aeration, drainage, moisture retention, and nutrient buffering, thereby creating a more suitable environment for the epiphytic root system of *D. officinale*. Studies on soilless cultivation have demonstrated that materials such as biochar, coconut coir, wood fibers, and organic residues can provide appropriate porosity, aeration space, and water-holding capacity after proper blending and stabilization. However, waste-derived materials may still exhibit variability in raw material quality, excessive salinity, phytotoxic compounds, and changes in substrate properties during cultivation. Therefore, standardized production, testing, and characterization procedures are required (Barrett et al., 2016; Gruda, 2019; Atzori et al., 2021).

In addition, the development of novel functional substrates is expected to become a major research focus in *D. officinale* cultivation. Recent advances in soilless cultivation systems provide valuable insights for substrate optimization. For instance, hydrochar derived from spent grains and combined with vermiculite and perlite can retain nutrients, reduce nitrogen and phosphorus losses, and provide low bulk density and high porosity, thereby improving crop growth (Miao et al., 2024). Bio-based hydrogel substrates composed of pectin and chitosan networks have been shown to promote seed germination, root vigor, yield, and polysaccharide accumulation in medicinal dandelion while enabling controlled nutrient release (Guo et al., 2026). Chitin and chitosan, owing to their high water-holding capacity, nutrient-binding ability, antimicrobial activity, and potential to stimulate plant hormones and beneficial microorganisms, have been recognized as promising substrate materials for future vertical farming systems (Jia et al., 2024). Applying these concepts to *D. officinale* cultivation suggests that future efforts should focus on developing peat-free, waste-based, biopolymer-enhanced, and microbe-carrier composite substrates. Such substrates could evolve from simple growth media into integrated platforms capable of water and nutrient buffering, rhizosphere regulation, and quality enhancement.

7.2 Strengthening research on substrate-microbe-quality interactions

In recent years, studies on rhizosphere ecology and plant microbiomes have emerged as important research areas in medicinal plant quality formation. For *D. officinale*, cultivation substrates not only determine the root growth environment but also influence the structure and function of rhizosphere and endophytic microbial communities, thereby regulating nutrient uptake, stress tolerance, metabolic activities, and the accumulation of bioactive compounds. Previous studies have shown that plant-associated microbial communities can promote plant growth, enhance stress resistance, and regulate the biosynthesis of secondary metabolites that determine medicinal quality (Lv et al., 2024). Reviews focusing on medicinal plants further indicate that rhizosphere and endophytic microorganisms can improve nutrient acquisition, restore degraded soils, induce systemic resistance, and directly stimulate the biosynthesis of alkaloids, phenolics, and other specialized metabolites, thereby enhancing medicinal quality and reducing contaminant accumulation (Kumari et al., 2023).

Future studies should pay particular attention to the roles of beneficial microorganisms, including mycorrhizal fungi, plant growth-promoting bacteria, and endophytic fungi, in the growth and quality formation of *D. officinale*. In *D. officinale* and related *Dendrobium* species, diverse endophytic fungi such as *Trichoderma*, *Epulorhiza*, and *Phomopsis*-related taxa have been associated with yield improvement, resource utilization, and plant protection, indicating their potential as microbial fertilizers and quality-enhancing agents. At the same time, plant secondary metabolites and microbiomes exhibit bidirectional interactions. On one hand, plant exudates and secondary metabolites shape rhizosphere microbial communities; on the other hand, microorganisms can reshape plant metabolomes through hormonal regulation, nutrient provision, induction of stress responses, and direct activation of defense pathways (Pang et al., 2021; Laffon et al., 2024; Lv et al., 2024). Therefore, merely comparing the effects of different substrates on growth and quality is no longer sufficient. Future studies should integrate substrate types, microbial communities, and metabolite profiles into a unified analytical framework.

With the rapid development of high-throughput sequencing, metagenomics, metabolomics, and transcriptomics, multi-omics approaches are expected to become essential tools for elucidating the mechanisms underlying quality formation in *D. officinale*. Controlled substrate-microbe interaction experiments could be employed to identify key microorganisms and optimal substrate conditions that synergistically enhance the accumulation of polysaccharides, dendrobine, flavonoids, and phenolic compounds. Furthermore, synthetic microbial consortia or