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Isotopic Nitrogen and Carbon Allocation in Soybean for Optimizing Food Yield and Minimizing Post-harvest Waste via Bacterial Symbiosis

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Abstract

Understanding the regulation of nitrogen (N) and carbon (C) allocation among plant organs is essential for maximizing the nutritional value of agricultural products while optimizing the management of crop residues in sustainable agroecosystems. Legume residues represent a significant source of organic matter, but their management determines whether nutrients are lost via leaching and emissions or retained in the circular food economy. Our study investigated the dynamics of N and C using stable isotope ratios in two soybean (Glycine max L.) varieties from different maturity groups (Merlin and Laulema). Plants were inoculated with distinct nitrogen-fixing Bradyrhizobium japonicum bacterial strains to evaluate their symbiotic efficiency under organic-compatible management practices. The total content and isotopic composition of N and C were analyzed across separate plant organs—roots, shoots, stems, pods, and seeds—at two critical phenological phases: full-flowering (R2) and full-maturity (R8). The results demonstrated excellent biochemical compatibility between the host varieties and the selected B. japonicum strains, producing up to 32 nodules per plant. From a physiological perspective, the isotopic N ratio values across all plant parts were significanlty modulated by both the specific variety and the bacterial strain, whereas isotopic C ratio variation was primarily governed by the plant genotype and remained less sensitive to the inoculation strategy. A substantial resource redistribution occurred during the reproductive phase. N content was highly concentrated within vegetative tissues (roots and shoots) at the R2 stage but fell drastically by twofold in roots and fivefold in the remaining aboveground vegetative biomass at the R8 stage. This rapid exhaustion of vegetative nitrogen reflects intensive remobilization directed entirely toward supporting seed formation and protein accumulation. From an agronomic and waste-reduction perspective, the high-efficiency strain AGF78 stood out as uniquely superior. It induced the highest nodulation frequency and secured significantly greater total N concentrations in the harvested seeds compared to other variants, including SEMIA5079 and the less effective RF10. Inoculation with AGF78 pushed the seed yield of the productive variety Merlin beyond 3 t ha^{-1} and elevated the performance of the less productive Laulema to comparable high-yield thresholds. These findings offer critical insights into how targeted microbial inoculation can alter internal source-sink relations to achieve zero-waste agricultural goals. By employing the AGF78 strain, the plant effectively funnels the absolute majority of fixed N away from vegetative structures and locks it securely into human-consumable seeds. This targeted allocation pattern enhances the protein content and functional food value of the harvest; systematically depletes the residual post-harvest biomass (stems and empty pods) of excess labile nitrogen. Consequently, this reduces the risk

of nitrogen mismanagement, such as agricultural waste runoff, volatile emissions, or groundwater leaching from decaying field residues, transforming crop management into a precise tool for clean food production and bio-resource efficiency.

Keywords: hihg latitudes, soybean, variety selection, post-harvest, N management

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