improve water and nutrient uptake and strengthen drought tolerance while reducing dependence on sole chemical fertilization (Kazemalilou et al., 2021). In medicinal and field crops under drought, organic amendments increased photosynthesis, membrane stability, proline and sugar accumulation, and the activities of antioxidant enzymes such as SOD, POD, CAT, APX, GR, and GPX, thereby mitigating oxidative damage (Ahanger et al., 2021; Najafi et al., 2021). Similar responses were reported in maize, where poultry manure and farmyard manure improved growth and yield under severe drought and enhanced antioxidant defense through SOD, POD, and CAT (Shah et al., 2023).

For medicinal plants, this stress-mitigation effect is especially important because resistance traits and secondary-metabolite accumulation are closely linked. In *Dracocephalum kotschyi*, organic and microbial fertilizers under mild to moderate drought increased CAT, POD, PPO, and APX activity together with proline, phenolics, flavonoids, and anthocyanins, indicating coordinated improvement in oxidative stress mitigation and phytochemical accumulation (Heidarzadeh et al., 2026). Biofertilizer treatments also improved biochemical stress indicators and increased flavonoid and anthocyanin contents under drought, while generally outperforming chemical fertilizer for stress tolerance and phytochemical enrichment (Heidarzadeh et al., 2026). In *Atractylodes* systems, vermicompost increased fungal diversity, available phosphorus, and enzyme activities, and humic substances in vermicompost can promote phenolic synthesis while enhancing root growth, soil structure, aeration, and water-holding capacity. Microbial fertilizers also help plants resist stress by recruiting beneficial rhizosphere organisms that compete with pathogens and induce systemic resistance, which provides a plausible mechanism for improved resilience in *A. macrocephala* under reduced chemical fertilizer input (Xing et al., 2025).

5.2 Reduction of agricultural non-point source pollution

Organic fertilizer substitution can reduce agricultural non-point source pollution, especially nitrogen leaching and runoff, when it replaces rather than simply adds to chemical fertilizer. A global meta-analysis of 129 studies found that organic inputs reduced overall nitrogen leaching by 15% and runoff by 29% without compromising yield, and substitution based on equal total nitrogen reduced both leaching and runoff by more than 30%. The same analysis showed lower loss ratios for organic fertilizer than chemical fertilizer and identified optimal substitution ranges of 40~60% for leaching control and 60~100% for runoff control under equal-total-N substitution (Wei et al., 2021). Field evidence is broadly consistent: in tobacco systems, combined organic-inorganic fertilization improved nutrient uptake while reducing runoff and leaching losses of both N and P compared with farmers' organic practice. In paddy fields, substituting more than 30% of chemical N with organic N significantly lowered TN concentrations in ponded water while maintaining rice yield at comparable levels (Zhou, 2023).

The ecological advantage, however, depends on management details. Partial organic substitution in vegetable production reduced N_2O emission, N leaching, and runoff, likely because it lowered inorganic nitrogen surplus, and it also prevented soil acidification (Tang et al., 2022). A short-term Tibetan incubation study found that 40% substitution with compost, straw, or sheep dung reduced cumulative N_2O emissions by 16.64~53.43%, but nitrate tended to accumulate, indicating possible leaching risk if nitrogen transformation is not synchronized with crop uptake. Another study reported that organic fertilizers can be more easily washed out because of their soluble components, but combining fertilizer reduction with biochar and microbial agents reduced nutrient concentrations in infiltration and runoff waters by 5~10% while maintaining yield similar to full fertilization. Therefore, for *A. macrocephala*, organic substitution appears most effective for reducing non-point source pollution when used at moderate substitution rates and in combination with practices that stabilize nitrogen and phosphorus in the soil-plant system.

5.3 Promotion of sustainable development of the *Atractylodes macrocephala* industry

For the *Atractylodes macrocephala* industry, organic fertilizer substitution supports sustainable development by linking medicinal-material quality, soil restoration, waste recycling, and long-term input efficiency. Excessive chemical fertilizer use is associated with soil degradation, declining fertility, nutrient-use inefficiency, and broader environmental crisis, with only 30~50% nitrogen-use efficiency in major cereal systems and large fractions of applied nutrients lost through volatilization or leaching (Xing et al., 2025). Balanced mineral-organic fertilization