

5.2 Combined model of understory ecological cultivation and germplasm expansion

A second restoration pathway is a combined model of understory ecological cultivation plus germplasm expansion, which fits the basic ecology of *Paris* spp. better than open-field domestication. Multiple ecological studies show that *P. polyphylla* grows and reproduces best in moist, humus-rich, well-drained forest soils under more than 80% canopy cover, with disturbed habitats supporting thinner populations and poorer regeneration. Light conditions are especially important, because less than 50% shade markedly reduces seed productivity, and the species shows poor adaptability to altered environments and climatic stress during reproduction. This explains why Nepal-based distribution and conservation work recommends conserving the species in forests and cultivating it in forest fringe areas across its potential range, rather than separating production completely from its ecological niche (Kunwar et al., 2020). Distribution modeling also indicates that ecological niches differ among medicinally used taxa, with *P. polyphylla* var. *chinensis* and var. *yunnanensis* responding differently to precipitation, temperature range, and human disturbance, so understory expansion should be matched to taxon-specific suitable zones rather than generalized across all planting areas (Wang et al., 2026).

Understory cultivation is not only a habitat-matching strategy; it also appears to support better medicinal chemistry under appropriate conditions. Metabolomic comparison of plants maintained for eight years under natural forest and greenhouse conditions found that naturally forest-grown roots were enriched in steroidal saponins, flavonoids, flavonols, lipids, vitamins, and veratramine alkaloids, supporting a strong association between growth environment and secondary metabolite accumulation (Yan et al., 2024). Even within understory systems, forest type matters: imitation-wild cultivation under Chinese fir and mixed forests generated higher soil organic carbon, microbial biomass carbon, water-soluble organic carbon, and enzyme activity than Moso bamboo forest, creating a more favorable soil microenvironment for *P. polyphylla* growth (Zhang et al., 2026). Community-level work in Arunachal Pradesh further shows that the species persists within diverse associated herb layers and that identifying such supportive ecosystems can guide conservation-oriented cultivation placement (Kalita et al., 2026). The practical implication is that germplasm expansion should use forest-compatible, site-screened understory systems that mimic native shade, litter, and soil conditions, because these systems better align with both species ecology and the formation of medicinally valuable metabolites (Rawat et al., 2023).

5.3 Germplasm renewal and industrial utilization model

The third pathway is a germplasm renewal and industrial utilization model in which elite lines are continuously renewed, authenticated, and routed into standardized production systems. This is necessary because the pharmaceutical value of *Paris* depends mainly on rhizome-derived steroidal saponins and polyphyllins, while current market demand continues to rise faster than wild or conventionally propagated supply (Qiang et al., 2020; Su et al., 2022). Germplasm renewal cannot rely on morphology alone, because interspecific hybridization and weak differentiation between some wild and cultivated materials can compromise raw-material uniformity and obscure breeding identity (Wang et al., 2023). Molecular infrastructure is therefore part of the renewal model itself. EST-SSR markers linked to polyphyllin biosynthesis, SSR population analysis, comparative barcoding, and dedicated biomolecular databases such as PPDP all provide tools to authenticate germplasm, trace origin, and connect genotype with medicinal-quality traits (Gao et al., 2022; Oliya et al., 2023; Wang et al., 2026). This matters for industry because traceable cultivated supply chains have already been recommended as a way to distinguish cultivated from wild-harvested stocks and support ex situ conservation without masking continued wild extraction (Rawat et al., 2023).

Industrial utilization also requires that germplasm renewal be tied to production-stage quality control, not just multiplication speed. Clonal propagation of selected elite wild accessions has already shown that candidate cultivars can be reproduced at scale while preserving morphology and active-ingredient contents, and field-grown clonal lines reached their greatest biomass increase and exceeded pharmaceutical-use polyphyllin requirements by the fifth year (Wang et al., 2023). Growth environment and management further shape industrial value. Elevated CO₂ responses differed between cultivars from different natural habitats, with the western Yunnan cultivar showing stronger growth and maintained total saponin content, which suggests that renewal programs should