reached a closely matching conclusion, finding that most photosynthetic indices peaked under 70% shading, with rapid-growth-stage values markedly higher than those in the slow-growth stage (Xu et al., 2018).

Physiologically, increasing shade raises chlorophyll a, chlorophyll b, and total chlorophyll content, while reducing the chlorophyll a/b ratio, which reflects adjustment to low-light capture under the canopy (Xu et al., 2018). Full sunlight and only light shading reduce electron transport and photochemical quenching while increasing non-photochemical quenching, showing that strong light imposes photoprotective stress rather than promoting efficient photosynthesis (Dai et al., 2009). Temperature interacts with shade rather than acting independently, because strong light, high temperature, and low humidity together reduce photosynthetic activity and slow growth, while seasonal evidence suggests a favorable temperature range around 17.5~24.1 ℃ for higher flavonoid accumulation and around 18 ℃ in natural habitats (Shi et al., 2022). More broadly, understorey ecology shows that shade modifies not only irradiance but also humidity, nocturnal temperature, and plant stress tolerance, so canopy conditions should be managed as a combined microclimatic system rather than as light reduction alone.

3.2 Effects of under-forest moisture and soil conditions on plant growth

Water availability and soil environment are major determinants of *T. hemsleyanum* growth because the species is best suited to moist hillsides or valleys and is recognized as drought-sensitive across its native range. Landscape-genomic analysis indicates that climatic variation explains more genomic variation than geographic distance, and precipitation-related variables are among the strongest predictors of population structure, which supports the ecological importance of moisture conditions for local adaptation. Seasonal metabolite studies further show that higher flavonoid levels occurred under moderate precipitation, 67.3~80.2% humidity, and 17.5~24.1 ℃ from April to May, while sterol accumulation was inhibited by excessively high humidity and temperature extremes. The same work found that phenolic accumulation was negatively correlated with precipitation and humidity but could be enhanced within controlled soil-moisture ranges, indicating that water supply must be sufficient but not excessive if both growth and quality are goals (Shi et al., 2022).

Soil effects extend beyond fertility to rhizosphere processes and microbial regulation of secondary metabolism. Wild Zhejiang material had higher total flavonoids and PAL activity than cultivated material, and its rhizosphere soil contained higher available phosphorus and potassium together with distinct microbial taxa and metabolic pathways linked to nitrogen, phosphorus, and phenylalanine metabolism. Stony soils supported larger tubers, greater bacterial diversity, and bacterial groups associated with phytohormone biosynthesis, photosynthesis, and stress resistance, showing that physical soil structure and microbiota jointly shape tuber development (Hong et al., 2021). Fertilization studies also show that biochar or pyrogenic organic matter improves plant height, fresh root weight, and total flavonoids by increasing soil pH, organic matter, available nutrients, and enzyme activities, and in bamboo-forest or forest-soil systems these effects appear partly mediated by reshaped fungal and bacterial communities (Zhang et al., 2020; Zhang et al., 2026).

3.3 Adaptability of *Tetrastigma hemsleyanum* to different forest stand types

Tetrastigma hemsleyanum shows real adaptability to multiple under-forest settings, but that adaptability is conditional on stand structure and microhabitat matching. Field surveys in Guangxi found it suitable in valleys, shrubs, and higher-altitude forests, where communities include tree, shrub, and herb layers with more than 50 accompanying species. The species occurs across warm-temperate evergreen forest regions spanning large climatic and elevational gradients, and populations from different regions show substantial morpho-agronomic, phytochemical, and genetic variation shaped by local climate adaptation. This means stand selection for industrial development should follow local provenance and ecological matching rather than assume uniform performance across forest types. Reviews of understorey medicinal-plant systems reach the same practical conclusion: under-forest cultivation can efficiently use land, light, and heat resources, but success depends on understanding the growth environment and forest-medicine symbiosis (Li et al., 2025).

Evidence from specific stand types suggests that some forest systems are especially promising. Under a Moso bamboo forest with about 80% canopy density, biochar-based organic fertilizer increased *T. hemsleyanum*