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Cultivation Practices Affecting Quality Formation in *Atractylodes macrocephala*

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Abstract *Atractylodes macrocephala* Koidz. is one of the most important cultivated medicinal plants in East Asia. Its market value depends on a balance among yield, rhizome appearance, the reputation of genuine medicinal materials (Daodi herbs), and the accumulation of bioactive compounds such as atractylone and atractylenolides. The quality of *A. macrocephala* is not determined by a single factor, but by the combined effects of planting materials, ecological conditions, rhizosphere microbial communities, cultivation practices, harvest timing, and post-harvest processing. This review explains how cultivation practices influence rhizome growth and the formation of medicinal quality in *A. macrocephala*. Studies from major production areas, including Pan'an and Tiantai in Zhejiang Province, show that ecological suitability and a balanced rhizosphere microbial community are closely associated with the accumulation of bioactive compounds and commercial grade. Current evidence supports a shift from production systems focused mainly on high yield to quality-oriented systems with strong regional characteristics. Germplasm selection, soil health, ecological adaptation, and standardized post-harvest processing should be managed as an integrated quality formation chain. These factors will continue to serve as the foundation for future quality standardization of *A. macrocephala*.

Keywords *Atractylodes macrocephala*; Medicinal plant cultivation; Rhizome quality; Atractylenolides; Daodi medicinal materials; Zhejiang; Continuous cropping; Post-harvest processing

1 Introduction

Atractylodes macrocephala Koidz. is the original plant of Atractylodis Macrocephalae Rhizoma, one of the most widely used traditional Chinese medicinal materials, and has long been cultivated as an important medicinal and edible crop in East Asia. Its medicinal part is the dried rhizome, which contains abundant sesquiterpenes, polysaccharides, polyacetylenes, and other bioactive compounds. These compounds are the main material basis for its pharmacological activities, including improving gastrointestinal function, anti-inflammatory effects, immune regulation, and other biological functions. Therefore, *A. macrocephala* has broad applications in traditional medicine, modern herbal preparations, and health products (Zhu et al., 2018; Xie et al., 2023).

With the growing demand for medicinal plants, the cultivation of *A. macrocephala* has expanded from its traditional Daodi production areas, such as Zhejiang Province, to emerging production regions including Anhui, Henan, Hebei, and other parts of China. However, Zhejiang-grown *A. macrocephala* still has a strong market reputation because of its favorable ecological conditions, long cultivation history, and well-established production practices. Noticeable differences in chemical composition, rhizome appearance, color, and aroma have been reported among production regions. Comprehensive evaluations have shown that samples from Zhejiang generally achieve higher overall quality than those from many other regions (Yang et al., 2024).

The quality of *A. macrocephala* cannot be evaluated by measuring a single chemical compound alone. Rhizome appearance, internal structure, aroma, and commercial characteristics should also be considered. According to the Chinese Pharmacopoeia and commercial grading standards, important quality indicators include rhizome size, firmness, aroma, cross-sectional texture, color, and the content and stability of characteristic bioactive compounds. In recent years, atractylone and atractylenolides I, II, and III have become the major chemical markers for quality evaluation. Chromatographic fingerprinting, multi-component quantification, comprehensive quality assessment, and pattern recognition have also been widely used to distinguish *A. macrocephala* from different production regions, harvest batches, and commercial grades (Zhan et al., 2022).

For commercial production, the main challenge is no longer simply increasing yield per unit area, but maintaining stable rhizome quality while expanding cultivation. At present, *A. macrocephala* production faces several problems, including the decline in planting material quality, increasing continuous-cropping obstacles, serious root rot, and unstable accumulation of bioactive compounds among different production regions (Gao et al., 2024). As cultivation continues to expand, growers are paying more attention to producing consistently high-quality medicinal materials rather than simply achieving successful cultivation.

Therefore, this review summarizes how planting materials and germplasm resources influence rhizome development and medicinal quality in *A. macrocephala*. It also discusses the effects of environmental factors, including soil conditions, temperature, water availability, light, and regional ecology, on quality formation. In addition, the effects of cultivation practices such as fertilization, irrigation, crop rotation, harvest timing, and disease management are comprehensively evaluated. Evidence from Zhejiang and neighboring production regions is incorporated to link field production with medicinal quality. Rather than relying only on laboratory analysis of chemical compounds, this review integrates germplasm resources, ecological conditions, field management, and market value to provide a more complete understanding of quality formation and to support the development of stable, science-based cultivation systems for high-quality *A. macrocephala*.

2 Effects of Cultivars and Planting Materials on Production

2.1 Differences among cultivars and germplasm resources

The production of high-quality *Atractylodes macrocephala* begins with the correct plant source. The genus Atractylodes includes several closely related species, such as *A. macrocephala*, *A. japonica*, *A. lancea*, and *A. chinensis*. Their rhizomes are similar in appearance and aroma, but they differ in chemical composition and medicinal uses. In addition, the botanical origin of Atractylodes medicinal materials is defined differently among East Asian countries.

Ma et al. (2023) collected 59 batches of Atractylodes samples and compared the volatile compounds of *A. macrocephala*, *A. japonica*, *A. lancea*, and *A. chinensis* using gas chromatography–mass spectrometry (GC–MS). A total of 50 volatile compounds were identified. Five compounds, including hinesol, β-eudesmol, atractylon, atractylodin, and atractylenolide I, showed strong discriminatory power and allowed accurate identification of the four species. These results indicate that even when rhizomes look similar, their chemical profiles can differ greatly. Therefore, closely related species should not be substituted based only on their external appearance.

The performance of a genotype is also influenced by the growing environment. The same planting material may produce different yields and accumulate different levels of bioactive compounds under different soil conditions, climates, and cultivation practices. Zhou et al. (2025) evaluated the same cultivar, "Second-Year Improved No. 1", in four production regions, including Pan'an in Zhejiang Province, Bozhou in Anhui Province, Zhoukou in Henan Province, and Anguo in Hebei Province. Significant differences in biomass and several bioactive compounds were observed among the production regions. Plants grown in Pan'an produced higher biomass and higher concentrations of several major bioactive compounds than those grown in the other regions.

2.2 Effects of seed and planting material quality on growth and yield

In *A. macrocephala* production, seeds, seedlings, and planting rhizomes are different propagation materials and should not be confused. Seeds are used for nursery production. The small rhizomes harvested from nursery beds in the first autumn are commonly called planting rhizomes, which are stored during winter and transplanted into the field in the following growing season. Seed quality mainly affects seedling emergence, whereas the quality of planting rhizomes has a more direct influence on field survival, plant uniformity, and subsequent rhizome development. Therefore, attention should be paid to seed freshness, the health of planting rhizomes, and uniform rhizome size before field planting (Figure 1).

The germination ability of *A. macrocephala* seeds declines rapidly during storage. Fresh, fully mature seeds with a known origin and no insect damage should therefore be used for nursery production. Seeding density is another important factor. Excessively dense sowing increases competition for light, water, and nutrients, resulting in smaller planting rhizomes. In contrast, very low sowing density provides more growing space for each plant but reduces the number of planting rhizomes produced per unit area. According to the Technical Regulations for the Cultivation of *Atractylodes macrocephala* (LY/T 2693-2016), the recommended seeding rate is 4~5 kg per 667 m² for row sowing and 7.5~10 kg per 667 m² for broadcast sowing. In practice, these rates should be adjusted according to seed germination, nursery soil fertility, and local sowing methods rather than applying a single standard rate.

In vitro propagation can also be used to preserve elite germplasm and support large-scale seedling production. Happy et al. (2026) established a tissue culture system using shoot tips of *A. macrocephala*. Under optimized conditions, each explant produced an average of 17.5 shoots, and each regenerated plant developed about 21.2 roots after rooting treatment. The survival rate after acclimatization and transplantation reached 93.33%. The regenerated plants showed chlorophyll content, photosynthetic performance, and genetic stability similar to those of the mother plants, and atractylenolide I was also detected in their roots.

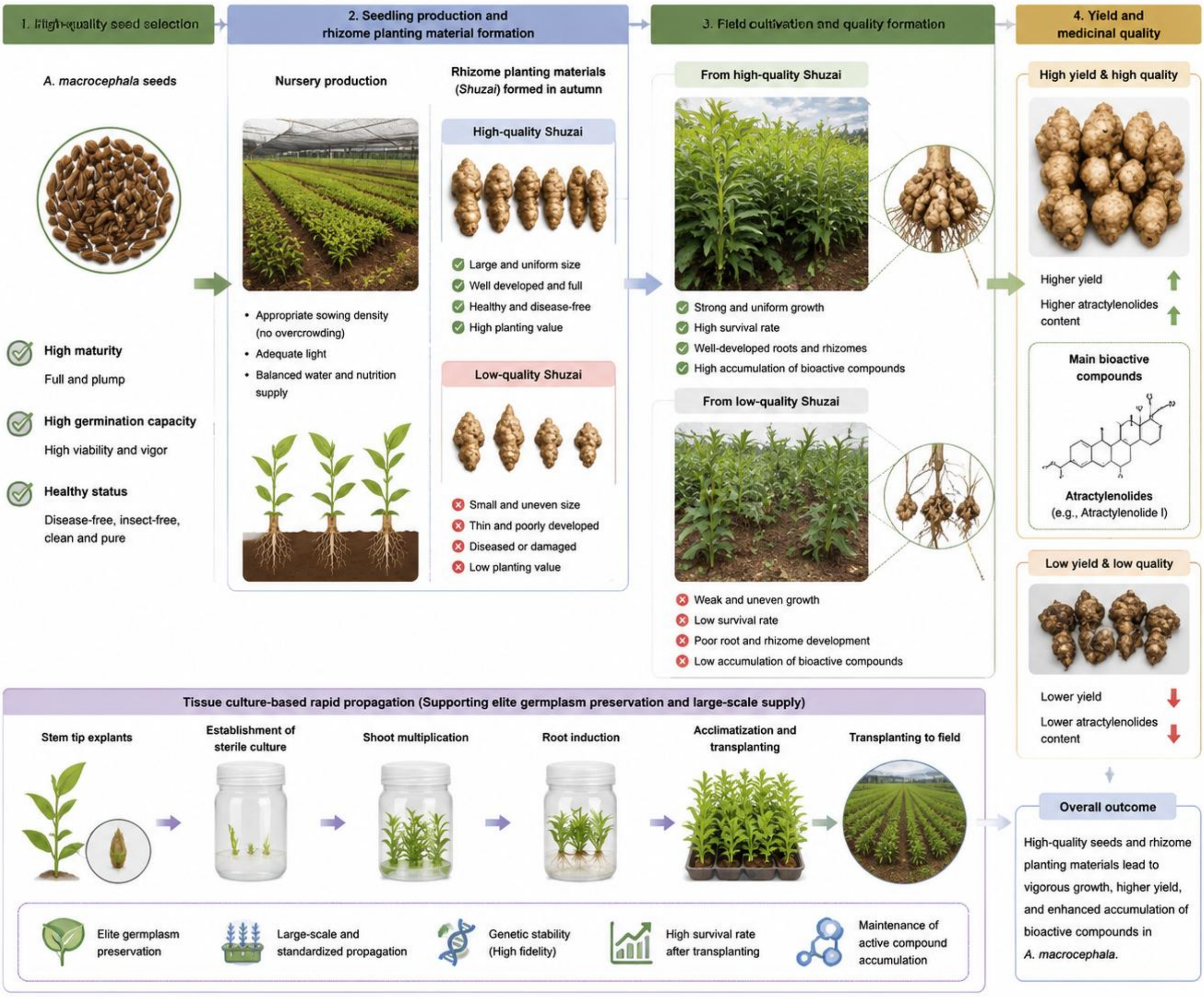

Figure 1 Effects of seed and rhizome planting material quality on growth performance, yield formation, and quality accumulation of *Atractylodes macrocephala*

2.3 Cultivar selection for high-quality production

The selection of cultivars or planting materials for *A. macrocephala* should consider yield, medicinal quality, disease resistance, and regional adaptability together. Selecting plants only because of their large rhizomes may result in high-yielding materials with low levels of bioactive compounds. On the other hand, selecting materials based only on a single chemical component may overlook field performance, survival rate, root rot resistance, and commercial appearance. Suitable planting materials should have uniform emergence, stable plant growth, high rhizome yield, good disease resistance, firm dried rhizomes, and relatively stable levels of the major bioactive compounds.

Quality evaluation of *A. macrocephala* usually focuses on atractylon, atractylenolides I, II, and III, together with polysaccharides. These indicators are useful for comparing the chemical quality of different germplasm resources. However, it is unnecessary for family farms or commercial growers to analyze every individual plant. A more practical approach is to first remove materials with poor emergence, severe disease, or low commercial quality based on field performance. Representative samples from the best-performing plots can then be submitted to professional laboratories for analysis of the major bioactive compounds.

Jeong et al. (2018) compared eight interspecific Atractylodes hybrids with a common *A. macrocephala* cultivar in Eumseong, Republic of Korea. Among the tested materials, "Sanwon" produced the highest rhizome dry weight per plant (53.8 g), followed by "Dachul" (50.0 g). Most hybrid lines had higher contents of atractylenolides I, II, and III, as well as higher yield per unit area, than the common cultivar. Based on both productivity and chemical quality, the authors concluded that "Dachul" has strong potential for commercial cultivation.

3 Environmental Factors Affecting Quality Formation in *Atractylodes macrocephala*

3.1 Soil conditions

The rhizome is the main commercial part of *A. macrocephala*, and both the roots and rhizomes remain in direct contact with the soil throughout the growing season. Therefore, soil structure, pH, aeration, moisture status, and microbial composition all influence plant growth. Heavy clay soils are prone to waterlogging and oxygen deficiency after rainfall, which restrict root respiration and nutrient uptake. In contrast, overly loose soils with poor water-holding capacity can increase drought stress during hot and dry periods. Deep, well-structured loam soils with good drainage and moderate water- and nutrient-holding capacity are generally more suitable for uniform rhizome development.

The effects of soil on medicinal quality cannot be explained simply by nitrogen, phosphorus, and potassium levels. Soil pH, electrical conductivity, and nutrient availability also shape the rhizosphere environment, influencing the balance between pathogenic microorganisms, beneficial microbes, and other members of the soil microbial community. Fan et al. (2024) compared healthy and root rot-infected *A. macrocephala* plants by analyzing root tissues, rhizosphere soil, and surrounding bulk soil. Root rot was associated with clear changes in soil physicochemical properties and microbial community structure. The bacterial and fungal communities differed significantly between healthy and diseased plants. Several potential pathogens were enriched in the roots and surrounding soil of diseased plants, while the stability of the microbial interaction network was also reduced.

3.2 Temperature and climate

Temperature and climatic conditions determine the length of the growing season, shoot growth, and rhizome enlargement in *A. macrocephala*. Suitable temperatures promote leaf development and photosynthesis, whereas prolonged high temperatures increase transpiration, accelerate soil water loss, and may suppress plant growth. Long periods of low temperature shorten the effective growing season and slow both shoot growth and rhizome biomass accumulation. Rainfall distribution is also important. Moderate rainfall supports normal plant development, but continuous heavy rain creates wet and oxygen-deficient soil conditions that increase the risk of root diseases. In contrast, prolonged drought limits leaf growth and reduces rhizome weight.

Direct evidence of environmental adaptation in *A. macrocephala* has been relatively limited. Lee et al. (2025) investigated 22 cultivation sites in the Republic of Korea and analyzed the relationships between meteorological conditions, topography, soil characteristics, rhizome growth, and atractylenolide accumulation. The environmental factors affecting rhizome biomass were not identical to those influencing atractylenolide content. In other words, conditions that favor rapid rhizome growth do not necessarily produce the highest concentrations of bioactive compounds, and conditions that enhance the accumulation of one atractylenolide may not improve all yield-related traits. These findings indicate that high yield and high medicinal quality are related but should not be regarded as the same production goal.

3.3 Light conditions

Light provides the energy required for photosynthesis in the aerial parts of *A. macrocephala*. The photosynthetic products are then transported to the underground organs, where they support rhizome enlargement and the synthesis of bioactive compounds. The effects of light are not limited to plant height, leaf number, and leaf color. Light can also influence the allocation of assimilates between shoots and roots, thereby affecting rhizome biomass and the accumulation of functional compounds.

Hwang et al. (2022) compared the effects of several artificial light sources on plant growth, physiological characteristics, and biological activity in *A. macrocephala*. Different light treatments produced significant differences in plant height, leaf development, chlorophyll content, and biological activity of rhizome extracts (Figure 2). Plants grown under microwave electrodeless lamps showed better overall growth and higher chlorophyll levels. Rhizome extracts from plants exposed to red light exhibited stronger DPPH radical-scavenging activity, while total phenolic and total flavonoid contents varied among the other light treatments. These results suggest that light quality influences both plant growth and bioactive compound accumulation. The treatment that promotes the most vigorous shoot growth does not necessarily produce the highest quality rhizomes.

(a) (b)

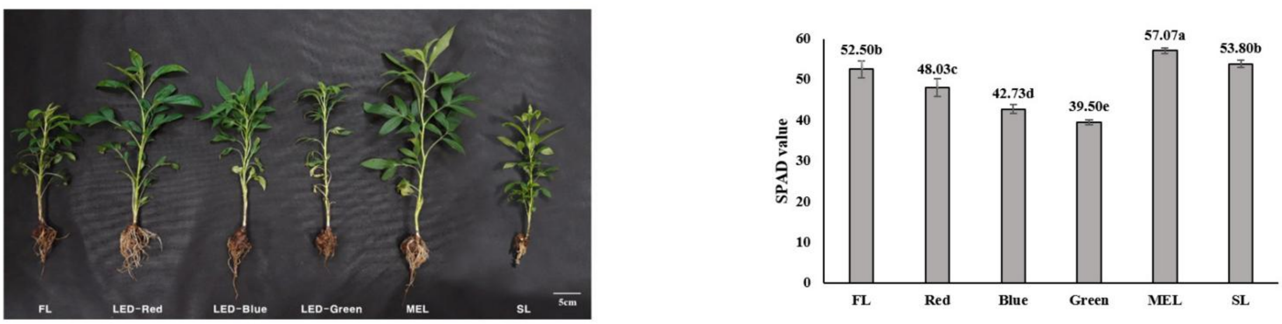

Figure 2 Growth characteristics (a) and chlorophyll contents (b) of *A. macrocephala* under different light sources. Values represent mean of data obtained from three independent experiments (p<0.05). Significance was indicated with different letters according to statistical analysis (Adopted from Hwang et al., 2022)

3.4 Regional differences

Even when the same species is cultivated, medicinal materials from different production regions often differ in appearance, elemental composition, stable isotope signatures, and chemical constituents. Therefore, the geographical characteristics of *A. macrocephala* are not determined by a single factor such as temperature, soil nutrients, or altitude. Instead, they result from the long-term interaction of multiple environmental factors.

Hai et al. (2023) collected 281 *A. macrocephala* samples from 10 production regions in China and analyzed their stable isotopes and elemental composition using chemometric methods. Significant regional differences were found in δ^2H, $\delta^{18}O$, Mg, Ca, and several rare earth elements. Variables such as Ca, K, Mg, and Na made major contributions to geographical discrimination. The classification model accurately distinguished samples from multiple production regions, with particularly high classification accuracy for several locations. These findings indicate that regional differences in water sources, soil parent materials, and mineral environments leave measurable signatures in *A. macrocephala* and contribute to its geographical characteristics.

4 Effects of Cultivation Practices on Yield and Bioactive Compound Accumulation in *Atractylodes macrocephala*

4.1 Fertilization management

Insufficient nitrogen, phosphorus, and potassium limit plant growth, whereas excessive fertilization may cause excessive shoot growth, delayed rhizome maturation, soil acidification, and salt accumulation. For medicinal plants, fertilization should not be evaluated by yield alone. The contents of bioactive compounds, rhizome commercial quality, and soil health should also be considered.

A foliar selenium application study clearly showed that nutrient supplementation has an optimal range. Zhou et al. (2021) applied five selenium levels (0, 2.5, 5.0, 10.0, and 20.0 $mg{\cdot}m^{-2}$) and found that the 5.0 $mg{\cdot}m^{-2}$ treatment significantly increased plant survival. Selenium application promoted rhizome yield when the application rate did not exceed 10.0 $mg{\cdot}m^{-2}$, whereas yield declined at 20.0 $mg{\cdot}m^{-2}$. Moderate selenium application also altered soil nutrient status and the rhizosphere microbial community, but it did not significantly affect the contents of atractylenolides in the rhizomes.

Field studies on fertilizer recommendations for *A. macrocephala* are still limited. However, fertilization strategies developed for closely related Atractylodes species provide useful references, particularly the use of balanced fertilization, stage-specific nutrient supply, and the combined evaluation of yield and medicinal quality. These approaches should be further optimized according to local soil fertility, planting materials, and cultivation systems. Sun et al. (2022) investigated the effects of different nitrogen, phosphorus, and potassium combinations on the growth and bioactive compound accumulation of *Atractylodes chinensis*. Basal fertilization followed by appropriate topdressing during the vegetative and reproductive stages promoted plant growth and rhizome development. The high-phosphorus treatment (T6; N 180, P_2O_5 225, and K_2O 105 $kg{\cdot}ha^{-1}$) achieved the best overall performance in yield and quality. At harvest, the atractylodin content reached 4.5589 $mg{\cdot}g^{-1}$, which was 1.71 times higher than that of the control. Another fertilizer combination promoted greater atractylon accumulation, indicating that different nutrient ratios may favor the accumulation of different bioactive compounds.

4.2 Water management

The rhizomes of *A. macrocephala* develop underground and are sensitive to both excessive and insufficient soil moisture. Appropriate soil moisture promotes plant establishment, leaf development, and rhizome enlargement. In contrast, prolonged drought reduces photosynthesis and limits the transport of assimilates to the underground organs, while continuous waterlogging creates oxygen-deficient conditions that increase the risk of root rot and rhizome decay. Therefore, the objective of water management is not to keep the soil continuously wet, but to maintain stable soil moisture according to the growth stage and weather conditions.

In Zhejiang, Anhui, and other production regions along the middle and lower reaches of the Yangtze River, water management should pay particular attention to the rainy season and periods of heavy rainfall. Production fields are usually designed with main drainage channels, secondary ditches, and furrows to remove excess water rapidly. Low-lying fields, heavy clay soils, and poorly drained sites are especially prone to oxygen deficiency after continuous rainfall, even when soil fertility is high. Therefore, drainage is not simply a supplement to irrigation but one of the key components of water management in *A. macrocephala* production.

4.3 Intercropping and continuous cropping

Continuous cultivation of *A. macrocephala* in the same field often results in weak plant growth, increased root rot, reduced survival, and poorer rhizome quality. These problems are not caused by a single pathogen or nutrient deficiency. Instead, they result from long-term changes in soil properties, root exudates, and the rhizosphere microbial community.

Zhu et al. (2020) reported that continuous cropping reduced the diversity of endophytic fungi in the roots, stems, leaves, and rhizomes of *A. macrocephala* and significantly altered the composition of the rhizosphere fungal community. Several Fusarium species became more abundant in plants affected by root rot, while soil pH, hydrolyzable nitrogen, and electrical conductivity were closely associated with changes in the fungal community. Increased disease severity under continuous cropping was accompanied not only by the enrichment of pathogens but also by reduced stability of the entire rhizosphere ecosystem.

Suitable rotation crops for *A. macrocephala* should preferably be cereals, legumes, or other non-Asteraceae crops that are distantly related, have different disease hosts, and possess complementary root systems. The length of the rotation period should be determined according to disease severity, soil conditions, and local land-use practices. For fields with severe root rot, rotating for only one season may not be sufficient to restore soil health. A longer rotation period or temporary fallowing is often a better option. During crop rotation, returning decomposed crop residues, growing green manure crops, and increasing soil organic matter can further improve soil quality. However, all organic materials should be fully decomposed before application to avoid oxygen deficiency in the root zone or the spread of soil-borne pathogens.

4.4 Pest and disease management

Root rot is one of the most destructive diseases in *A. macrocephala* production. Severe infections cause rhizome decay, plant wilting, and even complete plant death, resulting in substantial yield losses. Because the medicinal part is the underground rhizome, pathogen infection directly reduces rhizome integrity and commercial value, even if the plant survives. Therefore, disease management should emphasize prevention and integrated control rather than relying on pesticide application after severe outbreaks have already occurred.

Biological control has become an important approach for sustainable *A. macrocephala* production. Huang et al. (2021) reported that *Trichoderma brevicompactum* showed strong antagonistic activity against *Fusarium oxysporum*, the main pathogen causing root rot in *A. macrocephala*. Under laboratory conditions, this fungus significantly inhibited pathogen mycelial growth and reduced disease development. Zhu et al. (2025) isolated *Bacillus velezensis* Amzn015 from healthy *A. macrocephala* plants. This bacterial strain effectively suppressed *F. oxysporum* and several other pathogenic fungi, promoted plant growth, enhanced root activity, and induced plant defense responses. Pot experiments further demonstrated that *B. velezensis* Amzn015 significantly reduced the incidence of root rot while improving overall plant performance (Figure 3).

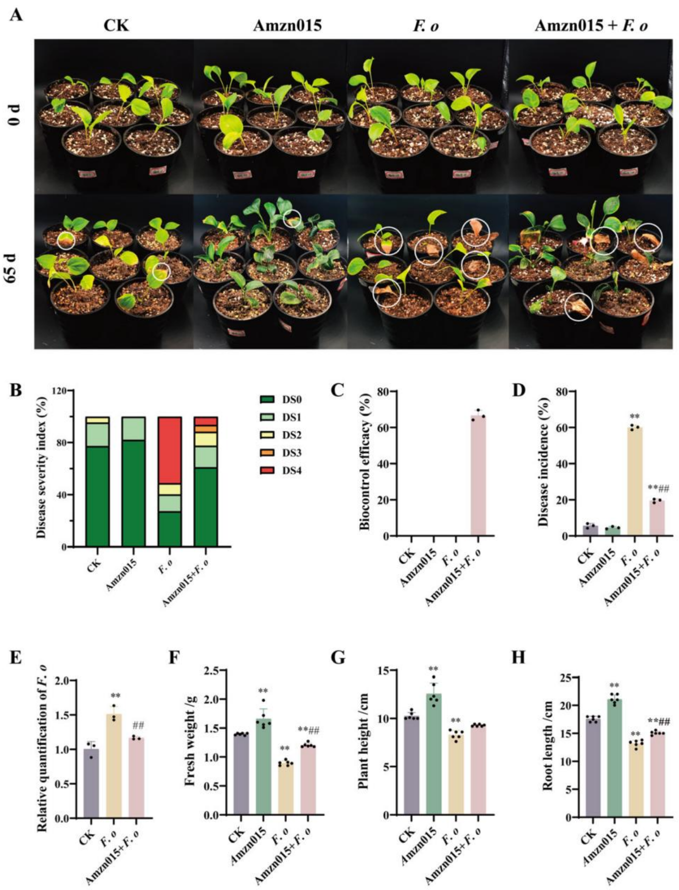

Figure 3 Pot experiment evaluating the biocontrol efficacy of strain Amzn015 against root rot of *A. macrocephala*. (A) Representative images of seedling phenotypes under different treatments. (CK: PBS control; *F. o: F. oxysporum* inoculation alone; Amzn015: Amzn015 treatment alone; *F. o* + Amzn015: combined treatment with Amzn015 and *F. oxysporum*.) (B-H) Disease progression and plant growth parameters were assessed 65 days post-inoculation, including: (B) disease index, (C) relative control efficacy, (D) disease incidence, (E) *F. oxysporum* biomass, (F) seedling fresh weight, (G) shoot height, and (H) root length. (n = 6). ** $p< 0.01$. ## $p< 0.01$ (Adopted from Zhu et al., 2025)

5 Effects of Harvest Time and Post-Harvest Processing on the Quality of *Atractylodes macrocephala*

5.1 Growth stage determines rhizome maturity

The medicinal part of *Atractylodes macrocephala* Koidz. is the underground rhizome, and its medicinal quality depends on full rhizome development and maturity. The rhizome is not only the main storage organ for nutrients but also the primary site for the accumulation of atractylenolides, volatile oils, and other sesquiterpenes. Therefore, the transition from vegetative growth to rhizome maturation is a key biological process that determines the final quality of the medicinal material. As the plant develops, the leaves continue to produce photosynthates through photosynthesis, which are transported to the underground organs to promote rhizome enlargement, vascular tissue development, and storage compound accumulation, eventually producing mature rhizomes suitable for medicinal use.

Ruan et al. (2021) compared the metabolite profiles and transcriptomes of five tissues, including the rhizome, root, stem, leaf, and bud. Sesquiterpenes were mainly accumulated in the rhizome, while their levels were much lower in the aerial tissues. Transcriptome analysis identified several highly expressed transcription factors in the rhizome and 73 candidate genes associated with sesquiterpene biosynthesis. The study also confirmed the important role of farnesyl pyrophosphate synthase (AmFPPS) in sesquiterpene production. Rhizome maturation was characterized not only by increased accumulation of bioactive compounds but also by the gradual specialization of metabolism among different plant tissues. However, a longer growing period does not necessarily result in better medicinal quality.

5.2 Harvest time

Harvesting too early results in incompletely developed rhizomes with insufficient dry matter and bioactive compound accumulation. In contrast, harvesting too late may increase the risk of rhizome decay, mechanical damage, and reduced market quality because of low temperatures, prolonged rainfall, or disease development. Therefore, selecting the proper harvest time is essential for achieving both high yield and good medicinal quality.

Jeong et al. (2022) continuously monitored rhizome growth and the accumulation of atractylenolides I, II, and III throughout the growing season. The aerial parts of the plants gradually senesced after mid-October, whereas the underground rhizomes continued to enlarge until mid-November. The total content of the three major atractylenolides reached its highest level in mid-November, with the second highest level occurring before flowering in August. These results indicate that the accumulation of bioactive compounds continues even after shoot growth has stopped. Harvesting after the rhizomes have fully matured is therefore more favorable for obtaining high-quality medicinal materials.

According to the Chinese Pharmacopoeia, *A. macrocephala* should be harvested in autumn after the aerial parts have withered. The fibrous roots and soil should be removed, followed by prompt post-harvest processing. This recommendation agrees well with the findings above, indicating that harvesting mature rhizomes provides a better balance between yield and quality. In major production regions such as Zhejiang, harvest timing should also be adjusted according to local rainfall and soil conditions. Harvesting during periods of continuous rainfall should be avoided because excessive rhizome moisture and soil contamination may reduce drying efficiency and commercial quality.

5.3 Post-harvest processing

Traditional post-harvest processing includes washing, trimming, drying, and, when necessary, further processing for medicinal use. The main objectives are to reduce moisture content, prevent mold development, and preserve volatile oils, atractylenolides, and other bioactive compounds as much as possible. Excessively high drying temperatures, rapid dehydration, or improper processing may cause the degradation of heat-sensitive compounds and reduce the quality of the final medicinal product.

Yang et al. (2021) systematically reviewed the processing methods of *A. macrocephala* and reported that natural sun drying and low-temperature drying are the two most commonly used methods. Both methods can produce medicinal materials that meet quality standards, although different processing methods may alter the composition of volatile oils and some bioactive compounds. To improve processing efficiency, sulfur fumigation has been used in some production areas to maintain rhizome color and suppress fungal growth. However, concerns about product safety and quality have limited its acceptance.

Sun et al. (2017) compared the chemical composition of *A. macrocephala* before and after sulfur fumigation using UFLC-QTOF-MS. Excessive sulfur fumigation caused dehydration and sulfurization of atractylenolides, producing new sulfur-containing derivatives and significantly changing the overall chemical fingerprint of the medicinal material. These newly formed compounds can be used as chemical markers to identify excessively sulfur-fumigated products. The results also indicate that although sulfur fumigation improves external appearance, it may reduce the authenticity and quality consistency of the medicinal material. For this reason, natural drying and low-temperature hot-air drying are currently recommended for *A. macrocephala* production, whereas excessive sulfur fumigation is no longer encouraged.

6 Field Evidence from *Atractylodes macrocephala* Production in Zhejiang Province

6.1 Ecological conditions and quality performance of Pan'an *Atractylodes macrocephala*

Pan'an is one of the most important Daodi production areas for *Atractylodes macrocephala* in Zhejiang Province. Zhou et al. (2025) compared four major production regions, including Pan'an (Zhejiang), Bozhou (Anhui), Zhoukou (Henan), and Anguo (Hebei). Five fields were selected from each region, giving a total of 20 experimental sites. All fields had approximately 10 years of *A. macrocephala* cultivation history, cereal crops had been grown previously, and the same planting material ("Second-Year Improved No. 1") was used at all locations. Plants and rhizosphere soil were sampled at the same harvest period in mid-October 2020. This experimental design minimized the effects of differences in cultivar, previous crop, and harvest time, allowing a more direct comparison of ecological conditions and medicinal quality among production regions.

Plants grown in Pan'an produced greater shoot and rhizome biomass than those from the other three regions. Among the four bioactive compounds analyzed, the average contents of Butenolide I and Butenolide III reached 0.513 $mg \cdot g^{-1}$ and 1.381 $mg \cdot g^{-1}$, respectively, which were significantly higher than those measured in the other production areas. In contrast, no significant differences were observed in atractylone or Butenolide II among the four regions. These results indicate that the advantages of Pan'an *A. macrocephala* are reflected mainly in plant growth and the accumulation of specific bioactive compounds rather than in every chemical constituent. Therefore, the evaluation of Daodi medicinal materials should not rely solely on production origin or on a single chemical marker. Rhizome growth, commercial appearance, and multiple quality indicators should all be considered.

Regional differences were also associated with soil characteristics. The rhizosphere soil of Pan'an plants contained higher organic matter levels and greater activities of several soil enzymes than soils from the other production regions. Fungal diversity was also higher, and interactions within the fungal community were stronger. The relative abundance of Saitozyma, an important genus in the fungal network, reached 2.19% in Pan'an but was below 0.1% in some newly developed production areas. These fungi may indirectly promote plant growth and bioactive compound accumulation by decomposing organic matter, improving nutrient cycling, and maintaining a healthy rhizosphere environment. However, the study identified correlations between soil properties, rhizosphere microorganisms, and medicinal quality rather than direct evidence that any single fungal species improves the quality of *A. macrocephala*.

6.2 Continuous cropping, growth duration, and field quality formation

Continuous cropping is one of the most common production problems in the *A. macrocephala* growing regions of Zhejiang Province. Xu et al. (2025) conducted a three-year field experiment in Lin'an District, Hangzhou, Zhejiang Province, using a randomized block design. The experiment included five treatments: land without *A. macrocephala*, one year of cultivation, two consecutive years of cultivation, one year of fallow after cultivation, and two years of fallow after cultivation. Each treatment included replicated plots of 20 m × 20 m. Plants were propagated from sprouting rhizomes, transplanted every March, harvested every November, and managed using the same cultivation practices throughout the experiment. The study closely reflected the actual production cycle of continuous cropping, fallow recovery, and replanting in Zhejiang.

Continuous cultivation altered both the soil bacterial community and the endophytic bacterial community of *A. macrocephala*, while increasing the risk of root rot. The abundance of several beneficial bacteria declined, whereas bacterial groups associated with disease became more abundant. Soil organic matter and the availability of some nutrients also decreased after continuous cropping. Beneficial genera such as Bacillus and Novosphingobium were reduced, while disease-associated genera including Pseudomonas and Ralstonia increased. The combined effects of continuous cropping and root rot further suppressed plant growth. After a fallow period, soil fertility and microbial community composition gradually recovered, and soil that had remained fallow for two years became similar to that of land where *A. macrocephala* had never been cultivated.

Growth duration is another important factor affecting medicinal quality. Cui et al. (2025) compared the rhizome morphology and chemical composition of 1-, 2-, 3-, 5-, and 10-year-old *A. macrocephala* plants. The 1- to 3-year-old plants were collected from Xinchang, Zhejiang Province, whereas the 5- and 10-year-old plants were collected from Taizhou, Zhejiang Province. Both sampling sites are located within the Tiantai Mountain region, where plants grew on yellow forest soils under hillside woodland conditions with annual rainfall of approximately 1 300-1 600 mm. All samples were harvested on October 20, 2023. Plants were established by direct seeding, and rhizome weight, length, internal structure, and bioactive compounds were compared among different growth durations.

As growth duration increased, rhizome weight and length also increased. The upper parts of the rhizomes became more slender in the 5- and 10-year-old plants, producing the characteristic "crane neck" morphology that is traditionally regarded as a feature of high-quality *A. macrocephala*. Older plants also accumulated higher levels of atractylenolide I, atractylon, chlorogenic acid, and several other bioactive compounds (Figure 4). Overall, the medicinal quality of the 5- and 10-year-old plants was superior to that of the 1- to 3-year-old plants. These findings suggest that an insufficient growth period may limit both the development of desirable rhizome morphology and the accumulation of important medicinal compounds.

7 Recommendations and Future Perspectives for High-Quality *Atractylodes macrocephala* Production

7.1 Quality-oriented cultivation system

The cultivation of *Atractylodes macrocephala* should gradually shift from a yield-oriented approach to a quality-oriented production system. High-quality production should be evaluated using multiple indicators rather than relying only on rhizome yield or alcohol-soluble extract content. The major bioactive compounds of *A. macrocephala* include sesquiterpenes, volatile oils, and polysaccharides. Among them, atractylenolides I, II, III, and atractylon are the main chemical markers used for quality control. Polysaccharides are also important active components because they contribute to immune regulation, gastrointestinal protection, and metabolic regulation (Liu et al., 2022).

Studies have shown that Daodi production areas generally produce plants with better rhizome growth, higher levels of bioactive compounds, and superior overall quality than many newly developed production regions. High-quality production areas also tend to have more stable and diverse rhizosphere microbial communities. These findings indicate that superior medicinal quality depends not only on genetic background but also on long-term ecological conditions and healthy soil microbial ecosystems. Therefore, cultivation should be prioritized in suitable ecological regions, traditional Daodi production areas should be protected, and regional cultivation practices should be developed according to local environmental conditions.

Traditional quality evaluation mainly relies on sensory assessment and laboratory chemical analysis. Although these methods satisfy pharmacopoeia requirements, they are time-consuming and are not suitable for rapid screening in large-scale production. Recently, electronic tongue technology combined with machine learning has been used to rapidly classify *A. macrocephala* samples while simultaneously predicting major quality indicators, including polysaccharides, volatile oils, atractylenolides I-III, biatractylenolides, and atractylon, with an overall classification accuracy of 95.56% (Yang et al., 2026). This technology provides a practical tool for raw material grading, post-harvest screening, and quality monitoring, and it is expected to become an important supplement to conventional laboratory analysis in the future.

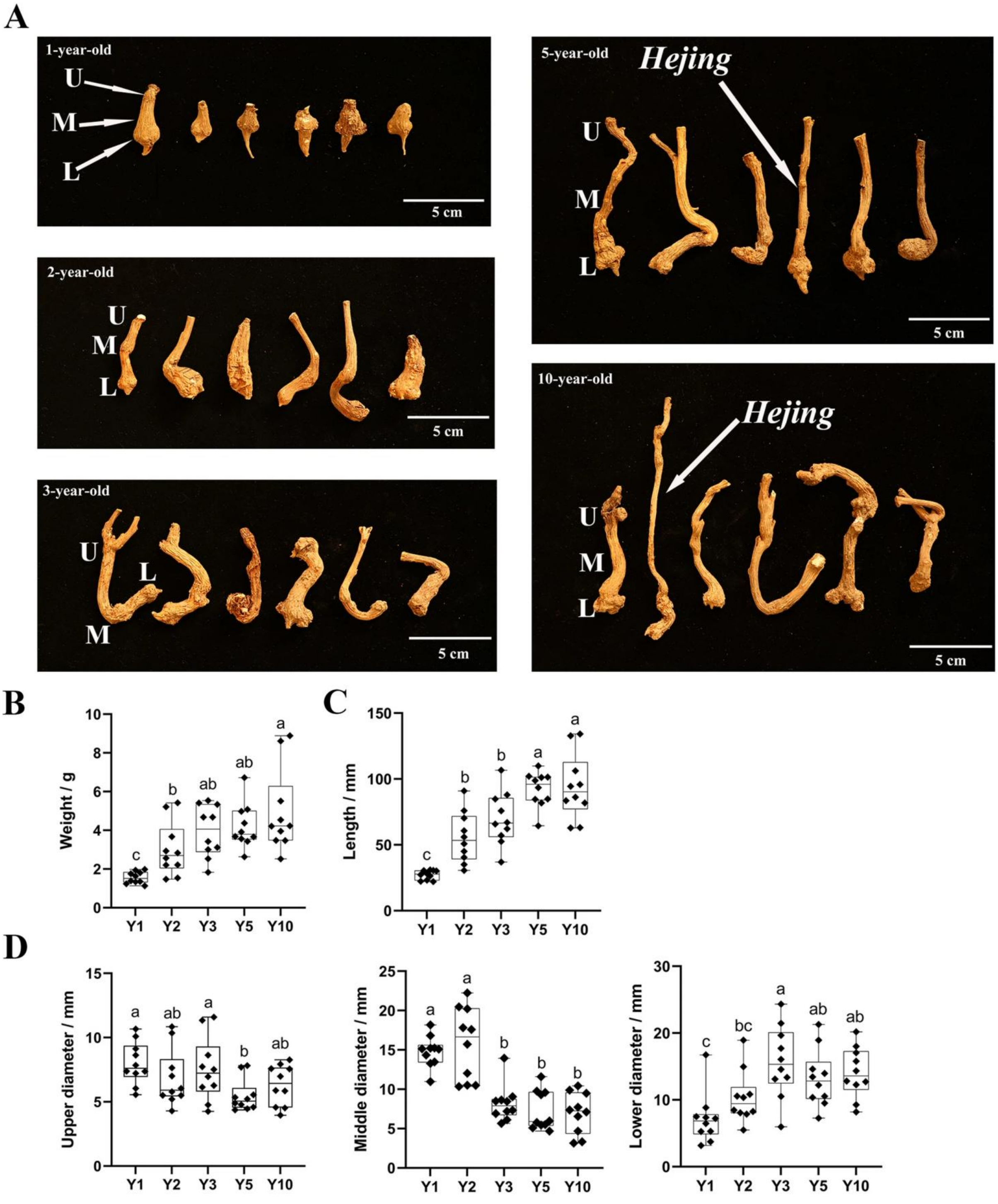

Figure 4 Morphological characteristics of *A. macrocephala* at different growth years. A Rhizomes of 1, 2, 3, 5, and 10-year-old *A. macrocephala* (scale bar: 5 cm). U, M, and L denote upper, middle, and lower measurement positions. B Rhizome weight (means ± SD, n = 10). C Rhizome length (means ± SD, n = 10). D Upper, middle, and lower diameters (means ± SD, n = 10). Letters indicate significant differences based on one-way ANOVA ($p < 0.05$) (Adopted from Cui et al., 2025)

7.2 Standardized nutrient and water management

The formation of high-quality rhizomes depends on both balanced nutrient supply and appropriate soil moisture. Therefore, nutrient and water management should support plant growth, rhizome development, and bioactive compound accumulation at the same time to improve both yield and medicinal quality.

Nutrient management should focus on balanced fertilizer application rather than simply increasing fertilizer input. Rhizome yield has been reported to be positively associated with available phosphorus, available potassium, and the abundance of beneficial microorganisms such as Burkholderia and Cupriavidus. In contrast, the total content of atractylenolides is negatively associated with soil alkaline nitrogen. Future fertilizer management should therefore optimize the balance of available phosphorus, potassium, and nitrogen while adjusting fertilization according to soil properties and changes in the rhizosphere microbial community.

A. macrocephala is sensitive to both prolonged waterlogging and continuous drought. Irrigation and drainage should therefore be adjusted according to different growth stages. During the early growth period, suitable soil moisture is essential for seedling emergence and establishment. During rapid rhizome enlargement, stable water supply should be maintained to support photosynthesis and assimilate transport. During the maturation stage, excess water should be removed promptly to reduce the risk of root rot and rhizome decay.

In the future, nutrient and water management should move from experience-based practices to precision management. Soil nutrient testing, soil moisture monitoring, rhizosphere microbial analysis, and plant nutritional diagnosis can be integrated to develop more efficient management strategies. Such approaches will improve fertilizer use efficiency, reduce resource inputs, and maintain stable medicinal quality.

7.3 Cultivar and planting material management

Because *A. macrocephala* and its related species differ considerably in chemical composition and medicinal quality, the authenticity of planting materials should be strictly guaranteed. Mixing different botanical origins or using closely related species by mistake should be avoided. *A. macrocephala* is characterized by atractylon as one of its representative chemical compounds, while the botanical origin recognized in pharmacopoeias differs among East Asian countries. Therefore, greater attention should be given to germplasm conservation and standardized seedling production to ensure cultivar purity and stable medicinal quality. In addition, the discovery of new bis-sesquiterpene lactones in wild *A. macrocephala* suggests that different germplasm resources possess distinct genetic potential. Strengthening the collection, conservation, and evaluation of local germplasm resources will provide valuable materials for future breeding programs (Li et al., 2017). Future breeding should focus on selecting superior parental lines and evaluating yield, medicinal quality, stress resistance, and genetic stability to develop new cultivars adapted to different ecological regions.

Traditional propagation by seed is limited by low germination, slow multiplication, and the short storage life of planting materials, making it difficult to satisfy the needs of large-scale commercial production. Tissue culture propagation can greatly improve the multiplication efficiency of elite planting materials. Therefore, future seedling production should establish standardized propagation systems based on elite cultivars and tissue culture technology. Such systems can provide disease-free, genetically stable, and traceable planting materials while supporting regional adaptability testing and graded seedling supply to improve production consistency.

7.4 Sustainable production system

High-quality *A. macrocephala* production also requires a modern production system that balances economic returns, environmental protection, and long-term resource sustainability. Unlike conventional production systems that rely heavily on chemical inputs and disease control, sustainable production places greater emphasis on soil health, rhizosphere restoration, and whole-process quality management. Improving the production environment is essential for maintaining both medicinal quality and long-term productivity.

Long-term continuous cropping reduces the diversity of endophytic fungi in the roots, stems, leaves, and rhizomes of *A. macrocephala*. It also changes the composition of rhizosphere and endophytic fungal communities while promoting the accumulation of soil-borne pathogens such as Fusarium. Soil pH, hydrolyzable nitrogen, electrical conductivity, and other environmental factors are closely associated with microbial community composition, indicating that continuous-cropping obstacles are fundamentally caused by long-term ecological imbalance in the soil ecosystem. Therefore, crop rotation, fallowing, soil improvement, and organic matter application should become routine components of long-term production management to restore soil ecological functions.

Establishing a complete quality traceability system is another important direction for sustainable production. With the development of stable isotope analysis, multi-element analysis, electronic nose technology, and electronic tongue technology, the geographical origin, commercial grade, and major bioactive compounds of *A. macrocephala* can now be identified more rapidly and accurately. These technologies provide reliable support for production base inspection, post-harvest grading, market circulation, and quality supervision.

In the future, high-quality *A. macrocephala* production should be built on suitable ecological regions, supported by elite cultivars and standardized planting materials, and strengthened through precision nutrient and water management and healthy soil maintenance. Combined with modern quality evaluation methods and full-process traceability systems, these approaches will help establish a sustainable production system that is efficient, high-quality, safe, and environmentally friendly, providing long-term support for the sustainable development of the *A. macrocephala* industry.

Author Contributions

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Conflict of Interest Disclosure

The authors affirm 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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