treatment scale, environmental responses are also non-monotonic: red light most strongly promoted UGPase expression under different light qualities, high light induced mannose-rich polysaccharide accumulation through DoHY5-dependent signaling, and a 25/13℃ day-night regime gave higher polysaccharide content than constant temperatures in protocorm-like bodies. Moderate light also appears superior to extremes, because 11 000 lx simultaneously maximized biomass, bioactive compound yield, and sensory quality, whereas extreme high light increased structural carbohydrates but compromised growth-related and edible-quality traits. The main unresolved issue, therefore, is not whether light, temperature, humidity, and nutrients matter, but how their nonlinear interactions, developmental dependence, and cultivation-mode dependence should be parameterized into transferable threshold models for production.

A second challenge is establishing a regulation system that balances biomass production with polysaccharide quality, because maximizing growth does not always maximize medicinal value. Temperature studies showed that photosynthesis and vegetative growth were more favorable at 30℃, whereas stem polysaccharide content was significantly higher at 20℃, directly demonstrating a source–sink tradeoff between biomass expansion and polysaccharide concentration. Different cultivation environments also produce different quality profiles: tree-epiphytic stems had significantly lower polysaccharide content than stone-epiphytic and greenhouse samples, but stone epiphytic cultivation often accumulated more differential metabolites and stronger antioxidant-related quality traits, indicating that equal polysaccharide levels do not imply equal overall quality. This matters because polysaccharides remain the main Pharmacopoeia quality marker, yet regional metabolomics showed that small-molecule profiles can vary inversely with polysaccharide rankings, making polysaccharide-only evaluation incomplete for judging medicinal quality. Future regulation systems should therefore optimize for multiple endpoints at once: biomass yield, polysaccharide content, polysaccharide composition, and broader metabolite quality markers, ideally with cultivation-mode-specific targets for greenhouse, stone-epiphytic, and bionic systems. This is also the practical path for scaling artificial cultivation, since greenhouse production now dominates supply because of stable output and fast growth, yet uncontrolled optimization for yield alone risks weakening the medicinal traits that originally define high-quality *D. officinale.*

A third priority is integrating environmental monitoring, quality prediction, and intelligent control into a true precision-regulation platform. Recent predictive work already shows that this is feasible: machine-learning models outperformed linear models for predicting polysaccharide content across production areas, with XGBoost performing best, and also revealed that facility agriculture shifts the dominant drivers of high-quality production from rainfall and temperature toward altitude and sunlight. Harvest optimization studies similarly achieved high-accuracy prediction of dry matter content and suitable harvest period using chemometrics, and identified November to April, especially December, as the suitable harvest window, with specific daily water and shading recommendations. At the systems level, an IoT edge-computing and hybrid digital-twin platform for *D. officinale* improved prediction accuracy to 92.7%, increased production by 23.6%, and reduced energy use by 42.6%, showing the technical plausibility of closed-loop intelligent cultivation. Broader precision-agriculture evidence indicates that smart sensors for moisture, pH, and plant stress, combined with IoT, AI, and automated control, enable real-time irrigation, fertilization, and predictive analytics, but adoption remains constrained by cost, data-management complexity, technical expertise, and connectivity limitations. Future precision regulation in *D. officinale* should therefore couple sensor networks, transcriptome-and metabolome-informed quality models, and automated environmental control so that quality prediction moves upstream from post-harvest testing to dynamic cultivation management.

Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References

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