

intensity regulation has been shown to alter photosynthesis, pigment content, and the levels of phenolics, flavonoids, and other bioactive compounds. The optimal state often occurs under moderate shading rather than full sunlight or deep shading (Xu et al., 2020; Gao et al., 2025). In shade-tolerant or understory herbaceous medicinal plants, appropriate shading can simultaneously increase aboveground yield and enhance the accumulation of specific medicinal metabolites, thereby improving overall medicinal value. However, plant responses to the light environment are highly species-specific and are jointly affected by light intensity, spectral quality, and duration. Therefore, it is difficult to directly apply a universal “light formula” to all medicinal crops.

This study explores the mechanisms by which shading environments affect the growth and medicinal quality formation of *T. hemsleyanum*. Existing studies on the physiological characteristics of *T. hemsleyanum* have only briefly addressed light effects, and there remains a clear knowledge gap regarding how the light environment shapes its growth process and medicinal quality formation. Given the increasing scarcity of wild resources and the rapid expansion of cultivated areas, it is necessary to clarify the mechanisms by which shading environments regulate the growth of *T. hemsleyanum* and the accumulation of key active components. On the one hand, standardized light and shading management is important for improving biomass, stabilizing quality markers such as flavonoids and polysaccharides, supporting quality control, and promoting industrial upgrading. On the other hand, clarifying how light intensity and shading affect photosynthesis, antioxidant defense, and secondary metabolism in this species will enrich the theoretical basis for precise light environment regulation in medicinal plants. This study focuses on analyzing the mechanisms by which shading environments influence the growth and medicinal quality formation of *T. hemsleyanum*, aiming to provide scientific reference for its standardized cultivation, quality evaluation, and sustainable industrial development.

## 2 Ecological Habits and Shading Adaptation Basis of *Tetrastigma hemsleyanum*

### 2.1 Natural habitat and low-light adaptation characteristics of *Tetrastigma hemsleyanum*

*Tetrastigma hemsleyanum* is a perennial herbaceous climbing vine belonging to the genus *Tetrastigma* in the family Vitaceae, and it is one of the important medicinal plant resources in China. Its natural distribution is mainly concentrated in warm evergreen forests in subtropical and tropical regions of China. It is commonly found in understory habitats, forest edges, valleys, streamside areas, and hillside shrublands at altitudes of 300-1300 m, and may also extend to regions such as Hainan and Taiwan (Ren et al., 2025). From an ecological perspective, *T. hemsleyanum* prefers cool and humid environments, relatively high air humidity, loose soils rich in humus, and yellow or yellow-brown soils. Its natural habitats are generally characterized by sufficient scattered light, weak direct sunlight, and relatively stable hydrothermal conditions (Ji et al., 2020; Hu et al., 2021). This indicates that *T. hemsleyanum* is not a typical heliophilous plant, but is more suitable for growth in semi-shaded and humid environments with a certain degree of canopy cover. This also provides an ecological basis for its application in understory cultivation, trellis cultivation, and intercropping systems.

During long-term adaptation to understory or semi-shaded environments, *T. hemsleyanum* has developed a series of low-light adaptation characteristics. The plant mainly grows as a climbing vine and can extend outward by relying on surrounding vegetation or supports, thereby obtaining suitable scattered light resources. As the main photosynthetic organs, leaves are highly sensitive to changes in light conditions. Under low-light conditions, they can improve light interception capacity by regulating leaf area, chlorophyll content, and spatial leaf distribution. Ensemble habitat modeling further indicates that the current highly suitable habitats of *T. hemsleyanum* are mainly concentrated in subtropical regions jointly constrained by specific temperature and precipitation conditions, showing strong climatic adaptation specificity. Genomic and landscape genomic studies also show that *T. hemsleyanum* exhibits obvious local adaptation to heterogeneous climates. Winter precipitation and other climatic factors can explain a considerable proportion of its genomic variation, and many adaptive loci are associated with stress responses and environmental adaptation (Ren et al., 2025). Although direct measurements of the natural canopy light environment of *T. hemsleyanum* remain limited, its distribution in evergreen forests, preference for cool and humid environments, and the need to avoid strong light in bionic cultivation collectively support the view that it has a shade-adapted, low-light ecological strategy (Xu et al., 2018; Hu et al., 2021).