organic fertilization-functionally analogous to many bio-organic fertilizers-substantially enhances dehydrogenase, β-glucosidase, protease, urease, arylsulfatase, and acid/alkaline phosphatases, and that enzyme activities correlate strongly and linearly with soil organic matter content.

5.2 Responses of enzymes related to carbon and nitrogen cycling

Enzymes involved in carbon acquisition, such as β-glucosidase and related glycosidases, frequently increase under biofertilizer or biochar-based fertilizer regimes, reflecting enhanced decomposition and turnover of plant residues and organic amendments. In a wheat-maize system, biofertilizer additions significantly elevated sucrase activity, interpreted as a sign of stimulated microbial metabolism and accelerated organic matter decomposition in maize soils (Ali et al., 2024). Long-term substitution of conventional fertilizer with biochar-based fertilizer increased activities of α-glucosidase, N-acetyl-β-D-glucosidase, and leucine aminopeptidase, with these C- and N-acquiring enzymes tightly linked to improved soil quality indices and higher maize yields, underscoring the central role of enzyme-mediated C and N cycling in productivity gains (Wang et al., 2025).

Nitrogen-cycling enzymes and associated processes also respond strongly to biologically enriched fertilization. The China-wide meta-analysis showed that biofertilizer use increased nitrification rates by over 70%, in parallel with the large increases in urease activity, and reduced ammonium losses, indicating more complete and efficient N mineralization and transformation in the soil-plant system (Pei et al., 2025). A global meta-analysis of biochar field trials further demonstrated that biochar application significantly enhanced N mineralization, nitrification, and N fixation as well as N-acetyl-glucosaminidase activity, while simultaneously increasing the abundance of key nitrification and denitrification genes (amoA, narG, nirS/nirK, nosZ), confirming that enzyme stimulation is coupled with upregulation of microbial N-cycling potential under organic-rich amendments (Zhang et al., 2021).

5.3 Enhancement of soil nutrient transformation efficiency

By jointly stimulating enzyme activities and reshaping microbial communities, biofertilizers improve the efficiency with which soils transform and retain nutrients. Across 107 field studies, biofertilizers increased total soil N by about 16.7% and available P by 11.0%, while markedly boosting urease and phosphatase activities, reducing nitrate losses, and lowering electrical conductivity, a pattern interpreted as more efficient N and P cycling together with improved ionic balance and organic matter accumulation (Pei et al., 2025). Metagenomic analysis of soils amended with a bacterial biofertilizer showed 46.7% and 88.6% increases in fast-acting (available) N and P, respectively, along with enrichment of nitrification genes and plant growth-promotion traits, indicating that nutrient transformation efficiency is enhanced through both biochemical (enzyme) and genetic (functional gene) pathways (Li et al., 2023).

Biofertilizer and organic-amendment strategies in intensive vegetable and arable systems can also alter ecoenzymatic stoichiometry, shifting microbial resource limitation and thereby optimizing nutrient capture. In greenhouse tomato soils, diverse organic materials (including biochar and manure) reduced C limitation while increasing microbial N demand, with biochar particularly effective at enhancing C-, N-, and P-acquiring enzyme activities and organic C sequestration across soil types (-). Studies of enzyme stoichiometry and N management in semi-arid croplands further show that fertilization regimes which intensify microbial P limitation can down-regulate the abundance of nitrification and denitrification genes, constraining N losses via gaseous pathways and highlighting how managing enzyme-mediated nutrient demand can be leveraged to synchronize N availability with crop uptake and reduce environmental leakage (Cui et al., 2020).

6 Indirect Impacts of Biofertilizers on Vegetable Yield and Quality

6.1 The relationship between soil biological activity and crop growth

Enhanced soil biological activity is a central pathway through which biofertilizers indirectly stimulate vegetable growth. A large meta-analysis in China showed that biofertilizers increased soil organic matter, boosted urease and phosphatase activities, and promoted beneficial microbial populations, while suppressing pathogens; these shifts in biological functioning were closely associated with higher root volume and reduced disease incidence, explaining much of the observed yield response across crops including vegetables (Pei et al., 2025). A global meta-analysis similarly linked biofertilizer use with improved nitrogen and phosphorus use efficiency,