

limited by nitrogen alone, likely because symbiotic fixation can supply part of the crop demand once nodulation is established. A similar conclusion emerges from rotational *Canavalia* research, where the legume derived 69% of its nitrogen from the atmosphere, yet soil nitrogen replenishment was still gradual and mineral nitrogen remained necessary in the short term to sustain production. Together, these findings suggest that nitrogen management for sword bean should emphasize moderate starter or supplemental application rather than heavy fertilization, balancing early vegetative support with preservation of nodulation and biological nitrogen fixation.

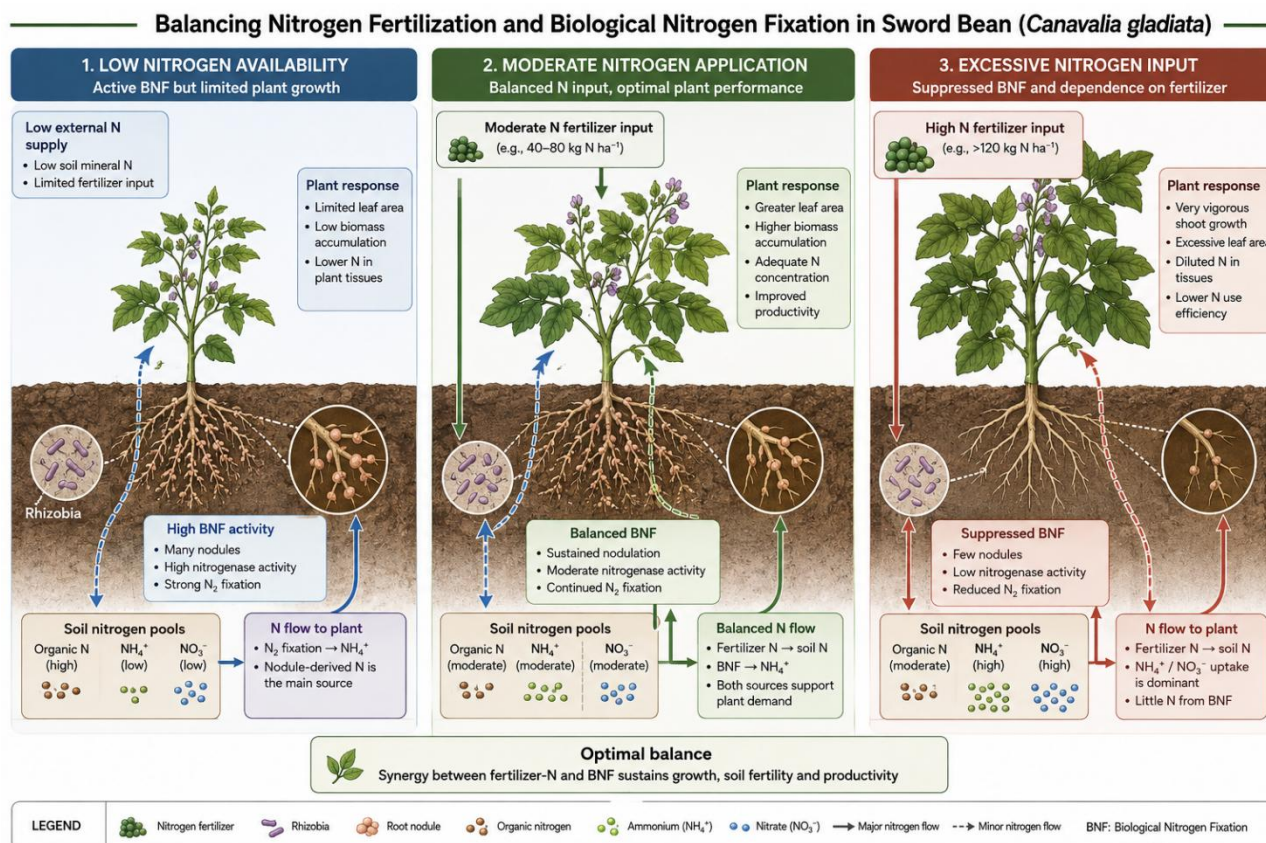


Figure 1 Conceptual model illustrating the effects of different nitrogen application levels on sword bean growth, root nodulation, and biological nitrogen fixation efficiency

3.2 Effects of phosphorus and potassium application on root development and yield

Phosphorus is central to root development, nodulation, and productive growth in sword bean, particularly in acidic or phosphorus-deficient soils. Experimental work on sword bean in acid upland soil showed that phosphorus fertilization significantly affected leaf phosphorus concentration, overall growth, and yield, while broader legume evidence indicates that phosphorus supports root proliferation and the energy-demanding process of biological nitrogen fixation. These responses are physiologically important because improved phosphorus nutrition strengthens the belowground structures that regulate nutrient acquisition and nitrogen fixation. Sword bean-specific yield data show that phosphorus application is essential for effective pod and seed formation, but the response can plateau above moderate rates. In East Lampung, increasing phosphorus increased sword bean yield, yet beyond 50 kg/P₂O₅ there was no further increase in biomass or pod weight, and crops receiving no phosphorus formed pods but failed to produce seed. A related study found that rock phosphate interacted with vesicular-arbuscular mycorrhiza in determining phosphorus uptake, with lower rates sometimes more efficient than higher ones. This indicates that optimizing phosphorus availability, rather than simply maximizing fertilizer dose, is more important for sword bean productivity.

Potassium complements phosphorus by supporting photosynthesis, enzyme activation, sugar transport, and nitrogen-use processes that ultimately influence legume growth and yield. In bean systems, adequate potassium improves nitrogen use efficiency and enhances nodulation and nitrogen fixation, indicating a strong functional