greater increases in fresh and dry weight, taller plants, thicker stems, and more new roots and tillers, indicating that mycorrhizal symbiosis can coordinately increase total biomass and promote biomass allocation to the stems, which are harvested as medicinal materials. From a broader ecological perspective, stem, leaf, and total biomass of *D. officinale* vary significantly among different provenances and environmental conditions, indicating that substrate-related environmental factors and genetic conditions jointly drive patterns of dry matter distribution. Therefore, from the dual goals of yield and quality improvement, selecting suitable substrates and combining them with beneficial microbial regulation is an important approach for promoting biomass accumulation and optimizing dry matter distribution in *D. officinale*.

4 Effects of Different Cultivation Substrates on Quality Formation in *Dendrobium officinale*

4.1 Effects on polysaccharide accumulation

Polysaccharides are among the most important bioactive constituents of *Dendrobium officinale* and serve as a core indicator for evaluating its medicinal quality. In addition to possessing immunomodulatory, antioxidant, and metabolic regulatory activities, polysaccharides directly influence the medicinal value and market competitiveness of *D. officinale*. Previous studies have demonstrated that polysaccharide content is highly responsive to growth conditions. Cultivation mode, root-zone physicochemical environment, nutrient availability, and water status can all affect polysaccharide accumulation, and these factors are largely regulated by cultivation substrates (Yuan et al., 2020). Comparative studies conducted across different production regions and cultivation systems have shown that variations in light intensity, temperature, water availability, and nutrient conditions can lead to substantial differences in polysaccharide content, indicating that polysaccharide biosynthesis exhibits considerable environmental plasticity (He et al., 2022).

Substrates with favorable water-holding capacity, aeration, and nutrient-buffering ability are generally more conducive to polysaccharide formation and accumulation. Pine bark, sphagnum moss, and their composite substrates provide a relatively stable rhizosphere environment, promoting photosynthate production, carbon accumulation, and carbohydrate metabolism, thereby enhancing polysaccharide content. Reviews have emphasized that appropriate artificial substrates and cultivation systems are among the most important agronomic strategies for increasing polysaccharide yield in modern *D. officinale* production systems (Chen et al., 2021). At present, epiphytic cultivation and wild-simulated cultivation have become major production approaches. These systems typically employ bark- or tree-based substrates and aim to produce green, organic medicinal materials with high polysaccharide content. Comparisons among cultivation sites and production techniques indicate that plants grown under more favorable microclimatic conditions and substrate-nutrient environments are more likely to meet or exceed the polysaccharide standards specified in the Chinese Pharmacopoeia, whereas lower compliance rates are often observed in environmentally less suitable regions (He et al., 2022).

It should be noted that polysaccharide accumulation does not necessarily increase in parallel with plant growth. Instead, it is jointly influenced by genotype, cultivation age, cultivation mode, and substrate conditions. Multi-year metabolomic analyses have shown that carbohydrates and glycosides are the predominant metabolites in *D. officinale*, and the third cultivation year may represent the optimal harvest period based on carbohydrate accumulation patterns. In standardized cultivation systems, tetraploid breeding materials have exhibited nearly double the stem polysaccharide content of diploid plants, indicating that polysaccharide accumulation depends not only on substrate optimization but also on genetic improvement and harvest timing management (Pham et al., 2019). Therefore, cultivation practices should balance yield and quality by optimizing substrate structure, nutrient supply, and harvest age to achieve the coordinated enhancement of both polysaccharide content and biomass production.

4.2 Effects on dendrobine, flavonoids, and other bioactive constituents

In addition to polysaccharides, dendrobine, flavonoids, phenolic compounds, bibenzyls, and phenolic glycosides are important functional constituents of *D. officinale*. Dendrobine and related alkaloids possess potential anti-inflammatory, neuroprotective, and immunomodulatory activities, whereas flavonoids and phenolic compounds are closely associated with antioxidant activity, free-radical scavenging, and stress defense. The