bulbs (Huang et al., 2024a; Liu et al., 2025a). The application of biocontrol agents during cultivation can not only improve plant growth, but also increase the contents of peimine, peiminine, and other steroidal alkaloids. This effect may be related to the regulation of key enzyme activities, oxidative phosphorylation, amino acid metabolism, cytochrome P450 enzymes, and transcription factors such as MYB and bHLH (Cheng et al., 2023). From the perspective of quality evaluation, the quality of *F. thunbergii* should not be judged solely by yield, but should be comprehensively evaluated based on bulb size, morphology, dry matter content, peimine and peiminine contents, safety, and pharmacological indicators. Given the central role of peimine, peiminine, and related steroidal alkaloids in antitussive, anti-inflammatory, and other pharmacological effects, they are widely regarded as core quality markers of *F. thunbergii*. They constitute an important basis for modern chromatographic quality evaluation systems and provide a foundation for linking cultivation environment with clinical efficacy (Nile et al., 2021; Zhou et al., 2023; Zou et al., 2026).

3 Effects of Light and Temperature Conditions on the Yield of *Fritillaria thunbergii* and Peimine Accumulation

3.1 Effects of light intensity and shading conditions on plant growth

Light is an important environmental factor affecting aboveground growth, photosynthesis, and dry matter accumulation in *Fritillaria thunbergii*. During growth, *F. thunbergii* relies on its leaves for photosynthesis, converting light energy into organic matter, which is subsequently transported to the underground bulbs for bulb enlargement and the accumulation of medicinal constituents. Appropriate light intensity helps improve leaf photosynthetic efficiency, promotes robust plant growth, and prolongs the functional duration of leaves, thereby providing sufficient material basis for subsequent bulb formation. Existing studies have shown that light intensity directly constrains photosynthesis and dry matter accumulation in *F. thunbergii*, and excessive shading significantly inhibits carbon assimilation and plant growth. Under strong shading conditions, namely approximately 5% light transmittance, bulb biomass and yield of *F. thunbergii* decline significantly; compared with full light, shading treatment can reduce bulb biomass and yield by approximately 17% and 9%, respectively (Liu et al., 2025a). Single-factor shading experiments have also shown that although shading can increase the content of active ingredients, shading alone can reduce bulb biomass by approximately 11%. This indicates that *F. thunbergii* still requires a certain light basis to achieve high yield, and yield loss increases when light intensity falls below its photosynthetic requirement.

However, *F. thunbergii* is not suitable for long-term growth under conditions of both strong light and high temperature. Excessively strong light can accelerate leaf water loss, damage the photosynthetic system, and promote premature senescence. Especially in late spring, when temperatures rise, strong light may aggravate heat stress, causing early withering of the aboveground parts and shortening the effective growth period. Since yield formation in *F. thunbergii* depends on the continuous transport of assimilates from the aboveground parts to the bulbs, premature leaf senescence directly affects underground bulb enlargement and dry matter accumulation. Therefore, in cultivation practice, light conditions should be reasonably regulated according to the climatic characteristics of the production area and the growth stage, so as to avoid growth imbalance caused by excessively weak or excessively strong light. Under low-light conditions, *F. thunbergii* exhibits certain morphological and physiological plasticity, such as enhancing light capture by adjusting leaf traits and chlorophyll content. This is similar to the phenomenon observed in crops such as strawberry, where low light reduces photosynthetic rate and growth but increases pigment content and alters leaf area (Liu et al., 2025a).

Moderate shading is an important measure for improving the field microclimate of *F. thunbergii*. Shading cultivation can reduce light intensity and surface temperature, alleviate damage caused by direct strong light to leaves, help maintain soil moisture, and improve the plant growth environment. Understory cultivation and sunshade-net cultivation can, to some extent, simulate the cool and humid ecological requirements of *F. thunbergii*, helping delay premature senescence of the aboveground parts and maintain relatively stable photosynthetic function. However, the degree of shading must be properly controlled, as excessive shading reduces photosynthetic accumulation and is unfavorable for bulb enlargement. Studies have shown that sufficient