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Environmental Regulation Affecting Growth and Quality of *Dendrobium officinale*

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Abstract *Dendrobium officinale* Kimura et Migo is a valuable medicinal orchid, and its medicinal properties and industrial applications mainly depend on stem yield and the accumulation of bioactive compounds, including polysaccharides, flavonoids, and alkaloids. However, with the rapid expansion of artificial cultivation, several challenges have emerged, such as unstable quality, poor environmental adaptability, and incomplete quality evaluation systems. Environmental conditions play an important role in regulating the growth and quality formation of *D. officinale*, affecting plant morphology, photosynthetic processes, biomass accumulation, and the biosynthesis of active compounds. This review summarizes the main growth and quality evaluation indicators of *D. officinale* and focuses on the effects of environmental factors, including light conditions, temperature and humidity, cultivation substrates, and water and fertilizer management, on plant growth and medicinal quality formation. In addition, typical cases involving local germplasm utilization, different cultivation systems, regional variation, and quality evaluation are discussed to clarify the role of environmental regulation in improving cultivar adaptation, enhancing active compound accumulation, and maintaining stable medicinal quality. Based on these findings, future development directions are proposed, including standardized environmental control, multidimensional quality evaluation systems, and intelligent cultivation technologies. This review summarizes the key environmental factors affecting high-quality production of *D. officinale* and provides theoretical support and practical references for its standardized, precise, and sustainable cultivation.
Keywords *Dendrobium officinale*; Environmental regulation; Quality formation; Medicinal compounds; Precision cultivation

1 Introduction

Dendrobium officinale Kimura et Migo is an important medicinal and edible orchid species and one of the traditional *Dendrobium* sources listed in the Chinese Pharmacopoeia. Its dried stems have long been used in traditional applications for nourishing the stomach, promoting body fluid production, and clearing internal heat. They are also important raw materials for the development of functional foods and health products. *D. officinale* contains various bioactive compounds, including polysaccharides, flavonoids, alkaloids, phenolic compounds, and bibenzyl derivatives. These compounds form the basis of its medicinal and nutritional value and support its applications in pharmaceuticals, health foods, and related industries (Chen et al., 2021a; Xu et al., 2022). Due to overexploitation of wild resources, limited natural reproduction capacity, and changes in ecological environments, *D. officinale* production has gradually shifted from traditional wild harvesting to artificial propagation and large-scale cultivation. In recent years, advances in tissue culture, facility cultivation, and ecological planting technologies have greatly improved production capacity and promoted the industrial development of *D. officinale* (Cheng et al., 2019).

Current quality evaluation of medicinal materials mainly relies on indicators such as polysaccharide content, moisture content, ash content, ethanol-soluble extract content, and the mannose/glucose ratio, among which polysaccharide content is the most commonly used quality indicator. However, the quality formation of *D. officinale* is not determined by a single compound. Its functional properties are associated with the combined effects of polysaccharides, flavonoids, alkaloids, phenolic compounds, and other secondary metabolites. Differences in geographical origin, cultivation methods, growth years, and plant tissues can result in significant variation in chemical composition. Therefore, polysaccharide content alone cannot fully reflect the quality differences among *D. officinale* medicinal materials (Li et al., 2025b). With the development of metabolomics and multi-component analysis technologies, increasing evidence indicates that quality evaluation of *D. officinale* should move from single-component assessment toward a multidimensional quality evaluation system to better reflect medicinal authenticity and quality stability (Hou et al., 2025).

As a typical epiphytic plant, *D. officinale* naturally depends on relatively stable light conditions, temperature, humidity, and root-zone environments. Therefore, environmental changes during artificial cultivation directly affect plant growth, photosynthetic efficiency, biomass accumulation, and active compound production. Light intensity and light quality regulate biomass formation and the accumulation of functional compounds such as polysaccharides and flavonoids, while temperature, humidity, substrate conditions, and nutrient supply jointly influence plant growth and medicinal quality (Zhang et al., 2024). Variations in ecological factors under different cultivation systems can also lead to differences in quality, as combinations of environmental conditions affect the levels of major compounds, including polysaccharides, flavonoids, and alkaloids. Improvements in substrate management, plant–microbe interactions, and intelligent environmental control technologies provide new opportunities for optimizing *D. officinale* production (Liu et al., 2025).

Previous studies have generated extensive knowledge on the chemical composition, pharmacological activities, and cultivation techniques of *D. officinale*. However, how different environmental factors interactively regulate plant growth and quality formation, and how environmental management can be converted into stable and high-quality production systems, still require further systematic evaluation. This review focuses on the growth and quality formation processes of *D. officinale* and summarizes the major environmental factors affecting production performance, including light, temperature and humidity, cultivation substrates, water and fertilizer management, and biological interactions. Typical production cases are also discussed to evaluate the effects of environmental regulation on yield and quality formation. Furthermore, future directions involving standardized environmental control, improved quality evaluation systems, and intelligent cultivation technologies are proposed. This review aims to provide theoretical support and practical references for high-quality and sustainable production of *D. officinale*.

2 Growth and Quality Indicators of *Dendrobium officinale*

2.1 Evaluation of growth characteristics

Stem length, stem diameter, internode length, and single-stem weight not only determine the appearance quality of medicinal materials but also directly affect yield per unit area and commercial value. The growth performance of *D. officinale* is jointly influenced by genetic characteristics, cultivation environment, and nutrient management. Under different environmental conditions, plants show clear differences in stem elongation and stem structure development. Du et al. (2023) found that calcium nitrate application promoted stem elongation and improved the growth performance of young *D. officinale* stems. Improved calcium and nitrogen availability enhanced physiological processes related to plant growth, promoted cell elongation and tissue development, and consequently increased stem length and structural strength. Therefore, appropriate nutrient management can improve the formation quality of medicinal stems by optimizing plant growth status.

In natural habitats, *D. officinale* usually forms symbiotic relationships with various microorganisms, among which mycorrhizal fungi play important roles in nutrient acquisition and seedling establishment. Wu et al. (2025) screened several core mycorrhizal fungal strains with growth-promoting effects and evaluated their influence on *D. officinale* seedling growth. Different *Tulasnella* strains showed different effects on plant development. Some strains significantly increased plant height and stem diameter, whereas others showed stronger effects on tiller production, new leaf formation, and root development. These results indicate that the growth of *D. officinale* is not controlled by a single environmental factor but results from the combined effects of nutrient conditions, biological interactions, and cultivation environments. In practical production, selecting suitable microbial combinations according to specific seedling growth targets may become an effective approach for improving seedling quality.

Zhang et al. (2021) analyzed the growth performance of *D. officinale* materials from different origins in Yunnan under different cultivation locations and found that both genetic origin and planting environment significantly affected biomass accumulation. The study evaluated nine germplasm sources cultivated at five different locations. Significant differences were observed in stem biomass, leaf biomass, and total biomass among different sources and among the same source grown under different environments, indicating strong genetic–environment interactions in *D. officinale* production performance. The study further compared stem traits and quality characteristics among different sources and showed that agronomic traits, including fresh stem weight, stem length, and stem diameter, could be combined with metabolic characteristics and antioxidant capacity for comprehensive evaluation.

2.2 Medicinal quality components

Because mature stems are the main medicinal part of *D. officinale*, polysaccharide content in stems directly affects the quality of commercial medicinal materials. Chen et al. (2021b) reported that polysaccharides are important active components of *D. officinale* and one of the major quality indicators listed in the Chinese Pharmacopoeia. In current production, polysaccharide content is commonly used as a primary indicator for evaluating medicinal quality, together with other parameters such as moisture content, ash content, and extract content. *D. officinale* polysaccharides are mainly composed of mannose and glucose, with small amounts of other monosaccharides, including galactose, xylose, and arabinose. Their structures and contents may vary depending on the plant origin and growth conditions.

Even when polysaccharide contents are similar, the composition of small-molecule active compounds may differ among samples from different regions or cultivation conditions. He et al. (2022) analyzed the chemical composition of *D. officinale* from different regions using UPLC-Q-TOF/MS and found significant differences in various small-molecule compounds among different samples. These results indicate that quality evaluation of *D. officinale* should gradually shift from single-component analysis toward comprehensive evaluation based on multiple compounds. Yuan et al. (2020) also used ecological factors to evaluate quality formation and selected polysaccharides, total flavonoids, and total alkaloids as major quality indicators. By comparing wild, simulated-wild, and greenhouse cultivation systems, they demonstrated that different environmental conditions significantly affected the accumulation of these active compounds.

Flavonoids and phenolic compounds are also important components for evaluating the quality of *D. officinale*. These compounds are generally associated with antioxidant capacity and environmental adaptation. Luo et al. (2023) analyzed *D. officinale* materials from different origins using HPLC combined with metabolomics approaches and found clear metabolic differences among samples. A total of 411 metabolites were identified, including 136 differential metabolites, which were mainly associated with flavonoid, phenolic acid, and alkaloid-related metabolic pathways. Some flavonoid metabolites showed significant correlations with antioxidant capacity, indicating that environmental conditions and genetic background influence not only the total content of active compounds but also the composition and distribution of bioactive substances.

3 Effects of Environmental Factors on Growth and Quality Formation of *Dendrobium officinale*

3.1 Light management

In natural habitats, *D. officinale* mainly grows on tree trunks or rock surfaces in forest environments and has therefore adapted to low-light and diffuse-light conditions. During artificial cultivation, either excessive or insufficient light intensity may negatively affect normal plant growth. Suitable light conditions can promote leaf photosynthesis and biomass accumulation, while also regulating the formation of active compounds such as polysaccharides, flavonoids, and anthocyanins. Guo et al. (2025) investigated the responses of *D. officinale* to different light intensities and found clear differences under various light conditions. Strong light could enhance antioxidant capacity and structural carbohydrate accumulation but also limited plant height increase, reduced photosynthetic performance, and increased oxidative stress. In contrast, insufficient light promoted certain aspects of morphological growth but did not result in optimal quality characteristics. Under moderate light intensity conditions of approximately 11 000 lx, plants showed better biomass production, active compound accumulation, and overall quality performance. These results indicate that stronger light is not always beneficial, and an appropriate light range should be maintained during production.

Different light wavelengths have different effects on plant growth and quality formation. Wang et al. (2017) studied the effects of different light qualities on *D. officinale* seedlings and found that blue light promoted stem thickening and chlorophyll accumulation, while red light enhanced plant elongation, biomass formation, and extract accumulation. Red and blue combined light improved photosynthetic efficiency and promoted the accumulation of quality-related compounds. Different light spectra can regulate sugar metabolism and polysaccharide biosynthesis processes, and red light has been shown to promote polysaccharide accumulation more effectively (Wang et al., 2024).

Shade management is one of the most commonly used approaches for regulating light conditions in commercial production. Van-Nguyen et al. (2023) compared the effects of different shading levels on *D. officinale* growth and quality and found significant differences among plants grown under 30%, 50%, 70%, and 90% shading conditions. Moderate shading treatments, especially 50% and 70% shading, were more favorable for plant growth, biomass accumulation, and the production of polysaccharides and alkaloids. The light environment of *D. officinale* also shows clear seasonal variation. Li et al. (2025a) conducted long-term dynamic monitoring and found that carbohydrate accumulation in stems and leaves changed with seasonal variations in temperature and humidity. The period from October to April of the following year showed rapid sugar accumulation in stems, suggesting that shading management and harvest strategies should be adjusted according to seasonal environmental changes.

3.2 Temperature and humidity regulation

Due to its special root structure, *D. officinale* is highly sensitive to air humidity and water availability. Excessively dry conditions may cause water loss, whereas excessive humidity can increase disease risks. Therefore, maintaining a suitable balance between temperature and humidity is essential for stable production. *D. officinale* has a special carbon assimilation strategy, and changes in water status can influence plant material accumulation. Zhang et al. (2014) found that under sufficient water conditions, *D. officinale* exhibited a combination of C3 and CAM photosynthetic pathways, while reduced water availability enhanced CAM characteristics to improve water use efficiency.

Under facility cultivation conditions, precise environmental control has gradually become an important strategy for improving production stability. Ding et al. (2018) developed an environmental monitoring and control system for *Dendrobium* cultivation, in which temperature, soil moisture, air humidity, and light intensity were continuously monitored, and automatic equipment was used to regulate greenhouse conditions. Although the study focused on *Dendrobium* plants in general, its technical approach provides valuable references for facility cultivation of *D. officinale*. Temperature, light, nutrients, and microbial interactions jointly influence plant growth and quality formation. Therefore, temperature and humidity management should be integrated with substrate regulation, water and fertilizer management, and biological approaches rather than controlled as isolated factors.

3.3 Substrate management

Because *D. officinale* naturally grows on tree trunks and rock surfaces, its roots require a well-aerated environment. Therefore, traditional cultivation systems commonly use organic materials such as tree bark, moss, and coconut fiber as cultivation substrates. Different substrates vary in water-holding capacity, aeration properties, and nutrient release characteristics, which further influence plant growth and quality formation.

Zuo et al. (2020) compared the effects of pine bark, coconut fiber, and a mixed substrate of pine bark and coconut fiber on the metabolic characteristics of *D. officinale*. Using metabolomic analysis, the study identified 529 metabolites and found clear metabolic differences among plants grown in different substrates. Among these metabolites, flavonoid compounds showed the most obvious changes. Pine bark treatment promoted flavonoid accumulation, and the differential metabolites were mainly enriched in flavonoid biosynthesis pathways. These findings indicate that substrates not only provide physical support and growth conditions but also influence medicinal quality formation through changes in the root-zone environment.

The effects of substrates should be evaluated together with cultivation systems. Hou et al. (2025) compared metabolic differences of *D. officinale* grown under tree epiphytic, rock epiphytic, and greenhouse cultivation conditions and found significant metabolic variation among different growth environments. Some flavonoid metabolites showed higher accumulation under rock epiphytic conditions. These results suggest that high-quality production cannot simply rely on selecting a single optimal artificial substrate. Instead, suitable root-zone environments should be designed according to the ecological characteristics of *D. officinale*.

3.4 Water and fertilizer management

In natural environments, nutrient availability for *D. officinale* is relatively limited. Therefore, its production does not require high-input and excessive fertilization systems but should adopt moderate nutrient supply according to different growth stages. Appropriate water and fertilizer management can promote photosynthesis, stem development, and active compound accumulation, whereas excessive fertilization may stimulate vegetative growth while reducing medicinal quality.

Jia et al. (2022) investigated the interaction between light conditions and potassium fertilizer on quality formation of *D. officinale* and found that suitable light combined with potassium application increased anthocyanin content and promoted flavonoid-related metabolic processes (Figure 1). Mineral nutrients not only regulate plant growth but also participate in the formation of quality-related compounds. Yin et al. (2026) studied the effects of coordinated carbon and nitrogen supply on *D. officinale* growth and quality and found that appropriate carbon–nitrogen combinations improved photosynthetic performance and increased soluble sugar and nutrient accumulation. However, excessive nitrogen supply reduced photosynthetic efficiency. These findings indicate that nutrient management in *D. officinale* should focus on balance rather than simply increasing fertilizer input.

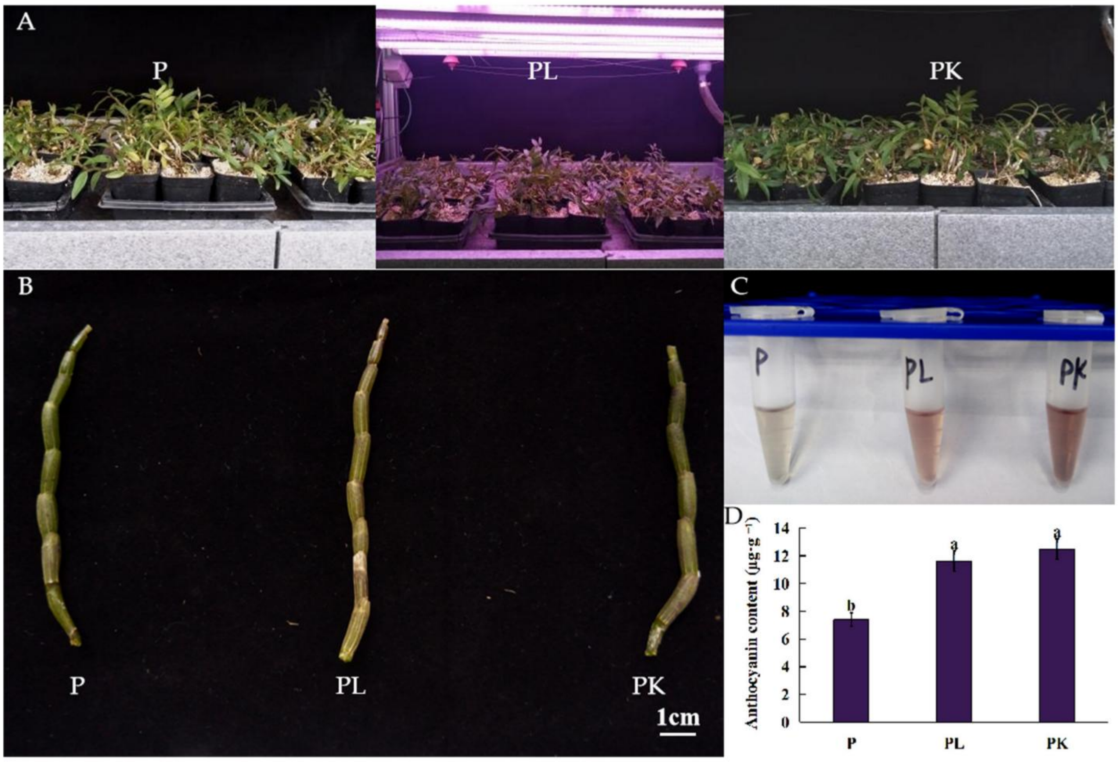

Figure 1 The changes in phenotype and anthocyanin content of *D. officinale* post light- or K-treatment. (A) The pseudobulbs (P) under natural light were used as the control, light-treated pseudobulbs (PL) were treated with red and blue light in 5:1, and K-treated pseudobulbs (PK) were treated with 3 mM KCl. (B) The phenotype of *D. officinale* pseudobulbs. (C) Anthocyanin extracted from pseudobulb of *D. officinale*. (D) The content of anthocyanins in *D. officinale* pseudobulbs post light- or K-treatment. The different letters represent significant difference at $p < 0.05$ (Adopted from Jia et al., 2022)

Water management also affects material accumulation in *D. officinale*. Considering its special water adaptation mechanism, cultivation systems should maintain sufficient substrate moisture while avoiding long-term waterlogging. Water-related environmental indicators show clear relationships with major medicinal quality components, indicating that appropriate water supply is an important basis for quality formation. With the development of facility agriculture, fertigation systems and precise nutrient supply technologies are increasingly applied in *D. officinale* production. By monitoring root-zone conditions in real time, these technologies can reduce water and fertilizer waste and improve production stability.

4 Typical Cases

4.1 Utilization of local germplasm and environment-adaptive variety improvement

During long-term natural selection, wild germplasm resources have developed strong adaptability to specific ecological conditions, including responses to temperature variation, water availability, and disease pressure. However, wild resources usually show disadvantages such as slow growth, low yield, and unstable performance, which limit their direct application in large-scale production.

Chen et al. (2026) conducted a new variety breeding study based on elite wild *D. officinale* resources collected from Yandang Mountain, Wenzhou, Zhejiang Province (Figure 2). The research team first screened superior plants from wild populations, followed by self-purification and systematic selection to obtain stable lines. These selected materials were further propagated through tissue culture, resulting in the development of a new cultivar named "Tiefeng No.1". From 2019 to 2023, multi-year regional comparative trials were conducted at several production sites. Yueqing, Zhejiang Province, a traditional production area of *D. officinale*, was selected for evaluating the production adaptability of the new cultivar. In the trials, "Tiefeng No.1" was compared with a locally dominant cultivar from Yueqing and "Xianhu No.2". Agronomic traits, yield performance, and quality indicators were evaluated among different materials. The main quality-related parameters included dry matter content, polysaccharide content, mannose content, and anthocyanin content.

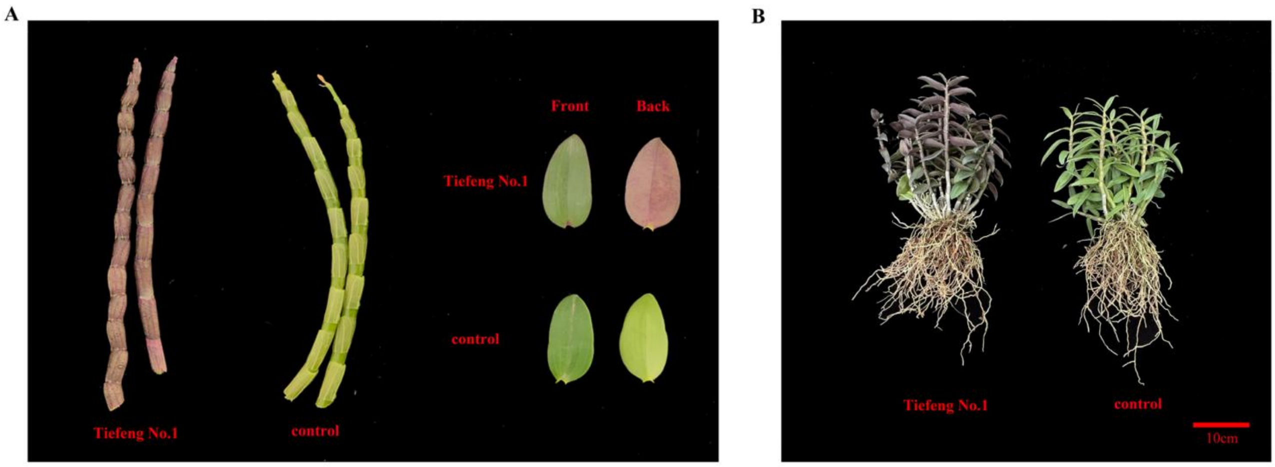

Figure 2 Plant morphological characteristics of 'Tiefeng No.1' ((A): whole plant phenotype, (B): stem and leaf phenotype) (Adopted from Chen et al., 2026)

"Tiefeng No.1" showed relatively stable quality performance across different cultivation environments. Its polysaccharide content ranged from 44.35% to 58.55%, and mannose content ranged from 14.03% to 22.38%, both meeting the quality requirements of the Chinese Pharmacopoeia (2020 edition). The anthocyanin content of "Tiefeng No.1" reached 94.76-115.43 μg/g, which was approximately twice that of the Yueqing local cultivar. In addition, "Tiefeng No.1" showed better cold tolerance and disease resistance, maintaining relatively stable growth and quality characteristics under variable production conditions.

4.2 Regulation of medicinal quality by cultivation environment and ecological factors

In natural habitats, *D. officinale* usually grows in mountain forests, on rock surfaces, and in other specialized ecological environments. With the expansion of artificial cultivation, production systems have gradually shifted from wild collection to ecological simulation cultivation and facility-based production. However, after environmental conditions are modified by human management, whether plant growth and medicinal compound accumulation are altered has become an important issue for high-quality production.

Yuan et al. (2020) investigated *D. officinale* from the Dabie Mountains in Anhui Province and compared differences in growth environments and medicinal quality among three production systems: wild growth, simulated ecological cultivation, and intelligent greenhouse cultivation. The study materials included artificially cultivated *D. officinale* produced by Anhui Lu'an Tongji Biotechnology Co., Ltd., and naturally growing wild plants from the Dabie Mountains. Artificial cultivation materials were obtained through tissue culture and transplanted after 18 months of growth. Wild materials were collected from two-year-old plants naturally growing on cliff edges in the Dabie Mountains. Two-year-old stems were selected from all samples for analysis, and the contents of major medicinal compounds were determined.

The researchers measured major medicinal components in stem samples from different cultivation systems, including polysaccharides, total alkaloids, and total flavonoids. Meanwhile, ecological data from different environments were collected to analyze the relationship between environmental variation and active compound accumulation. Significant differences in medicinal quality were observed among different growth systems, indicating that environmental conditions influence not only plant morphology but also the accumulation patterns of bioactive compounds.

Wild environments usually involve more complex temperature fluctuations, light conditions, and water variations, whereas simulated ecological cultivation reduces artificial disturbance and partially maintains natural growth characteristics. In comparison, intelligent greenhouses can provide more stable temperature, humidity, and light conditions, but highly controlled environments may alter the growth rhythms developed during long-term adaptation. Therefore, quality formation of *D. officinale* does not simply depend on environmental stability; instead, an appropriate balance between environmental stability and ecological adaptation is required.

4.3 Effects of geographical origin and ecological background on chemical composition

The medicinal quality of *D. officinale* is determined not only by cultivation practices and genetic characteristics but also by long-term adaptation to geographical origin and ecological environments. Different production regions vary in temperature, precipitation, light conditions, altitude, and epiphytic environments. These ecological factors influence plant growth, material accumulation, and metabolic regulation, resulting in differences in medicinal quality.

Hu et al. (2020) investigated *D. officinale* germplasm resources from Zhejiang, Fujian, Yunnan, and Jiangxi provinces and compared the volatile compound profiles of different origins using GC-MS metabolomic analysis. Six materials were selected, including Zhejiang purple-stem (ZB1), Zhejiang green-stem (ZB2), Fujian purple-stem (FB1), Fujian green-stem (FB2), Yunnan purple-stem (YA1), and Jiangxi purple-stem (JA1). Total ion chromatograms and volatile compound profiles were analyzed to evaluate chemical differences among samples. Significant differences in volatile composition were observed among materials from different regions. A total of 101 volatile compounds were detected across the four regions, including 23 esters and 22 alcohols. Different origins showed not only differences in compound abundance but also regional characteristics. For example, the content of hexacosane in Yunnan material YA1 reached 34.41%, while it was only 23.41% in Jiangxi material JA1. Some medicinally related compounds were detected only in specific materials, indicating that ecological origin and genetic background influence the accumulation of characteristic compounds in *D. officinale*.

Differences in geographical origin affect not only individual volatile compounds but also the overall metabolic patterns of *D. officinale*. Lan et al. (2022) conducted a metabolomic study on wild-simulated cultivated *D. officinale* from different origins. Using widely targeted metabolomics, the researchers analyzed metabolite composition among materials from different ecological backgrounds (Figure 3). The natural habitats of wild *D. officinale* in Danxia landform regions of Guangdong and Guangxi were investigated, and wild-simulated cultivation materials were compared. A total of 442 metabolites were detected and identified, including flavonoids, lipids, amino acids and derivatives, and alkaloids. Although materials from different origins contained similar metabolite categories, significant differences were observed in metabolite abundance. Differential metabolites were mainly associated with flavonoid and flavonol biosynthesis pathways. Further HPLC analysis showed that four major flavonoid compounds could serve as important indicators for distinguishing *D. officinale* from different origins. Long-term environmental adaptation influences plant metabolic networks and ultimately contributes to region-specific chemical characteristics.

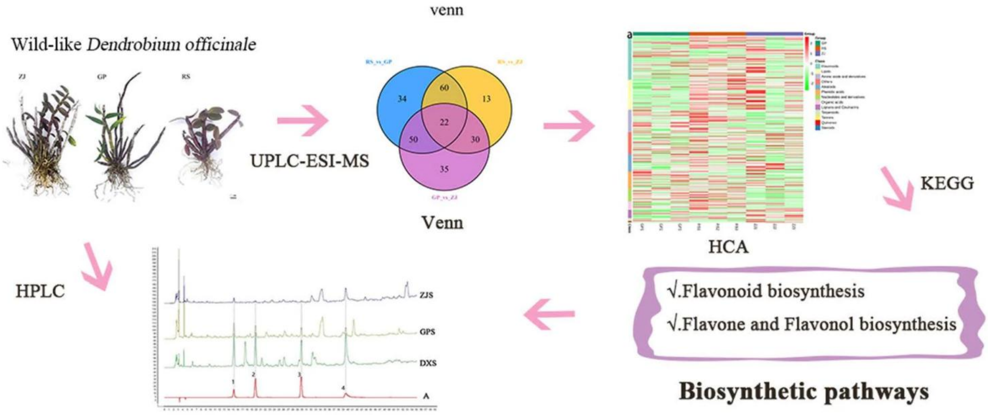

Figure 3 Comparative metabolomic analysis reveals differential flavonoid accumulation in wild-like Dendrobium officinale (Adapted from Lan et al., 2022)

4.4 Regional quality evaluation and origin traceability based on active compounds

Traditional quality evaluation of *D. officinale* mainly relies on a limited number of indicators, such as polysaccharide content. However, *D. officinale* contains various active substances, including flavonoids, phenolic acids, and glycosides, and single indicators cannot fully represent its quality characteristics. Therefore, evaluation systems based on multiple active compounds can improve quality control and further reveal the influence of environmental conditions on plant metabolic accumulation.

Zhang et al. (2025) investigated *D. officinale* produced in different regions of Yunnan Province and established an active compound detection method based on UHPLC-MS/MS. Samples from Xishuangbanna, Baoshan, Dehong, and Wenshan were compared for their active compound profiles. A total of 22 active compounds, including flavonoids, phenolic compounds, and glycosides, were detected. OPLS-DA multivariate analysis was applied to classify samples from different regions. Based on the content characteristics of these 22 compounds, *D. officinale* samples from different regions could be effectively distinguished, indicating that different ecological environments generate region-specific chemical characteristics within medicinal materials.

Active compound accumulation showed clear regional differences among *D. officinale* samples. Ten differential metabolites with strong regional discrimination ability were identified, including syringin, scutellarein, gallic acid, and gentisic acid. Samples from Dehong showed relatively higher levels of syringin, gentisic acid, protocatechuic acid, and gallic acid. Samples from Baoshan contained higher levels of apigenin, naringin, and 4-hydroxybenzaldehyde. Samples from Wenshan showed higher accumulation of epicatechin gallate, scopoletin, and scutellarein, whereas some phenolic acids were relatively lower in Xishuangbanna samples. These differences are closely related to the growth environments of *D. officinale*. Variations in temperature, water availability, light conditions, and ecological backgrounds among regions influence plant metabolic processes and consequently modify the accumulation patterns of active compounds.

5 Future Perspectives

5.1 Standardization of environmental control

In current production practices, many cultivation decisions still rely heavily on growers' experience, such as adjusting shading, irrigation, and ventilation according to weather changes. However, environmental conditions vary greatly among different regions and cultivation facilities, resulting in unstable yield and quality of medicinal materials. In the future, environmental management should shift from experience-based regulation toward a data-driven environmental standard system.

Recent studies on the standardized production of medicinal plants have increasingly emphasized the relationship between environmental parameters and quality traits. High-quality medicinal plant production requires an integrated management system combining ecological suitability assessment, production environment monitoring, and quality evaluation rather than relying only on yield-related indicators. For *D. officinale*, future environmental standards should not simply define fixed temperature or humidity ranges. Instead, differentiated management strategies should be developed according to different production systems, including facility cultivation, simulated ecological cultivation, and understory cultivation. These strategies should include environmental monitoring indicators, production process records, and quality evaluation standards.

Standardized production should also consider input management and ecological safety. With the expansion of the *D. officinale* industry, long-term high-input cultivation may lead to substrate degradation, increased disease occurrence, and quality fluctuations. Future production systems should integrate environmental regulation with green production practices, including reducing unnecessary chemical inputs, strengthening biological control, and improving ecological regulation to enhance production stability. For small-scale growers, standardization does not mean increasing complicated management procedures. Instead, it should focus on establishing simple and practical environmental recording systems to improve production traceability and consistency.

5.2 Improvement of quality evaluation systems

Currently, quality evaluation of *D. officinale* still relies mainly on traditional indicators such as polysaccharide content. However, with increasing research progress, single indicators are no longer sufficient to fully represent medicinal quality. Future quality evaluation systems should move from measuring individual compounds toward comprehensive assessment of multiple quality characteristics by integrating chemical composition, sensory properties, biological activity, and production environment information.

The development of rapid detection technologies provides new tools for medicinal material quality evaluation. Yang et al. (2022) used near-infrared spectroscopy combined with chemometric methods to conduct comprehensive evaluation of *D. officinale* from different origins, achieving rapid prediction of multiple quality indicators and identification of geographical origins. In future production systems, rapid detection technologies can partially replace traditional laboratory analysis and support efficient quality evaluation during harvesting, grading, and marketing.

In addition to chemical analysis, future quality evaluation should strengthen the relationship between quality characteristics and biological functions. Medicinal quality is not determined only by the content of a single compound but also by the combined effects of different components. Functional compounds in *D. officinale* show dynamic changes during growth and development, and quality formation is jointly affected by growth stage, environmental conditions, and processing methods (Wang et al., 2025). Therefore, future quality standards should gradually shift from “meeting content requirements” toward “stable quality, clear functional characteristics, and full-process traceability”.

For producers, this means that future competitiveness of *D. officinale* will depend not only on production quantity but also on stable quality performance. By establishing rapid detection, quality grading, and traceability systems, producers can better distinguish product value and improve market recognition of high-quality medicinal materials.

5.3 Integration of intelligent cultivation technologies

The production environment of *D. officinale* shows strong small-scale spatial variation, and traditional manual management cannot always detect timely changes in temperature, humidity, light, and water conditions. Therefore, an important direction for future intelligent cultivation is the use of sensors, Internet of Things (IoT), and artificial intelligence technologies to achieve real-time monitoring and precise environmental regulation.

With the rapid development of smart agriculture, multi-sensor integration systems have been increasingly applied in facility crop production. IoT technologies can continuously collect environmental data through sensors and optimize irrigation, greenhouse conditions, and production management through data analysis (Mansoor et al., 2025). However, intelligent agriculture still faces challenges related to equipment cost, data management, and technical accessibility. For specialty medicinal plants such as *D. officinale*, intelligent development should not simply focus on complex and expensive systems but should first address the most important production problems.

Future intelligent production of *D. officinale* can mainly develop in three directions. First, low-cost sensors can be used to monitor temperature, humidity, light intensity, and substrate moisture, enabling digital recording of production environments. Second, environmental and quality prediction models can be developed based on historical production data to provide decision support for cultivation management. Third, environmental monitoring, disease warning, and quality evaluation can be integrated to establish a complete production management system. Artificial intelligence technologies have already been applied to growth status recognition in orchid plants, providing technical support for future intelligent management of *D. officinale* (Chen et al., 2022).

Overall, intelligent cultivation is not intended to completely replace human management but to improve the accuracy of production decisions. For practical production, especially at the grower level, a combination of “human experience + digital tools” may be more suitable. Through simple and reliable data collection and analysis, environmental management can be gradually improved, supporting stable production of high-quality *D. officinale*.

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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