a short period, but these bulblets still require cold treatment to achieve synchronized sprouting. This indicates that the rhythm of “dormancy-cold induction-sprouting growth” is an important developmental pattern in *F. thunbergii* and related *Fritillaria* species.

Bulb development in *F. thunbergii* is also jointly regulated by plant hormones and genetic factors. Transcriptomic studies have found that the GGPS1 family gene FtGGPS can influence bulb development and differences in bulb size among cultivars by regulating the levels of gibberellin (GA) and abscisic acid (ABA) (Xu et al., 2026). Meanwhile, ABA-related signaling is also considered to be associated with increased bulb yield under certain fertilization regimes, indicating that the growth cycle of *F. thunbergii* is regulated not only by external environmental factors such as temperature, light, and water, but also by finely tuned endogenous hormone signaling (Huang et al., 2024a). Therefore, when understanding the growth and developmental patterns of *F. thunbergii*, it should be regarded as the result of the combined effects of environmental factors, hormonal regulation, photosynthate accumulation, and bulb storage function.

2.2 Major Factors influencing yield formation in *Fritillaria thunbergii*

The yield of *F. thunbergii* mainly depends on the number of effective plants per unit area, single-bulb weight, degree of bulb enlargement, and marketable traits. Among these factors, seed bulb quality is the fundamental condition for yield formation. Plump, healthy, disease-free seed bulbs usually have stronger sprouting capacity and growth vigor, which can improve emergence rate and population uniformity. In contrast, small, diseased, or improperly stored seed bulbs may easily cause uneven emergence, weakened growth, and disease transmission, ultimately affecting bulb enlargement and yield stability. Since the underground bulb is both the medicinal and