

2021). A local germplasm system should therefore begin with systematic surveys, provenance registration, and hierarchical conservation of wild and cultivated resources, especially materials from major producing regions and ecologically differentiated local populations (Bai et al., 2022). This is justified not only by conservation need, but also by utilization value, because the species contains abundant flavonoids, polysaccharides, and other metabolites with important medicinal and functional-food potential (Ji et al., 2021).

Elite germplasm utilization should then move from simple collection to targeted breeding and industrial seedling supply. Stress-screening evidence identified the Zhejiang ZJWZ strain as the strongest overall performer under cadmium, salt, and low-temperature stress, supporting its use as preferred parental material for resistance breeding. At the same time, large-scale production still suffers from low seed yield and limited cutting propagation, so micropropagation and organogenesis need to become routine components of germplasm utilization systems rather than isolated laboratory methods. Current regeneration protocols are already practical for this purpose, achieving a shoot proliferation coefficient of 6.73 within 30 days, 100% rooting of adventitious shoots, and over 98% survival after acclimatization (Pang et al., 2024). Beyond seedling multiplication, biotechnological approaches such as metabolic engineering and hairy-root systems should be incorporated into elite germplasm utilization strategy, because they can reduce dependence on wild materials and provide alternative routes for rapid production of target bioactive compounds.

7.2 Optimization of ecologically suitable and standardized under-forest cultivation technologies

Build ecologically matched and standardized under-forest cultivation technologies around the biological characteristics of the species. *T. hemsleyanum* naturally grows in shaded valley forests, cliffs, gullies, and moist mountain habitats, and both review and experimental evidence indicate that moderate shade is essential for stable growth and quality formation (Shi et al., 2022). The available physiological evidence shows that cultivation is most suitable under roughly 67% shade, while environmental studies further indicate that higher flavonoid accumulation occurs under moderate temperature, humidity, and seasonal moisture conditions rather than under uniformly intensified inputs. Standardization should therefore not mean uniform planting under any forest, but rather matching local provenance, canopy density, seasonal management, and site moisture to the ecological niche of the species. This is especially important because current studies still emphasize light and fertilizer more than broader under-forest ecological regulation, leaving many cultivation variables insufficiently standardized (Hu et al., 2021).

Standardization also needs to extend belowground, because quality formation depends strongly on soil properties, extracellular enzymes, and rhizosphere microbial communities. Biochar experiments show that dryland cultivation typically has 30~35% lower flavonoid concentrations than forest understory systems, but targeted amendment can partly bridge this gap by stimulating enzyme activity and restructuring fungal communities (Zhang et al., 2026). The same work indicates that medicinal quality depends more on functional bio-inorganic habitat regulation than on simple nutrient addition, which supports the use of rhizosphere engineering in non-native or degraded production sites. Controlled-environment studies suggest that UV treatments may provide a reference for quality-oriented stress regulation can markedly increase flavonoid accumulation and antioxidant-enzyme activity in leaves and roots (Bai et al., 2022). In practice, a standardized under-forest technical system should integrate provenance-matched seedlings, canopy-light regulation, moisture control, soil amendment, microbial optimization, and stress-quality monitoring to create production protocols that are both locally adaptable and reproducible across bases.

7.3 Promotion of deep processing, brand building, and integrated industrial development

Promote deep processing, whole-plant utilization, and regional brand construction so that local industries capture more value than raw-root sales alone. The development basis is already strong: around 142~150 compounds have been identified from *T. hemsleyanum*, especially flavonoids and polysaccharides, and these exhibit anti-inflammatory, antioxidant, antitumor, immunomodulatory, antipyretic, and hepatoprotective activities. Product development should therefore expand from tuber medicine into functional foods, antioxidant extracts, immune-enhancing polysaccharides, and aboveground-resource products (Hu et al., 2021; Ji et al., 2021). This