

In addition to substrate comparison studies, investigations involving different production regions and cultivation systems have also demonstrated that low-molecular-weight bioactive compounds are highly sensitive to environmental conditions. Metabolomic analyses of wild-simulated cultivation systems and materials from different geographical origins have identified numerous differentially accumulated metabolites, with significant enrichment of flavonoid and flavonol biosynthesis pathways and substantial variation in flavonoid content among habitats (Lan et al., 2022; Luo et al., 2023). Integrated proteomic-metabolomic studies have further shown that phenylpropanoid and flavonoid biosynthesis pathways are key targets affected by environmental variation. Critical enzymes such as phenylalanine ammonia-lyase and chalcone synthase exhibit differential regulation among production regions. Significant regional differences have also been reported for dendrobine and related alkaloids, suggesting that cultivation conditions, including substrate properties and soil nutrient status, can influence alkaloid accumulation (Guan et al., 2025). Therefore, selecting substrates with appropriate physical structure, nutrient characteristics, and moderate ecological stimulation effects may facilitate the accumulation of flavonoids, alkaloids, and other bioactive compounds, thereby enhancing the medicinal quality of *D. officinale*.

4.3 Effects on comprehensive evaluation of medicinal and commercial quality

Quality evaluation of *D. officinale* encompasses not only chemical indicators such as polysaccharides, alkaloids, and flavonoids, but also antioxidant capacity, morphological traits, stem quality, tissue texture, and commercial grading characteristics. High-quality *D. officinale* typically exhibits thick stems, uniform internodes, bright coloration, well-developed tissues, and elevated levels of bioactive constituents. Consequently, the dual effects of cultivation substrates on plant morphology and active constituent accumulation ultimately determine both medicinal and commercial quality. Previous studies have indicated that the medicinal quality of *D. officinale* is determined by a comprehensive profile of polysaccharides and various low-molecular-weight compounds, and is closely associated with functional activities such as antioxidant capacity (Chen et al., 2021; Xu et al., 2022; Wang et al., 2025; Yang et al., 2026).

In medicinal quality assessment, reliance solely on polysaccharide content has certain limitations. Comparative studies involving materials from different regions and cultivation environments have demonstrated that high polysaccharide levels do not necessarily coincide with elevated concentrations of flavonoids, phenolic glycosides, or other low-molecular-weight compounds. In some cases, regions producing materials with high polysaccharide content have exhibited relatively low levels of certain small-molecule constituents (He et al., 2022). Metabolomic and bioactivity studies have shown that flavonoids and phenolic acids are major contributors to the antioxidant capacity of *D. officinale*, and strong correlations have been observed between specific flavonoid glycosides and antioxidant indicators (Luo et al., 2023). Therefore, substrates or cultivation environments that promote flavonoid accumulation, such as pine bark-based systems, may enhance certain biological functions even when polysaccharide content remains relatively unchanged (Zuo et al., 2020; Lan et al., 2022).

From the perspectives of commercial quality and industrial application, substrate selection also influences stem thickness, fresh weight, uniformity, and processing suitability, thereby affecting commercial grading and market acceptance. Numerous studies have suggested that quality evaluation systems for *D. officinale* should incorporate representative low-molecular-weight biomarkers and biological activity indicators in addition to polysaccharides, because cultivation conditions—including substrate characteristics—can alter the balance among different classes of compounds, and such changes may not be directly reflected in appearance or yield (Chen et al., 2021; He et al., 2022). Regional comparisons under artificial shading cultivation have shown that *D. officinale* produced in southern cultivation regions generally contains higher levels of polysaccharides, flavonoids, and total polyphenols than material produced in newly established northern production areas, indicating that differences in regional environments and rhizosphere conditions may influence overall nutritional and medicinal value even under similar cultivation techniques. Therefore, future quality-oriented cultivation strategies should incorporate rational substrate selection and establish comprehensive evaluation systems that simultaneously consider polysaccharides, dendrobine, flavonoids, phenolic compounds, morphological traits, and commercial grade, thereby meeting the requirements of pharmacopoeial standards, functional food development, and market quality expectations.