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Analysis of the Mechanisms by Which Controlled-Environment Regulation Affects Polysaccharide Accumulation in *Dendrobium officinale*

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Abstract *Dendrobium officinale* is an important medicinal and edible plant, and polysaccharides are its major bioactive constituents and key indicators for evaluating medicinal quality. Their formation and accumulation are jointly influenced by multiple factors, including genetic background, developmental stage, and cultivation environment. This study systematically analyzes the effects of controlled-environment regulation on polysaccharide accumulation in *D. officinale* and the underlying mechanisms, with particular emphasis on the regulatory roles of light, temperature, water, air humidity, mineral nutrition, cultivation substrates, and the rhizosphere microenvironment. The analysis indicates that appropriate light intensity and light quality, suitable day-night temperature differences, and coordinated water and fertilizer supply can improve photosynthetic carbon assimilation, increase the supply of sugar precursors, and promote polysaccharide accumulation by regulating sucrose metabolism, sugar transport, and the expression of polysaccharide biosynthesis-related enzymes and genes. Moderate environmental stresses, such as drought, low temperature, and nutrient limitation, can also enhance soluble sugar and polysaccharide accumulation through stress responses and carbon reallocation, whereas excessive stress suppresses plant growth and photosynthesis. Meanwhile, substrate physicochemical properties, rhizosphere water–air conditions, and beneficial microorganisms can indirectly regulate polysaccharide formation by affecting root vigor, nutrient uptake, and source–sink relationships. Polysaccharide accumulation in *D. officinale* is therefore the integrated outcome of photosynthetic carbon supply, sugar metabolic conversion, source-sink transport, environmental stress responses, and aboveground–belowground environmental interactions. Future studies should further clarify the optimal thresholds and interaction patterns of multiple environmental factors, establish precise controlled-environment regulation systems that balance biomass production and polysaccharide quality, and integrate environmental monitoring, quality prediction, and intelligent control technologies to achieve high-quality, efficient, and standardized production of *D. officinale*.

Keywords *Dendrobium officinale*; Polysaccharide accumulation; Controlled-environment regulation; Sugar metabolism; Carbon allocation

1 Introduction

Dendrobium officinale is an important medicinal and edible orchid that has been used in China for centuries and is now valued as both a traditional medicine and a functional food. Modern studies consistently identify polysaccharides as its principal bioactive constituents and as the core material basis for many of its health-promoting effects (Chen et al., 2024). These polysaccharides exhibit broad biological activities, including immunomodulatory, anti-inflammatory, hypoglycemic, hepatoprotective, gastrointestinal protective, antioxidant, antitumor, and vasoregulatory effects, which explains why *D. officinale* has attracted sustained attention in medicine, food, and health-related industries (He et al., 2022; Xu et al., 2022). Recent work has further expanded the application prospects of *D. officinale* polysaccharides to anti-aging, neuroprotection, skin barrier repair, and biomaterial development, indicating that their medicinal value depends not only on content but also on structural features and downstream mechanisms of action (Okoro et al., 2023; Guo et al., 2025).

Polysaccharides are also central to the quality evaluation of *D. officinale*. Existing studies state directly that polysaccharide content is used as a criterion for quality assessment, and some reports describe polysaccharides as the only selected quality marker in current quality control practice. However, the quality characteristics of *D. officinale* polysaccharides are not captured by content alone. *D. officinale* polysaccharides are mainly composed of mannose and glucose, but their monosaccharide ratios, molecular weights, glycosidic linkages, and