

developed to relieve pressure on wild resources and meet expanding market demand (Yang et al., 2023). Its technical logic is to create a controllable microenvironment around this epiphytic orchid, because the accumulation of medicinal components is strongly affected by light, temperature, humidity, water, and nutrient conditions (Yuan et al., 2020; Jia et al., 2022). Greenhouse systems therefore regulate shade, irrigation, ventilation, humidity, and substrate conditions more intensively than wild-simulated systems, so that plants grow under relatively suitable and less fluctuating conditions while disease risk is reduced as much as possible (Liu et al., 2025b).

Standardized production in facility cultivation begins with industrial tube seedlings and high-quality transplant material, because seedling quality directly affects survival, vigor, and later yield (Cheng et al., 2019). Existing standards and technical procedures already provide guidance for cultivation, but national-level production standards are still incomplete, so further unification of germplasm, nursery, and production specifications remains necessary. Facility cultivation also supports precision regulation through monitored parameters such as soil or substrate temperature, moisture, air humidity, and light, and intelligent control models have been developed with prediction error below 2.5%, showing the feasibility of data-based environmental management (Ding et al., 2018). At the cultivation-operation level, standardized facility production usually includes seedling propagation, substrate optimization, disinfection, transplantation, shade management, water-fertilizer regulation, and eco-friendly pest control, with substrate, fertilization, and harvest timing all recognized as important determinants of final medicinal quality.

4.2 Yield formation and quality regulation

Under facility conditions, yield formation is shaped by the interaction of seedling quality, cultivation structure, environmental regulation, and growth duration. Greenhouse cultivation is widely adopted because it can provide a more stable production environment and generally higher biomass and stem yield than less protected systems (Yang et al., 2023). High-quality seedlings show higher survival, stronger growth vigor, and higher stem yield after transplantation, indicating that yield improvement begins at the nursery stage rather than only in field management. Growth duration also matters: dendrobine content increased with planting years in one cultivation study, but nutrient-accumulation comparisons under artificial-sheltered cultivation found the best harvest time in the third year in both southern and northern sites, indicating that the optimal harvest stage depends on the target quality trait rather than on biomass alone (Guo et al., 2021). Expanding facility cultivation northward further links yield to varietal adaptation, because low temperature is a major limitation in new production areas and cold-resistant strains can improve transplantation success, survival, and economic returns.

Quality regulation under facility cultivation depends on deliberate manipulation of environmental and nutritional signals. Light is one of the strongest regulators: moderate light intensity improved multifunctional traits, while red light promoted expression of a key polysaccharide-synthesis gene and also improved growth, biomass, and polysaccharide and alkaloid accumulation in greenhouse experiments (Wang et al., 2024). Light and potassium treatments significantly increased anthocyanin accumulation and shifted metabolite and transcript profiles toward flavonoid and phenylpropanoid biosynthesis, showing that facility quality control can act through coordinated metabolic regulation rather than simple stress avoidance (Jia et al., 2022). Temperature regime is likewise regulatable in protected production: a day-night temperature difference of 25/13°C was more favorable than constant-temperature treatments for chlorophyll, polysaccharides, and total flavonoids in protocorm-like bodies, with corresponding changes in genes related to sugar and flavonol metabolism (Chen et al., 2024). Substrate and growth regulators also affect quality, as pine bark substrate favored flavonoid accumulation, and field application of 2,4-epibrassinolide increased stem and leaf polysaccharide-related sugars, with dried-stem polysaccharide rising by as much as 61% after 35 days in one study (Lu et al., 2025).

4.3 Advantages, challenges, and industrial application prospects

The main advantage of facility cultivation is its suitability for standardized, large-scale production. It has been a core driver of the transition from wild collection to massive commercial artificial-sheltered cultivation and has effectively alleviated the historical supply-demand imbalance of *D. officinale*. Facility production supports stable