tissue of *F. thunbergii* is relatively tender, it is more susceptible to pathogenic microbial infection under poor aeration and excessive humidity. Therefore, water management should follow the basic principles of maintaining moderate moisture, avoiding long-term waterlogging, and preserving rhizosphere aeration, so as to maintain a balance among root growth, bulb development, and soil aeration.

4.2 Effects of drought, waterlogging, and wet injury on yield formation

Drought stress directly restricts the normal growth of *F. thunbergii*. When soil moisture is insufficient, plants first exhibit difficulty in root water uptake, leaf water loss, stomatal closure, and reduced photosynthetic efficiency. As drought persists, leaves may wilt, yellow, or senesce prematurely, shortening the functional period of the aboveground parts and resulting in insufficient accumulation of photosynthetic products. Since the yield of *F. thunbergii* mainly derives from the enlargement and filling of underground bulbs, inhibited aboveground growth reduces the assimilates transported to the bulbs, ultimately causing a decline in single-bulb weight, marketability, and total yield. Studies on medicinal plants have also shown that drought stress usually suppresses biomass and yield. A meta-analysis covering 27 medicinal plant species found that moderate and severe drought stress significantly reduced plant relative water content and yield while strongly activating enzymatic antioxidant systems (Tan and Gören, 2024). In field experiments on Balangu (*Lallemantia* spp.), moderate and severe drought reduced seed yield and oil content, although phenolic compounds and antioxidant enzyme levels increased (Omidi et al., 2018). These results suggest that although drought may induce certain defensive metabolic responses, long-term water deficiency is generally unfavorable for bulb yield formation in *F. thunbergii*.

Compared with drought, waterlogging and wet injury are equally serious hazards in *F. thunbergii* production, and may be even more severe in some rainy or poorly drained regions. Long-term soil waterlogging causes rhizosphere hypoxia, inhibits root respiration, reduces nutrient absorption capacity, and induces root rot and bulb rot. Reviews on waterlogging stress indicate that soil oxygen depletion after saturation leads to enhanced anaerobic respiration, reduced dry matter accumulation, impaired nutrient uptake, especially potassium and calcium uptake, and significant yield losses in many crops (Manghwar et al., 2024). Species-specific experiments have shown that complete waterlogging significantly reduces fine-root growth and transpiration, whereas partial waterlogging may promote root proliferation in non-flooded upper soil layers to compensate for damaged deep roots (Fujita et al., 2021). For underground bulb crops such as *F. thunbergii*, prolonged saturation around the bulbs and main root zone can easily cause root decay, wet injury symptoms, and reduced population stability, thereby decreasing marketable bulb size and yield.

Although drought and wet injury differ in their manifestations, both disrupt the physiological basis required for yield formation in *F. thunbergii*. Drought mainly reduces dry matter accumulation by lowering water supply, inducing stomatal closure, and limiting photosynthetic capacity, whereas waterlogging affects plant growth mainly by inhibiting root respiration, damaging the rhizosphere environment, obstructing nutrient uptake, and aggravating disease. In field studies on industrial hemp, both severe drought and waterlogging caused by excessive water reduced photosynthesis and decreased plant growth and yield by more than 50%, with only partial recovery after stress relief (Kumar et al., 2025). This further demonstrates that both excessively dry and excessively wet conditions can cause productivity losses. For *F. thunbergii*, cultivation should avoid large fluctuations in water supply, especially problems such as drought in the early stage affecting emergence, water shortage in the middle stage limiting growth, and waterlogging in the late stage causing rot. A stable, moderate, and well-coordinated irrigation and drainage environment is an important condition for ensuring stable yield in *F. thunbergii*.

4.3 Effects of rational water regulation on peimine accumulation and quality stability

Water conditions not only affect yield formation in *F. thunbergii*, but also influence the accumulation of secondary metabolites such as peimine. The synthesis and accumulation of peimine depend on normal physiological metabolism, while water supply affects photosynthesis, nutrient uptake, carbon-nitrogen metabolism, intracellular metabolic balance, and stress signal transduction. Appropriate soil moisture can maintain strong photosynthetic capacity and a relatively stable growth state, providing a material basis for peimine biosynthesis. If