7 Mechanistic Analysis of Cultivation Environment Regulation of Yield and Peimine Accumulation in *Fritillaria thunbergii*

7.1 Regulatory mechanisms of environmental factors on photosynthesis and dry matter accumulation

The basis of yield formation in *Fritillaria thunbergii* lies in plant photosynthesis, carbon assimilation, and dry matter accumulation, which are jointly affected by environmental factors such as light, temperature, water, soil fertility, and the root-zone environment. Leaves are the main organs for photosynthesis in *F. thunbergii*. Appropriate light can improve leaf light-use efficiency and promote organic matter synthesis, while suitable temperature helps maintain enzyme activity and cellular metabolism, allowing plants to sustain strong physiological activity. Existing studies have shown that, in *F. thunbergii*, shading within a certain range reduces the net photosynthetic rate, but plants can partially compensate by increasing chlorophyll content and adjusting leaf traits. However, excessive shading markedly inhibits biomass accumulation and bulb yield (Liu et al., 2025a). Meanwhile, appropriate potassium fertilization under shading conditions can alleviate the decline in bulb biomass, indicating that improved mineral nutrition can partially restore photosynthetic capacity and carbon fixation. Studies on other medicinal plants have also shown that moderate nitrogen application or balanced nitrogen, phosphorus, and potassium supply can optimize leaf dry weight, total biomass, and photosynthetic rate, whereas nitrogen deficiency or excessive nitrogen application may reduce photosynthesis by limiting chlorophyll formation, inducing reactive oxygen species damage, or downregulating photosynthetic antenna-related genes (Yang et al., 2024). Therefore, the influence of environmental factors on the yield of *F. thunbergii* is first reflected in the regulation of leaf photosynthetic carbon capture capacity.

The transport of dry matter from the aboveground parts to the underground bulbs is a key process in yield formation in *F. thunbergii*. During the vegetative growth stage, plants synthesize carbohydrates through leaves and use them for stem and leaf growth, root development, and bulb filling. After entering the bulb enlargement stage, assimilates are gradually transferred to the underground parts, and the bulbs become the main storage organs. At this stage, the stability of environmental conditions directly determines the efficiency of dry matter accumulation. Suitable soil moisture and nutrient supply can enhance root absorption capacity and maintain continuous photosynthesis in the aboveground parts, while good soil aeration supports root respiration and energy metabolism, thereby promoting the transport of assimilates to the bulbs. Temperature and root-zone conditions also regulate photosynthetic performance and biomass formation. Studies on hydroponically grown medicinal plants have shown that air temperature and root-zone temperature significantly affect photosynthesis, nutrient uptake, leaf growth, and secondary metabolite accumulation. Unsuitable temperatures can induce oxidative stress and reduce water uptake, whereas appropriate temperatures promote growth and metabolite formation (Venkatasai et al., 2025). Metabolomics-based stress studies have further shown that abiotic factors such as drought, salinity, extreme temperature, and pH can alter the levels of primary metabolites, including amino acids and carbohydrates. These substances function as osmotic regulators and energy reserves under stress conditions and also reflect adjustments in photosynthetic carbon flow and respiratory metabolism (Salam et al., 2023).

Different environmental factors do not act in isolation, but influence yield by comprehensively regulating plant growth status. For example, moderate shading can reduce strong light and high-temperature stress and delay premature leaf senescence; rational water and fertilizer management can maintain the functional period of leaves and enhance root vitality; and good soil structure can improve water and nutrient use efficiency. Only when light, temperature, water, fertilizer, and aeration conditions are coordinated can *F. thunbergii* establish a stable vegetative growth foundation and accumulate more dry matter in the bulbs. Therefore, the mechanism by which environmental factors regulate yield is essentially realized through their effects on photosynthesis, carbon assimilation, root absorption, assimilate transport, and bulb storage processes. At the same time, these primary metabolic processes also provide carbon skeletons and energy for the biosynthesis of steroidal alkaloids such as peimine.

7.2 Induction mechanisms of environmental stress on secondary metabolism and peimine biosynthesis

Peimine is an important steroidal alkaloid secondary metabolite in *F. thunbergii*, and its formation is closely related to plant growth status and environmental responses. Plant secondary metabolism is usually associated with