

instead improves soil structure, boosts water and nutrient retention, increases microbial biomass, and mitigates greenhouse-gas emissions and nutrient leaching while sustaining yields. In *Atractylodes* cultivation itself, suitable organic fertilizers increased rhizome yield and atractylenolide I content, showing that ecological fertilization can serve both production and medicinal-quality goals (Kim et al., 2016). Vermicompost studies in *Atractylodes* also demonstrate the value of converting agricultural wastes into high-value organic fertilizer, which broadens the utilization of organic residues while improving medicinal-herb yield and quality.

Sustainable industrial development also depends on profitability and risk control, not only on ecological outcomes. Partial substitution of chemical fertilizer with organic forms increased economic benefit per unit area by 37~46% in vegetable production and reduced agricultural inputs and environmental impacts per unit product by 22~44%, with 50% pig-manure substitution the most profitable strategy (Tang et al., 2022). Bio-organic fertilizer strategies in medicinal plants likewise provide an eco-friendly basis for reducing chemical fertilizer use while maintaining or improving medicinal-plant productivity and quality (Su et al., 2025). Microalgae-based biofertilizers offer an additional sustainability route because they improve nutrient cycling, reduce reliance on synthetic fertilizers, support beneficial soil microbiota, and can contribute to carbon sequestration (Gonçalves et al., 2023). Overall, organic fertilizer substitution appears to be a practical pathway for the sustainable development of the *A. macrocephala* industry, but the strongest evidence supports balanced substitution, not unconditional replacement, because some systems still show risks of nitrate accumulation, phosphorus mobilization, or pollutant wash-off under poorly matched organic inputs (Zhou, 2023; Xing et al., 2025).

6 Current Research Challenges and Future Development Directions

6.1 Optimization of organic fertilizer substitution ratios and application methods

At present, one major challenge is that the optimal substitution ratio of organic fertilizer for chemical fertilizer is not fixed, but varies with crop species, target traits, and local soil conditions. In *Epimedium pubescens*, 25% organic substitution produced the highest comprehensive score and was recommended for first-year production, even though fully or highly substituted treatments improved some soil indices or enzyme activities (Lai et al., 2024). In yam, the 25% organic plus 75% chemical treatment achieved the highest yield, commodity rate, and nitrogen use efficiency, while higher organic ratios reduced some yield traits. In contrast, *Euryales Semen* performed best at a 7:3 organic-to-chemical ratio, and tea responded most favorably to a 25% partial substitution treatment rather than complete replacement. These differences show that a single uniform substitution ratio cannot be directly transferred to *A. macrocephala* production.

Application method is another unresolved issue. Evidence across crops shows that substitution effects depend not only on proportion, but also on nutrient-equivalent design, fertilizer type, timing, and auxiliary amendments. The yam study maintained equal nitrogen input across treatments, which allowed a clearer comparison of substitution effects. In *Saposhnikovia divaricata*, the highest comprehensive scores came from a mode combining organic fertilizer, reduced chemical fertilizer, and biochar as a soil conditioner, indicating that optimization should include amendment combinations rather than ratio alone. A 20% commercial organic fertilizer substitution increased wheat yield and soil quality, but the authors emphasized that continued application requires monitoring soil organic matter and available nutrients to adjust fertilization over time (He et al., 2022). For *A. macrocephala*, future work should therefore move from simple ratio screening to multi-factor optimization that integrates substitution proportion, nutrient equivalence, fertilizer source, topdressing schedule, and soil-improving co-inputs under different production regions.

6.2 Insufficient research on the mechanisms of quality formation in *Atractylodes macrocephala*

A second major challenge is that the quality-formation mechanism of *A. macrocephala* remains insufficiently resolved. Environmental evidence shows that the factors regulating rhizome growth and those regulating atractylenolide accumulation are largely independent, and that optimizing yield and phytochemical quality may require different cultivation strategies. The same work argued that future cultivation should consider not only external conditions but also internal physiological mechanisms such as sink-source dynamics and storage-capacity