REVIEW ARTICLE Legume Research- An International Journal, Volume 49 Issue 11: 1827-1837 (November 2026)

Approaches for Fertility Management in Legume-based Cropping Systems: A Review

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10.18805/LR-5698

ABSTRACT

Grain and forage legumes occupy a special agronomic position through symbiotic biological nitrogen fixation (BNF) and favourable residual effects on soil fertility, yet legume-specific nutrient- and soil-fertility management is often addressed piecemeal rather than as an integrated system. This review synthesises agronomic and soil-fertility knowledge on legume-based systems, including BNF and rhizobia-legume symbiosis, cereal-legume intercropping and rotation, integrated and site-specific nutrient management, biofertilizer and PGPR technologies, organic amendments and residue management, soil organic carbon dynamics and precision nutrient management through digital tools, for the major pulse and oilseed-legume crops of India. Legumes vary widely in their capacity to supply soil nitrogen, typically deriving 60-70% of it from atmospheric sources and contributing 15-125 kg N/ha/season, depending on rhizobial compatibility, soil nitrate status and moisture. Intercropping with cereals generally raised system productivity by about 30-35%, while balanced P, S and micronutrient application, compatible microbial inoculation and integrated nutrient management sustained productivity while cutting chemical fertiliser dependence by up to 25%. These responses are agro-ecologically dependent rather than universal; priority research areas include site-specific nutrient calibration, inoculant-soil compatibility, quantification of residue effects on subsequent crops and digital decision-support tools for legumes. Wider adoption of legume-centred, integrated soil-fertility management, supported by precision-agriculture tools, offers a practical means toward more resilient, input-efficient and environmentally friendly cropping systems, especially for rainfed smallholder agriculture.

Key words: Biological nitrogen fixation, Integrated nutrient management, Intercropping, Legumes, Rhizobium, Soil fertility, Soil organic carbon.

Legumes (Fabaceae) play a key role in world agriculture as a dietary protein source, animal fodder and as the main biological pathway connecting the atmosphere with cultivated soils via fixation of nitrogen gas (N2). India accounts for approximately 25% of global pulse production, most under rainfed conditions with low soil fertility (Directorate of Pulses Development, 2024a; FAO, 2024). Legumes fix atmospheric N2 and produce plant-available ammonium in the soil, sparing the subsequent crop part of its synthetic nitrogen requirement (Barbieri *et al*., 2023; Ghafoor *et al*., 2024). Their deep, dense root systems mobilise sparingly soluble soil phosphorus, enhance soil aggregation and improve the soil carbon-to-nitrogen ratio, favouring mineralisation upon incorporation (Ansari *et al*., 2022; Kaur *et al*., 2018) and legume-based systems more broadly enhance nutrient cycling and long-term ecosystem sustainability (Sharma *et al*., 2025), making legumes essential for intercropping, rotation and green-manuring programmes restoring fertility in intensively cultivated areas such as the rice-wheat systems of the Indo-Gangetic Plains (Samal *et al*., 2017; Kumar *et al*., 2023).

Legume yields in most developing regions remain well below those in developed systems, a gap frequently attributed to nutrient imbalance, poor rhizobial establishment, inadequate phosphorus and micronutrient supply and suboptimal integration of organic and inorganic sources (Patel *et al*., 2026; Shukla and Behera, 2021;

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How to cite this article: Kumar, R., Singh, R.S.J., Huded, S., Dinkar, H.M., Suhara, K.K.S., Saral, R., Paliwal, A., Khan, W. and Deep, N. (2026). Approaches for Fertility Management in Legume-based Cropping Systems: A Review. *Legume Research*. **49(11):** 1827-1837. doi: 10.18805/LR-5698.

Submitted: 13-07-2026 **Accepted:** 18-08-2026 **Online:** 07-09-2026

Shukla *et al.*, 2021). This review consolidates recent agronomic and soil-fertility literature on legume-based systems, covering: (i) biological nitrogen fixation and its quantification, (ii) cropping-system design, (iii) nutrient and micronutrient management, (iv) biofertilizer and rhizobacterial technologies and (v) organic matter, residue and soil organic carbon dynamics.

Major legume crops of India: distribution and agronomic importance

India is the largest producer, consumer and importer of pulses, accounting for about 28% of world production and 37% of world pulse area (Directorate of Pulses Development, 2024a, 2024b). Total pulses production reached a record 252.38 lakh tonnes on about 277 lakh ha in 2024-25, up from 242.46 lakh tonnes in 2023-24, with notable gains in moong and tur (Ministry of Agriculture and Farmers' Welfare, 2025). *Rabi*-season pulses contribute more than 60% of national production, with chickpea alone accounting for almost 40% (Directorate of Pulses Development, 2024b). National productivity remains below the global average of about 910 kg/ha, largely because production occurs predominantly under rainfed, resource-limited conditions (FAO, 2024; Kumar *et al.*, 2024; Ministry of Agriculture and Farmers' Welfare, 2025).

Chickpea (gram), concentrated in Maharashtra, Madhya Pradesh and Rajasthan, is the single most important pulse, valued for its yield stability under residual soil moisture (Thakur *et al.*, 2024; Kumar *et al.*, 2024). Pigeonpea (tur/arhar), concentrated in Maharashtra, Karnataka and Gujarat, is a long-duration crop contributing substantial biomass and root-zone nitrogen enrichment (Directorate of Pulses Development, 2024a, 2024b). Mungbean and urdbean are important short-duration options for fitting a legume into intensive rice-wheat and cereal-based rotations, particularly in Rajasthan, Madhya Pradesh, Uttar Pradesh and southern India (Directorate of Pulses Development, 2024b; Kaur *et al.*, 2018). Lentil, concentrated in Madhya Pradesh, Uttar Pradesh, West Bengal and Bihar, was one of the few major pulses without a consistent positive production trend over 2010-2020 (Kumar *et al.*, 2024). Among oilseed legumes, soybean production reached a record 152 lakh tonnes, concentrated in Maharashtra, Madhya Pradesh and Rajasthan, while groundnut production reached a record 119 lakh tonnes, up nearly 17% year-on-year, concentrated in Gujarat, Rajasthan, Tamil Nadu and Andhra Pradesh (Ministry of Agriculture and Farmers' Welfare, 2025). Groundnut productivity, historically trailing the global average, has converged with recent global benchmarks in several states following expanded irrigation and improved sulphur-zinc nutrition (Srinivasarao *et al.*, 2008; Yadav *et al.*, 2019).

Table 1 summarises area, production and productivity for the principal legume crops using 2024-25 final crop statistics (Department of Agriculture and Farmers Welfare, 2026; Ministry of Agriculture and Farmers' Welfare, 2025).

Provisional 2025-26 third advance estimates point to further gains, with total pulses area and production placed at about 286 lakh ha and 274 lakh tonnes (Department of Agriculture and Farmers Welfare, 2026). Chickpea has historically shown the least year-to-year instability among major pulses, whereas mungbean and urdbean are markedly more variable, reflecting sensitivity to moisture stress at flowering and pod-fill; lentil instability has been linked to its frequent cultivation as a secondary or relay crop with lower input priority (Kumar *et al.*, 2024; Murugananthi *et al.*, 2024). These differences underline why nutrient and cropping-system recommendations for legumes must be calibrated to the specific crop, season and region.

Biological nitrogen fixation and the rhizobium-legume symbiosis

Biological nitrogen fixation is the process by which soil bacteria collectively termed rhizobia infect legume roots, inducing nodule formation within which the enzyme nitrogenase reduces atmospheric N2 to ammonia in exchange for photosynthate from the host plant (Ghafoor *et al.*, 2024; Peoples *et al.*, 2009; Vance, 2001). Because it depends on an active symbiosis rather than fertiliser inputs, BNF is the most sustainable route of nitrogen entry into agroecosystems and the second-largest natural source of fixed nitrogen after industrial ammonia synthesis (Barbieri *et al.*, 2023; Herridge *et al.*, 2008).

Table 1: Major legume and pulse crops of India: area, production, productivity and leading producing states.

Legume/pulse crop	Area 2024-25 (lakh ha)	Production 2024 -25 (lakh t)	Productivity (kg/ha)	Leading producing states
Chickpea/Gram (*Cicer arietinum* L.)	91.22	111.14	1218	Maharashtra, MP, Rajasthan
Pigeonpea/Tur (*Cajanus cajan*)	43.36	36.24	836	Maharashtra, Karnataka, Gujarat
Mungbean/Green gram (*Vigna radiata* L.)	58.99	42.44	719	Rajasthan, Maharashtra, MP
Urdbean/Black gram (*Vigna mungo* L.)	31.57	22.42	710	MP, Rajasthan, UP, Tamil Nadu
Lentil/Masoor (*Lens culinaris* L.)	16.99	16.54	973	MP, UP, West Bengal, Bihar
Field pea (*Pisum sativum* L.)	~7.5	~9	~1200-1220	UP, MP, Jharkhand
Soybean (*Glycine max* L.)	129.52	152.68	1179	Maharashtra, MP, Rajasthan
Groundnut (*Arachis hypogaea*)	57.62	119.42	2073	Gujarat, Rajasthan, Tamil Nadu
Total pulses (all crops)	277.20	256.83	926	MP, Maharashtra, Rajasthan, UP

The proportion of legume nitrogen derived from the atmosphere (Ndfa, estimated *via* 15N isotope-dilution) varies widely with species, rhizobial strain compatibility, soil nitrate status, moisture and temperature. A global meta-analysis of data from 1980-2018 reported Ndfa ranging from about 5% to 99%, averaging roughly 68%, with fodder legumes generally exceeding grain legumes (Ghafoor *et al.*, 2024; Herridge *et al.*, 2008). This reflects genuine differences in soil nitrate carry-over, rhizobial population density and moisture availability across trial environments and is the main reason blanket BNF or fertiliser-substitution values cannot be applied uniformly (Barbieri *et al.*, 2023; Giller, 2001).

Several factors govern BNF efficiency in the field. High residual soil nitrate suppresses nodulation because plants preferentially use the more energetically favourable mineral nitrogen, the physiological basis for restricting fertiliser N to a small starter dose in pulses (Barbieri *et al.*, 2023; Peoples *et al.*, 2009). Rhizobial strain specificity, host-cultivar compatibility, soil acidity, waterlogging and micronutrient status (particularly molybdenum and cobalt, nitrogenase cofactors) also strongly influence fixation rates (Peoples *et al.*, 2009; Shukla *et al.*, 2021; Vance, 2001). Legume-grass mixtures have been shown to enhance nodulation and nitrogen transfer to companion grasses through altered root architecture, an effect documented even on the Qinghai-Tibet Plateau (Luo *et al.*, 2024). Most precise BNF quantification still relies on isotopic or difference methods at experiment-station scale; farmer-field estimates show wider variance, so Table 2 values should be read as central tendencies rather than fixed constants (Herridge *et al.*, 2008).

Legume-based cropping systems: intercropping and rotation

Integrating legumes into cereal-dominated cropping systems, as intercrops or in rotation, is among the most extensively documented strategies for restoring and sustaining soil fertility. Cereal-legume intercropping enables more complete use of light, water and nutrient resources than sole cropping and consistently reduces soil bulk density, increases cation exchange capacity and organic matter and enhances soil enzymatic activity relative to monocultures, partly by intercepting raindrops before they strike bare soil and limiting erosion (Singh *et al.*, 2025; Dugassa, 2023).

Because the legume draws less heavily on soil mineral nitrogen than the companion cereal, intercropped systems extract fewer nutrients overall while returning nitrogen-rich residues; on smallholder farms in Eastern and Southern Africa, maize-pigeon pea intercropping has raised maize production by as much as 35% relative to sole maize and cowpea intercropped with millet has raised millet yield by around 30% (Akchaya *et al.*, 2025; Singh *et al.*, 2025). Reviews synthesising trials across diverse agro-climatic zones report yield gains of 30-35% together with fixed-nitrogen contributions of roughly 125 kg N/ha per season, alongside reduced tillage, lower bulk density, improved infiltration and gains in soil organic carbon and microbial biomass (Akchaya *et al.*, 2025). The land equivalent ratio (LER), the standard index of intercropping's resource-use efficiency relative to sole crops, consistently exceeds unity in cereal-legume systems, confirming a genuine productivity advantage, though the magnitude varies with row configuration, sowing density and seasonal rainfall; trials in moisture-limited years or poorly matched row ratios report LER closer to unity (Akchaya *et al.*, 2025; Dugassa, 2023; Willey, 1979).

Legume intercrops also promote a more diverse and beneficial rhizosphere bacterial community, including plant growth-promoting rhizobacteria (PGPR) that assist both intercropped species, thought to underlie part of the yield-stability advantage under environmental stress (Chamkhi *et al.*, 2022). In rotation-based systems, inclusion of a short-duration pulse such as mungbean or urdbean within the rice-wheat sequence of the Indo-Gangetic Plains improves soil water conservation, raises available N, P, K and micronutrient status and improves aggregate stability, bulk density and hydraulic conductivity relative to unbroken rice-wheat rotation (Samal *et al.*, 2017; Kaur *et al.*, 2018; Kumar *et al.*, 2023). Optimal intercrop configuration depends on relative maturity duration, planting density, row arrangement and local circumstances, so recommendations from one agro-climatic zone do not always transfer directly to another (Singh *et al.*, 2025; Dugassa, 2023).

Nutrient and micronutrient management in legume production

Legume nutrient requirements differ qualitatively from those of cereals. Because much of nitrogen demand is met through BNF, legumes generally require only a small starter dose (about 15-25 kg N/ha); larger applications tend

Table 2: Representative biological nitrogen fixation (BNF) contribution of major legume crops.

Legume crop	N derived from atmosphere (Ndfa, %)	Approx. N fixed (kg N/ha)	Representative source
Chickpea (*Cicer arietinum* L.)	30-70	15-45	Field studies, semi-arid tropics
Pigeon pea (*Cajanus cajan* L.)	40-80	40-70	Long-duration pulse trials
Mungbean (*Vigna radiata* L.)	40-70	20-45	Rice-wheat system studies
Soybean (*Glycine max* L.)	50-90	50-100	Global meta-analysis
Groundnut (*Arachis hypogaea* L.)	40-75	30-60	Green manure/intercrop studies
Fodder legumes (clover, lucerne)	60-99	60-125	Pasture BNF datasets

to depress nodulation and fixation without proportionate yield benefit (Barbieri *et al.*, 2023; Peoples *et al.*, 1995). Phosphorus and sulphur demand in pulses exceeds that of cereals, being required for root proliferation, nodule formation and protein synthesis, while potassium, often assumed adequate in Indian soils, is in practice deficient to medium in most surveyed districts owing to intensive cropping and inadequate replenishment (Patel *et al.*, 2026; Pathak *et al.*, 2026).

Micronutrients play a disproportionately important role. Molybdenum is a direct cofactor of nitrogenase and nitrate reductase, so its deficiency directly constrains BNF; zinc, iron and boron support enzymatic and reproductive functions and are widely deficient in intensively cultivated, alkaline or calcareous soils (Bouis and Saltzman, 2017; Shukla and Behera, 2021; Shukla *et al.*, 2021). Because pulses are also a dietary source of these micronutrients, correcting soil deficiency serves both agronomic and biofortification objectives (Bouis and Saltzman, 2017). These nutrient management options and their major agronomic roles are summarised in Table 3.

Field-scale studies from semi-arid India show how integrated nutrient management (INM), combining inorganic fertiliser, organic manures and microbial inoculants, improves both productivity and residual soil fertility. In a black gram-mustard system, combining fertiliser with organic manures and biofertilisers allowed a 25% reduction in inorganic fertiliser from the second year without loss of productivity (Pathak *et al.*, 2026). INM significantly improves nodulation, nutrient uptake, productivity and economic returns in soybean (Biswas *et al.*, 2025) and combining recommended fertiliser doses with farmyard manure more broadly enhances available soil N and P, raises organic carbon and reduces bulk density relative to fertiliser alone, with phosphorus-manure-biofertilizer combinations similarly improving pigeon pea and wheat yield and soil health indicators in rotation studies (Patel *et al.*, 2026; Kaur *et al.*, 2018).

Sulphur and micronutrient deficiency in indian soils: Implications for legumes

A nationwide soil-testing exercise covering more than 2.4 lakh surface soil samples from 615 districts across 28 states has documented widespread and geographically variable deficiencies of sulphur and micronutrients in Indian soils (Shukla and Behera, 2021; Shukla *et al.*, 2021). Because sulphur is essential to seed protein synthesis and zinc, boron and molybdenum are implicated in enzymatic, reproductive and nitrogen-fixation processes, these deficiencies translate directly into agronomic and nutritional shortfalls (Shukla *et al.*, 2021; Singh, 2008). The major micronutrient deficiencies and their agronomic significance for legumes are summarised in Table 4.

Field evidence from groundnut, India's leading oilseed legume by area and second globally in production, illustrates the practical consequences: trials combining sulphur and zinc fertilisation have shown substantial pod-yield gains over unfertilised controls, along with biofortification of kernel zinc and protein content, addressing agronomic and nutritional goals simultaneously (Ministry of Agriculture and Farmers' Welfare, 2025; Srinivasarao *et al.*, 2008; Yadav *et al.*, 2019). In semi-arid rainfed Rajasthan and elsewhere, sulphur deficiency continues to constrain yield, oil content and grain quality, reinforcing the case for including sulphur and zinc as standard components of legume fertiliser recommendations rather than optional supplements (Shukla *et al.*, 2021; Srinivasarao *et al.*, 2008). Much of India's remaining groundnut yield gap is likely addressable through targeted secondary- and micro-nutrient correction rather than new land or germplasm.

Biofertilisers and plant growth-promoting rhizobacteria

Microbial inoculants represent a century-old but continually evolving technology in legume agronomy, dating to the first

Table 3: Key nutrient management options and their agronomic role in legume-based systems.

Management option	Agronomic/soil fertility role	Reported effect
Starter N (15-25 kg/ha)	Supports seedling growth before nodulation is fully functional	Improves early vigour without suppressing nodulation.
Phosphorus and sulphur	99Promotes root proliferation, nodulation and nitrogenase activity	Higher requirement than cereals; boosts yield and protein.
Potassium	Regulates osmotic balance, water -use efficiency and disease tolerance	Frequently under-applied; widespread deficiency.
Micronutrients (Zn, Fe, B, Mo)	Mo essential for nitrogenase; Zn/Fe support enzymatic function	Corrects deficiency-induced losses; aids biofortification.
Rhizobium/PGPR inoculation	Enhances nodulation, N-fixation and nutrient solubilisation	Yield gains commonly 10-40%.
FYM/vermicompost/green manure	Builds organic carbon, improves structure, buffers release	Improves residual fertility for succeeding crop.
Integrated Nutrient Management (INM)	Combines inorganic, organic and biological sources	Sustains yield; cuts chemical fertiliser use up to 25%.

commercial Rhizobium-based inoculant marketed in the late nineteenth century (Aloo *et al.*, 2022). Modern formulations extend beyond rhizobial strains to phosphate- and potassium-solubilising bacteria, Azotobacter, Azospirillum and a broad group of PGPR acting through phytohormone synthesis, nutrient solubilisation, siderophore-mediated iron acquisition and induced systemic resistance (Shakila and Vijaya, 2025; Wang and Xu, 2026; Aloo *et al.*, 2022).

Across cropping systems, biofertiliser use has been associated with yield increases of roughly 10-40%, alongside improved grain protein, amino acid and micronutrient content (Shakila and Vijaya, 2025). In arid-grown chickpea, combined inoculation with nitrogen-fixing, phosphate-solubilising and potassium-solubilising rhizobacteria improved nutrient uptake and yield relative to uninoculated controls (Nabati *et al.*, 2025). Under drought stress, co-inoculation of *Rhizobium leguminosarum* with other PGPR strains has improved faba bean performance on poor-fertility, newly reclaimed soils and PGPR strains have also been reported to alleviate heavy-metal stress and improve salinity tolerance in other crops (Mansour *et al.*, 2021; Wang and Xu, 2026; Aloo *et al.*, 2022). The observed 10-40% variation in response is largely attributable to differences in indigenous rhizobial abundance, with the greatest responses where native rhizobia are scarce or poorly adapted to the host cultivar (Mansour *et al.*, 2021; Aloo *et al.*, 2022).

Field-level adoption nonetheless faces practical constraints, including inoculant shelf-life, compatibility with indigenous soil microbiota, sensitivity to pH and temperature and inconsistent commercial quality control (Aloo *et al.*, 2022). Recommendations continue to stress carrier-based formulation, seed-treatment technique and locally adapted strains over generic inoculants. Rhizosphere engineering-deliberate restructuring of root-zone microbial networks-is positioned as the next stage in biofertiliser development, moving toward designed consortia tailored to specific legume-soil combinations (Wang and Xu, 2026).

Organic amendments, residue management and soil organic carbon dynamics

Legume residues and green manures contribute organic matter of a comparatively low carbon-to-nitrogen ratio, favouring rapid microbial decomposition and nitrogen mineralisation relative to cereal residues (Tripolskaja *et al.*, 2023; Bolinder *et al.*, 2020). Long-term studies in the foothills of the Eastern Himalaya show that incorporating legume green manure with residue retention in maize-groundnut systems raises organic carbon stocks, improves soil aggregation and increases microbial biomass carbon over successive seasons (Ansari *et al.*, 2022). In the Indo-Gangetic Plains, a legume phase such as summer mungbean within conservation-agriculture rice-wheat systems is among the most efficient combinations for simultaneously sustaining yield, soil health and carbon sequestration, in contrast to continuous rice-wheat cultivation, which progressively depletes native reserves (Samal *et al.*, 2017).

A meta-analysis of 147 peer-reviewed studies across India's agro-ecological zones found that, among organic amendments, farmyard manure produced the largest gains in soil organic carbon after biochar, followed by green manure and compost, with conservation tillage and residue retention providing moderate but consistent benefits, most pronounced in semi-arid and sub-humid regions over periods exceeding five years (Patil *et al.*, 2025). A synthesis of twenty independent reviews similarly found the largest response under manure application, followed by residue retention and cover cropping, with nitrogen fertilisation alone producing the smallest carbon benefit (Bolinder *et al.*, 2020).

At the same time, legume-residue benefits are not unconditional. Rapid mineralisation can increase post-harvest nitrate leaching by roughly 25-33% relative to cereal residues (Tripolskaja *et al.*, 2023) and in calcareous soils legume green manure has been linked to a greater risk of soil inorganic carbon loss even as organic carbon accumulates (Xue *et al.*, 2025). These findings highlight the importance of

Table 4: Extent and agronomic significance of sulphur and micronutrient deficiencies in Indian agricultural soils.

Nutrient	Approx. share of soils deficient	Agronomic significance for legumes
Sulphur (S)	~40-44% of samples nationally	Essential for protein synthesis; deficiency depresses nodulation and seed protein/oil content.
Zinc (Zn)	~35-40% of samples	Enzymatic/hormonal co-factor; widespread under intensive HYV cropping.
Boron (B)	~20-25% of samples	Required for pollen viability, pod-set and seed development.
Iron (Fe)	~10-12% of samples	Lime-induced chlorosis common in calcareous soils; affects nodule function.
Molybdenum (Mo)	Localised but critical	Direct nitrogenase cofactor; caps BNF even with adequate inoculation.
Copper (Cu)/ Manganese (Mn)	~5-10% of samples	Localised deficiencies; more prevalent in coarse-textured, calcareous soils.

matching residue management to local soil type and cropping calendar rather than a uniform recommendation.

Climate-resilient agronomic practices for legume production

Because most Indian legumes are grown under rainfed conditions, moisture stress at flowering and pod-fill is the single largest source of yield instability, making moisture and canopy-microclimate management inseparable from soil-fertility management (Boraiah *et al.*, 2023; Tejaswini *et al.*, 2025). *In-situ* moisture conservation practices such as broad-bed-and-furrow layout, ridge-and-furrow sowing, residue mulching and timely weeding stabilise nodulation and yield under erratic rainfall, since water stress independently suppresses nitrogenase activity even where soil fertility is adequate (Boraiah *et al.*, 2023; Tejaswini *et al.*, 2025).

Genetic improvement complements these agronomic measures. Breeding programmes have identified drought-adaptive traits -early flowering, a stay-green phenotype, deep and hydraulically efficient rooting and stronger antioxidant defence- as key levers for yield stability (Rani *et al.*, 2020) and marker-assisted backcrossing has delivered drought-tolerant chickpea lines carrying an introgressed 'QTL-hotspot' region (Asati *et al.*, 2022; Rani *et al.*, 2020). Heat-tolerance screening in lentil and other cool-season legumes has similarly identified genotypes now used as breeding donors (Sarkar *et al.*, 2025). However, a drought-tolerant genotype on a sulphur- or zinc-deficient, poorly nodulated soil will not express its full potential, underscoring that variety choice and soil-fertility management are complementary strategies (Nath *et al.*, 2025). The principal agronomic strategies for stabilising legume productivity under climatic stress are summarised in Table 5.

Soil-test-based precision nutrient management: the soil health card experience

India's Soil Health Card (SHC) scheme, launched nationally in February 2015, illustrates how soil-test-based, site-specific nutrient management can be operationalised for legume and other field crops (Government of India, Department of Agriculture and Farmers Welfare, 2015). Soil samples are analysed for twelve core parameters- macronutrients (N, P, K), sulphur, micronutrients, organic carbon, electrical conductivity and pH - with each landholding reissued a card every two to three years. Fertiliser dosage recommendations are generated using Soil Test Crop Response (STCR) correlation equations maintained by ICAR and State Agricultural Universities, relating soil-test values to yield response for specific crop-soil combinations rather than a blanket recommendation (ICAR-Indian Institute of Soil Science, 2011), improving nutrient-use efficiency in grain legumes (Malathi *et al.*, 2025).

For legume growers, this framework is consequential because sulphur, zinc, boron and molybdenum deficiencies are widespread yet vary by district, so blanket NPK recommendations without micronutrient correction under-serve legume crops (Shukla and Behera, 2021; Shukla *et al.*, 2021). Where followed, soil-test-based recommendations reduce over-application of N and P while correcting previously unaddressed zinc and sulphur deficiency (Directorate of Agriculture, Government of Assam, 2024; ICAR-Indian Institute of Soil Science, 2011; Malathi *et al.*, 2025). Implementation challenges persist, including inconsistent sampling protocols, a reissue interval that can lag rapid nutrient depletion in intensive legume-cereal rotations and limited farmer follow-through; STCR equations were also mostly developed for major cereals, so validated equations for minor pulses remain sparse (Directorate of Agriculture, Government of Assam, 2024). The core parameters of the Soil Health Card and their relevance to legume nutrient management are summarised in Table 6.

Digital agriculture and precision nutrient management in legumes

Alongside soil-test-based and biological approaches, a growing body of work applies remote sensing, UAVs, machine learning and decision-support software to crop nutrient management, increasingly adapted for legume systems. UAV-mounted multispectral, hyperspectral and thermal sensors capture canopy reflectance at sub-metre resolution, from which indices such as NDVI infer canopy

Table 5: Agronomic strategies for stabilising legume productivity under climatic stress.

Practice	Agronomic function	Relevance to soil fertility/BNF
Broad-bed-and-furrow/ridge sowing	Improves *in-situ* moisture conservation and drainage	Prevents waterlogging-induced nodule loss
Residue mulching	Reduces evaporative loss and surface temperature	Maintains rhizosphere moisture for nodulation
Timely sowing/early-flowering cultivars	Escapes terminal drought and heat at reproductive stage	Preserves the grain-fill window for fixed N
Deep-rooting/stay-green genotypes	Enhances water and subsoil nutrient access under stress	Sustains nitrogenase activity later into stress
Marker-assisted/QTL-based breeding	Introgresses drought/heat-tolerance loci into elite lines	Requires matching nutrients for full expression

nitrogen status, water stress and, indirectly, nodulation vigour, at a resolution ground-based sampling cannot match (Yang *et al*., 2025; Xing *et al*., 2025). UAV-satellite data fusion has been used to build within-field prescription maps directing variable-rate fertiliser or gypsum to zones where sulphur, zinc or nitrogen status is limiting, rather than a single blanket rate (Chen *et al*., 2025; Xing *et al*., 2025).

Machine learning methods, particularly neural networks and random forests, increasingly translate remote-sensing and soil-test data into yield forecasts and nitrogen-status estimates, though accuracy depends heavily on ground-truth data density, a persistent constraint where digitised yield records remain sparse (Chlingaryan *et al*., 2018; Liakos *et al*., 2018). Decision-support systems integrating UAV or satellite-derived canopy status with soil-test databases such as those underpinning the Soil Health Card and STCR programmes could allow dosage recommendations to be updated within a single season rather than every two to three years (Chen *et al*., 2025; Government of India, Department of Agriculture and Farmers Welfare, 2015).

For legumes specifically this technology remains at an earlier stage than for cereals, reflecting smaller pulse-holding field size and the more limited canopy signal from short-statured, often heavily branched pulse crops. Canopy-based estimation of nitrogen and water status is nonetheless directly relevant, since both stresses independently suppress nodulation and nitrogenase activity, offering earlier correction than routine field-scout visits allow (Yang *et al*., 2025; Xing *et al*., 2025). Realising this potential will require dedicated calibration datasets linking canopy reflectance to nodulation status and BNF performance, rather than the cereal-derived thresholds applied by default - one of the more immediate research gaps identified here.

Comparative synthesis of nutrient management approaches

The preceding sections describe several distinct routes to correcting nutrient constraints in legume-based systems. Table 7 draws them together for direct comparison, making explicit the trade-offs a practitioner or policy-maker must weigh.

No single approach is sufficient alone: blanket recommendations are simple but nutrient-blind, soil-test-based and biofertilizer approaches add precision but depend on infrastructure or testing frequency inconsistently available at scale and digital tools remain least mature for legumes. The strongest documented outcomes combine at least two rows - for example soil-test-based dosing

Table 6: Core parameters and functions of India's soil health card scheme relevant to legume nutrient management.

Parameter group	Parameters tested	Significance for legume nutrient management
Macronutrients	N, P, K	Enables reduced starter-N and calibrated P/K dose instead of blanket recommendation.
Secondary nutrient	Sulphur (S)	Flags S-deficient fields constraining protein/oil formation and nodulation.
Micronutrients	Zinc, Iron, Manganese, Copper, Boron	Identifies fields needing corrective Zn/B for nodulation and biofortification.
Soil health indicators	Organic carbon, EC, pH	Guides liming/gypsum use and organic-matter build-up.
Reporting cycle	Reissued every 2-3 years	Tracks trends but may lag rapid depletion in intensive rotations.

Table 7: Comparative summary of major nutrient management approaches for legume production.

Approach	Basis	Typical productivity response	Key limitation for smallholder systems
Blanket/general recommendation	Uniform state/district dose, undifferentiated by soil test	Below yield potential; often omits S, Zn, B	Ignores field variability; risks under/over-application.
Integrated nutrient management (INM)	Inorganic fertiliser + organic manure/residue/biofertiliser	10-20% gain over sole fertiliser; improved NUE	Needs reliable organic input supply and skill.
Soil Health card/STCR-based	Field-specific dosage from soil-test values	Targeted deficiency correction	Reissued every 2-3 yrs; can lag depletion.
Biofertiliser/PGPR-based	Inoculants supplementing/ substituting chemical dose	~10-25% gain, strain - and site-dependent	Inconsistent; compatibility, shelf-life issues.
Organic amendment/residue-based	Green manure, residue, FYM building SOC	Builds long-term fertility and carbon	Slow, season-dependent; may miss peak demand.
Digital/precision management	UAV/satellite sensing with ML variable-rate dosing	Finer temporal/spatial precision	Nascent for legumes; needs calibration data.

supplemented with a compatible biofertilizer and residue return - rather than relying on any single instrument.

Constraints and future research priorities

Notwithstanding the well-documented soil-fertility benefits of legumes, several agronomic gaps constrain their fuller exploitation: highly variable BNF and residual-nitrogen quantification across genotype-environment combinations limits fertiliser-recommendation precision for succeeding crops (Barbieri *et al.*, 2023; Ghafoor *et al.*, 2024); micronutrient management, particularly molybdenum and zinc, remains under-addressed in routine soil-testing frameworks despite its bearing on nodulation efficiency (Shukla and Behera, 2021; Shukla *et al.*, 2021); biofertiliser quality control, strain-host compatibility and shelf-life continue to limit consistent field performance (Aloo *et al.*, 2022); and the interaction between residue management and nitrate leaching or soil inorganic carbon loss requires more region-specific evaluation (Xue *et al.*, 2025; Tripolskaja *et al.*, 2023).

Future research would benefit from long-term, multi-location trials coupling isotopic BNF quantification with site-specific nutrient recommendations; from breeding efforts targeting rhizobial compatibility and nodulation efficiency under stress; and from integrating precision-agriculture tools across legume-growing agro-ecological zones (Government of India, Department of Agriculture and Farmers Welfare, 2015; ICAR-Indian Institute of Soil Science, 2011).

Closing the yield gap in lentil, mungbean, urdbean and groundnut deserves particular attention, since these crops have shown negative or unstable production trends over the past decade despite steady demand growth (Kumar *et al.*, 2024); continued yield improvement, rather than area expansion, will be necessary for pulse self-sufficiency (Murugananthi *et al.*, 2024).

CONCLUSION

Legumes are an agronomically strategic crop in the design of cropping systems as they provide biologically fixed nitrogen, enhance soil physical and biological properties and create beneficial residual effects to following crops. Achieving these benefits at scale is not just about adding a legume to the rotation, but also about ensuring a balanced supply of phosphorus, sulphur, potassium and micronutrients, as well as carefully planning the inoculation of rhizobia or PGPRs and the deliberate inclusion of organic and inorganic nutrient sources. Legume-based systems can increase system productivity by about 33% compared to cereal monocultures, decrease reliance on chemical fertiliser and increase soil organic carbon, providing a viable approach to more resilient, input-efficient agriculture in smallholder, rainfed settings.

There are three priorities for the next ten years. The most significant scientific gaps are the lack of legume-specific calibration data for canopy and soil-sensor signals with nodulation status and biological nitrogen fixation (BNF) performance. Soil-testing infrastructure, such as Soil Health Card and Soil Test Crop Response (STCR) programmes, would benefit from a faster reissue cycle and expanded coverage for minor pulses, institutionally. Finally, the adoption of this evidence to extension programmes and input subsidy packages that directly benefit smallholder, rainfed farmers will be necessary to close the yield gap between Indian and global legume productivity, particularly for lentil, mungbean, urdbean and groundnut.

ACKNOWLEDGEMENT

The authors acknowledge the Department of Agronomy, School of Agriculture, Lovely Professional University, for institutional support during preparation of this review. No specific grant was received from public, commercial or not-for-profit funding agencies.

Disclaimers

The views expressed are solely those of the authors and do not necessarily represent their affiliated institutions. The authors are responsible for the accuracy of the information provided but accept no liability for losses resulting from its use.

Informed consent

Not applicable. This is a literature review; no primary human or animal data were collected.

Conflict of interest

The authors declare no conflicts of interest regarding this article. No funding or sponsorship influenced its design, analysis or preparation.

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