

differences in peimine content and bulb marketability. Existing studies show that *F. thunbergii* is usually cultivated in mid- to low-altitude areas, such as Pan'an County in Zhejiang Province at an altitude of approximately 600 m. The warm and humid monsoon climate and relatively favorable soil fertility in this region are conducive to vigorous plant growth and high bulb productivity (Huang et al., 2024a). For *F. thunbergii* production, selecting production areas with stable ecological environments, suitable soil conditions, and low disease pressure is beneficial for achieving high and stable yield and quality. Therefore, evaluating production-area ecological factors and defining suitable cultivation regions are important prerequisites for promoting standardized production and quality control of *F. thunbergii*.

6.2 Environmental characteristics of geo-authentic production areas and quality advantages of *Fritillaria thunbergii*

As a traditional geo-authentic medicinal material of Zhejiang Province, the quality advantages of *F. thunbergii* are closely associated with the long-established ecological environment of its production areas. Geo-authentic production areas usually possess suitable climatic conditions, soil types, rhizosphere microecology, and cultivation experience. These factors together shape a relatively stable growth environment and quality characteristics for *F. thunbergii*. Suitable temperature and humidity conditions meet the ecological requirements of *F. thunbergii*, which prefers cool and moist conditions but is intolerant of waterlogging. Good soil structure supports root growth and bulb enlargement, while mature cultivation management techniques further guarantee medicinal material yield and commercial quality. Shi et al. (2011) compared three major production areas, namely the Ningbo geo-authentic production area, Pan'an, and Nantong, and found that soil pH ranged from 4.48 to 7.73 across different regions, indicating that *F. thunbergii* can tolerate acidic to slightly alkaline soil conditions. Among them, Ningbo, as the geo-authentic production area, had the highest soil organic matter content, phosphatase activity, and urease activity, reflecting superior soil fertility and enzyme activity (Shi et al., 2011).

The advantages of geo-authentic production areas are reflected not only in natural ecological conditions, but also in cultivation systems and quality awareness formed through long-term production practice. Growers can usually arrange sowing, fertilization, irrigation and drainage, shading, and harvesting reasonably according to local climatic changes and soil characteristics, enabling *F. thunbergii* to obtain suitable environmental conditions during key growth stages. This coordinated relationship among “ecological environment-cultivation technology-medicinal material quality” is an important basis for the formation of geo-authentic medicinal quality. It is worth noting that geo-authentic areas are not the only spaces where quality can form. Shi et al. (2011) showed that Nantong, a non-geo-authentic production area with relatively alkaline soil, had higher rhizobacterial diversity and bulb alkaloid content, suggesting that alkaline pH and abundant microbial communities may also favor secondary metabolite accumulation. This indicates that both geo-authentic areas and high-quality non-geo-authentic areas may possess favorable soil nutrient status, active microbial processes, and suitable ecological environments, jointly shaping bulb quality.

From the perspective of quality formation, geo-authentic production areas provide a relatively stable environment for material accumulation and secondary metabolism in *F. thunbergii*. Within Zhejiang Province, the soil properties of Pan'an and Ningbo are relatively similar, which provides a practical basis for large-scale cultivation of *F. thunbergii* in Pan'an while maintaining quality comparable to that of the geo-authentic area (Shi et al., 2011; Huang et al., 2024a). Multi-regional LC-MS chemometric studies further found that *F. thunbergii* bulbs produced in Zhejiang differed significantly in alkaloid profiles from samples from other provinces. Through targeted quantification of key alkaloids and non-targeted analysis, Zhejiang-produced bulbs could be distinguished from non-Zhejiang samples, and 11 characteristic markers associated with bulb appearance traits were identified (Zhang et al., 2026). This indicates that geo-authentic ecological conditions not only affect the external morphology of *F. thunbergii*, but also confer specific alkaloid fingerprints. In the future, based on the protection of traditional production-area advantages, ecological suitability evaluation, metabolomics, and modern quality testing technologies should be combined to further clarify the relationships between environmental factors in