

greenhouse nursery stages because of its loose texture, strong water absorption capacity, favorable pore structure, and suitable pH. Studies have shown that, during the hardening stage of *D. officinale*, pure sphagnum moss promotes faster root emergence, enhances tillering, produces thicker leaves and stems, and increases plant biomass compared with bark alone, while maintaining a similar root-shoot ratio, indicating its clear role in promoting early adaptation and recovery growth of seedlings. In addition, compared with bark-based substrates, sphagnum moss substrates can also increase chlorophyll, carotenoid, and polysaccharide contents, suggesting that they not only favor vegetative growth but may also promote the accumulation of medicinal components.

Bark-based substrates mainly include pine bark, fir bark, and related materials, and are commonly used in seedbed cultivation, pot cultivation, and wild-simulated cultivation of *D. officinale*. Pine bark has high porosity and strong drainage capacity, providing a favorable aerated environment for the aerial roots of *D. officinale* and reducing the risk of root decay caused by prolonged high humidity. Meanwhile, during slow decomposition, pine bark can release certain organic nutrients and support sustained plant growth. Previous studies have shown that pine bark is widely used as an important component of seedbeds and mixed substrates for *D. officinale*. Under field-like cultivation conditions, it can support high survival rates, rapid growth, and high stem yield. During tissue-cultured plantlet acclimatization, the combined use of pine bark and fern fiber can achieve a 100% survival rate and favorable greenhouse growth performance in *D. officinale* (Luan et al., 2021).

From the perspective of quality formation, bark-based substrates may also affect the accumulation of secondary metabolites in *D. officinale*. Zuo et al. (2020) conducted metabolomic analysis of *D. officinale* stems cultivated in pine bark, coconut coir, and a 1:1 mixture of the two substrates, and found that pine bark alone was more conducive to the accumulation of flavonoids, with “flavonoid biosynthesis” identified as the main regulated pathway. This indicates that natural organic substrates not only affect root attachment and plant growth, but may also participate in quality formation by altering the rhizosphere environment and metabolic status. However, natural organic substrates still have certain limitations. For example, sphagnum moss largely depends on natural harvesting, and long-term use may face pressures related to resource conservation and rising costs. Bark-based substrates also have limited nutrient content, a long decomposition cycle, and considerable batch-to-batch variation. Therefore, improving the utilization efficiency of natural organic substrates and developing alternative, sustainable composite materials have become important directions in substrate research for *D. officinale*.

## 2.2 Agricultural waste-based substrates such as coconut coir, peanut shells, and rice husks

With the development of agricultural waste recycling and green cultivation concepts, agricultural by-products such as coconut coir, peanut shells, rice husks, mushroom residues, corncobs, and wood chips have gradually been applied in the cultivation of *D. officinale* and other *Dendrobium* species. These substrates are widely available and relatively low in cost. They can reduce environmental pressure caused by agricultural waste accumulation while lowering cultivation costs, and therefore have good ecological value and industrial application potential. Coconut coir and coconut husk are common organic substrates in *Dendrobium* orchid cultivation. Owing to their strong water-holding capacity, high porosity, and suitable aeration, they can support favorable survival and growth performance (Nuammee et al., 2024; Tt et al., 2024; Olasehinde, 2025).

In *D. officinale* cultivation, coconut coir can be used alone or mixed with materials such as pine bark. Zuo et al. (2020) found that, compared with pure pine bark, coconut coir alone or a 1:1 mixture of coconut coir and pine bark altered the stem metabolite profile of *D. officinale* but did not change the types of metabolites, indicating that it mainly affected metabolite contents rather than composition. In ornamental *Dendrobium* cultivars, pure coconut husk substrates can increase plant height, shoot number, inflorescence length, and floret number, and their overall performance is superior to that of most mixed substrates. This further demonstrates the importance of an appropriate water-air balance for the growth of *Dendrobium* plants (Tt et al., 2024). Therefore, coconut coir substrates have good substitution potential in green cultivation systems for *D. officinale*.

Peanut shells, rice husks, and other agricultural residues also have the advantages of light weight, good aeration, and structural improvement. After crushing, fermentation, composting, or disinfection, these materials can be used