

input-output ratio, and significant economic benefit overall. One study reported prices approximately 5~10 times higher than greenhouse products, even though greenhouse cultivation had higher yield (Hu et al., 2024). Wild-simulated systems also align better with conservation-compatible and ecologically friendly industry development, because they connect medicinal-material production with habitat restoration, biodiversity protection, and lower chemical-residue expectations (Cheng et al., 2019). Their limitations remain clear: they are more labor-intensive, more dependent on suitable sites and microclimates, and less suited to rapid volume expansion. Overall, facility cultivation is the main route for large-scale industrial supply, whereas wild-simulated cultivation is better suited to quality-oriented, high-value, and ecological segments of the *D. officinale* industry (Zhang et al., 2020).

6 Optimization and Future Development of *Dendrobium officinale* Cultivation Modes

6.1 Promoting integrated cultivation systems combining the advantages of wild-simulated and facility modes

The future direction of *D. officinale* cultivation is not a simple replacement of one mode by another, but the construction of integrated systems that combine the stability of facility cultivation with the quality advantages of wild-simulated cultivation. Earlier work had already identified bionic-facility cultivation, original ecological cultivation, and pot cultivation as parallel technical routes, indicating that hybridized mode design is a recognized development path in *D. officinale* production (Yuan et al., 2020). This integrated logic is biologically reasonable because *D. officinale* depends on strict environmental conditions, while its quality remains tightly linked to ecological factors such as humidity, temperature, sunshine duration, pH, and substrate nutrient status (Ding et al., 2018). At the same time, simulated habitat systems more closely reproduce the wild environment and often deliver better plant form, higher medicinal-component accumulation, and stronger overall quality performance in related *Dendrobium* comparisons (Yi et al., 2021).

An optimized integrated system should therefore use facility conditions mainly for seedling propagation, transplantation buffering, and early-stage growth stabilization, then guide plants toward bionic, epiphytic, or understory production environments during quality-formation stages (Hou et al., 2025). Such a system can be further strengthened by matching variety breeding, site selection, and co-culture with endophytic fungi, which recent synthesis identifies as a key route for efficient cultivation. Wild-mimic integrated techniques already show that tissue-culture seedlings can be transplanted into breathable understory substrates with survival rates above 95%, while maintaining high effective-component content, low residue, and relatively convenient management. Under carbon-neutrality goals, this integration also has ecological significance, because simulative habitat cultivation in related *Dendrobium* systems produced far lower CO₂ emissions and global warming potential than facility cultivation, supporting the value of shifting at least part of production toward carbon-friendly hybrid systems (Tian et al., 2025).

6.2 Strengthening precision environmental regulation and green cultivation technologies

Precision environmental regulation should become the technical core of future facility and semi-facility cultivation, because the main medicinal components of *D. officinale* are strongly shaped by environmental variables rather than by cultivation mode label alone (Yuan et al., 2020). Greenhouse control research shows that soil temperature, soil moisture, air humidity, and light can be monitored and modeled for real-time regulation, with average prediction error below 2.5%, providing a workable basis for precision cultivation (Ding et al., 2018). More recent intelligent agriculture work goes further: an IoT edge-computing and digital-twin control system improved temperature-control precision to $\pm 0.7^{\circ}\text{C}$, increased production by 23.6%, and reduced energy use by 42.6% across climates. Data-driven rule mining from greenhouse climate sensors also replicated about 80% of the climatic conditions associated with successful past cultivation, indicating that knowledge-based environmental replication can help maintain more consistent quality (Sun et al., 2018).

Future green cultivation should not pursue high inputs alone, because increased planting density and greater use of fertilizers, growth regulators, and pesticides in greenhouse systems can raise toxic and hazardous residues (Yuan et al., 2020). Recent industrial reviews therefore emphasize reducing chemical fertilizer and pesticide use,