water is insufficient or excessive, normal plant metabolism may be disrupted, leading to unstable accumulation of active components and affecting medicinal quality. Studies on related medicinal plants have shown that moderate water deficit can sometimes increase alkaloids or other secondary metabolites, whereas severe stress leads to decreased biomass and quality fluctuations. For example, in summer snowflake (*Leucojum aestivum*), moderate water deficit stress, namely 50% deficit irrigation, resulted in higher levels of bulb alkaloids such as galanthamine and lycorine, as well as phenolic compounds and antioxidant capacity, whereas severe stress or waterlogging reduced fresh weight and did not further increase alkaloid content (Baba et al., 2024).

Moderate water regulation helps achieve coordinated improvement of yield and quality. In the early growth stage of *F. thunbergii*, soil should be kept moderately moist to promote sprouting, emergence, and root formation. During vegetative growth and bulb enlargement, stable water supply should be ensured to avoid premature leaf senescence caused by water shortage. In the late growth stage and before harvest, water should be appropriately controlled according to soil conditions and weather changes to reduce waterlogging and disease occurrence and promote bulb maturation and filling. Studies on *Atractylodes chinensis* have shown that moderate irrigation levels can maintain relatively high yield while maximizing alkaloid-related enzyme activities and quality indicators; the quality peak occurs at an intermediate irrigation level rather than under maximum water supply (Lv et al., 2026). In *Datura stramonium*, gradient irrigation creates different tropane alkaloid profiles in different organs, indicating that soil water supply can serve as a cultivation measure for regulating the accumulation of specific alkaloids (Moreno-Pedraza et al., 2019). These studies provide insights for water regulation in *F. thunbergii*: controlled and non-severe mild water deficit may help enhance peimine accumulation, provided that bulb biomass and marketability are not significantly sacrificed.

In production practice, water regulation should be integrated with soil improvement, ridge and ditch construction, disease control, and water-fertilizer coordinated management. Selecting well-drained fields, adopting high-ridge cultivation, improving ditch drainage systems, applying mulching for moisture conservation, and conducting scientific irrigation according to rainfall conditions can all help maintain suitable soil moisture. Reviews on drought and medicinal plant physiology indicate that mild to moderate stress usually stimulates the formation of secondary metabolites such as phenols, flavonoids, and alkaloids, whereas severe or prolonged stress leads to yield collapse and unstable quality (Bistgani et al., 2024; Tan and Gören, 2024). Studies combining water and nutrient management have also shown that under 70%~75% of maximum water-holding capacity combined with moderate nitrogen supply, *Sophora alopecuroides* can achieve relatively high biomass and alkaloid accumulation while promoting the formation of specific rhizosphere microbial communities (Huang et al., 2024b). Therefore, for *F. thunbergii*, water management should avoid long-term drought and frequent waterlogging, with stable soil moisture close to field capacity as the basic goal. After experimental verification, short-term, precise, and mild water deficit treatments may be explored to promote peimine accumulation. Establishing a management system centered on soil moisture monitoring, rational irrigation and drainage, and rhizosphere environment optimization can improve yield stability and consistency of peimine content in *F. thunbergii*, thereby providing support for the production of high-quality medicinal materials.

5 Effects of Soil Environment on the Yield of *Fritillaria thunbergii* and Peimine Accumulation

5.1 Relationship among soil texture, aeration, and bulb development

Soil is an important medium for root growth, bulb enlargement, and active constituent accumulation in *Fritillaria thunbergii*, and its texture and structure directly affect the development of underground organs. Since the bulb is the medicinal part of *F. thunbergii*, whether the underground part can fully enlarge is closely related to soil looseness, pore distribution, water and nutrient retention capacity, and mechanical resistance. Soil texture determines pore size distribution, aeration, and water-holding capacity, thereby influencing root penetration capacity and the supply of carbohydrates to underground storage organs. Relevant meta-analyses have shown that coarse sandy soils drain rapidly but have weak nutrient retention capacity, whereas heavy clay soils have stronger water and nutrient retention capacity but are prone to poor aeration and waterlogging. Loamy soils with appropriate proportions of sand, silt, and clay usually balance aeration, water retention, and fertility, making them