geo-authentic areas and peimine accumulation, thereby providing a basis for quality improvement and origin authentication of *F. thunbergii*.

6.3 Effects of open-field cultivation, understory cultivation, facility cultivation, and other patterns on yield and quality

Open-field cultivation is a relatively common production pattern for *F. thunbergii*, with the advantages of relatively simple management, low production cost, and suitability for large-scale cultivation. In suitable production areas and under good field management conditions, open-field cultivation can meet the basic growth requirements of *F. thunbergii* and produce relatively stable bulb yield. Traditional open-field cultivation of *F. thunbergii* in areas such as Pan'an mainly depends on local climatic conditions and fertilization management, while optimized organic fertilizer application and potassium fertilization have been shown to simultaneously increase bulb yield and peimine content (Sui et al., 2021; Huang et al., 2024a). However, open-field cultivation is highly dependent on natural climate and is vulnerable to strong light, high temperature, continuous rainfall, drought, and disease. Without effective shading, drainage, and soil management measures, premature senescence of aboveground parts, poor bulb development, or quality fluctuations may occur. Therefore, open-field cultivation should focus on coordinated management of light, temperature, water, and fertilizer, as well as disease control. Especially in years with large climatic fluctuations, cultivation stability should be improved through shading, water-fertilizer regulation, and drainage measures.

Understory cultivation and semi-wild cultivation patterns can improve the growth environment of *F. thunbergii* to some extent. Understory environments are characterized by moderate shading, buffered temperature changes, higher air humidity, richer soil organic matter, and more complex microbial communities. These conditions help alleviate strong light and high-temperature stress, prolong the functional period of leaves, and create a relatively stable ecological environment for bulb enlargement and active constituent accumulation. Reviews on understory cultivation indicate that the lower light intensity, buffered temperature and humidity, altered soil fertility, and microbial communities in understory environments may significantly increase or decrease the yield and quality of medicinal plants compared with open-field cultivation, depending on species characteristics and stand structure (Li et al., 2025; Wen et al., 2025). For *F. thunbergii*, understory cultivation combined with soil amendments such as organic fertilizer and biochar can optimize soil and rhizosphere microecology, helping improve bulb yield and alkaloid quality compared with traditional cultivation patterns (Liu et al., 2026). However, understory or semi-wild patterns also have limitations, such as greater management difficulty, larger yield fluctuations, and limited mechanization. Therefore, refined regulation should be carried out according to forest stand type, canopy closure, soil conditions, and water status.

Facility cultivation provides a new approach for precise environmental regulation in *F. thunbergii*. Through temperature and humidity control, shading management, water-fertilizer regulation, and disease control under facility conditions, the adverse effects of extreme weather on production can be reduced, while emergence uniformity, plant growth stability, and yield controllability can be improved. Studies on other medicinal plants help explain the mechanisms of different cultivation patterns. For example, in *Epimedium pubescens*, inter-row understory cultivation under different tree species can produce yields and active constituent contents comparable to or higher than open-field controls when microclimatic conditions such as air humidity are suitable, whereas excessive shading under dense canopies reduces yield (Li et al., 2026). Shading experiments and agroforestry studies on aromatic and medicinal plants have also shown that mild to moderate shading, approximately 30%~40%, usually slightly reduces biomass but can increase essential oil or active constituent contents; heavy shading, exceeding 50%~75%, significantly reduces yield and does not necessarily bring further quality improvement (Zubay et al., 2021; Şeker et al., 2023). Therefore, different cultivation patterns each have advantages and limitations. They should be selected according to production-area conditions, production goals, and cost effectiveness. Guided by ecological and omics data, the advantages of open-field cultivation, understory cultivation, and facility cultivation should be integrated to construct standardized production patterns that balance high bulb yield, high peimine content, and ecological sustainability.