Studies on bulbous medicinal plants such as *Pinellia ternata* have shown that phosphorus application alone can increase bulbil biomass by 43%, while combined phosphorus and potassium fertilization can double biomass compared with the unfertilized control, highlighting the importance of balanced macronutrient supply for the development of underground storage organs (Ng et al., 2023). Therefore, for *F. thunbergii*, organic fertilizer should be used as the basis, combined with appropriate supplementation of nitrogen, phosphorus, potassium, and medium and trace elements, while emphasizing coordination among vegetative growth, bulb enlargement, and active constituent formation. Long-term improper fertilization may also lead to salt accumulation, aggravated soil acidification, and microbial community imbalance, further affecting the growth and medicinal quality of *F. thunbergii*.

Soil pH affects nutrient availability, root vitality, microbial activity, and photosynthetic performance, and is one of the important factors determining the ecological suitability of *F. thunbergii*. Excessively acidic or alkaline environments may reduce the availability of certain mineral elements, impair root absorption capacity, and induce nutrient imbalance. In medicinal plants such as *Melissa officinalis*, *Taraxacum officinalis*, and *Ocimum basilicum*, germination, growth, and photosynthetic efficiency are significantly affected by soil pH, and pH changes also alter the uptake of micronutrients such as manganese, copper, and zinc (Adamczyk-Szabela and Wolf, 2022). Studies on continuous cropping obstacles further emphasize that pH and cation exchange capacity are key factors determining soil biochemical and biological properties, and they can regulate microbial community structure and nutrient accessibility. Under continuous cropping conditions, soil acidification or alkalization can intensify nutrient imbalance and weaken root nutrient absorption capacity (Haq et al., 2023; Li et al., 2024). Therefore, in production, soil pH can be regulated through soil testing and formula fertilization, increasing organic matter, and rational application of lime or soil conditioners, so that nitrogen, phosphorus, potassium, and trace elements remain highly available while beneficial microbial activity is promoted, thereby providing a stable soil chemical environment for yield formation and peimine biosynthesis in *F. thunbergii*.

5.3 Effects of soil microecology and continuous cropping obstacles on peimine accumulation

Soil microecology is an important hidden factor affecting the healthy growth and quality formation of *F. thunbergii*. Rhizosphere microorganisms participate in organic matter decomposition, nutrient transformation, pathogen suppression, and plant stress regulation, playing important roles in root growth, bulb development, and secondary metabolite formation. A healthy soil microecology can improve soil nutrient cycling efficiency, promote root uptake of nutrients and water, and enhance plant adaptability to unfavorable environments. In *F. thunbergii* cultivation, organic fertilizer can significantly reshape fungal communities by increasing saprotrophic fungal groups such as Pezizales and Sordariales, reducing the proportion of pathotrophic fungi, enhancing enzyme activities, lowering the soil NH_4^+/NO_3^- ratio, and increasing bulb yield by nearly sevenfold compared with the unfertilized control (Du et al., 2024). This shift toward beneficial saprotrophic fungal communities is associated with improved soil health and nutrient turnover capacity, and may help support both biomass formation and the accumulation of alkaloids such as peimine in *F. thunbergii*. Broader studies have also shown that beneficial microorganisms can enhance stress resistance, suppress pathogens, improve nutrient absorption, and regulate secondary metabolite biosynthesis in medicinal plants, making them environmentally friendly tools for improving medicinal material quality (Wang et al., 2022).

Continuous cropping obstacles are common in *F. thunbergii* cultivation. Long-term continuous planting in the same field can easily lead to imbalanced soil nutrient ratios, soil acidification or alkalization, accumulation of harmful root exudates and autotoxic substances, increased pathogens, and reduced beneficial microorganisms, thereby disrupting the balance of rhizosphere microecology (Haq et al., 2023). Continuous cropping obstacles not only reduce emergence rate, weaken plant growth, and aggravate disease, but also affect bulb development and active constituent accumulation. Studies on other medicinal plants can provide references for *F. thunbergii*. For example, in long-term monoculture systems of *Codonopsis pilosula*, soil total phosphorus and available potassium increased, whereas pH decreased, bacterial diversity declined, and autotoxic compounds such as 2,6-di-tert-butylphenol accumulated. These changes were associated with declines in yield and quality (Li et al.,