beneficial microbes can directly stimulate plant growth (Robas-Mora et al., 2026). More broadly, biofertilizer-associated microorganisms can enhance nutrient acquisition, stress tolerance, and pathogen suppression, all of which contribute to improved vegetative development (Fasusi et al., 2021). For *A. macrocephala*, this suggests that partial replacement of chemical fertilizer with well-matured organic inputs is likely to favor seedling establishment, canopy growth, and root system activity when nutrient release is matched to crop demand.

3.2 Effects on rhizome expansion and yield formation

For a rhizome medicinal plant such as *A. macrocephala*, the central agronomic question is whether organic substitution promotes assimilate accumulation into the underground organ. Direct evidence indicates that organic fertilizer can do so. In *A. macrocephala*, application of organic fertilizer 1 at 2.0 times the standard amount increased yield to 203.0 kg per 10 a, compared with 134.0 kg under conventional fertilization, and this difference was statistically significant (Kim et al., 2016). In Rhizoma atractylodis, vermicompost bio-organic fertilizer increased yield by 70% compared with the control while also increasing key sesquiterpenoid constituents, showing that organic fertilization can simultaneously support underground biomass accumulation and medicinal-quality formation in *Atractylodes* species. Similar rhizome responses were observed in *Paris polyphylla* var. *yunnanensis*, where inoculation with organophosphate-degrading bacteria increased rhizome biomass by 134.58% in the best treatment and raised steroidal saponins together with soil available phosphorus.

Yield formation under organic substitution is closely tied to better phosphorus activation, carbon turnover, and beneficial microbial recruitment in the rhizosphere. In *Polygala tenuifolia*, substituting 40% of chemical fertilizer with microalgae increased underground biomass by 29.30%, and the abundance of *Chloroflexi* was positively correlated with both underground biomass and active-compound content (Su et al., 2025). A global meta-analysis found that replacing chemical fertilizers with organic fertilizers increased crop yield by 10.89%, and yield gains were positively related to increases in total nitrogen, available phosphorus, AM fungal richness, and soil health index (Figure 1) (Wang et al., 2025). Long-term greenhouse vegetable data further showed that organic substitution increased enzyme activity, microbial PLFAs, and soil nitrogen transformation, and these changes improved soil nitrogen supply capacity and yield (Yuan et al., 2024). Taken together, these findings indicate that rhizome expansion in *A. macrocephala* under organic substitution likely results from a coordinated improvement in nutrient activation, root-microbe interactions, and sustained assimilate supply to the underground storage organ.

3.3 Regulation effects of different organic fertilizer substitution modes on *Atractylodes macrocephala* yield

Different organic fertilizer substitution modes do not produce the same yield response, and moderate substitution usually outperforms both sole chemical fertilization and excessive organic replacement. In *Polygala tenuifolia*, 40% chemical fertilizer substitution with microalgae gave the strongest growth-promoting effect, whereas microbial inoculant treatments with reduced chemical fertilizer showed no significant difference from full chemical fertilizer in underground growth (Su et al., 2025). In muskmelon, 15% and 30% organic substitution increased yield by 5.60~11.9% compared with conventional chemical fertilization and also improved economic returns (Yu et al., 2025). In rice, long-term green manure substitution improved yield sustainability only within a moderate range, with 0~40% substitution in early rice and 0~20% in late rice improving both soil quality and yield stability, whereas further increases reduced the sustainability yield index (Zhang et al., 2023).

This pattern is reinforced across broader substitution experiments. In soybean, 30% organic plus 70% inorganic fertilization was identified as the optimal strategy, outperforming both full chemical and full organic treatments for growth and yield (Zhang et al., 2026). In maize dryland production, a relatively low substitution rate of 12.5% increased grain yield by 6.60% and biomass by 4.59% compared with chemical fertilizer, and 12.5~37.5% substitution improved key carbon fractions linked to yield (Chen et al., 2025). In double-rice systems, substituting 20% of phosphorus fertilizer with organic manure increased grain yield by 4.59% and soil Olsen-P by 25.48%, while reduced-phosphorus substitution maintained yields comparable to conventional fertilization (Jin et al., 2025). However, evidence from Huajuhong shows that organic fertilizer is not inherently superior in all cases and may increase pathogenic fungi abundance under long-term use, so complete substitution is not always the best option.