development (Lee et al., 2025). This means that current fertilizer studies on *A. macrocephala* still explain outcomes mainly through correlations with soil properties, while the causal chain linking nutrient regulation to rhizome metabolite accumulation remains incomplete.

Mechanistic gaps also exist at the levels of microbiome, metabolism, and molecular regulation. Rhizosphere studies showed that 16 bacterial and 10 fungal genera were correlated with the accumulation of polysaccharides, atractylone, and lactones, but these results remain largely associative rather than functional (Song et al., 2023). Regional analysis further showed that authentic production areas had higher biomass and active-component levels, and that decomposer-associated fungi such as *Mortierella* and Basidiomycota were linked to quality formation (Zhou et al., 2025). At the plant level, *A. macrocephala* quality involves volatile oils, polysaccharides, and lactones (Liu et al., 2022; Yu et al., 2023); older rhizomes accumulate more sesquiterpenoids and phenolic acids, with upregulation of terpenoid and phenylpropanoid biosynthetic genes such as *HMGR, DXS, idi, GPS,* and *GGPS* (Cui et al., 2025). However, there is still no integrated framework showing how organic fertilizer substitution alters nutrient transformation, microbial networks, carbon allocation, and biosynthetic gene expression to jointly determine medicinal quality. Future research should combine controlled fertilization experiments with metabolomics, transcriptomics, enzyme assays, and rhizosphere microbiome manipulation to identify the key regulatory nodes of quality formation.

6.3 Establishment of green and precision fertilization technology systems

A third challenge is the lack of a green and precision fertilization technology system specifically tailored to *A. macrocephala*. Precision fertilization is increasingly recognized as a core pathway for optimizing nutrient application, improving productivity, and minimizing environmental harm through site-specific management, real-time monitoring, and variable-rate application. Reviews of specialty crops similarly show that precision systems should integrate crop and soil diagnostics, variable-rate fertilizer and irrigation management, and decision-support tools, while also incorporating organic and bio-based fertilizers into adaptive management frameworks (Khoddamzadeh et al., 2026). For *A. macrocephala*, this is especially relevant because soil texture, cation exchange capacity, humidity, and temperature all affect active-component accumulation, so fertilization should eventually be linked to fine-scale environmental diagnosis rather than uniform field application (Lee et al., 2025).

The future direction is to establish a fertilization system that combines soil testing, sensor monitoring, decision models, and organic substitution strategies. Site-specific nutrient management aims to match nutrient supply with spatial and temporal crop demand using tools such as remote sensing, GPS, GIS, and variable-rate technology, thereby improving nutrient-use efficiency and economic return rather than simply increasing inputs (Akhil et al., 2025). Precision water-fertilizer reviews further emphasize the need to couple nutrient management with irrigation, improve soil testing, refine predictive models, and build standardized indicator systems that account for soil heterogeneity and nutrient transformation processes (Xing and Wang, 2024). Practical experience from SSNM decision-support systems also shows that precision fertilization can improve productivity, soil fertility, microbial activity, and nutrient-use efficiency while remaining operational for extension and farm use (Pooniya et al., 2015). Accordingly, future *A. macrocephala* research should build region-specific green fertilization models for authentic and emerging production areas, develop quality-oriented nutrient recommendation standards, and integrate organic fertilizer substitution into digital, scalable precision management systems.

7 Conclusions and Prospects

Organic fertilizer substitution for chemical fertilizers should be regarded as an important approach for improving the production quality of *Atractylodes macrocephala*, but the evidence supports balanced substitution more strongly than complete replacement. In *A. macrocephala* itself, HA organic fertilizer maintained or exceeded conventional yield and significantly increased atractylenolide I content from 0.023% under customary fertilization to 0.036%, while the highest yield reached 203.0 kg per 10 a at the appropriate HA application rate. In related *Atractylodes* research, vermicompost increased yield by 70% and raised atractylenolide II, β-eudesmol, atractylenol, and atractylenolone by 34%, 175%, 72%, and 24%, respectively, while also increasing available