improved antioxidant and digestive enzyme inhibitory activity, and reduced the herbal odor while increasing fruity and woody notes (Xie et al., 2026). At the same time, chemometric polysaccharide fingerprinting can distinguish major medicinal species and link structural differences to antioxidant activity, supporting species-specific raw material grading and higher-value functional food development (Liu et al., 2025). Overall, *Polygonatum* appears poised to move from selling rhizomes as generic raw materials toward a portfolio of precision-processed medicinal, food, nutraceutical, and biomaterial products (Hu et al., 2023; Yang et al., 2025).

6.2 Transition from single cultivation to an ecological industrial system

A second major trend is the transition from single-crop planting toward an ecological industrial system built around understory cultivation, agroforestry, and multi-functional forest use. Understory medicinal plant cultivation is increasingly valued because it makes efficient use of land, light, and heat resources, while also contributing to forest-resource protection, biodiversity maintenance, and sustainable forestry development. Agroforestry more broadly is recognized as a resource-complementary land-use system that improves soil functions, microclimate, biodiversity, and resilience compared with monocropping, which makes it a strong structural fit for *Polygonatum* and other shade-tolerant medicinal plants (Fahad et al., 2022). Evidence from compound forest-medicinal plant systems further shows that introducing medicinal plants in the understory can improve soil nutrient status, enrich rhizosphere microbial communities, and enhance soil carbon-source utilization, indicating that future *Polygonatum* development can create ecological as well as economic returns (Yu et al., 2023).

The likely next stage is therefore a forest-based composite industry, not a planting industry alone. Studies on medicinal plant agroforestry report higher species richness, better soil health, and increased farmer income, while also reducing pressure on wild medicinal plant populations, which aligns directly with *Polygonatum*'s dual need for conservation and industrial supply (Kholiya et al., 2025). However, this transition requires coordination beyond cultivation because present understory systems still face weak service systems, low market alignment, high input-low output problems, and unclear boundaries between ecological protection and utilization (Guo et al., 2026). Long-term agroforestry research also emphasizes that future management must evaluate multifunctionality, temporal dynamics, and trade-offs among yield, soil fertility, ecological services, and socioeconomic outcomes rather than optimize one variable in isolation (Cardinael et al., 2020). For *Polygonatum*, the most promising prospect is an integrated system combining understory production, ecological restoration, forest economy, and rural livelihood diversification rather than simple expansion of planted area.

6.3 Transition from experience-based production to digital and precision management

A third trend is the transition from experience-based cultivation toward digital and precision management. Precision agriculture is increasingly defined as a data-driven management approach that uses sensors, IoT, remote sensing, AI, and machine learning to improve production efficiency while reducing input losses and environmental impact (Sishodia et al., 2020; Miller et al., 2025). These systems enable real-time monitoring of soil moisture, pH, plant stress, water status, pest occurrence, and environmental conditions, which supports targeted irrigation, fertilization, pest management, and yield forecasting (Fuentes-Peñailillo et al., 2024; Mansoor et al., 2025). Remote sensing and UAV platforms have become especially important because they provide high-resolution crop monitoring, disease and pest detection, irrigation management, and yield prediction, while cloud computing and machine learning expand the ability to process large image and sensor datasets.

For *Polygonatum* understory systems, this means future production can shift from generalized field experience to site-specific ecological regulation. Smart sensing and spectroscopic/remote-sensing technologies under stress, enabling earlier intervention and better management of plant health and yield formation (Mansoor et al., 2025). AI-integrated sensing, high-throughput phenotyping, and automated platforms can also lower labor intensity and improve the precision of harvest, sorting, weed detection, and growth regulation, although the evidence is still mostly from general agriculture rather than Polygonatum-specific systems. The main constraints are clear: high