

Effects of Different Cultivation Substrates on Growth and Yield of *Dendrobium officinale*

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Abstract *Dendrobium officinale* is an important medicinal plant whose growth performance and quality formation are highly dependent on cultivation conditions, among which the substrate plays a critical role in regulating water availability, aeration, and nutrient dynamics in the root zone. This study systematically reviews the effects of different cultivation substrates on the growth and yield of *D. officinale* based on existing literature and production practices. The results indicate that bark-based substrates provide good aeration and support root development but exhibit moderate water retention. In contrast, organic substrates such as coconut coir show strong water-holding capacity and are associated with enhanced accumulation of bioactive compounds, particularly polysaccharides. Wood-derived substrates, including sawdust, are cost-effective but may cause nitrogen immobilization, requiring careful nutrient management. Mixed substrates, combining different materials, demonstrate improved overall performance by balancing aeration and moisture conditions, leading to higher survival rates and better growth indices. In addition, substrate structure evolution, microbial community interactions, and regional environmental differences can significantly influence cultivation outcomes. Practical applications suggest that optimized substrate combinations and stratified designs can enhance plant establishment while reducing production costs. Overall, substrate selection should aim to balance aeration and water retention, while being adapted to specific cultivation systems and management strategies. These findings provide a theoretical basis and practical guidance for efficient cultivation and substrate standardization in *D. officinale* production.

Keywords *Dendrobium officinale*; Cultivation substrate; Aeration; Water retention; Yield formation

1 Introduction

In contemporary research and industry discussions, *D. officinale* is typically positioned as a high-value medicinal and functional food resource, with stem polysaccharides often treated as a key quality attribute. A widely cited benchmark is that polysaccharide content should exceed 25% as a quality criterion in the Chinese Pharmacopoeia (2020 edition), reflecting the central place of polysaccharides in quality control and commercialization (Chen et al., 2021). Market expansion has also been framed as one driver of cultivation intensification. A supply-demand assessment of the Chinese medicinal *Dendrobium* industry described a historical transition from wild collection to large-scale artificial cultivation and more diversified ecologically friendly systems, emphasizing how seedling production, substrate improvement, and integrated cultivation technologies support rapid expansion-while also noting persistent doubts about quality consistency and the lack of strong product standards in parts of the value chain (Cheng et al., 2019).

Current cultivation practices for *D. officinale* can be grouped into protected facility cultivation, such as shaded greenhouses using container or bed media, and “simulated natural” epiphytic modes that tie plants to tree trunks or place them on rock or cliff-like surfaces (Zhu et al., 2022). From a biological perspective, these choices matter because *Dendrobium* roots are specialized for epiphytic life. Comparative trait analyses across *Dendrobium* species show that thicker velamen tends to co-occur with thicker roots and anatomical traits linked to water conservation, and that velamen-related traits respond to environmental gradients (Qi et al., 2020).

Substrate selection is often treated as a “silent determinant” of performance because it governs the root-zone water-air-nutrient environment at the spatial scale where most management decisions are felt. Modern substrate science emphasizes that containerized media differ from field soils in water retention behavior, hydraulic

conductivity, and nutrient buffering (Gohardoust et al., 2020). For *D. officinale* specifically, substrate selection is also tied to quality formation rather than yield alone. When cultivation media differ in aeration and water-holding performance, the plant may shift physiological pathways and carbohydrate accumulation. One metabolomics-oriented comparison reported that weaker substrate “air-water supply capacity” was associated with reduced sugar accumulation, while substrates with higher aeration porosity and better water-holding performance were more favorable for carbohydrate accumulation (Zuo et al., 2022).

A recurring theme in both industry-facing and research-focused writing is that rapid expansion has not automatically produced uniform quality. From an industry lens, gaps include limited product standards and uneven technical guidance (Cheng et al., 2019). Substrate-related problems are not only economic, such as cost and supply continuity, but also biological. In orchid systems, microbial interactions, including mycorrhizal and non-mycorrhizal relationships, are integral to establishment, and cultivation mode can shape microbial communities in both plants and their substrates. Work on *D. catenatum* showed that cultivation mode influenced bacterial and fungal communities and that some microbial taxa correlated with major chemical components such as stem polysaccharides (Zhu et al., 2022; Xu et al., 2023).

In this review, I aim to clarify how common substrate types used in *D. officinale* production differ in their water retention, drainage, aeration, nutrient behavior, and biological stability—and how those differences translate into measurable outcomes such as growth performance, survival rate, and yield-related indices. I also synthesize practical recommendations for substrate selection and management across greenhouse and simulated-natural systems, and summarize a well-documented applied trial as a case study.

2 Role of Cultivation Substrates in Plant Growth

2.1 Water retention and drainage

In container-based cultivation, the substrate is fundamentally a porous hydraulic system: it must hold plant-available water while preventing stagnation and oxygen deprivation. Detailed characterization work on common soilless substrates and mixtures shows why this is nontrivial: water retention curves and hydraulic conductivity can shift sharply over narrow matric-potential ranges, and mixtures (e.g., coir with perlite or tuff) are often designed explicitly to tune water availability and drainage behavior (Gohardoust et al., 2020).

A practical complication is the “container effect,” where a vertical moisture gradient forms after irrigation and the lower portion of the container nears saturation, potentially reducing root health. Research on stratified soilless substrates explains this mechanism and reports that engineered layering can reduce water storage in coarse sub-strata and alter root development patterns (Criscione et al., 2025). Although these studies are not on *Dendrobium*, the underlying physics is relevant because *D. officinale* roots are sensitive to prolonged hypoxia and rot in poorly aerated zones.

2.2 Aeration and root development

Aeration is not just “nice to have” for epiphytic orchids; it is close to a biological requirement. Comparative trait work on *Dendrobium* shows that velamen thickness and related anatomical traits are part of a coordinated water-conservation strategy in exposed aerial roots (Qi et al., 2020).

At the microbial-physiological interface, oxygen status can influence symbiosis itself. A study on *D. catenatum* protocorms and *Serendipita indica* reported that hypoxia-responsive genes were strongly induced in symbiotic protocorms, suggesting that fungal colonization may be associated with localized hypoxia responses during early development (Xu et al., 2023). While this does not imply that low oxygen is beneficial, it highlights the importance of maintaining proper oxygen dynamics through substrate design.

2.3 Nutrient supply and stability

Nutrient behavior in substrates includes both supply and stability. In soilless systems, adsorption behavior for nutrients such as phosphorus and ammonium can strongly influence fertigation efficiency, and the limited volume of containers reduces nutrient buffering capacity (Gohardoust et al., 2020).

Organic substrates may also compete with plants for nitrogen through microbial immobilization. A study on wood fiber substrates reported significant nitrogen immobilization, reduced availability of readily usable nitrogen, and decreased plant biomass unless nitrogen inputs were adjusted (Wu et al., 2025). This is particularly relevant for sawdust-based substrates commonly used in horticulture.

2.4 Influence on plant health and yield

Substrates influence plant health through multiple pathways, including oxygen availability, water status, nutrient dynamics, and microbial interactions (Figure 1). In *D. catenatum*, cultivation mode was shown to shape microbial communities in both substrates and plant tissues, and some microbial groups were correlated with polysaccharide content and other chemical traits (Zhu et al., 2022). For *D. officinale*, substrate physical properties are also closely linked to carbohydrate accumulation. A comparative study of pine bark, coconut coir, and mixed substrates found that coir and composite substrates exhibited better aeration and water-holding capacity, and that polysaccharide content followed the trend: coir > mixed substrate > pine bark (Zuo et al., 2022).

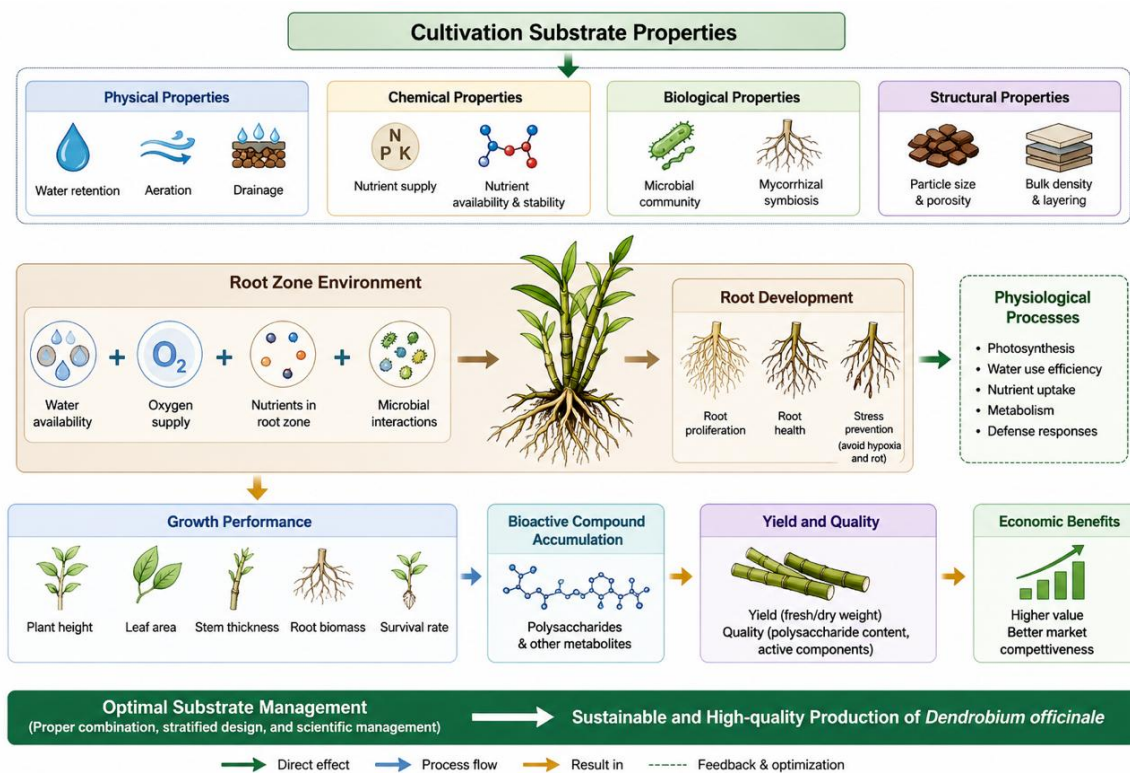


Figure 1 Conceptual diagram illustrating the mechanisms by which cultivation substrate properties influence root-zone environment, plant physiological processes, growth performance, and yield quality of *Dendrobium officinale*

3 Types of Common Cultivation Substrates and Their Characteristics

3.1 Bark-based substrates

Bark-based substrates are widely used in epiphytic orchid production because their coarse structure can maintain air-filled porosity and reduce waterlogging risk. In container-substrate research, bark is frequently identified as a major organic component, often mixed with inorganic materials such as perlite or pumice to optimize physical properties (Gohardoust et al., 2020). In practical cultivation of *D. officinale*, bark type and particle size distribution play an important role. A cultivation experiment using Chinese fir bark and pine bark in different combinations showed that certain mixtures improved survival rates and growth performance compared with single-substrate treatments (Li, 2020).

3.2 Sawdust and wood-based substrates

Sawdust and other wood-derived substrates are widely used due to their low cost and availability, but their decomposition behavior can complicate nutrient management. A high carbon-to-nitrogen ratio may lead to

microbial nitrogen immobilization, reducing plant-available nitrogen and inhibiting growth unless additional nitrogen is supplied. This mechanism has been clearly demonstrated in controlled experiments on wood fiber substrates (Wu et al., 2025). From a structural perspective, decomposition also means that substrate porosity changes over time. Studies on container substrates indicate that pore structure is dynamic, affected by root growth, particle rearrangement, and organic matter degradation, which can alter water retention and aeration properties during cultivation cycles (Criscione et al., 2025).

3.3 Coconut coir and organic substrates

Coconut coir is widely regarded as a sustainable alternative to peat due to its strong water retention capacity, although its properties vary depending on processing and origin. Substrate characterization studies have shown that coir-based mixtures can effectively regulate water retention and aeration, making them suitable for controlled cultivation systems (Gohardoust et al., 2020). In *D. officinale* cultivation, coconut coir has been shown to influence both growth conditions and metabolite accumulation. Comparative studies of pine bark, coconut coir, and mixed substrates found that coir-based media exhibited better aeration and water retention, and resulted in higher polysaccharide content (Zuo et al., 2022).

3.4 Mixed substrates

Mixed substrates combine different materials to balance aeration and water retention, forming a more stable root-zone environment. This approach is widely supported in substrate science, where organic materials are often combined with inert components to improve physicochemical stability and water management (Gohardoust et al., 2020). In practical *D. officinale* cultivation, mixed substrates have shown clear advantages. For example, composite treatments combining Chinese fir bark and pine bark demonstrated improved survival rates and growth indices compared with single-material substrates (Li, 2020).

4 Effects of Different Substrates on Growth and Yield

4.1 Effects on growth performance

Growth performance in *D. officinale* is commonly assessed with indices such as plant height, stem diameter, root length, and root number, because these indicators reflect establishment success and biomass accumulation potential. In a fir-bark-based cultivation trial, a composite substrate (fir bark mixed with pine bark at a 2:1 ratio) resulted in higher plant height and better root development compared to some single-material bark treatments after six months (Li, 2020).

From a mechanistic perspective, these differences can be explained by substrate physical properties. Research on soilless substrates shows that water retention and hydraulic conductivity regulate both water availability and aeration in confined root zones, and this is particularly important for epiphytic orchids such as *Dendrobium*, whose roots are highly sensitive to oxygen conditions (Gohardoust et al., 2020).

4.2 Effects on survival rate

Survival rate is often the most direct indicator of substrate suitability, especially during early establishment. Mortality at this stage is typically caused by root rot under excessive moisture, dehydration due to poor water retention, or transplant shock from poor root-substrate contact. In the fir-bark trial, the composite substrate (fir bark + pine bark, 2:1) achieved a survival rate of 96.7%, whereas some single bark treatments showed lower survival rates, such as 80.9% in fine fir bark (Li, 2020).

These findings are consistent with general container substrate principles. After irrigation, the lower part of the container often approaches saturation, reducing oxygen availability, and substrate structure may degrade over time. Substrates that maintain sufficient air-filled porosity during early growth stages are therefore more favorable for plant survival (Criscione et al., 2025).

4.3 Effects on yield

In *D. officinale*, yield is not always directly expressed as harvested biomass in short-term studies, as the crop is typically harvested after longer growth cycles. Instead, proxy indicators such as plant fresh weight, stem thickness,

and root system development are used. In the applied cultivation experiment, average plant fresh weight differed under different fertilization treatments, with decomposed sheep manure significantly increasing plant weight compared to a water-only control, along with improvements in stem thickness and root development (Li, 2020). In addition to biomass, quality-related yield is also critical. A substrate comparison study (pine bark vs coconut coir vs mixed substrate) found that polysaccharide content was highest in plants grown in coconut coir, suggesting that substrate properties can influence not only growth but also bioactive compound accumulation (Zuo et al., 2022). This aligns with broader findings that substrate conditions and cultivation modes are associated with variations in chemical composition in *Dendrobium* species (Zhu et al., 2022).

4.4 Comparative analysis

Across different studies, the effectiveness of a substrate is not determined solely by its type, but by how it interacts with irrigation and environmental conditions (Table 1). Bark-based substrates generally provide good aeration and reduce the risk of waterlogging, but may require more frequent irrigation in dry environments. Coconut coir offers strong water retention and has been associated with higher polysaccharide content, but may require careful management to prevent compaction (Zuo et al., 2022). Wood-derived substrates, including sawdust and wood fiber, are cost-effective and sustainable but may lead to nitrogen immobilization due to microbial activity. This increases the need for precise nutrient management and monitoring during early growth stages (Wu et al., 2025). Therefore, such substrates should be regarded as biologically active rather than inert, as their decomposition can affect both porosity and nutrient availability over time.

Table 1 Comparative analysis of physical properties and cultivation performance of different substrate types used for *Dendrobium officinale*

Substrate Type	Substrate Type	Water Retention Capacity	Nutrient Stability	Root Development	Growth Performance	Yield Quality
Bark-based	High	Moderate	Moderate	Good	Stable	Medium
Coconut coir	Moderate	High	Moderate	Good	Vigorous	High
Sawdust / Wood	Moderate	Moderate	Low (N immobilization)	Variable	Unstable	Medium
Mixed substrates	High	High	High	Excellent	Best	Best

5 Application in Production Practice

5.1 Substrate selection under different cultivation systems

In greenhouse cultivation, the most controllable lever is often the engineered substrate, because light and temperature are moderated by shade and ventilation while water and nutrients are delivered via irrigation systems. Substrate science suggests competitive advantages for media whose hydraulic properties match the irrigation strategy: for example, coir-inert mixes can be calibrated for fertigation, while bark-based or stratified systems can be designed to reduce saturated zones that compromise root respiration (Gohardoust et al., 2020).

Under-forest or simulated natural cultivation changes the substrate question. When plants are tied to living trees or placed on rocks, the “substrate” becomes bark surfaces, thin organic films, and mineral contexts that differ chemically and microbiologically from pots. In *D. catenatum*, different epiphytic modes were shown to shape microbial communities in plant tissues and substrates (Zhu et al., 2022). Furthermore, studies in karst environments demonstrated that calcium-rich substrates can induce distinct physiological and metabolic responses in *D. officinale* (Du et al., 2025). These findings suggest that substrate strategies should be region-specific rather than universally standardized.

5.2 Cost and availability considerations

Cost pressure plays a critical role in *D. officinale* cultivation and can directly influence substrate selection at scale. A cultivation study highlighted the large substrate demand in production and emphasized that low-cost and suitable substrates are essential for efficient and high-yield cultivation. In that context, fir-bark-based substrates were reported to reduce costs compared to pine bark, supporting the economic feasibility of alternative substrate materials (Li, 2020). From a broader perspective, studies on agro-industrial residues as cultivation media indicate that the transition away from peat toward renewable materials such as bark, coconut coir, and composted residues

is driven by both environmental and economic considerations. However, their practical application is often limited by variability in material quality and performance stability (Agarwal et al., 2023).

5.3 Practical management factors

Irrigation management should be considered inseparable from substrate design. Research on container substrates indicates that water distribution and aeration are influenced by gravitational gradients and structural changes over time. As substrates decompose or are modified by root growth, their hydraulic properties change, requiring adjustments in irrigation frequency and intensity (Criscione et al., 2025). Substrate replacement cycles are not yet standardized in *D. officinale* cultivation, but evidence suggests that periodic replacement is necessary, especially for substrates prone to decomposition or compaction. The dynamic nature of substrate porosity and moisture retention supports a management approach based on continuous monitoring of physical indicators such as drainage rate, odor, and root health to determine optimal replacement timing (Criscione et al., 2025).

6 Case Study

6.1 Background of a planting base

A representative applied cultivation trial was conducted at a *D. officinale* planting base associated with the Sanming Academy of Agricultural Sciences (Sanming, Fujian, China), using shaded greenhouse facilities and bed-style cultivation in small plots. The experimental design was randomized with replicated plots, and seedlings were transplanted in April with measurements taken by October, aligning with a practical establishment window in protected cultivation (Li, 2020).

6.2 Substrate application methods

The study compared bark-based substrate treatments built from different particle-size grades of fir bark and pine bark combinations (Table 2). Substrates were prepared by blending bark fractions in specific ratios and included an added coarse component (light wood particles) to support structure. This approach reflects a common production logic: the bark provides the epiphytic-compatible matrix, while the coarse fraction helps maintain aeration and reduces compaction (Li, 2020).

Table 2 Effect of different substrates on the growth of *Dendrobium officinale* (Adopted from Li, 2020)

Treatment	Substrate	Survival Rate (%)	Plant Height (cm)	Stem Diameter (cm)	Root Length (cm)	Root Number
1	Chinese fir bark (large)	90.0 Bb	10.93 Aa	0.62 Aa	4.40 Ab	5.67 ABa
2	Chinese fir bark : pine bark = 2:1	96.7 Aa	10.97 Aa	0.62 Aa	5.17 Ba	6.33 Aa
3	Chinese fir bark (small)	80.9 Cc	7.50 Bb	0.52 Bb	2.67 Cd	3.67 Cb
4	Pine bark	84.8 BCc	8.47 ABb	0.54 Bb	3.80 Bc	4.33 BCb

Note: Values represent the mean of three replicates. Different lowercase and uppercase letters indicate significant differences at the 0.05 and 0.01 levels, respectively

6.3 Growth and yield performance

After six months, survival rates and growth indices differed across substrate treatments. The fir-bark-pine-bark composite at a 2:1 ratio was reported to achieve the highest average survival rate (96.7%), with plant height and root number also among the better-performing outcomes. The improved performance was attributed to the balanced aeration and water-holding capacity of the mixed bark substrate compared with single-material substrates (Li, 2020).

The same report also compared fertilizer regimes on the selected substrate and found that decomposed sheep manure was associated with higher average plant weight, increased stem thickness, and longer roots than the control. Although fertilizer is not part of the substrate itself, this result highlights that substrate provides the physical foundation, while nutrient management further determines yield outcomes (Li, 2020).

6.4 Economic benefit analysis

The economic analysis emphasized that substrate accounts for a significant proportion of production cost due to large-volume demand. The authors reported that replacing pine bark with fir bark could reduce substrate cost by

approximately 30%, indicating that substrate optimization can directly improve profitability (Li, 2020). However, because the study did not provide a complete cost-benefit accounting system, including labor and market fluctuations, precise profit margins cannot be calculated. Nevertheless, the combination of reduced substrate cost and improved survival rate provides a realistic pathway to enhanced economic returns.

6.5 Practical experience and insights

Two practical insights emerge from this case. First, particle size distribution and mixing ratio are critical factors, sometimes even more important than the material type itself. Fine particles may reduce aeration, while overly coarse substrates may limit water retention, indicating the importance of structural optimization. Second, the study aligns with broader findings that substrate physical properties evolve over time, requiring adaptive irrigation strategies and continuous monitoring of root health to maintain optimal growth conditions (Agarwal et al., 2023).

7 Existing Problems and Limitations

7.1 Lack of unified standards

A persistent structural limitation is the lack of unified standards, both for end products and for production inputs such as substrates. Industry-level assessments have emphasized that limited product standards can hamper market trust and utilization, and substrate variability is one contributor to inconsistent quality because it shapes both growth and metabolite accumulation (Cheng et al., 2019).

7.2 Instability of substrate performance

Substrate performance instability can arise from multiple sources, including heterogeneity of raw materials (such as differences in bark origin or coconut coir processing), biological changes (decomposition and microbial shifts), and physical changes (settling and compaction). Research on soilless substrates highlights that porosity is not static but dynamic, as root growth and particle rearrangement can significantly alter pore distribution and water retention over time (Criscione et al., 2025). In practice, this means that a substrate that performed well under one condition may not maintain the same performance under slightly different irrigation regimes or material batches.

7.3 Regional differences

Regional differences extend beyond climate factors such as temperature and rainfall; they also involve variations in substrate chemistry and microbial ecology. For instance, in karst regions, substrates derived from limestone environments often contain high calcium levels and distinct microbial communities. Studies have shown that *D. officinale* exhibits specific physiological and transcriptomic responses under calcium-rich conditions, reflecting adaptation to such environments (Du et al., 2025). These findings suggest that cultivation practices and substrate selection should be region-specific rather than universally applied.

7.4 Limited technical guidance

Although research on *D. officinale* cultivation is expanding, technical guidance remains insufficient in translating experimental findings into practical and adaptable management strategies. Many studies identify optimal treatments under controlled conditions but do not provide flexible decision-making frameworks for growers. For example, studies on wood fiber substrates demonstrate that nitrogen immobilization can significantly affect plant growth if fertilization strategies are not adjusted (Wu et al., 2025). Additionally, research on microbial communities in *Dendrobium* cultivation shows that both substrate type and cultivation mode can reshape microbial composition, further complicating the development of standardized cultivation protocols (Zhu et al., 2022).

8 Optimization Strategies and Recommendations

8.1 Selection of suitable substrate combinations

The most practical strategy is to design substrate combinations based on functional requirements rather than tradition. Typically, a structural component that promotes aeration, such as coarse bark, should be combined with a moisture-buffering component, such as coconut coir or fine organic fractions. In addition, stratified substrate design can be considered to reduce saturated zones in deeper containers. Research on container substrates shows that stratification can significantly influence moisture gradients and root morphology, thereby improving root

system uniformity in early growth stages (Criscione et al., 2025). For *D. officinale*, experimental evidence also supports this approach. A cultivation study using a Chinese fir bark-pine bark composite substrate (2:1) demonstrated better survival rate and growth performance compared with other substrate treatments, indicating that even within bark-based materials, the balance between coarse and fine fractions plays a critical role (Li, 2020).

8.2 Improvement of cultivation management

Optimizing cultivation management requires establishing a dynamic feedback relationship between substrate characteristics and irrigation or fertigation practices. In soilless systems, irrigation ranges are often narrow and highly dependent on the water retention properties of substrates. Therefore, irrigation strategies should be adjusted promptly when substrate composition changes, rather than waiting for visible plant stress symptoms (Gohardoust et al., 2020).

When wood-based substrates are used, nitrogen management becomes especially important. Studies have shown that wood fiber substrates can significantly immobilize nitrogen, thereby reducing its availability to plants and limiting growth. This implies that growers should either reduce the proportion of high carbon-to-nitrogen materials or adjust fertilization strategies during early growth stages when nitrogen immobilization is most pronounced (Wu et al., 2025).

8.3 Promotion of standardized practices

Standardization in substrate use does not necessarily mean adopting a single universal formula. Instead, it involves standardizing measurement and reporting systems, including parameters such as particle size distribution, bulk density, water-holding capacity, drainage performance, and nutrient characteristics. Studies on substrate characterization have demonstrated that systematic evaluation of water retention, hydraulic conductivity, and nutrient adsorption is feasible and necessary. In addition, research on biomass-based substrates emphasizes the importance of consistent characterization when introducing new renewable materials (Agarwal et al., 2023). For *D. officinale*, adopting standardized evaluation methods would improve the reproducibility and transferability of substrate formulations across different regions and cultivation conditions.

8.4 Future development trends

Future development in substrate technology is likely to focus on three main directions. The first is “precision substrates,” where substrate mixtures are engineered to create predictable moisture and aeration profiles that match different plant developmental stages. The second is “biologically informed substrates,” recognizing that microbial communities within substrates are closely linked to plant physiological processes and chemical composition. Studies have shown that microbial communities in *Dendrobium* cultivation systems are associated with metabolite accumulation, and symbiotic interactions can involve hypoxia-related physiological responses (Zhu et al., 2022; Xu et al., 2023). The third direction is the development of sustainable substrates. Increasing attention is being given to renewable materials such as bark, coconut coir, wood fibers, and composted residues as alternatives to peat. However, successful adoption depends on managing variability and ensuring stable performance, which remains a key challenge for large-scale *D. officinale* cultivation (Agarwal et al., 2023).

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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