phosphorus and lowering nitrate nitrogen. Across medicinal and field crops, partial substitution often performs best: 40% microalgae substitution increased underground biomass and active components in *Polygala tenuifolia* 25% partial substitution improved tea soil quality and amino acid quality traits while raising nitrogen use efficiency, and 20~40% mineral replacement is repeatedly associated with lower environmental risk while sustaining productivity. Because long-term chemical-fertilizer dependence reduces soil organic matter and disrupts soil biological activity, whereas organic inputs improve soil structure, nutrient retention, and microbial function, organic substitution should be treated as a core pathway for coordinating rhizome yield, medicinal quality, and ecological safety in *A. macrocephala* production.

Nutrient regulation is the key driver connecting fertilization mode with quality formation in *A. macrocephala*, because active-component accumulation depends not simply on nutrient quantity but on the balance among nutrient supply, rhizosphere transformation, and secondary-metabolite biosynthesis. In *Atractylodes chinensis*, precise NPK regulation showed that high-phosphorus fertilization increased yield and promoted sesquiterpene and polyacetylene accumulation by increasing ACC and FPPS expression, while HMGR responded more strongly under a different formula, indicating that different nutrient ratios regulate different biosynthetic branches (Sun et al., 2022). More broadly, medicinal-plant studies show that appropriate N and P improve biomass, essential oils, and bioactive compounds, but species differ in their optimal ratios and excessive or imbalanced fertilization can reduce target metabolites. Nitrogen also changes metabolic allocation: low N increased phenolic acids and flavonoids in *Artemisia argyi*, whereas high N increased volatile oil and terpene-related gene expression. At the system level, organic substitution improves soil organic matter, available nutrients, microbial diversity, and nutrient-use efficiency, while compost optimization with biochar can reduce nitrogen loss by 28.1% and preserve phosphorus availability before the fertilizer even reaches the field. Future work on *A. macrocephala* should therefore focus on how nitrogen, phosphorus, potassium, organic carbon, and rhizosphere microbes jointly regulate lactones, volatile oils, and polysaccharides rather than evaluating fertilizer treatments only by yield response.

The future prospect for *A. macrocephala* is the construction of a green and efficient cultivation technology system that integrates organic substitution, formula fertilization, soil testing, and precision management. Precision agriculture in medicinal plants is defined by site-specific monitoring and response, using tools such as GIS, GPS, crop scouting, remote sensing, and variable-rate technology to optimize output with lower resource use. Smart-farming reviews further show that data-driven irrigation and nutrient management can improve medicinal-plant yield, phytochemical consistency, and sustainability by directly regulating photosynthesis, nutrient uptake, stress response, and secondary-metabolite biosynthesis, although cost and scalability remain constraints. For fertilization practice, soil testing and formula-based nutrient management are recommended because proper fertilization improves bioactive compounds, whereas excess or imbalance can have the opposite effect. Organic-inorganic integration also improves drought tolerance and resource-use efficiency, and nano-organic fertilizer has been shown to enhance antioxidant metabolism, osmolyte accumulation, mineral nutrition, photosynthesis, and membrane stability under drought stress. Accordingly, future *A. macrocephala* cultivation should establish region-specific nutrient recommendation models for authentic and emerging production areas, dynamically monitor soil organic matter and available nutrients during long-term substitution, and combine ecological fertilization with digital decision support so that high yield, stable quality, stress resistance, and environmental protection can be achieved simultaneously.

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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