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

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Abstract *Dendrobium officinale* is an important orchid species in China with dual medicinal and food uses, and its stem growth and biomass accumulation are directly related to medicinal yield and commercial value. As a key component of artificial cultivation systems, cultivation substrates significantly affect the growth and yield formation of *D. officinale* by regulating root-zone moisture, aeration, nutrient supply, and the rhizosphere microecological environment. This study focuses on the effects of different cultivation substrates on stem growth characteristics and yield formation of *D. officinale*. The types and physicochemical properties of organic, inorganic, and mixed substrates were systematically analyzed, with particular emphasis on their effects on plant height, stem length, stem diameter, node number, new stem formation, root growth, biomass accumulation, and yield per plant and per unit area. The results indicate that substrates with moderate water-holding capacity, good aeration, and stable nutrient supply are more favorable for root growth and the maintenance of root activity, thereby promoting stem elongation, stem thickening, new shoot formation, and dry matter accumulation. Among them, rationally formulated mixed substrates based on bark, sphagnum moss, coconut coir, and agricultural and forestry residues can improve plant growth and yield performance by coordinating water, aeration, and nutrient conditions. Substrate effects are also jointly regulated by water and fertilizer management, environmental conditions, and rhizosphere microorganisms. In the future, unified substrate evaluation standards should be established, research on coordinated substrate-water-fertilizer-environment regulation should be strengthened, and the application of renewable substrates and beneficial microbial technologies should be promoted, thereby providing a theoretical basis and technical reference for high-yield, high-quality, and sustainable cultivation of *D. officinale*.

Keywords *Dendrobium officinale*; Cultivation substrate; Stem growth; Biomass accumulation; Yield formation

1 Introduction

Dendrobium officinale is a perennial orchid with high medicinal, nutritional, and economic value, and its dried stem is the officially used medicinal part recorded in the Chinese Pharmacopoeia (Li et al., 2025a). It has been used in China for thousands of years as a superior-grade tonic for nourishing the stomach, promoting body fluid production, nourishing Yin, clearing heat, and supporting general health (Cheng et al., 2019; Yuan et al., 2020; Zhang et al., 2023). Modern studies show that *D. officinale* contains abundant bioactive substances, including polysaccharides, flavonoids, alkaloids, bibenzyls, phenanthrenes, amino acids, and other phenolic compounds, which together underpin its wide range of pharmacological activities (Li et al., 2023b; Zhang et al., 2023; Bao et al., 2024). Among these constituents, polysaccharides are regarded as the most abundant and one of the principal active components, while flavonoids and other secondary metabolites also make important contributions to quality and efficacy. Experimental and review studies further indicate that *D. officinale* exhibits antioxidant, anti-inflammatory, immunomodulatory, gastrointestinal-protective, hypoglycemic, hepatoprotective, cardioprotective, anticancer, and neuroprotective effects, supporting its dual use as both medicine and functional food (Xu et al., 2022; Wang et al., 2025). Recent policy developments have further strengthened this positioning, as *D. officinale* stems have been incorporated into the catalogue of substances traditionally used as both food and herbal medicine in China, reflecting recognized long-term consumption safety and broad industrial prospects (Bao et al., 2024; Hou et al., 2025).

Driven by growing demand from pharmaceutical, health food, and related consumer markets, *D. officinale* has gradually developed from a wild-harvested medicinal resource into an important cultivated industry (Cheng et al., 2019; Bao et al., 2024). However, wild resources are scarce because the species has a specialized habitat requirement, slow growth, low natural reproduction rate, and a long growth cycle, while historical overexploitation further intensified resource pressure. To relieve the contradiction between supply and demand, artificial rapid propagation, seedling production technology, and diversified cultivation systems have been widely developed and adopted, effectively supporting sustainable resource use and market expansion (Li et al., 2025b). At present, most commercial *D. officinale* products come from artificial cultivation rather than wild collection, but product quality remains uneven, and doubts about the quality and efficacy of artificially cultivated material still constrain high-quality industrial development (Zuo et al., 2020). Existing research also shows that the quality of *D. officinale* is highly sensitive to cultivation, storage, and processing conditions, whereas national-level production standards remain incomplete, making standardized cultivation and quality evaluation urgent tasks for the industry (Xu et al., 2022).

Among the many cultivation factors affecting *D. officinale*, the cultivation substrate is especially important because it directly determines the root-zone water supply, aeration status, nutrient availability, physicochemical environment, and microbial interactions that support stem growth and yield formation (Rianawati et al., 2022). Ecological studies have shown that medicinal quality in cultivated *D. officinale* is closely related to environmental conditions, and key factors such as substrate pH, total nitrogen, total phosphorus, and available phosphorus significantly influence major medicinal constituents (Yuan et al., 2020; Zuo et al., 2020). Metabolomic analyses further demonstrate that different cultivation substrates do not necessarily change the categories of compounds present, but they significantly alter metabolite abundance, with flavonoids being among the most responsive groups; in one comparison, pine bark favored higher flavonoid accumulation and was identified as the best substrate among the tested treatments for improving this quality trait (Zhang et al., 2024). At the seedling stage, substrate effects are already evident: sphagnum moss promoted faster rooting, stronger tillering, greater stem diameter, greater biomass, and healthier seedlings than bark substrate. Other transplant studies likewise found clear substrate-dependent differences in survival and vegetative growth, with alder bark mixed with fine sawdust outperforming other tested media in survival rate, plant height, root growth, stem diameter, and leaf number. Patent and applied studies also suggest that optimized compound substrates formulated from agricultural and forestry residues can raise survival above 98%, increase plant height and stem thickness, improve polysaccharide content, reduce root and soft rot, and ultimately enhance yield. Evidence from orchid systems more broadly supports the same principle, showing that media with suitable moisture retention and aeration promote better growth and yield performance, whereas poorly balanced media constrain development (Narute et al., 2024).

This study examines the effects of different cultivation substrates on the stem growth characteristics and yield formation of *Dendrobium officinale*, with particular emphasis on the relationships between substrate conditions and plant height, stem diameter, biomass accumulation, growth vigor, and yield components. The stem is the principal medicinal and commercial organ of *D. officinale*, and its growth status not only directly affects medicinal yield and harvest efficiency but is also closely related to the accumulation of bioactive compounds and the formation of medicinal quality. Therefore, the selection of suitable cultivation substrates should take growth, yield, and quality into comprehensive consideration. Based on this premise, this study compares the physicochemical properties of different cultivation substrates and evaluates their effects on root growth, stem morphology, biomass accumulation, and yield formation in *D. officinale*. It further analyzes the regulatory roles of substrate water-holding capacity, aeration, nutrient supply, and the rhizosphere microenvironment, and explores coordinated optimization strategies integrating substrates with water and fertilizer management. The study aims to identify suitable substrates or substrate combinations that promote vigorous growth and efficient production of *D. officinale*, thereby providing a theoretical basis and technical reference for substrate optimization, standardized cultivation, and the sustainable development of the *D. officinale* industry.

2 Types and Physicochemical Properties of Cultivation Substrates for *Dendrobium officinale*

2.1 Major types of organic, inorganic, and mixed cultivation substrates

Dendrobium officinale cultivation substrates are commonly divided into organic, inorganic, and mixed types, and this classification is consistent with broader substrate science (Bao et al., 2024; Yang et al., 2025). In practical *D. officinale* production, organic materials include bark, sphagnum moss, coconut coir, peanut shells, and fungal or biowaste residues, whereas inorganic materials include vermiculite, perlite, charcoal, gravel, and related mineral components (Wang et al., 2024). Mixed substrates are widely used because they combine the moisture retention of organic fractions with the structural stability and aeration of mineral fractions, giving stronger control over water, air, and fertilizer supply than single-component media (Gohardoust et al., 2020; Malík and Tlustoš, 2025).

Current *D. officinale* studies illustrate this diversity clearly. Tested substrates include pine bark, coconut coir, and a 1:1 pine bark-coconut coir mixture (Zuo et al., 2020); bark and sphagnum moss during hardening; wood shavings plus fine sawdust, alder bark plus fine sawdust, and fir bark plus fine sawdust for transplant establishment; and composite agricultural-residue substrates containing mushroom residue, herbal residue, chestnut shell, peanut shell, mulberry stem, corncob, wood chips, clay, and mineral nutrients. Industry reviews further show a shift from simple bark-based media toward diversified composite substrates and ecologically oriented cultivation systems, reflecting the need to balance seedling survival, growth, medicinal quality, and standardization (Cheng et al., 2019; Bao et al., 2024).

2.2 Water-holding, aeration, and nutrient characteristics of different cultivation substrates

For *D. officinale,* the key substrate functions are water retention, drainage, aeration, and nutrient-moisture buffering, because seedling survival and later stem formation depend on a root zone that is moist but not waterlogged and porous but not excessively dry (Bao et al., 2024). Broader soilless research shows that water-holding capacity, air-filled porosity, capillary conductivity, cation exchange capacity, and nutrient adsorption jointly determine root-zone control (Gohardoust et al., 2020; Tang et al., 2023). These traits vary sharply among materials: coconut coir retains moisture well and buffers nutrients, inert aggregates emphasize gas exchange but store less water, and vermiculite or microporous substrates tend to show stronger cation exchange and nutrient adsorption (Malík and Tlustoš, 2025).

Evidence from *D. officinale* aligns with these principles. The three substrates compared in metabolomic work differed in water-holding capacity and in nitrogen, phosphorus, and potassium content, and these physicochemical differences were considered sufficient to alter plant metabolism markedly (Zuo et al., 2020). In applied cultivation, a mushroom-dreg and pine-scale composite substrate was reported to be superior in quality, polysaccharide content, and water retention (Bao et al., 2024), while pine bark improved survival, plant height, stem diameter, and dry weight in northern cultivation (Zhang et al., 2024). At the seedling stage, sphagnum moss promoted faster rooting, stronger tillering, larger stem diameter, and greater biomass than bark, and alder bark plus fine sawdust outperformed the other tested transplant media in survival, root growth, stem diameter, and leaf number.

2.3 Relationships between substrate physicochemical properties and the rhizosphere environment of *Dendrobium officinale*

The physicochemical properties of the substrate shape the rhizosphere environment of *D. officinale* by regulating pH, nutrient availability, moisture status, and microbial habitat, which together influence both stem growth and active-component accumulation (Zuo et al., 2020; Hou et al., 2025). Ecological analysis identified soil pH, total nitrogen, total phosphorus, and available phosphorus among the key factors associated with the main medicinal qualities of cultivated *D. officinale* (Yuan et al., 2020). This is consistent with general rhizosphere studies showing that changes in substrate physicochemical properties modify microbial community structure, and that microbial groups often track organic matter and available nitrogen, phosphorus, and potassium (Yang et al., 2025; Zhang et al., 2025).

Recent *D. officinale* work also shows that rhizosphere responses are substrate-specific rather than purely nutritional. In karst cultivation, black limestone soil with high calcium content was associated with shifts in dominant microbial groups, and total calcium accumulation correlated positively with organic matter and pH (Du

et al., 2025). In the plant, long-term calcium-rich conditions induced calcium accumulation and mannose synthesis, while high soluble calcium increased mannose, ascorbic acid, and calcium oxalate in stems. More broadly, lower bulk density and higher porosity tend to favor root biomass and beneficial rhizosphere assemblages in soilless systems (Yang et al., 2025), which helps explain why substrate optimization in *D. officinale* should target not only physical support and yield, but also a stable rhizosphere microenvironment conducive to nutrient uptake, stress resistance, and medicinal-quality formation (Hou et al., 2025).

3 Effects of Different Cultivation Substrates on Stem Growth Characteristics of *Dendrobium officinale*

3.1 Effects of different substrates on stem length, plant height, and internode elongation

Different substrates produce measurable differences in stem length and plant height in *D. officinale* seedlings and young plants. During the seedling hardening stage, sphagnum moss significantly increased plant height relative to bark substrate, indicating that a substrate with higher moisture retention and better early root support favors aboveground elongation. In transplant culture, alder bark mixed with fine sawdust produced the greatest plant height at 60 days, outperforming wood shavings plus fine sawdust and fir bark plus fine sawdust, which shows that bark-based mixed media can promote more rapid vertical stem growth after establishment. A compound cultivation substrate formulated from agricultural and forestry residues was associated with an average plant height of 78 cm after one and a half years, together with high survival and yield, suggesting that optimized composite substrates can sustain long-term stem extension under production conditions. Evidence from broader *Dendrobium* cultivation points in the same direction, as coconut-husk-based media produced the best plant height in cv. Sonia Red, emphasizing that media with balanced water retention and aeration are favorable for elongation growth in this genus (Narute et al., 2024).

The evidence for internode elongation is more limited and less substrate-specific than the evidence for total plant height. Direct *D. officinale* substrate studies often record plant height and leaf number, but some do not detect significant differences in node number even when height differs, implying that substrate-driven height gains can reflect elongation of existing stem segments rather than increased node formation. Comparative and genetic studies support treating plant height, internode number, internode length, and stem diameter as partly separable traits rather than a single growth dimension (Niu et al., 2021; Abduallah et al., 2026). In induced polyploids of *D. officinale*, some treatments decreased plant height and shortened internode length while increasing stem diameter, confirming that elongation and thickening can respond in opposite directions under altered growth conditions (Liu et al., 2023). Fungal symbiont studies further show that stem elongation is biologically responsive but time-dependent: after 30 days, mycorrhizal inoculation caused no significant plant-height difference, whereas by 90 days one core fungus significantly increased seedling height, and a dark septate endophyte increased stem length by 11.25% and seedling height by 16.97% (Long et al., 2022; Wu et al., 2025). Taken together, substrate effects on elongation appear real, but they are likely mediated through rhizosphere moisture, nutrient supply, and symbiotic status rather than through a simple one-to-one effect on internode extension alone (Zuo et al., 2020; Zhang et al., 2024; Wang et al., 2025).

3.2 Effects of different substrates on stem diameter, node number, and stem morphology

Stem diameter is one of the most responsive stem traits to substrate differences in *D. officinale*. At the hardening stage, sphagnum moss produced a very significant increase in stem diameter over bark substrate, together with thicker leaves and greater biomass, indicating that favorable early substrate conditions promote both stem thickening and overall seedling vigor. In transplant experiments, alder bark plus fine sawdust produced thicker stems than the other tested media, again supporting the value of bark-based mixed substrates for stem robustness. Under longer-term production, the compound residue-based substrate yielded stems averaging 7.5~8.2 mm in thickness, linking composite substrate optimization to commercially important stem morphology. Broader cultivation evidence is consistent with this pattern: stem diameter is strongly affected by plant growth conditions, and both GWAS and polyploid studies identify it as a distinct morphological trait with partially independent regulation (Niu et al., 2021; Liu et al., 2023).

By contrast, node number appears less sensitive than stem diameter in the available direct substrate studies. In the bark-versus-sphagnum comparison, node number did not differ significantly despite clear increases in plant height, stem diameter, and biomass under sphagnum moss, indicating that superior substrates can improve stem quality without necessarily increasing node production at the seedling stage. This distinction matters because stem morphology is a composite outcome of thickness, length, node spacing, tissue fullness, and branching tendency rather than any single index (Liu et al., 2023). Comparative morphology across *Dendrobium* species also shows that plant height, internode number, and internode diameter vary independently and can even correlate in opposite directions, which helps explain why one substrate may favor thicker stems while another favors taller but less compact plants (Duggireddy et al., 2024; Abduallah et al., 2026). In *D. officinale*, stem morphology is also plastic under non-substrate factors: tetraploids develop shorter but thicker stems, and some induced plants show occasional branching growth, reinforcing that substrate effects on morphology should be interpreted together with genotype and developmental status (Pham et al., 2019). Therefore, when evaluating substrates, stem diameter is a more sensitive and practical indicator than node number, while morphological assessment should integrate both compactness and biomass potential (Niu et al., 2021).

3.3 Effects of different substrates on new stem formation and stem growth dynamics

Substrate effects on new stem formation are most evident when growth is followed over time rather than measured at a single endpoint. During hardening, sphagnum moss promoted faster root initiation and stronger bud tillering than bark, which indicates a higher capacity to support the initiation of new shoots and subsequent stem establishment. In broader *Dendrobium* media studies, coconut-husk-based media produced the maximum number of shoots, and earlier work cited within that study likewise associated mixed charcoal, brick, and cocopeat media with improved new growth (Narute et al., 2024). Although these are not all *D. officinale*, they support the same horticultural principle that media with suitable moisture retention and aeration promote repeated shoot emergence. Evidence from the related medicinal species *D. huoshanense* is especially relevant here: among nine substrates and four cultivation measures, the optimal regime produced the largest number of new stems and the highest stem growth, showing that substrate choice can directly regulate the formation rate of new canes in medicinal *Dendrobium* cultivation.

Stem growth dynamics in *D. officinale* also depend on interactions between substrate conditions and beneficial fungi. Mycorrhizal cultivation with *Mycena* sp. showed a slower initial growth rate than the control, but the treated plants later surpassed the control, and after 19 months plant dry weight and stem dry weight were 2.69 and 2.87 times higher, respectively. The number of seedlings in the mycorrhizal treatment increased earlier than in the control, with the rise appearing after 9 months and the control lagging by about 3 months, which suggests earlier activation of new shoot or clump expansion processes under a favorable root-zone biotic environment (Chen et al., 2016). More recent symbiosis studies show the same time dependence: core orchid mycorrhizal fungi differ in which growth traits they enhance, one strain increased tillering by 4.47-fold, and mixed fungal inocula did not necessarily produce additive benefits (Wu et al., 2025). Direct seeding work also found strong fungus-substrate interactions, with one substrate favoring rapid early germination and another favoring later seedling establishment, confirming that the dynamic formation of new stems begins with substrate-mediated effects on establishment phase trajectories (Figure 1) (Li et al., 2025b).

4 Effects of Different Cultivation Substrates on Biomass Accumulation and Yield Formation of *Dendrobium officinale*

4.1 Effects of different substrates on root growth and aboveground biomass accumulation

Different substrates first affect biomass accumulation through their effects on root growth and seedling establishment. During the hardening stage, sphagnum moss produced significantly greater root length, root number, plant height, and biomass per ten plantlets than bark, indicating that a moisture-retentive substrate can promote both belowground and aboveground accumulation early in development. In transplant culture, alder bark mixed with fine sawdust gave the best survival, plant height, root length, root number, and stem diameter among three tested media, showing that bark-based mixed substrates can also support vigorous biomass formation after transplanting. Pine-bark-based systems likewise supported rapid establishment, with one cultivation method

reporting more than 98% transplant survival and yield above 250 kg per unit area while avoiding waterlogging-related root rot.

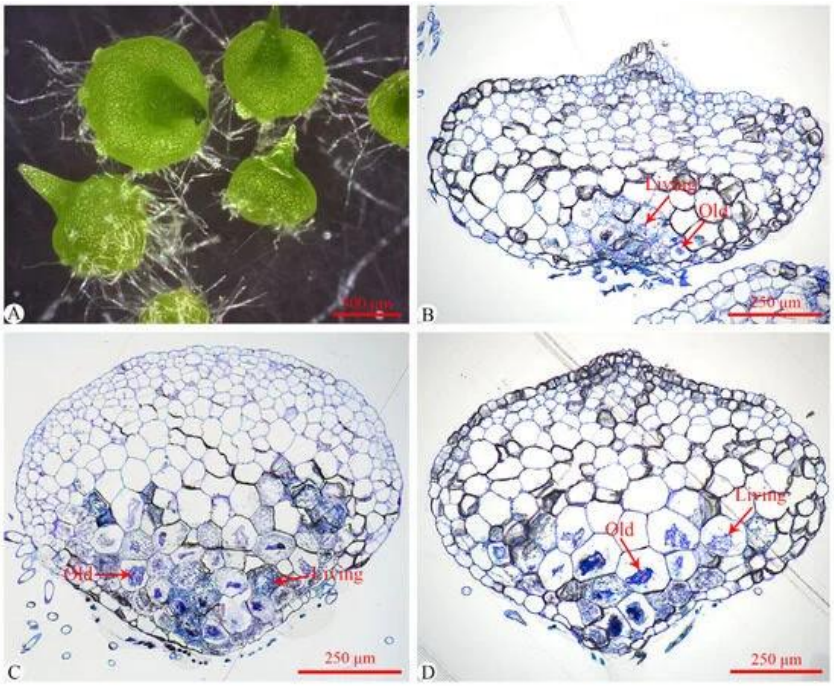


Figure 1 The colonization of different fungi in *Dendrobium officinale* protocorms (Adopted from Li et al., 2025b)
Image caption: A: Protocorms germinated by fungus-seed symbiosis for 60 d at different locations; (B~D) represent the colonization of SI, SO, SO and SI in *Dendrobium officinale* protocorms, respectively; Red arrows: mycelial clusters (Adopted from Li et al., 2025b)

Evidence from microbial and symbiotic amendments further shows that the substrate effect is partly mediated by the root-zone biological environment. Endophytic-fungus inoculants prepared in peat, mushroom compost, and corncob matrices increased plant height, root length, root surface area, root volume, fresh weight, and dry weight relative to uninoculated controls, with dry weight gains of 67.9%~101.9%. Mycorrhizal fungi also promoted organ-specific growth: *Tulasnella* strains increased stem growth and organic matter accumulation, while other strains preferentially increased roots or leaves (Wu et al., 2025). In field cultivation, *Mycena* inoculation eventually raised plant dry weight and stem dry weight to 2.69 and 2.87 times the control, despite a slower initial phase, which indicates that substrate conditions that favor stable fungal colonization can substantially increase long-term biomass accumulation (Chen et al., 2016). More broadly, biomass accumulation in *D. officinale* remains environmentally plastic across cultivation sites, and is also enhanced by favorable light and carbon-nitrogen regimes (Nguyen et al., 2023; Yin et al., 2026; Zhang et al., 2021).

4.2 Effects of different substrates on individual stem weight, number of effective stems, and yield per plant

Substrate effects on yield per plant are expressed through individual stem filling, survival of productive shoots, and the number of stems that reach harvestable status. Direct substrate comparisons show that mixed and bark-based media improve the stem traits that usually precede heavier stems, including plant height, stem diameter, leaf number, and biomass. In a metabolomic comparison, pine bark, coconut coir, and their mixture differed in water-holding capacity and nutrient properties, and the authors concluded that substrate selection supports higher biomass yield, even though that study emphasized quality metabolites rather than reporting yield components directly (Zuo et al., 2020). A composite grain substrate prepared from mushroom residue, herbal residue, shells, corncob, wood chips, and mineral supplements achieved survival above 98%, stem thickness of 7.5~8.2 mm, and average yield of 580 kg per mu, supporting the value of complex organic substrates for productive stem formation.

The number of effective stems depends not only on stem enlargement but also on new shoot formation and shoot retention. In seedlings, sphagnum moss promoted stronger bud tillering than bark, and core mycorrhizal fungi increased tillering, with one *Tulasnella* strain raising it 4.47-fold (Wu et al., 2025). In longer-term cultivation, *Mycena* inoculation advanced the rise in seedling number by about three months compared with the control (Chen et al., 2016), which is relevant because shoot number contributes to later economic yield. Genetic evidence also supports this interpretation: when shoot number was below 4.5, both biological and economic yields increased with additional shoots, but above that threshold the marginal effect weakened. Thus, substrates that favor early tillering, maintain stem survival, and support stem thickening are most likely to increase individual stem weight and yield per plant, especially when coupled with cultivation modes that preserve beneficial root fungal communities (Cheng et al., 2026).

4.3 Relationships between stem growth traits and yield per unit area

The relationship between stem growth traits and yield per unit area is supported most directly by correlation and dynamic growth studies. Across 14 F1 families, plant height, stem diameter, leaf number, leaf length, and leaf width were all significantly correlated with biological and economic yield, and stem diameter, leaf number, and leaf length were the most informative predictors. Stem length also matters mechanistically, because the stem is the medicinal organ and longer stems contribute directly to yield formation; calcium nitrate promoted stem elongation by increasing gibberellin biosynthesis, longitudinal cell elongation, and vascular development (Du et al., 2023). These findings explain why substrate-induced changes in plant height and stem diameter are agronomically meaningful rather than merely morphological.

Yield per unit area in *D. officinale* also reflects growth dynamics over time. Vegetative growth followed an S-shaped curve, with the fastest growth from February to September, and unit-area yield among nine germplasms ranged from 90.65~407.08 g/m². Environmental effects on biomass allocation were significant across cultivation sites (Zhang et al., 2021), and light regulation strongly altered growth and biomass, with 50%~70% shade producing the highest values (Nguyen et al., 2023). Substrate should therefore be viewed as one of the central drivers linking root vigor to stem growth and then to area-based yield: better root growth increases water and nutrient uptake, stronger stems raise individual harvest weight, and adequate shoot number determines how that per-stem advantage scales to the planting population. The evidence supports using well-aerated, moisture-retentive organic or mixed substrates, especially bark- or residue-based systems with compatible fungal inoculation, to improve biomass accumulation and yield formation of *Dendrobium officinale* (Wu et al., 2025).

5 Mechanisms by Which Cultivation Substrates Regulate Stem Growth and Yield Formation of *Dendrobium officinale*

5.1 Regulation of stem growth by substrate water retention and water supply capacity

Substrate water retention and water supply capacity regulate stem growth first by determining whether *D. officinale* experiences a stable moisture regime or repeated water stress. *D. officinale* is highly sensitive to environmental stress, and water scarcity in wild-simulated cultivation is associated with slow growth and low yield (Figure 2) (Yuan et al., 2020; Luo et al., 2024). In direct substrate comparisons, different cultivation media differ in water-holding capacity, and these differences are large enough to alter plant metabolism and quality traits (Zuo et al., 2020). Ecological analyses further show that humidity-related variables are among the key factors influencing major medicinal components, indicating that water status affects both growth and stem quality (Wang et al., 2026).

The mechanism is physiological as well as morphological. *D. officinale* is a facultative CAM plant, and decreasing substrate water content shifts it toward a stronger CAM pattern, while rewatering restores the concomitant C3-CAM state, showing that substrate moisture directly regulates carbon assimilation strategy. Under stress, improved water retention helps preserve relative water content, reduce membrane damage, and sustain biomass accumulation, as shown by ABA-treated seedlings under cold stress, where enhanced water retention increased biomass and reduced electrolyte leakage (Wang et al., 2026). By contrast, disturbed water metabolism increases physiological disorder: in vitro osmotic imbalance raised total and free water content, increased

membrane permeability, and disrupted antioxidant systems in *D. officinale* plantlets (Gao et al., 2020). Because *Dendrobium* species are epiphytes adapted to intermittent drought, they rely on coordinated water conservation and storage traits, including low leaf water loss and pseudobulb water buffering, so substrate water supply must be sufficient but not excessive to support continuous stem elongation and filling (Yang et al., 2016).

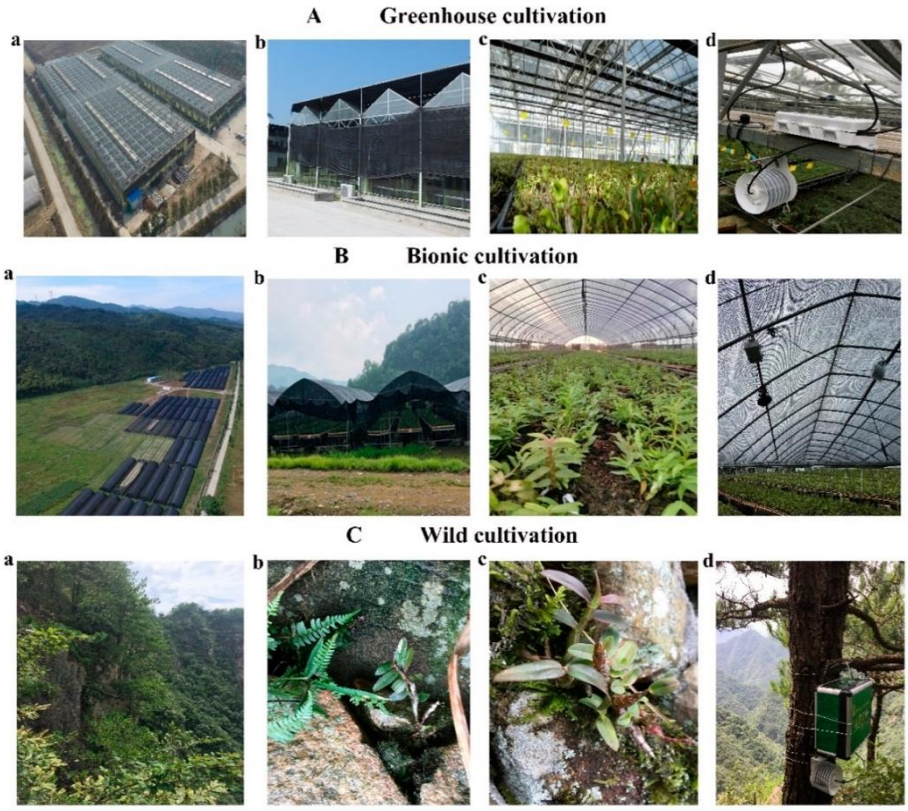


Figure 2 Different cultivation modes of *Dendrobium officinale* (Adopted from Yuan et al., 2020)

Image caption: (A) Greenhouse cultivation mode; (a-c) The growth environment of *Dendrobium officinale* in the greenhouse cultivation mode; (d) The position where the EM50 instrument (Decagon Devices Inc., Pullman, WA, USA) is placed in the greenhouse; (B) Bionic cultivation mode; (a-c) The growth environment of *Dendrobium officinale* in the bionic cultivation mode. (d) The position where the EM50 instrument is placed in the bionic cultivation mode; (C) Wild cultivation mode; (a-c) The growth environment of *Dendrobium officinale* in wild cultivation mode; (d) The growth environment of *Dendrobium officinale* in a wild environment (Adopted from Yuan et al., 2020)

5.2 Effects of substrate aeration and root activity on biomass formation

Substrate aeration regulates biomass formation mainly by controlling root respiration, root activity, and the balance between oxygen supply and moisture retention in the rhizosphere. In soilless systems, microorganisms and roots remain active only when moisture and aeration are jointly appropriate: overly dry substrates reduce water films and nutrient diffusion, whereas overly wet substrates suppress aeration and disadvantage aerobic microorganisms (Tuxun et al., 2025). Most beneficial rhizosphere microorganisms involved in nitrogen fixation and phosphate solubilization are aerobic and require a loose, well-aerated substrate structure (Tuxun et al., 2025). This explains why *D. officinale* seedlings perform best in substrates described as having strong aeration, permeability, and moisture retention rather than in media optimized for only one of these traits (Zuo et al., 2020).

The growth response shows that aeration acts through root system performance and then aboveground biomass accumulation. In forest nursery substrates, shoot dry mass and root collar diameter declined when air-filled porosity and saturated hydraulic conductivity were excessive under dry irrigation management, indicating that over-aeration can reduce growth when water supply becomes limiting (Boudreault et al., 2023). In orchid bioreactor culture, aeration volume changed biomass and bioactive-compound accumulation, with lower aeration favoring biomass and higher aeration favoring some secondary metabolites, which supports a trade-off rather than

a simple “more aeration is better” model (Cui et al., 2014). In *D. officinale*, substrates or inoculants that improve root growth also increase plant biomass: microbial carrier matrices promoted root length, root surface area, root volume, fresh weight, and dry weight (Hakim et al., 2021; Pan et al., 2021), and metabolite-microbiome experiments in maize showed that rhizosphere chemistry can increase root activity, nutrient content, and biomass, but not in sterilized soil, emphasizing that active roots and living rhizosphere processes are mechanistically linked (Jiang et al., 2024). In *D. officinale* itself, physiological indices of water use, nutrient transport, and metabolic capacity track growth status under drought, reinforcing that substrate effects on biomass are mediated through root-supported transport activity (Luo et al., 2024).

5.3 Integrated regulation of yield formation by substrate nutrient supply and the rhizosphere microenvironment

Yield formation is regulated in an integrated way by substrate nutrient supply and the rhizosphere microenvironment, because the substrate determines not only total nutrient content but also nutrient transformation, microbial recruitment, and disease pressure around roots. In cultivated *D. officinale*, soil pH, total nitrogen, total phosphorus, and available phosphorus are among the key ecological factors associated with medicinal quality (Yuan et al., 2020). More generally, rhizosphere nutrient availability directly regulates plant growth, and higher microbial nitrogen cycling in the rhizosphere increases available nitrogen, while phosphorus commonly becomes a zone of intense plant–microbe competition accompanied by elevated phosphatase activity (Liu et al., 2022). Substrate composition therefore matters because it sets both the nutrient reservoir and the chemical environment in which roots and microbes interact (Hakim et al., 2021).

This integrated mechanism is visible in both yield and quality outcomes. Rhizosphere microorganisms improve nutrient supply by nitrogen fixation, phosphate solubilization, potassium mobilization, phytohormone production, and pathogen suppression, and these functions repeatedly increase shoot and root biomass and yield components across crops (Thepbandit and Athinuwat, 2024). In *Dendrobium*, the rhizosphere microbiome enhances nutrient uptake, stress resilience, and disease suppression, while plant metabolites and exudates help recruit beneficial taxa and stabilize preferred niches (Sarsaiya et al., 2025). Recent *D. officinale* evidence further shows that rhizosphere bacteria are linked to polysaccharide accumulation, with Bacteroidetes contributing to ecological stability and *Pandoraea* showing potential to enhance polysaccharide production (Zhu et al., 2025). Practical substrate formulations support the same mechanism: a mixed substrate containing mushroom residue, shells, corncob, wood chips, soil, and mineral supplements reduced root rot and soft rot, raised survival above 98%, and achieved high stem thickness and yield. Taken together, yield formation in *D. officinale* depends on a substrate-root-microbe system in which balanced water, adequate aeration, and sustained nutrient conversion jointly support stem biomass and medicinal-quality accumulation (Tuxun et al., 2025).

6 Optimization and Management Strategies for High-Yield Cultivation Substrates of *Dendrobium officinale*

6.1 Selection of suitable cultivation substrates based on epiphytic characteristics

As an epiphytic orchid, *D. officinale* is best grown in substrates that simulate tree bark or rock-surface habitats rather than dense field soil. Wild plants typically grow on tree trunks or rocks in humid forests, and like other epiphytes they rely on exposed roots for moisture capture, physical anchorage, and rapid gas exchange (Wu et al., 2025). This biology argues for porous, coarse, low-compaction media such as bark, moss, charcoal, brick fragments, fern fiber, and similar materials already used widely in *Dendrobium* acclimatization (Nuammee et al., 2024). Epiphytic simulation can also be literal: tying moss-wrapped roots to living trees reduced disease incidence by about two-thirds in one tree-epiphytic method, while living-tree and cliff-epiphytic cultivation are already recognized as major simulated-natural production modes for *D. catenatum*/*D. officinale* (Zhu et al., 2022).

Within this epiphytic framework, substrate choice should still be stage-specific. During hardening, sphagnum moss promoted faster rooting, stronger tillering, thicker stems, and greater biomass than bark alone, indicating that newly transplanted plantlets need higher short-term water buffering than older plants. After transplanting, alder bark mixed with fine sawdust outperformed wood shavings and fir bark mixtures for survival, plant height,

root length, root number, stem diameter, and leaf number, showing that bark-based media become more effective once plants enter active vegetative growth. Pine bark is also a strong candidate for production systems because it increased survival, stem diameter, and dry weight in prior work and was the best substrate for flavonoid accumulation in a comparative metabolomic study (Zuo et al., 2020; Zhang et al., 2024). The practical implication is to select moss-rich media for acclimatization and bark-dominant media for sustained cultivation, while retaining the epiphytic requirement for loose structure and rapid drainage (Li et al., 2023a; Nuammee et al., 2024).

6.2 Optimization of mixed substrate ratios and coordination of water, aeration, and nutrient conditions

High-yield substrate optimization depends less on a single material than on achieving a stable balance among water retention, aeration, and nutrient buffering. Across orchid studies, the best media consistently combine a water-absorbing fraction with a structural fraction: brick and charcoal improve aeration and support, while moss, cocopeat, or coconut husk improve moisture retention (Nuammee et al., 2024; Luthfi et al., 2025). In *D. farmeri*, a 1:1:2 mixture of brick chips, charcoal chips, and sphagnum moss gave the highest survival and best long-term growth, while in other *Dendrobium* systems a 1:1:1 mix of charcoal, brick, and cocopeat supported strong plant height, leaf size, new growth, and root length (Narute et al., 2024). Related seedling work also found that a medium containing peanut-shell compost, stem charcoal, and husk charcoal in a compost-rich ratio gave the best leaf growth and wet weight, supporting the value of combining inert coarse particles with a modest nutrient-providing organic fraction (Hanik et al., 2022).

For *D. officinale*, mixed-substrate optimization should therefore target three coordinated properties. The substrate must hold enough water to buffer irrigation intervals but not remain saturated, because excessive humidity can favor rot while insufficient moisture limits root activity and seedling survival. It must maintain moderate aeration and permeability, since orchid acclimatization performs best in substrates with high water-holding capacity, strong permeability, and moderate aeration rather than maximum porosity alone (Narute et al., 2024; Nuammee et al., 2024). It should provide slow, non-excessive nutrient release. Composite media based on mushroom residue, herbal residue, shells, corncob, wood chips, and small mineral additions improved disease resistance, supported stem thickness of 7.5~8.2 mm, and reached 580 kg per mu, which suggests that mixed media can serve as both physical substrate and nutrient carrier. Because substrate performance differs by species, climate, and cultivation area, ratio screening should remain local rather than fixed as a universal formula.

6.3 Development of a high-yield cultivation management model integrating substrates with water and fertilizer management

A high-yield cultivation model for *D. officinale* should integrate substrate formulation with irrigation, fertilization, and rhizosphere biological management rather than treating them separately. Production-oriented methods that simulated the natural habitat with pine-bark substrate, raised beds, and dedicated nutrient solution achieved more than 98% survival, earlier growth, and yield above 250 kg per unit area, showing that substrate choice works best when paired with controlled water and fertilizer supply. An understory ecological model similarly used breathable artificial medium or humus-rich woodland ground together with mist irrigation, biogas slurry, silkworm feces, and spring water, and reported over 95% transplant survival with high active-component content and low chemical residue. Greenhouse bark-mixture cultivation in *Dendrobium* commonly maintains partial shade and substrate moisture around 65%~75%, which is consistent with the water-sensitive epiphytic physiology of the genus (Li et al., 2023a).

The management model should also incorporate targeted nutrient delivery and beneficial microbial inputs. Foliar fertilizer interacted with planting medium during orchid acclimatization, and cocopeat combined with foliar feeding gave the best relative growth rate in one study, supporting a split strategy in which the substrate provides physical buffering and external fertilization supplies adjustable nutrition (Luthfi et al., 2025). In *Dendrobium nobile*, substrate and nutrient solution required joint optimization by cultivation area, reinforcing that fertilizer regime cannot be separated from medium composition. For *D. officinale* specifically, mycorrhizal fungi promoted nitrogen uptake, biomass, tillering, and polysaccharide accumulation, and root inoculation during transplantation improved long-term growth and stem dry weight, making fungal co-formulation a realistic part of substrate

management (Wu et al., 2025). Cultivation mode also reshapes substrate-associated microbial communities and correlates with chemical quality, so high-yield management should combine bark- or residue-based mixed media, stage-specific irrigation, moderate nutrient supplementation, and symbiotic microbial management rather than relying on substrate alone (Zhu et al., 2022).

7 Current Problems and Future Directions for *Dendrobium officinale* Substrates

Current research on cultivation substrates for *Dendrobium officinale* still relies largely on empirical formulations, and a unified and quantifiable comprehensive evaluation system has not yet been established. Although previous studies have proposed suitable ratios of pine bark, coconut coir, mushroom residues, and various mixed substrates, the results are often affected by regional climate, cultivation stage, material source, and management practices, making direct comparison and broad application difficult. Future studies should establish an integrated evaluation system covering aeration, water-holding capacity, nutrient status, pH, disease incidence, root activity, stem biomass, and active-component accumulation, and develop more standardized substrate-selection criteria according to different ecological regions and growth stages. In addition, greater attention should be paid to the consistency of physicochemical properties among different batches of substrate materials to improve the stability and reproducibility of substrate formulations.

Moreover, substrate effects do not occur independently but interact with water, nutrients, light, temperature, and cultivation practices. Existing studies mainly focus on simple comparisons among different substrates, whereas interactions between substrates and irrigation, fertilization, and environmental conditions remain insufficiently investigated. Future research should strengthen multifactorial experiments, with particular emphasis on the relationships among substrate moisture content, aeration status, nutrient availability, rhizosphere microbial changes, stem length, stem diameter, biomass accumulation, and yield formation. Appropriate water and fertilizer supply levels under different substrate conditions should also be clarified. On this basis, an integrated substrate-water-fertilizer-environment management model can be gradually developed to improve resource-use efficiency and the stability of yield formation.

As the *D. officinale* industry moves toward standardized, large-scale, and ecological production, substrate optimization should also take into account long-term stability, production cost, resource-use efficiency, and environmental sustainability. Agricultural and forestry residues such as mushroom residues, herbal residues, peanut shells, corncobs, and wood chips are widely available and have considerable development potential, and their utilization value can be improved through composting, particle-structure optimization, and rational mixing. At the same time, mycorrhizal fungi, biofertilizers, and non-chemical disease-control technologies can be incorporated to improve the rhizosphere microecological environment and reduce chemical inputs and disease risks. Future research should further establish an integrated technical system covering raw-material selection, substrate formulation, cultivation management, and recycling, thereby promoting the development of *D. officinale* cultivation substrates toward higher efficiency, better quality, lower cost, and greater sustainability.

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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