commercial part of *F. thunbergii*, yield formation is essentially the result of a continuous process involving aboveground photosynthetic establishment, assimilate accumulation, and underground bulb enlargement. Therefore, production should emphasize germplasm selection, seed bulb grading, pre-sowing treatment, and population establishment quality to lay a foundation for high yield in later stages.

Cultivation environment is the core external factor affecting yield formation in *F. thunbergii*. Nutrient management, light conditions, and rhizosphere microecology are currently key research directions. Field experiments have shown that different types of basal fertilizers have significant effects on the yield and quality of *F. thunbergii*. Among them, organic fertilizer treatment can produce higher bulb yield and higher peimine and peiminine contents than raw chicken manure or plant ash, indicating that organic fertilizer has a better coordinating effect between biomass accumulation and alkaloid formation (Huang et al., 2024a). Potassium nutrition is also an important factor affecting dry matter formation. Within an appropriate application range, potassium fertilizer significantly increases bulb biomass and yield by approximately 4%~11% compared with the unfertilized control, suggesting that potassium contributes to assimilate transport, bulb filling, and yield formation (Liu et al., 2025a). Therefore, rational fertilization, especially the combination of organic fertilizer input and appropriate potassium application, is an important technical pathway for improving the yield and quality of *F. thunbergii*.

Light intensity and its associated microclimate exert dual effects on yield formation in *F. thunbergii*. Suitable light is beneficial for leaf photosynthesis and dry matter accumulation, whereas insufficient light limits carbon assimilation and reduces bulb biomass. However, moderate shading may also improve field temperature and humidity conditions and alleviate strong light and high-temperature stress. Studies have shown that strong shading can significantly increase the concentration of bioactive components in bulbs, but it reduces biomass and overall yield, and severe yield reduction may occur under extremely low light transmittance. Moderate shading combined with appropriate potassium supply can partially compensate for shading-induced yield reduction while maintaining or increasing active component content (Liu et al., 2025a). In addition, rhizosphere microbial communities are also involved in regulating the balance between yield and quality. Shading and potassium can jointly alter soil pH and available nutrient status, enriching bacterial and fungal groups positively correlated with bulb growth and medicinal constituent accumulation, such as *Allorhizobium-Neorhizobium-Pararhizobium-Rhizobium*, *Burkholderia-Caballeronia-Paraburkholderia*, *Chryseobacterium*, *Brevundimonas*, and *Phoma*. This indicates that yield formation in *F. thunbergii* is not determined by a single factor, but by the coordinated effects of light, nutrients, rhizosphere microecology, and field management.

2.3 Types, accumulation characteristics, and quality evaluation significance of peimine

Peimine is an important steroidal alkaloid active component in *F. thunbergii* and serves as an important material basis for evaluating its medicinal quality. Among these components, peimine is a cevanine-type steroidal alkaloid and often coexists in *F. thunbergii* bulbs with peiminine, peimisine, imperialine, and other steroidal alkaloids (Nile et al., 2021; Shan et al., 2022). Metabolomic studies have shown that peimine, peiminine, and related cevanine-type alkaloids are relatively abundant alkaloid components in *Fritillaria* species, especially in bulb tissues, where their contents are usually higher than those in aboveground parts (Liao et al., 2023). In aqueous and hydroethanolic extracts of *F. thunbergii* bulbs, peimine, peiminine, peimisine, and their glycosides have been identified as major components using UPLC-QTOF-MS and other techniques, with characteristic fragmentation patterns further confirming the structures of these compounds (Huang et al., 2024a; Jeong et al., 2024; Zou et al., 2026). Therefore, peimine-type components are not only important constituents of the pharmacodynamic basis of *F. thunbergii*, but also provide detectable and quantifiable chemical indicators for modern quality evaluation.

Peimine accumulation shows obvious organ specificity and stage specificity. Since the bulb is the medicinal part of *F. thunbergii*, it is both the core site of yield formation and an important site of peimine accumulation. In the early growth stage, vegetative growth and leaf establishment predominate, and photosynthetic products are mainly used for the development of aboveground parts and roots. As growth progresses, assimilates are gradually transported to the underground bulbs, bulb enlargement and secondary metabolic activity are enhanced, and the