

structure and polyphyllin biosynthesis therefore provide an important foundation for quality-oriented breeding, accession identification, and traceable production (Oliya et al., 2023). At the same time, clonal systems help preserve the natural morphology and active-ingredient profiles of elite wild founders, offering a practical route to homogeneous medicinal germplasm (Wang et al., 2023). Standardized production should therefore integrate authenticated founder selection, clonal multiplication, and batch-level chemical evaluation rather than relying on unverified mixed-origin planting stocks (Gao et al., 2022).

Chemical evidence shows that quality in cultivated *Paris* is strongly shaped by plant age, culture conditions, and soil management, so standardized production must define these variables explicitly (Wang and Li, 2018; Zhang et al., 2025). Multiple studies found that major steroidal saponins vary with cultivation year and generally peak around the seventh or eighth year, with one UHPLC-MS/MS study reporting a maximum of 22.65 ± 1.65 mg/g in the eighth year and recommending harvest at year 7 or 8. In vitro systems also affect chemical quality: mini-rhizome cultures showed 1.41-fold higher total steroidal saponins than field rhizomes under one BAP treatment, and salicylic-acid elicitation increased total saponins to 3.6 times the in vivo level, although growth slowed under elicitation. Field management also matters, because biochar and organic fertilizer significantly increased total saponin, polyphyllin I, II, VI, and VII contents through linked changes in soil nutrients, enzyme activity, and microbial communities (Liu et al., 2024). Taken together, standardized artificial germplasm production in *Paris* spp. should be built around authenticated elite lines, stage-specific propagation protocols, defined cultivation years, and chemical quality benchmarks supported by chromatographic and metabolomic evaluation.

5 Ecological Adaptation-Based Models for *Paris* spp. Germplasm Restoration

5.1 Integrated model of wild resource conservation and artificial propagation

An ecological adaptation-based restoration model for *Paris* spp. should begin by coupling in situ protection of wild populations with targeted artificial propagation, because wild populations remain genetically valuable but are increasingly threatened by overcollection, habitat fragmentation, and slow natural renewal (Su et al., 2022; Thakur et al., 2023). This integrated approach is supported by studies showing that cultivation is already a major route for conserving and sustainably using wild *P. polyphylla* var. *yunnanensis*, while in situ and ex situ measures are both necessary for long-term persistence. Population genetic work further indicates that wild germplasm should not be collected indiscriminately, because wild populations retain clear geographic structure and some regions, especially Guizhou and parts of Sichuan and western Yunnan, contain higher-diversity lineages that are better treated as priority conservation and provenance-selection zones (Huang et al., 2019; Yan et al., 2024). SSR analyses in Nepal likewise show that most variation occurs within populations, but germplasm from similar geographic origins clusters together, supporting region-specific conservation sampling and core germplasm construction rather than mixed, undocumented transfer (Oliya et al., 2023).

Within that framework, artificial propagation should serve as a buffer against harvest pressure and as a renewal tool for selected wild founders rather than a replacement for wild conservation. Reviews and field studies agree that in vitro propagation, ex situ cultivation, and ecologically informed niche-based planning can reduce unorganized collection from natural habitats and help design more effective conservation programs (Kunwar et al., 2020; Rawat et al., 2023). Somatic embryogenesis and related clonal systems are especially suited to this model because they can rapidly multiply elite wild accessions, preserve morphology and active-ingredient profiles, and produce plantlets with about 94% survival after transplanting to soil (Wang et al., 2023). Other regeneration platforms, including mini-rhizome production, also provide conservation-ready planting stock, with more than 95% acclimatization success and increased steroidal saponin content relative to field-grown rhizomes. The most defensible integrated model is therefore a closed loop: identify and protect high-value wild populations, select elite accessions from them, propagate those accessions under controlled conditions, and use the propagated material to supply cultivation systems and, where appropriate, reinforce depleted populations.