

growing and capable of converting solar light energy into chemical energy, which helps explain its reputation for high biomass production under tropical conditions. Evidence from closely related *Canavalia* systems also shows that higher photosynthetically active radiation increases biomass, photosynthesis, and water use, supporting the view that light capture is a central driver of canopy development and dry matter accumulation in this genus.

Biomass accumulation is also strongly shaped by growth stage, season, and nutrient-acquisition processes. In *Canavalia*, biomass production rises toward later vegetative-reproductive stages, with the highest fresh forage yield recorded at pod development rather than at earlier growth stages, indicating continued assimilate accumulation beyond flowering. Nutrient-management studies in sword bean further show that vesicular-arbuscular mycorrhiza increased nitrogen uptake and interacted with rock phosphate to affect phosphorus uptake, although dry matter itself was not significantly altered, suggesting that management can modify physiological efficiency even when visible biomass responses are limited.

2.3 Reproductive growth and yield formation processes

Sword bean reproductive development is relatively prolonged, and yield formation depends on successful transition from flowering to pod filling and seed maturation. Morphological field observations indicate that the vegetative phase lasts about 4-5 months before flowering begins, while pod maturation may continue for 5-6 months or longer, showing that reproductive growth extends over a large part of the crop cycle. Reproductive ecology studies add that the species flowers throughout the year, with more prominent flowering and fruiting during the rainy season, and that year-long prolific flowering helps sustain continual seed production.

Yield formation in sword bean is constrained not only by flowering intensity but also by pollination biology, fruit set, and the timing of seed physiological maturity. Comparative reproductive work found high pollen viability in *Canavalia gladiata* but a low seed-set percentage relative to flower number, likely because of abscission of young floral buds, while ecological study showed that the crop is pollinator-dependent and sets relatively low fruit numbers that are partly compensated by high seed set per successful fruit. Seed maturation data further show that pods and seeds reach physiological maturity around 80 days after anthesis, when pod and seed dry weight, germination, seedling vigor, and seed protein content are maximal, making this stage critical for harvest decisions aimed at maximizing yield quality.

3 Effects of Nutrient Management on Sword Bean Growth

3.1 Influence of nitrogen fertilization on vegetative growth

Nitrogen fertilization can stimulate vegetative growth in legumes, but the response is often moderate and depends strongly on dose. A global meta-analysis showed that nitrogen enrichment increased total legume biomass by 30.9% and tissue nitrogen content by 13.2%, while a pot study on long bean found that higher nitrogen input increased plant biomass and leaf greenness during reproductive onset (Tang et al., 2024). For sword bean, this broader pattern suggests that supplemental nitrogen can enhance canopy development and plant vigor, especially in nutrient-poor systems, but the benefit is unlikely to increase indefinitely with fertilizer rate.

At the same time, excessive nitrogen can weaken the root-nodule system that supports biological nitrogen fixation in legumes. Across legume datasets, nitrogen enrichment reduced nodule number by 21.2%, nodule weight by 29.3%, and the proportion of plant nitrogen derived from fixation by 27.1%, while field research in common bean showed that nitrogen fertilizer significantly reduced root length, secondary roots, and nodulation in most varieties (Figure 1) (Tang et al., 2024). This tradeoff is especially relevant to sword bean because the crop has inherent nitrogen-fixing capacity, so large nitrogen inputs may favor short-term shoot growth at the expense of longer-term physiological efficiency.

Evidence from sword bean itself indicates that modest nitrogen inputs may be more useful for improving forage quality than for substantially increasing biomass. In a urea-fertilization experiment, different nitrogen rates produced similar fresh and dry matter production, but crude protein and crude fiber changed significantly, and the 50 kg/ha treatment was judged most efficient because it saved urea while allowing rhizobial activity to function effectively. This indicates that, under some management conditions, sword bean vegetative growth is not strongly