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Growth Characteristics of Sword Bean under Different Management Practices

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Abstract Sword bean (*Canavalia gladiata*) is an important leguminous crop with high nutritional value, strong environmental adaptability, and potential applications in sustainable agricultural systems. However, its growth performance and productivity are strongly influenced by cultivation conditions and management practices. This review summarizes the effects of different management strategies, including nutrient management, water regulation, cultivation practices, and environmental control, on the growth characteristics of sword bean. The morphological development, physiological responses, biomass accumulation, and yield formation processes of sword bean under different management conditions are systematically discussed. Nutrient management, particularly the balanced application of nitrogen, phosphorus, potassium, and organic amendments, plays a critical role in promoting vegetative growth, improving photosynthetic efficiency, and enhancing nutrient use efficiency. Water availability and environmental factors such as temperature and light intensity further regulate root development, physiological activity, and stress adaptation capacity. In addition, cultivation practices, including planting density, tillage methods, intercropping, and crop rotation, influence canopy structure, resource utilization, and final productivity. A case study based on integrated management practices demonstrates that optimized combinations of fertilization, irrigation, and field management can significantly improve sword bean growth traits, yield performance, and agricultural sustainability. Despite these advances, further research is needed to clarify the interactions among genotype, environment, and management practices using physiological, molecular, and digital agricultural approaches. Future efforts should focus on developing precise and sustainable cultivation systems to maximize the production potential of sword bean. Overall, improving management practices provides an effective pathway for enhancing sword bean growth, productivity, and ecological benefits in modern agricultural systems.

Keywords Sword bean; Growth characteristics; Management practices; Nutrient management; Sustainable cultivation

1 Introduction

Sword bean (*Canavalia gladiata*) is an underutilized legume with clear potential for sustainable agriculture because it combines nutritional value with agronomic resilience. It has been described as a cheap source of protein and calories, and it also shows favorable agronomic traits for tropical cultivation, with average yields reported as comparable to soybean in suitable environments. Its broader significance lies in the fact that underutilized legumes can diversify food systems while improving resilience and food security, and sword bean has specifically been noted as having good agronomic properties that make it resilient to adverse climate conditions in the tropics.

Beyond its direct food value, sword bean also fits the ecological logic of low-input farming systems because, like other legumes, it can contribute to soil fertility and reduce reliance on synthetic nitrogen inputs. Reviews of legumes in sustainable systems emphasize that symbiotic nitrogen fixation is a major pathway by which legumes support environmentally friendly production and crop diversification, while bean-based systems more broadly can buffer productivity under variable weather and reduce dependence on environmentally unfriendly inputs. Sword bean itself has been described as a high-biomass, drought-tolerant, pest-resistant species with nitrogen-fixing ability expressed through root nodulation, traits that make it attractive not only as a grain crop but also as forage, green manure, and a multipurpose component of integrated farming systems.

Crop growth in legumes is strongly shaped by management, and sword bean is unlikely to be an exception. Across legume systems, phosphorus application and rhizobial inoculation consistently increase grain yield, biomass yield,

and biological nitrogen fixation, while response size varies with species, soil organic carbon, and soil pH, indicating that management recommendations must be adapted to local conditions rather than generalized (Muoni et al., 2022). Parallel evidence from grain legumes shows that crop performance is also influenced by sowing density, irrigation, fertilization, tillage, and inoculation strategy, and that these factors interact with genotype and developmental stage to determine both yield and crop quality (Karavidas et al., 2022).

The available sword bean literature already points to several management-sensitive growth responses that justify dedicated study. Climatic adaptation is one major issue: sword bean tolerates drought better than many legumes but does not tolerate waterlogging, prolonged low temperatures during flowering reduce growth, and low light reduces flower and pod number; in cooler regions, transplanting may be needed to compensate for a shorter growing season. Experimental work also shows that management alters crop performance in more specific ways: moderate urea application changed forage quality more than biomass production, suggesting partial replacement of fertilizer N by biological fixation, while vesicular-arbuscular mycorrhiza and rock phosphate improved nutrient uptake pathways, especially nitrogen and phosphorus acquisition.

Research on sword bean growth has progressed, but it remains fragmented and much less developed than work on major legumes. Existing studies have examined seed production in non-native environments, forage production under nitrogen fertilization, nutrient uptake under mycorrhiza and phosphate application, and seed maturation physiology. These studies show, for example, that early cultivars can produce well-germinating seed under Polish conditions whereas late cultivars fail to mature fully, and that physiological seed maturity occurs around 80 days after anthesis with maximum germination and seed vigor at that stage. Even so, the crop remains underutilized and comparatively overlooked despite the recognized protein potential of Canavalia species and their possible contribution to future food strategies.

Against this background, the objective of a study on the growth characteristics of sword bean under different management practices is clear. A focused experiment can help determine how key agronomic variables influence vegetative growth, biomass accumulation, reproductive development, and yield formation in this species, while also clarifying which management combinations best express its potential under specific production conditions. Such work is needed because legume responses to management are often species- and environment-dependent, and because broader reviews show that improved agronomic practice, together with breeding and adaptation to stress conditions, is central to making legumes more productive and sustainable in modern agriculture.

2 Growth Characteristics and Physiological Development of Sword Bean

2.1 Morphological characteristics and growth dynamics

Sword bean is a vigorous climbing legume with a pronounced vegetative habit, and its morphology helps explain its adaptation to diverse tropical production systems. It is described as a perennial climbing plant with stems that can reach about 3-10 m, while its leaves are trifoliate and relatively large, supporting an expansive canopy during vegetative development. Broader agronomic descriptions likewise characterize sword bean as a tropical legume with favorable agronomic features and distinct morphological attributes, indicating that vegetative growth is one of its defining biological strengths .

Growth dynamics in sword bean show both species-level regularity and substantial genotypic variation. Field characterization of 20 genotypes found clear variation in days to germination, pod size, pod weight, and seed weight, with germination ranging from 3 to 6 days and pod length from 16.45 to 32.87 cm, which indicates that early establishment and subsequent structural development are strongly genotype-dependent (Debbarma et al., 2023). Quantitative growth analysis also showed that whole-plant weight increased early after sowing, leaf area expanded markedly after 50 days, and the reddish type expressed stronger early growth than the white type because specific leaf area, leaf area ratio, and leaf weight ratio were higher in the initial stage.

2.2 Photosynthetic characteristics and biomass accumulation

Sword bean appears to have strong biomass-forming ability because of its capacity to build large vegetative structures and convert intercepted radiation into dry matter. Agronomic work describes the crop as rapidly

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

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.

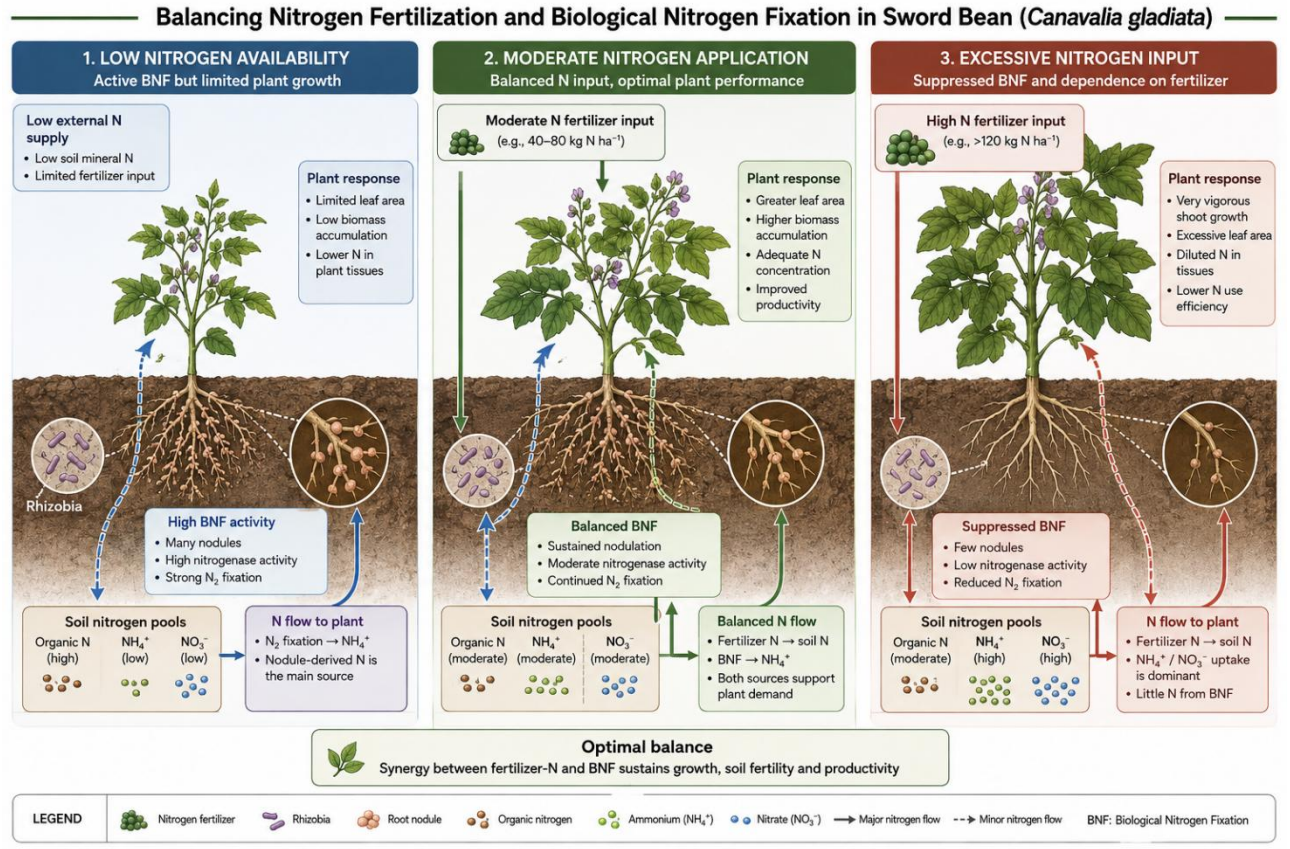


Figure 1 Conceptual model illustrating the effects of different nitrogen application levels on sword bean growth, root nodulation, and biological nitrogen fixation efficiency

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/P_2O_5 hathere 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

link between potassium supply and legume physiological performance. Field evidence from common bean further showed that crops responded strongly to combined phosphorus and potassium fertilization, reaching grain yields up to 3,600 kg/ha and requiring calibration of both nutrients even where soil tests suggested relatively high availability. However, potassium effects in Canavalia appear to be more pronounced in reproductive traits than in early vegetative growth. In jack bean, potassium source and timing did not significantly affect plant height, leaf number, or productive branches, although the study identified flower and pod drop as a major production constraint and recommended further work on potassium management during the generative phase (Eklemis et al., 2025). Consistent with this, cowpea achieved its highest nodulation and grain yield when inoculation was combined with both phosphorus and potassium, showing that potassium is most effective when integrated with other nutrient and biological inputs rather than applied in isolation (Emmanuel et al., 2020).

3.3 Organic fertilizers and integrated nutrient management strategies

Integrated nutrient management generally outperforms sole reliance on mineral fertilizers because it improves nutrient availability, root-rhizosphere function, and fertilizer-use efficiency. In faba bean, the combined application of organic and inorganic fertilizers produced the highest yield when organic nitrogen accounted for about half of total nitrogen, and this treatment also increased seed nitrogen accumulation and nitrogen harvest efficiency (Liu et al., 2023). Similarly, French bean studies report broad agreement that integrated plant nutrient systems are superior to exclusive chemical-input strategies for sustaining production and soil health. The mechanism behind this advantage is that organic inputs create a more favorable rhizosphere for nodulation and nutrient assimilation while mineral inputs provide readily available nutrients during periods of rapid demand. In faba bean, the 50% organic treatment increased total nodule number by 52.5%, fresh nodule weight by 55.8%, and nitrate reductase activity by 70.7%, while integrated nutrient use in French bean was associated with higher growth and better yield attributes than unfertilized controls (Liu et al., 2023). This mechanism is highly relevant to sword bean, whose growth depends on balancing external nutrient supply with its inherent biological nitrogen-fixing capacity.

Recent legume research also supports combining organic amendments, inoculation, and moderate phosphorus rather than increasing single-input rates alone. In haricot bean, the sole and combined application of vermicompost, phosphorus, and Rhizobium significantly improved growth, yield, and nitrogen fixation, and the combination of 30 kg P/ha with 5 t vermicompos/ha gave the highest yield among tested treatments. Long-term practical recommendations from vegetable legumes point in the same direction, with integrated nutrient management treatments combining inorganic fertilizer with vermicompost producing the highest plant height, pod number, and yield under acidic soil conditions (Changkiri et al., 2023). For sword bean, integrated strategies are especially promising because they can reduce overdependence on mineral nitrogen while improving phosphorus availability and biological nutrient capture. Research on root-focused nutrient management in French bean argues that sustainable production requires combining chemical, organic, and biofertilizer sources, and that biofertilizers with organic manure enhance root biomass and nutrient absorption. Sword bean studies also show that mycorrhizal inoculation increased nitrogen uptake and that phosphorus uptake depended on its interaction with rock phosphate, supporting the view that coordinated nutrient and biological management is more effective than single-factor fertilization.

4 Effects of Water Management and Environmental Conditions on Sword Bean Growth

4.1 Responses of sword bean growth to water availability

Water availability strongly regulates legume growth, and sword bean is expected to follow the general pattern seen across related species in which water deficit suppresses vegetative development, photosynthetic function, and final productivity. In grain legumes, drought reduces leaf area, shoot and root growth, chlorophyll content, stomatal conductance, CO_2 influx, nutrient uptake, and water-use efficiency, while severe stress also causes stunted growth and damage to the photosynthetic apparatus (Khatun et al., 2021). Because sword bean is managed for vigorous canopy growth and prolonged reproductive development, these drought-driven reductions in assimilatory capacity are likely to translate directly into lower biomass accumulation and weaker yield formation

when water supply is inadequate. The effect of drought on growth is closely tied to root performance, since deeper and more extensive root systems improve access to subsoil moisture and support better recovery under episodic stress. Across legumes, deep rooting, greater root length, and higher rooting density are repeatedly identified as promising traits for drought avoidance, whereas drought in common bean reduced rooting depth by 14%, root biomass by 29%, and total root length by 35%, with parallel declines in pod set and pod weight. For sword bean, this suggests that irrigation practices and soil-water management that maintain root activity during both vegetative and early reproductive stages will be essential for sustaining aboveground growth and reproductive success.

Water stress effects also depend on stress timing, intensity, and recovery opportunities rather than on soil moisture status alone. Reviews of legume drought responses note that yield loss varies by species and variety according to phenology, soil texture, and agro-climatic conditions, while intermittent drought can differ biologically from terminal drought because recovery capacity becomes part of the response (Khatun et al., 2021). This distinction is important for sword bean because a long growth cycle increases the chance that the crop will encounter both short-term water deficits and later-season moisture decline, making stage-specific water management more relevant than a single uniform irrigation strategy. Some legume responses to limited water are adaptive rather than purely damaging. Drought escape through faster development, early flowering, and earlier seed set is recognized as a major legume strategy, and plants with indeterminate growth can partly compensate after short drought by producing new organs during recovery. In practical terms, sword bean management under water-limited environments may benefit from synchronizing planting date and moisture availability so that the most drought-sensitive phases do not coincide with severe soil drying.

4.2 Effects of temperature and light conditions on physiological performance

Temperature and light conditions have major effects on legume physiological performance, and both factors interact strongly with water relations. Legume cover crop experiments that included jack bean (*Canavalia ensiformis*) showed that increasing light intensity significantly increased leaf, shoot, and root growth, while also increasing net assimilation rate, SPAD index, net photosynthesis, stomatal conductance, and transpiration (Baligar et al., 2020). These findings indicate that sword bean performance under different management systems will be highly sensitive to canopy light environment, especially in intercropping or shaded production settings where reduced irradiance can constrain carbon gain. Reduced light does not simply lower growth; it also changes leaf structure and biomass partitioning. Under shade, legumes developed thinner but larger leaves, had higher leaf-to-stem and leaf-to-total dry weight ratios, and accumulated more chlorophyll per unit area, yet final biomass still declined by about one-third relative to full sun. For sword bean, this suggests that shaded plants may show morphological adjustment that helps maintain light capture, but this acclimation is unlikely to fully offset losses in dry matter production where radiation is substantially limited.

Temperature stress imposes a parallel physiological burden because extreme heat alters water relations, photosynthesis, and reproductive metabolism. In legumes, high temperature increases transpiration and water loss, disturbs turgor and physiological processes, and impairs osmotic adjustment partly through damage to photosystem II, increased respiration, and reduced sugar concentrations. More generally, each legume species has specific minimum, maximum, and threshold temperatures, and extreme deviations can disrupt every stage of plant development and cause severe productivity loss. The interaction of temperature and light is especially important because hotter environments often increase evaporative demand at the same time that radiation drives canopy function. Greenhouse work on tropical perennial legumes was conducted near 30/28°C to reflect warmer tropical conditions, and the same study showed that increasing photosynthetic photon flux density improved water-use efficiency as well as nutrient-use efficiency across species (Baligar et al., 2020). This implies that sword bean physiological performance will be best when adequate radiation is matched with sufficient soil moisture, since light can promote carbon gain and efficiency, but high temperature without water supply is more likely to shift the balance toward dehydration and stress.

4.3 Adaptation mechanisms under abiotic stress conditions

Under abiotic stress, legumes activate integrated morphological, physiological, and biochemical defense systems

that help maintain cellular function but often at the cost of growth rate. Plants exposed to drought, salinity, or extreme temperatures adjust growth strategically rather than passively, and stress signaling can actively suppress anabolic activity and plant growth even before energy status collapses. For sword bean, this means that slower growth under adverse conditions should not be interpreted only as injury, but also as part of an adaptive reallocation of resources toward survival and stress resistance. A central adaptation mechanism is osmotic adjustment, in which plants accumulate solutes to maintain turgor and protect sensitive cellular processes during dehydration. Compatible solutes such as proline, soluble sugars, and other osmolytes help maintain water uptake, cell turgor, and redox balance, and across 26 studies in 12 crops osmotic adjustment was positively associated with yield under drought in 24 cases. This evidence supports the view that osmotic adjustment is not merely a survival response, but a trait with direct relevance to sustained growth and productivity under water-limited conditions.

Antioxidant defense is another key mechanism because abiotic stress commonly triggers oxidative damage through excess reactive oxygen species. Drought reduces CO_2 fixation through stomatal closure and is associated with increased ROS production, while major enzymatic antioxidants such as superoxide dismutase, catalase, ascorbate peroxidase, and glutathione reductase are central to restoring ROS homeostasis. In legumes broadly, oxidative burst, membrane instability, and metabolic disruption are early features of stress exposure, so stronger antioxidant capacity is likely to support more stable sword bean physiological performance under heat or drought (Furlan et al., 2021). Morphological escape and avoidance traits also contribute substantially to tolerance in stressed legumes. Early maturity, small leaves, deep rooting, strong remobilization under stress, and stomatal control can combine to improve drought resistance, while reduced leaf number and size, improved root system architecture, and stress-induced hormonal signaling are recognized as major tolerance traits in grain legumes (Khatun et al., 2021). Taken together, these mechanisms suggest that sword bean adaptation under different management practices will depend on combining water-conserving morphology, efficient physiological adjustment, and stress-mitigating field management to preserve growth under variable environments.

5 Effects of Cultivation Practices on Sword Bean Growth Performance

5.1 Influence of planting density and spatial arrangement

Planting density and spatial arrangement strongly influence legume growth by regulating canopy light interception, dry matter accumulation, and competition among neighboring plants (Musana et al., 2020). In soybean, higher density increased canopy light interception and dry matter accumulation and raised seed yield by 22.8%, while in common bean optimized density improved growth rate and yield by increasing light capture and reducing unnecessary competition. Uniform spatial arrangement is as important as plant number because it reduces plant-to-plant variability and improves population-level resource use (Xu et al., 2021). Soybean under uniform spacing increased seed yield by 9.5% and reduced variation in seed weight per plant by 71.5%, while faba bean evidence shows that very low density limits yield through too few plants and very high density reduces yield through pod abortion and barren stalks, indicating that sword bean should also have an optimum intermediate density rather than a simple “more plants is better” response.

Plant density also changes plant architecture, with dense stands often producing taller but less individually vigorous plants. In common bean, the highest density increased plant height, but biomass was greatest at 250,000 plants/ha and pod number per plant declined as density increased, while high-density stands can also raise risks of lodging, disease, and reduced photosynthetic efficiency under low within-canopy light (Musana et al., 2020). More detailed spacing studies show that within-row arrangement affects both vegetative growth and reproductive output. In common bean, intra-row spacing significantly altered leaf area, branch number, shoot dry weight, pods per plant, seeds per pod, and grain yield, and a 5 cm spacing gave the highest yields in the tested environments, showing that spatial precision can influence multiple components of crop performance at once (Bakure et al., 2025). For sword bean, which forms a vigorous canopy and climbing habit, these findings imply that spacing should be optimized not only for stand establishment but also for light penetration, branching pattern, and support of sustained biomass production.

5.2 Effects of tillage and soil management practices

Tillage affects legume growth mainly through its effects on soil structure, aeration, moisture, temperature, and microbial activity, all of which influence nodulation and nitrogen fixation. Conservation tillage often improves soil quality and biological processes by preserving structure and microbial diversity, but its effects on performance are not universally positive because reduced tillage can also lower pH or increase compaction under some conditions. Across legume systems, conservation tillage tends to enhance nodulation and nitrogen fixation by improving soil moisture retention and microbial biomass. Residue retention strengthens this effect by conserving soil moisture, lowering soil temperature, and improving seed emergence, suggesting that sword bean growth may benefit most where reduced tillage is combined with mulch or retained residues rather than implemented alone (Virk et al., 2024).

However, field yield responses to tillage remain context-dependent. A three-year legume experiment found that no-till gave lower average yields (2.24 t/ha) than standard tillage (2.58 t/ha) and deep tillage (2.62 t/ha), and deep tillage also reduced soil stiffness and improved seed nitrogen content. Mediterranean evidence likewise notes contradictory year-to-year responses between conventional and conservation tillage, partly because plowing can improve drainage and spring warming in poorly drained soils, which may favor early crop growth in some environments. These mixed results indicate that the best soil management system for sword bean will depend on local constraints rather than ideology. Where moisture conservation, erosion control, and long-term soil biological quality are priorities, reduced tillage is likely advantageous, but where compaction or slow warming restricts establishment, some soil loosening may still be necessary (Virk et al., 2024). This is consistent with broader rotation evidence showing that tillage interacts with residue management and soil properties, so cultivation systems should be designed as integrated packages rather than as single isolated practices (Zhao et al., 2022).

5.3 Effects of intercropping and rotation systems

Intercropping and rotation improve legume-based systems by increasing biodiversity in space or time, which enhances soil fertility, pest regulation, and input efficiency while sustaining productivity (Liu et al., 2023). In global synthesis, legume-based rotations increased the main crop yield by 20% on average, and the benefits were strongest in low-input, low-diversity systems, which is highly relevant to sword bean as a multipurpose legume suited to sustainable production (Zhao et al., 2022).

Intercropping benefits arise partly from complementary resource capture. Vertical stratification reduces competition for light and nutrients, row and strip arrangements improve sunlight interception and resource distribution, and effective spatial design can raise yields by 10%~20% in intercrop systems (Akchaya et al., 2025). A broader meta-analysis also found that cereal-grain legume intercrops had higher yield stability than sole legume crops, with lower yield variation than the respective monocultures, indicating that sword bean intercropping could improve system reliability as well as mean output.

Rotation effects are not uniform, because the identity of the legume species, background fertility, and fertilization regime all shape the strength of the legacy effect on following crops (Zhao et al., 2022). In a seven-year field experiment, legume inclusion increased subsequent wheat yield by 52% without fertilization and 26% with fertilization, while also improving yield stability, resilience, and topsoil multifunctionality, showing that legume rotations can strengthen both productivity and soil performance over time (Liu et al., 2023).

At the same time, intercrops can impose early competition if species combinations or root interactions are poorly matched. Some systems showed a 15%~20% reduction in legume shoot dry matter during early growth, which means sword bean mixtures will require careful choice of companion crop, row arrangement, and planting density (Akchaya et al., 2025). Overall, the evidence favors intercropping and rotation as effective cultivation strategies for sword bean, especially when designed to exploit complementarity, reduce external inputs, and match local soil and climate conditions (Liu et al., 2023).

6 Case Study: Evaluation of Sword Bean Growth under Integrated Management Practices

6.1 Experimental design and management treatments

A suitable case study should use a field-based comparative design that tests integrated management as a treatment package rather than as isolated inputs. In legumes, integrated crop management is defined as a site-specific combination of nutrient management, residue recycling, tillage, water management, crop diversification, varietal choice, and crop protection, and recent synthesis shows that the strongest benefits arise when rotation, conservation tillage, organic amendments, and microbiome management are combined rather than evaluated separately (Choudhary et al., 2020; Liang et al., 2025). For sword bean, this supports an experimental framework in which a control treatment is compared with several integrated packages differing in fertilizer source, irrigation regime, soil management, and cropping arrangement.

The treatment structure can be modeled on established legume experiments that compare organic, inorganic, and mixed nutrient strategies under replicated field conditions. A split-plot chickpea study used four nitrogen-management strategies-100% organic, 50:50 organic-inorganic, 75:25 organic-inorganic, and 100% inorganic RDF-with three replications, while a long-term maize-chickpea experiment tested 12 combinations of recommended NPK, FYM, poultry manure, compost, residues, and soil-test-based fertilization in a randomized complete block design. In sword bean, a comparable design could assign management packages to main plots and, where relevant, plant density or cropping system to subplots so that both main effects and interactions can be evaluated clearly.

Management treatments should also include practices beyond fertilization, because integrated performance depends on coordinated control of water, weeds, and soil physical condition. Legume reviews identify irrigation, sowing density, tillage, rhizobia application, and biostimulants as major agronomic levers affecting growth and quality, while integrated weed management remains important because weed competition can reduce legume yield by about 10-35% if not controlled during critical early growth stages (Karavidas et al., 2022). A sword bean case study is therefore strongest when nutrient treatments are paired with standardized weed control, stage-specific irrigation, and a clearly defined tillage or residue regime (Figure 2).

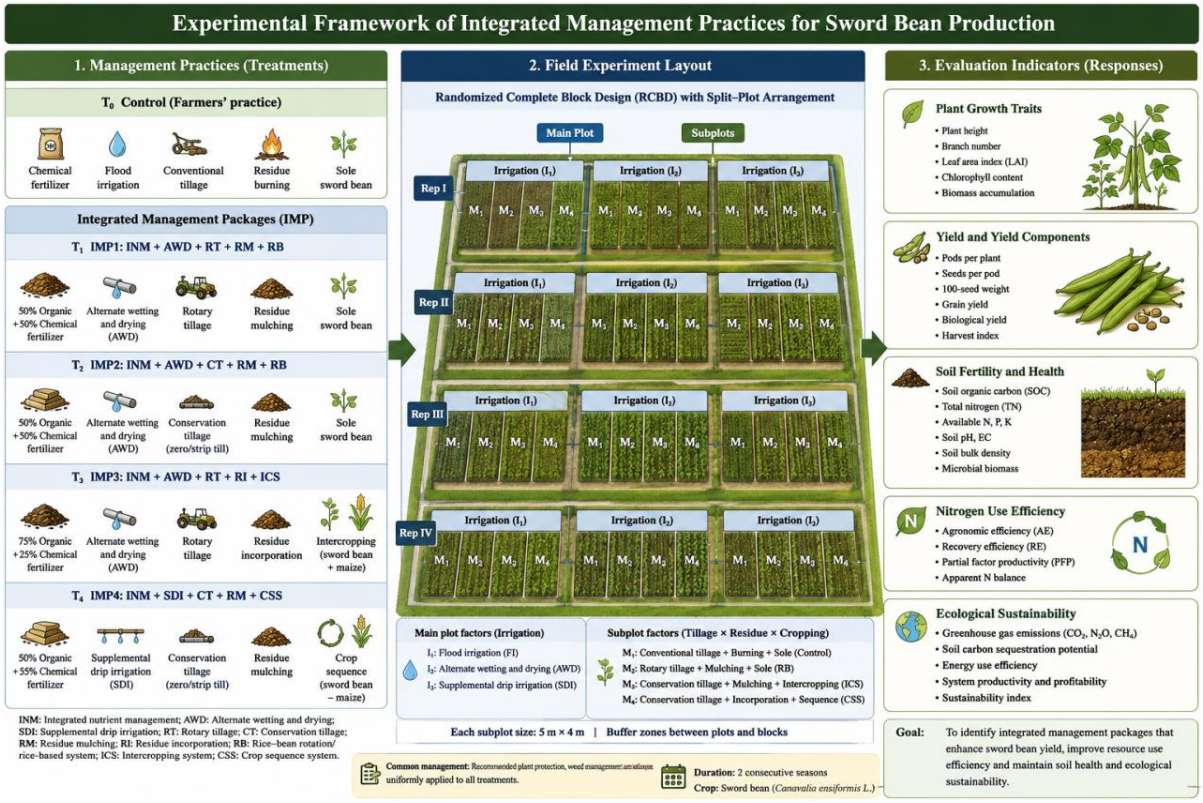


Figure 2 Experimental framework for evaluating integrated management strategies in sword bean production through combined manipulation of nutrient management, water regulation, soil practices, and cropping systems

Intercropping or rotation can be incorporated as an additional integrated-management factor where the objective

includes system productivity and resilience rather than sole-crop growth alone. Meta-analysis shows that intercropping often reduces legume grain and biomass yield relative to sole cropping but increases total land-equivalent productivity, with total LER values of 1.2-1.9, while broader review evidence shows that optimized row arrangement in legume intercrops can improve land productivity and resource-use efficiency. In a sword bean case study, this justifies comparing sole-crop sword bean with a carefully designed intercrop or rotational sequence if the aim is to assess integrated management at both crop and system level.

6.2 Effects of management practices on growth and physiological traits

Integrated management tends to improve vegetative growth and physiological vigor when balanced organic and inorganic nutrient sources are combined. In chickpea, the 50% organic plus 50% inorganic nitrogen treatment produced the highest plant height, dry matter accumulation, crop growth rate, relative growth rate, branch number, nodule number, and SPAD chlorophyll reading, outperforming both fully organic and 75: 25 treatments, and common bean reviews likewise conclude that reducing mineral nitrogen dependence through better biological fixation and stage-adjusted agronomy is central to optimizing crop performance. For sword bean, similar responses would be expected as improved nutrient synchrony promotes canopy development, chlorophyll retention, and nodulation without the inefficiencies of excessive single-source fertilization. Physiological improvements under integrated management are not limited to shoot growth, because belowground responses are equally important. Organic and inorganic nutrient combinations improve soil physical, chemical, and biological properties, which enhances nutrient availability and microbial conversion of less available forms, while biofertilizer inoculation can further stimulate nutrient supply and crop growth through rhizosphere colonization. In a sword bean experiment, these mechanisms would likely appear as stronger root development, more active nodulation, and improved nitrogen and phosphorus capture, especially where management includes microbial inoculants or residue-based amendments.

Water and soil management can further amplify these growth responses when integrated with nutrient treatments. Conservation tillage with crop-residue retention and organic manures improves macro-aggregation, soil-water storage, and bulk density, and legume intercropping systems can improve water-use efficiency by about 20-25% and nutrient-use efficiency by about 25%~30% across diverse environments (Choudhary et al., 2020; Akchaya et al., 2025). In sword bean, such conditions would be expected to support steadier physiological performance during vegetative and reproductive transition phases by buffering short-term water stress and maintaining more favorable root-zone conditions. Growth responses should still be interpreted cautiously because management effects vary with species, soil, and companion crop. A meta-analysis across smallholder legume systems found that inoculation and phosphorus application consistently increased grain and biomass yield, whereas minimum tillage showed no clear productivity effect and intercropping reduced legume biomass to varying extents depending on the associated non-legume crop. A sword bean case study should therefore analyze interactions carefully, since an integrated package that improves chlorophyll status and biomass in one soil or cropping context may not produce the same magnitude of response in another.

6.3 Impacts on yield, quality and agricultural sustainability

Integrated management usually improves yield most when nutrient supply is balanced and matched to crop demand over time. In the long-term maize-chickpea system, 75% soil-test-based NPK plus FYM at 5 Mg/ha increased mean grain yield by 20.9% in maize and 13.08% in chickpea over the general recommended dose, while broader INM evidence reports crop-yield gains ranging from 1.3% to 66.5% over conventional nutrient management across major cropping systems (Paramesh et al., 2023). For sword bean, this supports the expectation that integrated packages can improve pod and seed yield more reliably than either low-input or fully mineral-fertilizer strategies alone. Quality responses are also important because integrated nutrient supply can improve protein and nutrient accumulation rather than only total biomass. Reviews of pulse seed quality report that combining organic and inorganic nutrient sources with biofertilizer inoculation significantly increased phosphorus uptake, protein content, nitrogen, and potassium compared with other treatments, and integrated legume-management reviews identify yield and quality together as major targets of fertilization, irrigation,

inoculation, and density management (Karavidas et al., 2022). In a sword bean case study, measurements of seed protein, crude fiber, and nutrient concentration would therefore be as informative as yield alone for assessing treatment value.

The sustainability case for integrated management is stronger than the yield case alone because it includes soil health, resource efficiency, and environmental protection. Balanced organic-inorganic fertilization is widely described as the most logical strategy for sustaining long-term soil health and productivity, and integrated systems can increase crop yields by up to 15%~30% while also improving soil organic carbon and broader ecosystem services (Liang et al., 2025). In sword bean production, this means the most desirable treatment may not be the one with the absolute highest short-term yield, but the one that maintains soil function and resource-use efficiency while producing stable biomass and seed output. System-level sustainability also depends on how integrated management uses legumes to reduce external inputs and strengthen agroecosystem resilience. Legume-based systems improve soil health by reducing bulk density, increasing soil organic matter, fixing substantial atmospheric nitrogen, and reducing the need for inorganic N fertilizer, while legumes more broadly are valued because they support crop diversity, conserve resources, and fit low-input and conservation systems (Akchaya et al., 2025). Overall, a sword bean case study should evaluate integrated management not only by growth and yield, but by its capacity to deliver stable productivity, better seed quality, and more sustainable use of soil, water, and nutrient resources.

7 Advances and Future Perspectives in Sword Bean Production Management

7.1 Application of precision agriculture technologies in sword bean cultivation

Precision agriculture offers a practical pathway for improving sword bean management because it uses data-driven tools to optimize inputs while reducing resource waste and environmental impact (Mansoor et al., 2025). Across field crops, remote sensing, IoT, GIS, GPS, big-data analytics, and AI are increasingly used to monitor crop status, characterize spatial variability, and support site-specific management decisions that improve production efficiency. For sword bean, these tools are especially relevant where growth varies across fields because of uneven soil moisture, nutrient supply, or pest pressure. Recent sensor platforms suggest that sword bean cultivation could benefit from real-time monitoring of soil, canopy, and weather conditions linked to automated responses. IoT-enabled systems can integrate soil-moisture sensing, air sensing, automatic watering, pesticide application, and crop-health diagnostics, while bean-specific AI models have already shown accurate real-time discrimination between healthy and diseased leaves with lower computation time (Devi et al., 2023). More broadly, soil-moisture sensors, automated irrigation, and predictive analytics can improve water management and help forecast yield, pest outbreaks, and disease occurrence before losses become severe.

Remote sensing is likely to become one of the most useful precision tools for sword bean because it can monitor crop status across space and time without destructive sampling. Multispectral and hyperspectral imaging already support crop-health monitoring and spatially variable input application, and the fusion of spectral data with LiDAR can detect changes even within different parts of individual plants. Proximal sensing and UAV-based sensing also improve the fidelity of structural and physiological measurements by reducing environmental noise and increasing spatial resolution, which is valuable for detecting subtle stress responses in legumes (Berlingeri et al., 2025). The main future challenge is not the lack of digital tools, but their adaptation to real farm conditions and smallholder systems. Reviews of smart agriculture emphasize that broader adoption still depends on solving problems of startup cost, connectivity, data integration, real-time decision support, and farmer-friendly interfaces. For sword bean, future research should therefore move beyond technology demonstration and develop affordable, field-validated decision systems that translate sensor data into clear management recommendations for irrigation, fertilization, disease control, and planting windows.

7.2 Integration of physiological, molecular and ecological approaches

Future sword bean improvement will depend on integrating physiological understanding with molecular tools rather than treating them as separate research domains. In legumes, integrated frameworks that combine genomics, systems biology, physiology, breeding, and crop modeling are proposed as the most effective way to improve

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 × environment × 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.

8 Conclusions

Sword bean shows broad agronomic potential because it combines favorable tropical adaptation with comparatively high yield potential among underutilized legumes. Its growth pattern is vigorous but relatively long, with a vegetative phase of about 4-5 months and pod maturation often extending another 5-6 months or more, so management effects accumulate across a long crop cycle. Nitrogen management improves quality more consistently than biomass, since urea treatments produced similar forage yields but altered crude protein and crude fiber, and the 50 kg/ha treatment was considered efficient while preserving rhizobial function. Phosphorus management is more decisive for reproduction, because P fertilization increased yield on acid upland soil, whereas crops without P formed pods but failed to produce seed.

Growth responses also depend strongly on biological and environmental management. VAM inoculation increased nitrogen uptake in sword bean leaves and interacted with rock phosphate to influence phosphorus uptake, showing that nutrient efficiency depends partly on symbiosis rather than fertilizer dose alone. Climatic adaptation is equally important, because under Western Poland conditions only the early cultivar produced viable seed, while the late cultivar remained immature, indicating strong sensitivity to temperature and season length. Field emergence above 60% under those conditions still showed that the crop can establish outside its usual range, but weather remained a crucial determinant of flowering and seed filling. Genotypic diversity adds another management opportunity, since evaluation of 20 native genotypes revealed variation in germination time, pod size, pod weight, and seed weight that breeders can exploit for local adaptation.

The main implication for productivity is that sword bean should be managed as a resource-efficient legume, not as a crop that simply requires high mineral inputs. Evidence from sword bean shows that moderate nitrogen can maintain forage quality efficiently, while broader legume evidence indicates that inclusion of legumes in cropping systems can reduce dependence on synthetic nitrogen through biological fixation. This makes phosphorus availability, root activity, and microbial functioning particularly important targets for management improvement on marginal or acidic soils. In practical terms, productivity gains are likely to come from combining moderate fertilization with inoculation, moisture support, and suitable cultivars rather than from maximizing one input alone.

Productivity improvement also depends on matching sword bean to systems where its ecological functions create added value. The crop grows well in poor or marginal soils and has potential as food, feed, and green-manure material, so its performance should be evaluated at both crop and system level. Reviews of legume intercropping show gains in land productivity, soil health, water-use efficiency, and nutrient-use efficiency, which suggests that sword bean can contribute more through diversified systems than through isolated monoculture evaluation alone. This system perspective is especially relevant for underutilized legumes, whose commercial value often depends on multiple outputs such as seed, forage, soil improvement, and resilience under low-input conditions. Accordingly, improving sword bean productivity means increasing not only yield per hectare, but also stability, nutritional value, and contribution to agroecosystem function.

Future work should focus first on locally adapted agronomic packages for sword bean, because available studies still show large knowledge gaps in cultivation technology, especially for marginal soils and nontraditional environments. Region-specific recommendations are needed for spacing, sowing time, water management, phosphorus strategy, and integrated nutrient use, since sustainability outcomes in legume systems depend strongly on local climate, soil conditions, and field management. Longer-term studies should also test sword bean in intercrops and rotations, because legume-based systems improve soil structure, microbial activity, nutrient cycling, and resilience, but adoption still depends on practical design and economic feasibility. In that context, sword bean is a strong candidate for sustainable intensification because it fits low-input production goals while contributing protein and soil-restorative functions.

A second priority is genetic and physiological improvement linked directly to management needs. Sword bean genotypes already differ substantially in germination and pod traits, and related Canavalia improvement studies

show that growth rate, net assimilation rate, and forage yield can be increased through selection and introgression. Mutation-based studies in Canavalia also indicate that plant height, leaf area, and dry seed weight can be altered experimentally, although ideal trait combinations remain unresolved. At the same time, sustainable breeding must address anti-nutritional factors, local adaptation, and compatibility with diversified cropping systems rather than pursuing yield alone. Overall, future sustainable cultivation systems for sword bean should integrate adaptive genetics, moderate-input agronomy, and diversified legume-based farming to improve growth performance, productivity, and long-term soil health.

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Conflict of Interest Disclosure

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