

biomass production, stress tolerance, and adaptation under climate change (Palit et al., 2020). This is especially relevant for sword bean because its growth performance is shaped by strong genotype $\times$ environment $\times$ management interactions across water, nutrient, and cropping-system conditions. Systems biology strengthens this integration by linking multiple biological layers to complex field traits. Multi-omics datasets from genomes, transcriptomes, proteomes, metabolomes, and epigenomes are now generated routinely, but they need integrated analysis and predictive modeling to explain the biological networks underlying yield and stress tolerance. A broader plant-systems perspective also argues that conventional gene-centered improvement is inadequate for multiscale stress responses, and that predictive crop design requires integrating molecular control, physiology, ecology, and biotechnology.

For sword bean breeding and management, this means selecting not only for yield potential but also for traits that function well in diversified and low-input systems. Legume breeding literature emphasizes the value of genetic variability for architecture, phenology, cycle duration, root development, stress tolerance, and symbiosis with rhizobia and mycorrhiza, all of which influence adaptation to intercropping, nutrient capture, and water use. It also argues that future ideotypes should be designed holistically across cropping systems and stakeholder needs, using models to predict performance from climate, soil, input, and management conditions. Ecological integration is equally important because crop performance depends on interactions with soils, microbes, companion crops, and climate. Legume inclusion in diversified systems supports ecosystem services linked to soil fertility, greenhouse-gas mitigation, weed and pest control, and yield stabilization, while ecological and evolutionary perspectives show that plant-microbe interactions help shape adaptive capacity along environmental gradients (Liu et al., 2023). For sword bean, future research should therefore connect physiological screening and molecular selection with ecological testing under intercropping, rotation, and climate-stress scenarios rather than relying only on isolated station trials.

7.3 Optimization strategies for sustainable sword bean production

Sustainable sword bean production will likely depend on integrated optimization rather than maximizing any single input. Reviews of legume management consistently argue for site-specific integrated crop management that combines nutrient management, residue recycling, tillage, water management, crop diversification, varietal selection, and crop protection (Choudhary et al., 2020). A broader systems perspective similarly concludes that legumes can deliver their full production and soil-health benefits only when managed through integrated system approaches rather than compartmentalized interventions. Among field-level strategies, legume-based diversification remains one of the strongest routes to sustainability. Intercropping with legumes improves soil health by reducing bulk density, erosion, and fertilizer dependence while increasing soil organic matter and biological nitrogen fixation, and it can raise yield by 30%~35%, water-use efficiency by 20%~25%, and nutrient-use efficiency by 25%~30% (Akchaya et al., 2025). Long-term rotation studies likewise show that legume-based systems increase soil nutrients, microbial activity, and profitability, with some systems producing 68.97% higher rice-equivalent yield than conventional cereal systems.

Optimization will also require better design of mixed and diversified cropping systems rather than simply adding sword bean to existing rotations. Mixed cropping studies show that seeding ratio and canopy structure strongly affect dry matter yield, crude protein yield, water-use efficiency, radiation-use efficiency, and land-equivalent ratio, with intermediate mixture designs sometimes performing best. On-farm system-optimization studies further show that legume inclusion under zero tillage, residue retention, and improved management can reduce water use and global warming potential while increasing grain yield, energy-use efficiency, and net returns (Radheshyam et al., 2025). The future perspective for sword bean is therefore not only higher yield, but resilient multifunctionality across productivity, quality, soil restoration, and environmental performance. Legume-based systems can maintain crop yields while reducing external inputs and strengthening ecosystem services, but region-specific research and tailored management remain necessary because species choice and local conditions strongly influence outcomes (Liu et al., 2023). Overall, the most promising path for sword bean production is the combination of digital monitoring, systems-level trait integration, and site-specific diversified management that improves growth while sustaining soil, water, and agroecosystem health.