2 Physiological and Metabolic Basis of Polysaccharide Formation and Accumulation in *Dendrobium officinale*

2.1 Composition, distribution, and accumulation characteristics

Polysaccharides are the principal bioactive constituents of *Dendrobium officinale*, and the medicinal stem is their main storage organ (Lai et al., 2024; Liang et al., 2025). Structurally, *D. officinale* polysaccharides are dominated by mannose and glucose, although galactose, xylose, arabinose, and rhamnose can also occur in different fractions and tissues (Guo et al., 2025). Cytochemical and compositional analyses indicate that the stem polysaccharides are mainly non-starch glucomannans or mannan-rich polymers, with water-soluble polysaccharides reaching about 35% of stem dry weight, whereas starch generally accounts for less than 10% (He et al., 2017). At the fine-structure level, several studies consistently report backbones enriched in 1→4-linked β-D-Manp and β-D-Glcp residues, although fermented or differently processed fractions can also contain α-linked motifs and distinct branching patterns, showing that DOPs are chemically diverse rather than a single uniform product (He et al., 2022; Zhong et al., 2022).

Polysaccharide distribution in *D. officinale* is strongly tissue-and stage-dependent. Histochemical observations show abundant polysaccharide granules in stem parenchyma cells, stored in plastids, which supports the central medicinal role of the stem as a sink tissue (He et al., 2017). Comparative organ analyses further indicate that stems have the highest polysaccharide content, whereas leaves and flowers also contain recoverable polysaccharides and represent underused biomass resources (Zhong et al., 2022; Chen et al., 2025). Accumulation is dynamic rather than static: stem water-soluble polysaccharides increase and then decline across development, peaking before flowering, while seasonal monitoring shows that stem sugars accumulate mainly from October to April, with especially rapid accumulation from October to February (Yang et al., 2025). This developmental and seasonal variation explains why polysaccharide content is widely used as a quality marker in cultivation and harvest management, but it also implies that quality depends on both amount and structure, since molecular weight, monosaccharide ratio, and conformation differ among stem, leaf, fermented, and extraction-derived fractions (Chen et al., 2025).

2.2 Photosynthetic carbon assimilation

Photosynthetic carbon assimilation provides the primary material source for polysaccharide biosynthesis in *D. officinale*. This species is a facultative CAM plant that can exhibit concomitant C3 and CAM photosynthesis under non-stressed conditions, while substrate moisture and light-dark cycle can shift the balance between these pathways. As substrate water declines, *D. officinale* shifts toward a more typical CAM pattern, and rewatering restores mixed C_3/CAM behavior, showing that environmental regulation directly changes the mode of carbon capture and therefore the carbon supply available for downstream sugar synthesis (Zhang et al., 2014). Because CAM and C_3 differ in the timing and efficiency of CO_2 fixation, this photosynthetic plasticity is a key physiological basis by which controlled environments can alter carbohydrate production and ultimately polysaccharide accumulation.

Recent physiological and transcriptomic evidence further shows that photosynthetic performance is tightly coupled to sugar accumulation. Seasonal analyses found that genes associated with sugar metabolism in stems and leaves were enriched not only in starch and sucrose metabolism but also in photosynthesis-related pathways, and identified hub genes that likely maintain sugar metabolism under low-temperature and drought conditions by regulating photosynthetic responses. Temperature-regulation experiments in protocorm-like bodies similarly showed that diurnal temperature difference increases chlorophyll and favors polysaccharide accumulation, while differentially expressed genes include photosystem components such as PSAB and PSBA together with sugar-metabolism genes (Chen et al., 2024). These findings indicate that carbon assimilation is not merely a background source process; rather, regulated photosynthesis determines source strength, precursor availability, and source-sink coordination, thereby setting the upper physiological limit for polysaccharide synthesis in *D. officinale*.