Temperature integrates with light signals to jointly regulate developmental processes and metabolic allocation in *F. thunbergii*. Low-temperature treatment can regulate bulb dormancy and phenolic metabolism, indirectly affecting the length of the growth period available for alkaloid accumulation; subsequent moderately warm conditions help enhance photosynthetic capacity and biomass formation (Marković et al., 2020). Controlled-environment studies have shown that higher temperature can synergize with lower light intensity and extended photoperiod to promote leaf expansion and total photon capture, thereby increasing biomass without reducing secondary metabolite levels under suitable spectral conditions (Jeong et al., 2025). In *Fritillaria* systems, in vitro studies have shown that a defined temperature of approximately 25°C combined with controlled light quality can significantly increase the contents of peimine and related isosteroidal alkaloids in callus or seedlings (Chen et al., 2020; Peng et al., 2024). Therefore, in the cultivation of *F. thunbergii*, light and temperature management should take into account both yield formation and peimine accumulation. Through moderate shading, sufficient low-temperature treatment, suitable growing-season temperature, field ventilation, and microclimate regulation, high peimine content can be promoted while maintaining acceptable bulb yield.

4 Effects of Water Conditions on the Yield of *Fritillaria thunbergii* and Peimine Accumulation

4.1 Effects of soil moisture on root growth and bulb development

Water is an important ecological factor affecting the growth, development, and yield formation of *Fritillaria thunbergii*. *F. thunbergii* prefers moist conditions but is intolerant of waterlogging. Since both its roots and bulbs grow in the soil, they are sensitive to changes in soil water content and its spatial distribution. Appropriate soil moisture can maintain normal root extension and absorption functions, promote the uptake and transport of mineral nutrients, and provide necessary conditions for aboveground growth and underground bulb enlargement. Rhizobox and soil column studies have shown that root growth is mainly driven by the vertical distribution of soil moisture. Roots tend to proliferate in moist soil layers, whereas root elongation is inhibited when soil moisture falls below a critical threshold. After local soil rewetting, roots can dynamically adjust growth allocation within 48 h, showing a clear “hydromatching” phenomenon (Maan et al., 2023; Ceolin et al., 2025). This suggests that maintaining a suitable and relatively uniform moisture environment within the main rooting depth of *F. thunbergii* is conducive to continuous root exploration of the soil space, stable water and nutrient supply, and sustained bulb enlargement.

In the early growth stage of *F. thunbergii*, suitable soil moisture helps promote seed bulb sprouting, uniform emergence, and root establishment. Well-developed roots enhance plant utilization of water and nutrients and improve population growth uniformity. After entering the vegetative growth and bulb enlargement stages, the plant’s demand for water supply further increases. At this stage, if soil moisture is sufficient and aeration is good, leaves can maintain high photosynthetic efficiency, allowing assimilates to be continuously transported to underground bulbs and promoting bulb filling and dry matter accumulation. Studies have shown that as roots develop, they can alter soil structure and form subzones with high, medium, and low moisture levels. After irrigation, moisture changes rapidly in the near-root zone, whereas soil moisture farther from the roots remains relatively stable (Zhang et al., 2021). This indicates that water management in *F. thunbergii* should focus not only on overall field soil water content, but also on the spatiotemporal changes in moisture within the rhizosphere microenvironment.

It should be noted that the water requirement of *F. thunbergii* does not mean that more water is always better; instead, it emphasizes the coordination between moisture and aeration. Soil moisture stability is as important as absolute water content. Studies on tomato seedlings have shown that, compared with fluctuating moisture conditions, maintaining stable soil moisture through precise water replenishment can improve shoot and root morphology, photosynthesis, and water-use efficiency, even when the average water content is similar (Li et al., 2023). For *F. thunbergii*, which depends on a healthy fibrous root system to provide carbohydrates and precursors for steroidal alkaloid biosynthesis, avoiding large fluctuations between dry and wet soil conditions may be important for uniform bulb development and stable peimine accumulation. If soil moisture is excessive, soil pores become filled with water, restricting root respiration and reducing root vitality. Meanwhile, because the bulb