2024). Reviews focusing on the rhizosphere of medicinal plants have pointed out that autotoxic substances and pH shifts can disrupt microbial structural stability, reducing beneficial microorganisms while increasing harmful microorganisms, thereby impairing nutrient acquisition and secondary metabolite profiles (Liao and Xia, 2024). Although direct data on changes in peimine under continuous cropping conditions in *F. thunbergii* remain limited, it can be inferred that soil microecological degradation, increased pathogens, and intensified chemical stress may interfere with steroidal alkaloid biosynthesis and regulation, leading to fluctuations in medicinal quality.

Improving soil microecology and alleviating continuous cropping obstacles are important directions for enhancing yield and quality stability in *F. thunbergii*. In production, soil-borne disease pressure can be reduced and soil microbial diversity restored through rational crop rotation, intercropping, application of well-decomposed organic fertilizer and microbial fertilizer, removal of diseased residues, and necessary soil disinfestation and ecological restoration. Meanwhile, excessive use of chemical fertilizers and pesticides should be reduced to avoid further disruption of the rhizosphere ecological environment. Studies have shown that crop rotation, organic amendments, and targeted microbial inoculation have demonstrated potential in other medicinal plants to restore microbial balance, alleviate continuous cropping obstacles, and increase secondary metabolite levels (Wang et al., 2022; Haq et al., 2023; Li et al., 2024). By constructing a healthy and stable soil microecological system, it is possible not only to improve stress resistance and bulb yield in *F. thunbergii*, but also to promote stable peimine content, thereby supporting the production of high-quality geo-authentic medicinal materials.

6 Effects of Regional Ecological Conditions and Cultivation Patterns on Quality Formation in *Fritillaria thunbergii*

6.1 Effects of altitude and production-area ecological environment on the growth of *Fritillaria thunbergii*

Regional ecological conditions constitute an important external basis affecting the growth, development, and quality formation of *Fritillaria thunbergii*. Different production areas vary in altitude, air temperature, precipitation, light, diurnal temperature difference, soil type, and field moisture conditions. Together, these factors determine the growth rhythm, degree of bulb enlargement, and level of active constituent accumulation in *F. thunbergii*. The suitable distribution of *Fritillaria* species is clearly constrained by macroecological factors. Jiang et al. (2022) modeled the potential geographical distribution of three *Fritillaria* species and found that precipitation, altitude, and temperature were the dominant variables determining suitable habitats. In particular, annual precipitation below approximately 336 mm significantly reduced the probability of occurrence. Suitable precipitation around the sowing period, namely September to October, and during the bulb filling period, namely May, was especially important for seed germination, early growth, and nutrient accumulation, whereas imbalanced water supply increased the risk of disease (Jiang et al., 2022). Therefore, for *F. thunbergii*, ecological suitability evaluation should not focus on a single climatic factor alone, but should comprehensively analyze the matching relationships among temperature, precipitation, light, soil drainage, and disease pressure.

Altitude changes affect the growth of *F. thunbergii* by regulating temperature, light intensity, air humidity, and diurnal temperature difference. A relatively suitable altitude environment usually provides mild or cool climatic conditions, which can delay aboveground senescence to some extent, prolong the photosynthetic functional period of leaves, and allow more assimilates to be transported to the underground bulbs. Meanwhile, an appropriate diurnal temperature difference helps reduce nighttime respiratory consumption and promotes dry matter accumulation and bulb filling. A review on the taxonomy and cultivation of *Fritillaria* species indicated that biomass and morphology change systematically with altitude: *Fritillaria* species growing at high altitudes, namely 2 700~4 000 m, are usually shorter and single-flowered, whereas species distributed below 1 500 m tend to be taller, multi-flowered, and have greater biomass. Altitude also changes together with thermal regime and solar radiation, thereby regulating plant height, phenology, and the skeleton types of isosteroidal alkaloids (Qu et al., 2022). This indicates that higher altitude is not necessarily more favorable. If temperature is too low or the growing season is too short, sprouting, leaf expansion, and bulb enlargement may also be restricted.

The ecological environment of the production area also affects the quality stability of *F. thunbergii*. Interannual climatic variation, soil fertility basis, and field management conditions differ among regions, which may lead to