more favorable for crop productivity (Bhatt et al., 2025). Therefore, for bulbous medicinal plants such as *F. thunbergii*, deep, loose, well-aggregated loamy soils with good drainage are more conducive to root extension, assimilate transport, and continuous bulb enlargement. In contrast, overly heavy, compacted, or extremely sandy soils may restrict bulb development due to excessive root penetration resistance, rhizosphere waterlogging, or insufficient water and nutrient retention.

Soil aeration is an important factor affecting the physiological activities of the underground parts of *F. thunbergii*. Roots and bulbs require normal respiration during growth to maintain cellular metabolism, energy supply, and nutrient absorption. Well-aerated soil can ensure oxygen supply in the rhizosphere, promote root vitality and nutrient absorption efficiency, and reduce the risk of root diseases. Conversely, poorly drained soils, low porosity, or long-term excessive moisture easily create hypoxic conditions, inhibiting root respiration and leading to root weakness, bulb rot, and pathogen proliferation. Studies on crops such as maize and tomato have shown that soil aeration-enhancing technologies, including aerated seepage irrigation and micro/nano-bubble systems, can increase soil oxygen content, soil respiration, microbial biomass, root length, and root surface area, and significantly improve yield. At the same time, soil aeration can also increase the activities of nutrient-cycling enzymes such as urease, thereby enhancing nitrogen transformation and the supply of available nutrients to roots (Li et al., 2022; Yu et al., 2024). These findings suggest that good soil aeration not only directly affects root respiration, but also indirectly promotes the development of underground storage organs by regulating microbial activity and nutrient cycling.

In production practice, priority should be given to selecting fields with loose and fertile soil, convenient irrigation and drainage, and good soil permeability for *F. thunbergii* cultivation. During land preparation, deep plowing and soil exposure, high-ridge cultivation, and the application of well-decomposed organic fertilizer can be used to improve soil aggregate structure, reduce compaction, and enhance the coordination between water retention and drainage. Heavy clay soils or low-lying waterlogged fields should be avoided for large-scale continuous cultivation of *F. thunbergii*, or the rhizosphere environment should be improved through ditch drainage, soil replacement or amendment, increased organic matter input, and improved irrigation and drainage systems. In highly moist or compacted soils, limited oxygen diffusion reduces root respiration and nutrient absorption capacity and promotes root diseases. Even when nutrient inputs are sufficient, poor aeration may restrict fertilizer effectiveness (Yang et al., 2025). Given that *F. thunbergii* bulbs are sensitive to rot and require a relatively high oxygen supply in the rhizosphere, maintaining suitable soil structure and aeration is an important basis for supporting healthy bulb development, stable yield, and peimine accumulation.

5.2 Effects of soil fertility and ph on nutrient absorption and yield formation

Soil fertility is directly related to nutrient supply and yield formation in *F. thunbergii*. During growth, *F. thunbergii* needs to absorb nitrogen, phosphorus, potassium, and various medium and trace elements from the soil to support leaf establishment, root development, and bulb enlargement. Nitrogen promotes vegetative growth and leaf formation, phosphorus contributes to root development and energy metabolism, and potassium is closely associated with assimilate transport, stress resistance, and bulb filling. Studies on fertilization in medicinal crops have shown that yield responses to nutrient inputs depend largely on soil properties and climatic context. Long-term high fertilizer input or unfavorable water conditions may increase biomass in the short term, but may also weaken medicinal quality (Yang et al., 2025). A systematic review of nitrogen management in medicinal plants further indicated that moderate nitrogen application generally improves both yield and plant metabolite content, whereas excessive nitrogen reduces quality and may even suppress yield (Hao et al., 2024). This suggests that fertilization in *F. thunbergii* should not simply pursue high input, but should provide balanced nutrients according to the soil fertility basis and growth-stage requirements.

Soil nutrient supply should remain coordinated, rather than focusing excessively on a single nutrient or fertilizer type. Excessive nitrogen application may lead to excessive aboveground vegetative growth, tender plant tissues, reduced disease resistance, and impaired assimilate accumulation in bulbs. Insufficient phosphorus and potassium supply, meanwhile, can restrict root development, energy metabolism, assimilate transport, and bulb filling.