traits, and that mycorrhizal fungi enhance drought and disease resistance, which would be expected to stabilize root uptake under controlled production (Zhang et al., 2024).

**5.2 Regulation of polysaccharide accumulation by rhizosphere water–air conditions and nutrient supply**

Rhizosphere water, aeration, and nutrient supply regulate polysaccharide accumulation by controlling root respiration, nutrient flux, and the balance between growth and stress metabolism. Across *Dendrobium*, soil total nitrogen, available phosphorus, ammonium nitrogen, and pH are among the strongest drivers of rhizosphere microbial composition, and soil is considered the dominant factor shaping these microbial communities. In cultivated *Dendrobium* rhizospheres, dominant bacterial groups repeatedly include Proteobacteria, Bacteroidetes, Actinobacteria, and Acidobacteria, indicating a fairly consistent microbial core that still shifts with species and environment (Zuo et al., 2021). Because rhizosphere microbes promote nutrient absorption and can improve medicinal-plant yield and quality, shifts in water and nutrient conditions are likely to affect polysaccharide accumulation partly through microbial mediation rather than only through direct plant physiology (Sarsaiya et al., 2025). This interpretation is supported by recent *D. officinale* data linking polysaccharide accumulation closely to rhizosphere bacteria and identifying *Pandoraea* as a candidate polysaccharide-promoting genus (Zhu et al., 2025).

Water–air status in the rhizosphere is especially important because excess moisture can drive hypoxia and impair aerobic root metabolism. Broader rhizosphere evidence shows that hypoxia caused by waterlogging or compaction inhibits root aerobic respiration, disrupts energy metabolism, and alters rhizosphere microecology, while micro-nano bubble aeration can improve pore structure, continuously release oxygen, regulate microbial communities, and increase aeration in irrigation systems (Zheng et al., 2025). Although this was not tested directly in *D. officinale*, it fits the crop's dependence on an aerated epiphytic root zone and suggests a plausible controlled-environment strategy for avoiding carbon loss belowground (Zhu et al., 2022). Nutrient supply interacts with water status rather than acting independently: in another medicinal plant, the highest biomass and alkaloid accumulation occurred under an intermediate water–nitrogen regime, illustrating that water-fertilizer coordination can optimize rhizosphere physicochemical status and metabolite accumulation better than maximizing either input alone (Huang et al., 2024). In *D. officinale*, recent karst-environment work further showed that high-calcium limestone soils altered both rhizosphere properties and stem metabolism, with long-term calcium-rich conditions promoting calcium accumulation and mannose synthesis in stems, linking root-zone chemistry directly to polysaccharide-related carbon flow (Du et al., 2025).

**5.3 Synergistic effects of the rhizosphere microenvironment and aboveground controlled environment**

The strongest current model is that polysaccharide formation depends on synergy between the rhizosphere microenvironment and the aboveground controlled environment, rather than on either domain alone. Cultivation mode alters both substrate-associated and plant-associated bacterial and fungal communities, and some of these taxa are positively correlated with the main chemical components of *Dendrobium catenatum*, including stem polysaccharides. The same work showed that pot cultivation differed significantly from living-tree and cliff-epiphytic modes in microbial community structure, indicating that cultivation architecture and aboveground conditions feed back onto the rhizosphere and root microbiome (Zhu et al., 2022). More broadly, rhizosphere microbial communities vary among *Dendrobium* species and rhizocompartments, and the root environment acts as a selective interface for bacteria and fungi that support nutrient cycling, pathogen suppression, and stress resilience (Xie et al., 2024; Sarsaiya et al., 2025). In stressful Danxia habitats, the *D. officinale* microbiome showed diverse taxonomic and metabolic functions, including abundant carbohydrate- and energy-metabolism potential, which likely helps sustain plant growth in nutrient-poor environments.

This belowground support interacts with aboveground regulation through carbon supply and plant signaling. Root exudation dynamics shape microbial interactions, and beneficial rhizosphere bacteria and fungi enhance nutrient uptake, phytohormone status, stress tolerance, and root growth, which together increase the plant's capacity to convert photosynthate into polysaccharides (Sarsaiya et al., 2025). Orchid mycorrhizae likely contribute not only nutrients but also carbon, because photosynthetic orchids can be mixotrophic and recover carbon from root-associated fungi (Chen et al., 2016). Consistent with this, beneficial taxa such as *Sphingomonas paucimobilis*