4.3 Effects of mineral nutrition and water-fertilizer interactions on polysaccharide formation

Mineral nutrition affects polysaccharide formation by changing both precursor metabolism and the transcription of mannan-biosynthetic genes. Ecological-factor analysis in cultivated *D. officinale* identified soil total nitrogen, total phosphorus, and available phosphorus as important variables affecting medicinal ingredients, indicating that nutrient supply is a major component of quality formation. Nitrogen responses are not linear: under low nitrogen, growth and photosynthesis were inhibited, but polysaccharide and flavonoid contents increased significantly, suggesting that nutrient limitation can redirect carbon away from growth and toward secondary and storage metabolism (Wu et al., 2023). Phosphorus limitation shows a similar pattern. Moderate phosphorus deficiency had little effect on stem height inhibition but promoted polysaccharide accumulation and increased the mannose-to-glucose ratio, while expression of active-ingredient pathway genes including DoCSLA6 increased significantly (Liu et al., 2021).

Mechanistic work now links phosphorus starvation directly to mannan synthesis. Low-phosphorus environments promoted polysaccharide accumulation, and *DoCSLA6*, a CSLA-family gene directly involved in mannose synthesis, was highly positively correlated with that accumulation (Feng et al., 2024). The DoSPX1-DoMYB37-DoCSLA6 pathway explains part of this response: *DoSPX1* and *DoMYB37* reduced phosphate accumulation and increased *DoCSLA6* expression, providing a direct regulatory bridge between phosphate status and polysaccharide biosynthesis. Nutrient interactions can also enhance quality when supply is balanced rather than restrictive. Carbon–nitrogen co-application improved photosynthetic performance and quality, and the 0.4AN/20KG treatment increased stem soluble sugar, micronutrient content, carbon-metabolism enzyme activity, and metabolite accumulation more than single-factor treatments, whereas high nitrogen alone had adverse effects on photosynthetic trends (Yin et al., 2026). Supporting evidence from another *Dendrobium* species showed that optimized N-P-K fertilization increased polysaccharide content by 26.84% and that nitrogen had the strongest overall effect, while rhizosphere bacteria such as *Pandoraea* may further promote polysaccharide production and provide a basis for microbiome-informed fertilizer design (Fan et al., 2023; Zhu et al., 2025).

5 Effects of Cultivation Substrates and the Rhizosphere Environment on Polysaccharide Accumulation in *Dendrobium officinale*

5.1 Effects of substrate physicochemical properties on root growth and nutrient uptake

D. officinale is now cultivated mainly under epiphytic or simulated-natural systems, so the substrate is not just physical support but a primary regulator of water retention, nutrient availability, and root-zone microhabitat (Zhu et al., 2022). Comparative metabolomics showed that different cultivation substrates have distinct physical properties such as water-holding capacity and distinct chemical properties such as nitrogen, phosphorus, and potassium content, and that these differences strongly reshape *D. officinale* metabolism. The same study found clear metabolic separation among substrate groups, indicating that substrate-driven differences are large enough to alter global metabolite profiles rather than only isolated compounds (Zuo et al., 2020). At the cultivation-scale ecological level, soil pH, total nitrogen, total phosphorus, and available phosphorus were identified as key quality-related factors in cultivated *D. officinale*, reinforcing that substrate chemistry is tightly linked to medicinal-component formation.

These substrate effects are expressed first through the root system. Mycorrhizal inoculation increased peloton formation in root cortical cells and produced more flourishing roots than uninoculated plants, showing that a biologically compatible root-zone environment can directly improve root vigor. In field cultivation, the same mycorrhizal treatment ultimately increased plant and stem dry weight to 2.69-fold and 2.87-fold of the control after 19 months, indicating that improved root symbiosis can translate into substantially greater sink capacity for polysaccharide accumulation (Chen et al., 2016). Substrate choice also changes downstream chemical quality: pine bark, coconut coir, and mixed substrates produced similar classes of metabolites but significantly different abundances, and pine bark favored flavonoid accumulation, while stone-epiphytic and greenhouse systems produced higher polysaccharide content than live-tree epiphytic cultivation (Zuo et al., 2020; Yang et al., 2023). Case-based cultivation analyses similarly suggest that pine bark substrate has high potential for improving quality