5 Mechanisms by Which Cultivation Substrates Influence Growth and Quality of *Dendrobium officinale*

5.1 Regulatory effects of substrate physicochemical properties on the rhizosphere environment

The physicochemical properties of cultivation substrates are fundamental factors influencing the growth and quality formation of *Dendrobium officinale*. These properties mainly include porosity, bulk density, water-holding capacity, aeration, pH, cation exchange capacity, and nutrient contents such as nitrogen, phosphorus, and potassium. As a typical epiphytic plant, *D. officinale* possesses roots that are highly sensitive to oxygen availability and fluctuations in water status. Therefore, substrates with good aeration and appropriate water retention can maintain normal root respiration, nutrient uptake, and metabolic activities, thereby creating a stable rhizosphere environment for plant growth. In contrast, substrates with poor aeration, excessive bulk density, or prolonged waterlogging may lead to root-zone hypoxia, suppress root activity, and even induce root rot, ultimately impairing plant growth and quality formation.

Significant differences exist among substrates in terms of water retention, drainage capacity, and nutrient availability, and these variations further influence metabolic processes within the plant. Zuo et al. (2020) conducted a widely targeted metabolomic analysis of *D. officinale* stems cultivated in pine bark, coconut coir, and a 1:1 mixture of the two substrates. Their results showed substantial differences among substrates in water-holding capacity and nutrient contents, particularly nitrogen, phosphorus, and potassium, which were closely associated with distinct metabolite profiles in the plants. Although the overall categories of metabolites were similar among substrate treatments, considerable differences were observed in metabolite abundance. Multivariate analyses, including principal component analysis (PCA) and orthogonal partial least squares-discriminant analysis (OPLS-DA), clearly distinguished samples derived from different substrates, indicating that substrate physicochemical properties exert strong regulatory effects on plant metabolism (Zuo et al., 2020). Furthermore, studies comparing greenhouse cultivation, simulated-natural cultivation, and wild growth conditions demonstrated that soil pH, total nitrogen, total phosphorus, and available phosphorus are important environmental factors affecting polysaccharide, total alkaloid, and flavonoid contents in *D. officinale*, further highlighting the close relationship between root-zone chemical environments and medicinal quality (Yuan et al., 2020).

The hydraulic characteristics of substrates also influence root-zone water-oxygen distribution and plant performance. Studies on coconut coir-and perlite-based soilless media have shown substantial differences in water retention curves, saturated hydraulic conductivity, pore-size distribution, and bulk density among substrates. These characteristics collectively determine the distribution of water and air within the confined root zone. Substrates possessing high total porosity, appropriate levels of plant-available water, and adequate aeration space generally create a low-stress rhizosphere environment that supports healthy growth in container cultivation systems (Gohardoust et al., 2020). Research on other horticultural crops has similarly demonstrated that combining organic materials such as coconut coir with inorganic components such as perlite and tuff can optimize water retention and aeration, thereby improving nutrient-use efficiency, plant growth, and yield (Tang et al., 2024). Therefore, for *D. officinale*, substrates capable of maintaining a balance among water retention, drainage, aeration, and nutrient buffering are more conducive to sustaining stable root-zone water-oxygen dynamics and nutrient supply, thereby promoting both growth and quality formation.

5.2 Effects of substrate microorganisms on nutrient uptake and metabolic activities

In addition to physicochemical properties, microbial communities within cultivation substrates are important factors affecting the growth and quality formation of *D. officinale*. Cultivation substrates serve not only as physical supports for root attachment and growth but also as habitats for diverse microorganisms, including bacteria, fungi, and actinomycetes. These microorganisms participate in organic matter decomposition, nutrient cycling, rhizosphere metabolism, and plant stress regulation, thereby exerting substantial effects on root