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Effective Management of Legumes for Maximizing Biological Nitrogen Fixation and Other Benefits

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ABSTRACT

The importance of legumes in sustainable crop production systems is well recognized. In the rice and wheat cropping systems of the Indo-Gangetic Plain, several legumes such as chickpea, lentil, pea, soybean, groundnut, mung bean, black gram, cowpea, and pigeonpea are grown depending upon rainfall pattern, water resources, geo-morphological features, domestic needs, and cropping systems. In the rice-wheat sequential cropping, short-duration legumes such as mung bean and cowpea offer great promise, but at present their adoption is negligible due to several management and social constraints.

The productivity of legumes in general is low due to low genetic yield potential and sub-optimal management practices. Several studies under the All India Coordinated Pulses Improvement Project (AICPIP) have clearly shown that with better management, the present level of productivity of most of the legumes could be almost doubled. Tillage, planting time, plant population, plant nutrition, irrigation, and weed management considerably influence biological nitrogen fixation and productivity of legumes and therefore their management needs to be optimized for the agroecological regions and production systems. A decrease in nodulation and nitrogenase activity in many legumes has been observed due to late planting, high plant population, drought, excess moisture, high dose of mineral nitrogen, and soil application of herbicides (oxyfluorfen, linuron, oxadiazon, and metribuzin). Enhanced nodulation and higher yield have been reported with timely planting, application of 20–40 kg sulfur ha^{-1} along with 17.5–26.5 kg phosphorus ha^{-1}, dual inoculation with *Rhizobium* and vesicular-arbuscular mycorrhizal fungi, irrigation at critical growth stages under moisture stress conditions, and efficient weed management. Deficiency of micronutrients such as zinc, molybdenum, and iron, which impair nodulation and grain yield, have been observed in some of the areas.

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The Indo-Gangetic Plain (IGP) is spread over Sind, Punjab, Baluchistan, and part of the North-West Frontier Province of Pakistan; part of Punjab, Haryana, Uttar Pradesh, Bihar (excluding Chhota Nagpur plateau), part of Madhya Pradesh, and West Bengal states of India; western part of Bangladesh, and the southern (Terai) part of Nepal. Rice (*Oryza sativa*) and wheat (*Triticum aestivum*) are the main cereal crops of this region grown either in sequential cropping or rotated with other crops depending upon rainfall, irrigation facilities, geo-morphological features, and domestic needs.

Rice-wheat crop rotations occupy the largest area under input-intensive agriculture for providing food security to this region. However, cultivation of rice and wheat in sequential cropping over years has led to several problems such as "soil sickness", deficiency of some of the plant nutrients [sulfur (S) and zinc (Zn)], lowering of the water table, and soil salinization. This has sensitized agricultural scientists, policy makers, and the farming community to seek sustainable cropping systems having legumes as one of the components.

The important food legumes grown in the IGP are chickpea (*Cicer arietinum*), pigeonpea (*Cajanus cajan*), black gram (*Vigna mungo*), mung bean (*Vigna radiata*), soybean (*Glycine max*), groundnut (*Arachis hypogaea*), lentil (*Lens culinaris*), pea (*Pisum sativum*), and cowpea (*Vigna unguiculata*). Rice-chickpea, rice-lentil, rice-pea, pigeonpea-wheat, soybean-wheat, groundnut-wheat, black gram-wheat, and rice-mustard (*Brassica* sp.)/potato (*Solanum tuberosum*)-black gram/mung bean are the popular crop rotations involving legumes. In rice-wheat sequential cropping, efforts have been made to introduce short-duration mung bean or fodder cowpea as a catch crop during summer (Apr–Jun). With good management, 800–1000 kg seed yield ha^{-1} of mung bean has been obtained in the northeast plains of India. However, the availability of irrigation water and mung bean genotypes of 50–60 days duration are the major constraints to large-scale adoption of this system.

An effort has been made to review the current status of knowledge on influence of agronomic management practices on nodulation, biological nitrogen fixation (BNF), and productivity of various grain legumes in the IGP and focus on future research priorities.

LEGUMES IN CROPPING SYSTEMS

Legumes are considered to be an important component of subsistence cropping systems of the semi-arid tropics because of their ability to convert atmospheric nitrogen (N) into the assimilable form of ammonia, to add substantial amounts of organic matter to the soil, and to grow better than many other crops with low inputs under harsh climatic and edaphic conditions. The global concern about sustainable agricultural systems further highlights the significance of legumes, which offer a renewable source of energy through BNF. Annual global BNF has been estimated at around 175 million t of N of which about 79% is accounted by terrestrial fixation (Burns and Hardy 1975). This clearly shows that legumes offer an economically attractive and ecologically sound means of reducing external fertilizer N input and improving the quality and quantity of internal resources. Depending upon physical, environmental, and biological factors, legumes can fix N_2 up to 450 kg ha^{-1} (e.g., soybean). A considerable part of N_2 fixed by legumes is, however, harvested and removed as grains (Table 1). The N left in the legume residue generally benefits succeeding crops. Myers and Wood (1987) proposed a simple conceptual model for the utilization of N by a following crop as:

$$Nc = N1 \times P \times (1 - NHI)\ Fm \times E$$

where Nc is the amount of N derived from the previous crop taken up by the following crop, N1 is the amount of N in the previous legume crop, P is the proportion of the legume N derived from fixation, NHI is the nitrogen harvest index ideally defined as the ratio of N in seed to N in total plant biomass usually at maturity, Fm is the proportion of residual N that is mineralized, and E is the efficiency of utilization of this mineral N. This suggests that the N contribution of legumes to the succeeding crops depends on both amount of N fixed as well as its partitioning. To maximize the contribution of N to subsequent crops it is necessary to maximize N_2-fixation, minimize NHI, maximize N mineralization from the legume residue, and maximize E. The distribution of fixed N_2 by soybean, mung bean, and *Sesbania* was measured by Myers and Wood (1987) using the isotope dilution method. In this study (Table 1), 70% of N in soybean, 52% in mung bean, and 30% in black gram was translocated to seeds. The remaining 83–141 kg N ha^{-1} was left in the crop residue, of which 54–98 kg N ha^{-1} was attributable to fixation.

Table 1: Estimates of nitrogen (N) fixation and removal by some legume crops.

Crop	N fixed (kg ha^{-1})	NHI[1]
Groundnut	240–260	0.49
Chickpea	120–140	0.80
Soybean	93–138	0.80–0.89
Cowpea	47–188	0.53–0.69
Mung bean	112	0.69–0.81
Sesbania	126–141	NR[2]
Black gram	55–72	0.41–0.65
Lablab bean	66–208	0.48–0.56
Pigeonpea	150	0.52–0.62

[1] NHI = nitrogen harvest index.
[2] NR = not recorded.
Source: Myers and Wood (1987).

The mineralization of this N depends on the C/N ratio of the residue (Nnadi and Balasubramanian 1978), soil moisture, soil temperature, and the duration of mineralization. It has been estimated in experiments that a good crop of summer mung bean benefits the subsequent rice crop to an extent of 20–30 kg N ha^{-1} (Chandra 1988). Maskina et al. (1987) reported that the inclusion of summer green manure increased yield of rice by 141% over fallow, and 15% over mung bean grown for grain purposes. Sharma et al. (1985) reported an increase in soil nitrate from 73 kg N ha^{-1} in Apr to 223 kg N ha^{-1} in Jun during the growth of a mung bean crop between wheat and rice crops on a sandy loam soil in Punjab, India. However, it is not clear if the increase in soil nitrate reported in the study came from the fixation by the mung bean crop or was due to the effect of soil heating during summer (Chauhan et al. 1988).

The beneficial effect of legumes in cropping systems is not solely due to BNF but due to several other associated mechanisms such as increased nutrient availability, improved soil structure, reduced disease incidence, and increased mycorrhizal colonization (Wani and Lee 1995). Bullock (1992) concluded that rotation with legumes does not provide as much N as fertilizer replacement methodology estimates and that much of the yield benefit which has been credited to N contributions is actually due to other factors. Introduction of legumes in crop rotation can influence soil-borne pathogens such as nematodes, in addition to improving soil structure (Karlen et al. 1994). Hulugalle and Lal (1986) found that bulk density was always lower in plots with pigeonpea and maize (*Zea mays*) rotation than in well-fertilized continuous maize. One of the reasons for lowering of bulk density could be that many legumes return considerable organic matter through fallen leaves, which can be as high as 15% of the total above-ground recoverable dry matter. Increased soil organic matter also enhances the water infiltration rates and water-holding capacity (Hudson 1994).

PRODUCTIVITY OF LEGUMES

The genetic yield potential of legumes compared with cereals is, generally, low. The primitive characters associated with legumes, e.g., indeterminate growth, perennial habit, prolonged flowering period, deep root system, compound leaves, considerable flower drop, and shattering of mature pods are testimony of the fact that their domestication was aimed at survival under adverse conditions rather than high yield. Such criteria of domestication led to several weak links in productivity of legumes which is far below the potential level of productivity obtained at research stations and well-managed demonstration plots. The average productivity of important legumes grown in the IGP of India is below 1.2 t ha^{-1} (Table 2). The productivity of winter legumes is comparatively higher than the rainy season legumes due to more favorable weather conditions.

Results of frontline demonstrations under the All India Coordinated Pulses Improvement Project (AICPIP) during 1992/93 showed that with the component technology, the productivity of pulse crops could be considerably increased. The mean yield of 37 demonstrations of pigeonpea with fertilizer management was 1.41 t ha^{-1} as against 1.10 t ha^{-1} with no fertilizer (Table 3). Similarly, improved weed management recorded 1.52 t ha^{-1} grain yield as against 1.28 t ha^{-1} with traditional practice. Insect management technology alone resulted in a 56% increase in seed yield (Lal et al. 1994). Similar trends have also been observed in chickpea, mung bean, and black gram (Table 3).

Table 2: Area, production, and productivity of important legumes in the Indo-Gangetic Plain of India, 1995/96.

State	Description[1]	Chickpea	Pigeonpea	Black gram	Mung bean
Uttar Pradesh	A	112.0	510.0	278.4	138.5
	P	780.0	490.0	123.7	65.8
	Y	0.7	1.0	0.4	0.5
Bihar	A	120.0	70.0	70.2	181.8
	P	90.0	60.0	36.4	101.0
	Y	0.7	0.9	0.5	0.6
Haryana	A	380.0	20.0	1.3	11.4
	P	390.0	20.0	0.6	5.1
	Y	1.0	0.8	0.5	0.4
Punjab	A	20.0	9.8	6.2	52.5
	P	20.0	8.6	2.1	43.8
	Y	0.9	0.9	0.3	0.8
West Bengal	A	20.0	3.8	77.3	5.3
	P	20.0	2.4	31.6	3.2
	Y	0.8	0.8	0.4	0.6
Madhya Pradesh	A	2660.0	400.0	513.3	131.0
	P	1990.0	300.0	175.2	42.6
	Y	0.8	0.8	0.3	0.3

[1] A = area ('000 ha); P = production ('000 t); Y = yield (t ha^{-1}).
Source: GOI (1997).

Table 3: Effect of management technology on the productivity of legumes during 1992/93.[1]

Technology	Legume crop	Number of demon-strations	Grain yield (t ha^{-1}) Improved techno-logy	Grain yield (t ha^{-1}) Local techno-logy	Increase in yield (%)
Fertilizer management	Pigeonpea	37	1.41	1.10	38
	Mung bean	1	0.60	0.50	20
	Lentil	4	1.43	1.11	29
Weed management	Pigeonpea	20	1.52	1.28	26
	Chickpea	3	1.76	1.57	12
	Mung bean	1	1.09	0.93	18
	Black gram	13	0.88	0.75	18
Insect management	Pigeonpea	29	1.11	0.71	56
	Chickpea	25	1.25	0.98	28
	Mung bean	9	0.76	0.53	45
	Black gram	2	1.21	0.86	42

[1] All India Coordinated Pulses Improvement Project trial.

Bahl and Baldeo (1981) analyzed chickpea data of coordinated trials and minikits in some states of northern India and found a gap of 71% between research station yield and state average yield. A range of climatic, edaphic, and biotic factors constrained the productivity of chickpea. The relative importance of each factor, however, varies from region to region due to diversity of agroecological conditions.

MANAGEMENT OF LEGUMES

As indicated above, management factors play a key role in enhancing BNF and productivity of legumes. Tillage practices, planting time, plant population, plant nutrition, irrigation practice, and weed management considerably influence BNF and crop productivity. The effect of each of these factors is discussed briefly.

Tillage

In the IGP, legumes are cultivated on a wide range of soils varying in texture, from loamy sand in Punjab to heavy clay in West Bengal. In the light-textured soils, tillage techniques to ensure optimum moisture availability in the seeding zone need greater attention whereas in the heavy-textured soils good seed bed preparation, especially after rice, is of immense significance.

During winter, legumes such as chickpea and lentil are grown on residual moisture and deep planting is often done to ensure placement of seeds in the moist zone. This reduces nodulation and N_2-fixation due to low concentration of soil oxygen. Similarly, in heavy-textured soils, poor aeration and soil compactness often lead to poor nodulation. Work on tillage management of rice-based sequential cropping systems at the Indian Institute of Pulses Research (IIPR), Kanpur showed that relay planting of legumes [chickpea, lentil, pea, khesari (*Lathyrus sativus*), and faba bean (*Vicia faba*)] and oilseed [linseed (*Linum usitatissimum*)] in the standing crop of rice under zero tillage gave low yields as compared with that grown after harvest of rice followed by cross harrowing (Table 4) (Kumar and Ali 1995). Among various *rabi* crops, khesari recorded highest yield (2.33 t ha^{-1}) followed by faba bean (1.41 t ha^{-1}). Tomar and Singh (1991) also reported higher uptake of N and phosphorus (P) by lentil with one plowing as compared with zero tillage on sandy loam soils at Agra, Uttar Pradesh.

In rainy season legumes, especially pigeonpea, groundnut, and soybean, plant population is often vitiated due to water stagnation or poor drainage. Raised and ridge-furrow beds have been found quite effective in ensuring optimum plant stand and increased crop productivity. In multilocational studies on short-duration pigeonpea in the northwest plain zone of India, raised beds of 2.7-m width gave mean yield of 1.63 t ha^{-1} as against 1.25 t ha^{-1} in flat beds (Table 5). Planting on ridges in a ridge-furrow bed system was also beneficial (Ali 1995).

Table 4: Yield of legumes and oilseeds as influenced by cropping sequence and tillage treatments.

Treatment	Rice yield (t ha^{-1}) Grain	Straw	*Rabi* crop grain yield (t ha^{-1})
Rice-lentil	4.43	9.29	1.11
Rice-pea	4.41	9.29	1.15
Rice-linseed	4.47	9.14	1.20
Rice-faba bean	4.49	9.42	1.41
Rice-khesari	4.43	9.25	2.33
Rice-chickpea	4.47	2.22	1.12
SE	±1.13	±0.18	±0.04
LSD (P = 0.05)	NS[1]	NS	0.13
Tillage practice			
No tillage	4.43	9.27	1.32
Tillage (2 harrowings)	4.47	9.26	1.46
SE	±0.05	±0.10	±0.03
LSD (P = 0.05)	NS	NS	0.07

[1] NS = not significant.
Source: Kumar and Ali (1995).

Table 5: Grain yield of pigeonpea as influenced by bed configuration at three locations in northwest plain zone of India, 1994–95.

Planting method	Grain yield (t ha^{-1}) Hisar	Ludhiana	Pantnagar	Mean
Flat bed	0.71	1.69	1.34	1.25
Planting on ridges	0.96	1.40	1.95	1.44
Raised bed at 2.7 m width	1.18	NT[1]	2.08	1.63
Flat sowing and making furrows 30 DAS[2] at 2.7 m width	1.02	2.05	1.53	1.53
SE	±0.03	±0.04	±0.05	

[1] NT = not tested. [2] DAS = days after sowing.
Source: Ali (1995).

Planting Time

Planting time is a non-monetary input which can have a profound effect on productivity and success of the high intensity crop production systems. It causes a considerable change in the plant environment in respect to temperature, photoperiod, and availability of soil moisture. The optimum time of sowing of chickpea in northern Indian states is from mid-Oct to mid-Nov. Studies on planting dates of chickpea at Ludhiana during 1991/92 to 1992/93 showed that delayed planting beyond 5 Nov significantly reduced number of nodules, nodule dry weight, and leghaemoglobin content in chickpea (Sharma et al. 1995). The optimum planting time for maximizing nodulation was between 20 Oct and 5 Nov.The leghaemoglobin content in the 20 Oct planting was 2.29–2.73 mg g^{-1} of nodule as against 1.28–1.37 mg g^{-1} of nodule in the 20 Nov planting (Table 6). Govind Reddy et al. (1991) reported that 15 Oct was the optimum time of planting for *rabi* (post-rainy season) pigeonpea at Kharagpur (West Bengal). When compared to the 15 Oct planting yield losses of 31.8% occured in 30 Oct planting and 66.6% in 14 Nov planting. During the rainy season, advance planting of pigeonpea (5 May) registered an increase of 17.6% in grain yield over a 20 May planting on loamy sand soil of Ludhiana (Rana and Malhotra 1993). The yield attributes, nodule number, and dry weight as well as seed yield of soybean were increased significantly when the crop was sown on 18 Jul in comparison with 29 Jun and 7 Aug sowings under West Bengal conditions (Majumdar and Behra 1991).

Table 6: Effect of dates of planting on nodulation and leghaemoglobin content of chickpea at Ludhiana, India.

Planting date	Nodules (number $plant^{-1}$)	Dry weight of nodules (mg $plant^{-1}$)	Leghaemoglobin content (mg g^{-1} nodule)
1991/92			
20 Oct	18.4	67.1	2.29
5 Nov	20.3	66.3	1.66
20 Nov	11.8	45.8	1.28
SE	± 0.52	± 4.16	± 0.07
1992/93			
20 Oct	24.4	74.1	2.73
5 Nov	23.1	73.5	1.73
20 Nov	15.2	51.1	1.37
SE	±1.36	±0.28	±0.57

Source: Sharma et al. (1995).

Plant Population

Low plant stand is one of the major constraints for low productivity of pulses especially under rainfed conditions. Several studies under AICPIP have shown that the grain yield of pigeonpea and lentil increased with the corresponding increases in plant density up to certain limits. In the case of short-duration pigeonpea, 15–16 plants m^{-2} were adequate. In the case of chickpea, 22–30 plant m^{-2} for timely planting (mid Oct) and 30–40 plants m^{-2} for late (mid-Dec) planting were found optimal under northern Indian conditions. Under late-sown conditions, the plant growth is often restricted and therefore a higher population is desired for compensating the yield loss $plant^{-1}$.

Adverse effects of high seed rates on nodulation have been reported. Venkateshwarlu and Ahlawat (1993) found that a seed rate of 60 kg ha^{-1} significantly depressed nodulation in lentil at Delhi, India as compared to a seed rate of 40 kg ha^{-1}. However, grain yield was more at the high seed rate.

Vaishya et al. (1995) studied the effect of seed rates on nodulation and yield of chickpea at Faizabad, Uttar Pradesh. They found that on silty clay loam soils increasing seed rate from 75 kg ha^{-1} significantly decreased number of nodules $plant^{-1}$ counted at 90 days after sowing (DAS). The grain yield also decreased progressively with increasing seed rate (Table 7).

Table 7: Effect of seed rates on nodulation and grain yield of chickpea grown at Faizabad, Uttar Pradesh, India on a silty clay loam during 1987/88.

Seed rate (kg ha^{-1})	Nodules[1] (number $plant^{-1}$)	Grain yield (t ha^{-1})
75	29.5	1.81
100	19.7	1.73
125	17.2	1.67
LSD (P = 0.05)	1.6	NS[2]

[1] Counted at 90 days after sowing.
[2] NS = not significant.
Source: Vaishya et al. (1995).

Nutrient Management

Adequate and balanced supply of plant nutrients is essential for achieving and sustaining high productivity. Nutrient management in legumes in multiple cropping systems is rather complex and has received low priority in the past. Most of the studies on fertilizer use in legumes are individual crop based and thus the results have only limited application in various cropping systems involving cereals and pulses.

Macronutrients

Nitrogen is the most critical plant nutrient for growth and yield of cultivated crops. However, legumes derive a large proportion of their N requirement through BNF and consequently only a starter dose of 20–25 kg N ha^{-1} is usually recommended. In fertilizer experiments on farmers' fields under the All India Coordinated Agronomy Research Project (AICARP), chickpea showed substantial response to 20 kg N ha^{-1}. The N-use efficiency was 8.5–19.5 kg grain kg^{-1} N (Prasad and Subbiah 1982). When the N_2-fixing system is operative, chickpea does not respond to N beyond 20 kg ha^{-1} (Saxena and Sheldrake 1980). However, in rice fields where the rhizobial population is often low, late-sown chickpea responds well up to 40 kg N ha^{-1} (Ali 1994a). Pea, generally grown under irrigated conditions, has also shown good response to high doses of N. Multilocational studies under AICPIP during 1991–94 showed that dwarf pea cultivar Aparna responded favorably to 40–60 kg N ha^{-1} (Ali et al. 1994). These results clearly show that response to N is considerably influenced by native *Rhizobium* population and moisture status of soil. Common bean (*Phaseolus vulgaris*), which has been introduced as a winter crop in the frost-free belt of northern India, does not nodulate with native *Rhizobium* strains and consequently responds well up to 120 kg N ha^{-1} (Ali and Lal 1989).The application of N may not only be directly beneficial to the legume but may also benefit the succeeding crops. For example, in a rice-wheat rotation experiment, application of 80 kg N ha^{-1} as urea to the rice crop had no effect on wheat yield, but application of 40 kg N ha^{-1} as urea to *Sesbania aculeata* grown as green manure to rice combined with 40 kg N ha^{-1} as urea to rice increased wheat yield by 0.7 ha^{-1} (Mahapatra amd Sharma 1989). This was attributed to improvement in soil physical conditions after puddling of the field for rice production.

Phosphorus is the second most critical plant nutrient overall, but for legumes it assumes primary importance. The soils of the IGP are generally low to medium in available P content and therefore application of 17–26 kg P ha^{-1} has shown favorable effects in grain legumes (Ahlawat and Ali 1993). Compared with other pulses, chickpea is more efficient in taking up P from soil as it secretes acid exudates from roots which helps in solublizing Ca-P (Ae et al. 1991). In pigeonpea, response to applied P varies considerably from 17 kg ha^{-1} to 43 kg ha^{-1} P depending upon P status of soil (Chauhan and Singh 1981). Kasturi (1995) reported that application of 26.4 kg P ha^{-1} significantly improved seed yield, nodulation, and nitrogenase activity in pea (Table 8).

Table 8: Effect of moisture stress and nutrients on root nodulation, nitrogenase activity at 90 days after sowing and yield of pea grown on loamy soil at New Delhi, India.[1]

Treatment	Nodules (number $plant^{-1}$)	Dry weight of nodules (mg $plant^{-1}$)	Nitrogenase activity (μmoles C_2H_4 $plant^{-1}$ h^{-1})	Grain yield (t ha^{-1})
Moisture stress				
At vegetative stage	27.9	51.7	3.96	1.82
At flowering stage	33.7	59.6	4.59	1.55
At pod filling stage	33.6	64.3	4.95	1.73
No stress (control)	33.9	66.8	5.14	2.11
Nutrient level[2] (kg ha^{-1})				
0 P (Control)	27.6	49.3	3.76	1.47
13.2 P	32.4	62.1	4.78	1.87
26.4 P	35.5	72.9	5.43	2.07
0 S (control)	29.4	54.9	4.22	1.65
40 S	32.1	61.2	4.72	1.83
40 S + 5 Zn	33.8	65.7	5.05	1.93

[1] Data are mean of 1992/93 and 1993/94.
[2] P = phosphorus; S = sulfur; Zn = zinc.
Source: Kasturi (1995).

Sharar et al. (1976) found that yield of lentil in Pakistan increased with increasing levels of P. However, no improvement in yield with P application on soils rich in P was observed. Late-sown lentil responded up to 28 kg P ha^{-1} on sandy loam soils of Delhi (Watt 1988).

Experiments on farmers' fields were conducted under AICARP to determine the response of pulse crops to applied P. Based upon results of 709 trials on chickpea, 583 on pea, 173 on mung bean, and 177 on black gram, it was found that the mean response to each kg of P applied at 29.4 kg P ha^{-1} was 3.1, 6.0, 1.6, and 3.0 kg grain respectively (Prasad 1979).

In summer mung bean, application of 26 kg P ha^{-1} significantly increased nodulation and yield in West Bengal (Sarkar and Banik 1991). Nitrogen application beyond 20 kg ha^{-1} depressed nodulation but the yield increased significantly. The P needs of one legume intercropped with another is usually higher than that of the sole crop. In pigeonpea/groundnut intercropping, when both crops received 17 kg P ha^{-1}, productivity was higher than that of sole crops (Pareek and Turkhede 1991). Since the soils of the IGP are generally rich in potassium (K), response to applied K is either low or absent.

In recent years, S deficiency has been observed in the rice-wheat belt of northern India due to increased cropping intensity and use of S-free fertilizers, e.g., urea and diammonium phosphate. The S deficiency is more pronounced on productivity of legumes than cereals due to comparatively higher S need of the former for producing grain. In multilocational studies under AICPIP during 1991–94, pigeonpea responded favorably to 40 kg S ha^{-1} whereas chickpea, lentil, black gram, and mung bean showed significant response only up to 20 kg S ha^{-1} (Table 9). The mean extra productivity at these levels of S was 392 kg ha^{-1} in pigeonpea, 476 kg ha^{-1} in chickpea, 450 kg ha^{-1} in lentil, 166 kg ha^{-1} in black gram, and 194 kg ha^{-1} in mung bean (Ali and Singh 1995).

Table 9: Productivity (t ha^{-1}) of different grain legumes as influenced by sulfur use in the Indo-Gangetic Plain of India during 1991–94.

		Sulfur rate (kg ha^{-1})		
Legume	No. of locations	0	20	40
Chickpea	5	1.42	1.86	1.90
Lentil	3	1.02	1.47	1.46
Pigeonpea	6	1.19	1.35	1.52
Black gram	3	0.83	1.00	0.95
Mung bean	3	0.99	1.18	1.16

Source: Ali and Singh (1995).

High nodulation, nitrogenase activity, and seed yield in pea with soil application of 40 kg S ha^{-1} has also been reported by Kasturi (1995). Combined use of 5 kg Zn ha^{-1} and 40 kg S ha^{-1} further improved BNF and grain yield (Table 8). Kandpal and Chandel (1993) studied effect of levels and sources of S on nodulation and N_2-fixation in soybean on silty clay loam soils of Pantnagar in Uttar Pradesh. They found that irrespective of sources of S, nitrogenase activity and N_2-fixation increased with increasing level of S up to 40 kg ha^{-1} (Table 10). The amount of N_2 fixed at 40 kg S ha^{-1} as gypsum was 170.1 kg ha^{-1} and as pyrite 175.2 kg ha^{-1}, as against 49.2 kg ha^{-1} without S. Similarly, the nitrogenase activity at 40 kg S ha^{-1} was 43.6

μmoles C_2H_4 plant^{-1} h^{-1} with gypsum and 44.9 μmoles C_2H_4 plant^{-1} h^{-1} with pyrite as compared with 12.7 μmoles C_2H_4 plant^{-1} h^{-1} without S. Ali and Singh (1995) reviewed results of coordinated trials of AICPIP and concluded that different sources of S, i.e., gypsum, pyrite, and single superphosphate (SSP) were almost identical in their efficacy.

Table 10: Effect of sulfur on nitrogenase activity and nitrogen fixation in soybean cv. PK 327 at 60 days after sowing on silty clay loam soil at Pantnagar, Uttar Pradesh, India.

Source and level of sulfur	Nitrogenase activity (μmoles C_2H_4 plant^{-1} h^{-1})	Nitrogen fixed (kg ha^{-1})
Gypsum		
10 kg S ha^{-1}	14.9	58.3
20 kg S ha^{-1}	23.7	98.2
30 kg S ha^{-1}	31.0	120.9
40 kg S ha^{-1}	43.6	170.1
Pyrite		
10 kg S ha^{-1}	15.0	58.4
20 kg S ha^{-1}	24.0	93.7
30 kg S ha^{-1}	30.6	119.5
40 kg S ha^{-1}	44.9	175.2
Control (inoculated)	12.7	49.2
LSD ($P = 0.05$)	1.7	6.2

Source: Kandpal and Chandel (1993).

Micronutrients

Response of legumes to micronutrients, including Zn, molybdenum (Mo), iron (Fe), and manganese (Mn) have also been observed. In chickpea, application of 25 kg $ZnSO_4$ ha^{-1} improved nodulation, root growth, and yield (Singh and Gupta 1986) and also increased uptake of Zn, Fe, and P (Dravid and Goswami 1987). Lentils are highly susceptible to Zn deficiency and an improvement in yield with soil application of 12.5–15.0 kg $ZnSO_4$ ha^{-1} has been observed. Foliar spray of 0.5 kg $ZnSO_4$ ha^{-1} with 0.25 kg lime has also been found effective in correcting Zn deficiency in chickpea and lentil (Saxena and Singh 1977).

Molybdenum, being a constituent of nitrate reductase and nitrogenase enzymes, considerably influences BNF. Srivastava (1993) observed that application of Mo increased number of nodules, dry weight of nodules, nitrogenase activity, and grain yield of pea. With application of 0.5 kg Mo ha^{-1}, the number of nodules was 22.8 plant^{-1}, dry weight of nodules was 24.2 mg plant^{-1}, nitrogenase activity was 4.2 μmoles C_2H_4 plant^{-1} h^{-1}, and grain yield of pea was 1.6 t ha^{-1} whereas in the control the respective values were 21.7 plant^{-1}, 22.9 mg plant^{-1}, 3.7 μmoles C_2H_4 plant^{-1} h^{-1}, and 1.5 t ha^{-1}. In calcareous soils of northern Bihar, application of 5–10 kg borax ha^{-1} has proved quite effective in improving yield of chickpea (Ali 1995). Multilocational trials on micronutrients showed that foliar application of 0.5 kg $FeSO_4$ ha^{-1} improved productivity of chickpea by 450 kg ha^{-1} over the control (Takkar and Nayyar 1986). Since genotypic variation in susceptibility to deficiency of micronutrients has been observed in chickpea, lentil, and pigeonpea, efforts should be made to choose cultivars which do comparatively better in soils deficient in micronutrients (Ahlawat and Ali 1993).

Biofertilizers

The value of biofertilizers in sustainable crop production is well recognized. Legumes possess the intrinsic capacity of fixing atmospheric N in their root nodules through *Rhizobium* which needs to be fully exploited.

The quantum of N_2 fixed by legumes is influenced by several physical, environmental, and biological factors (Kumar Rao and Rupela 1998). The level of native rhizobial population appears to be one of the major constraints for poor nodulation. Under AICPIP, soil samples from 506 locations were collected to estimate the population of *Rhizobium*. It was observed that 79% of the samples had low to medium bacterial population. Favorable effects of inoculation on nodulation and yield have been reported by several workers. In a multilocational study under AICPIP, seed inoculation enhanced the productivity of different pulses by 10–15% (Chandra and Ali 1986). Tilak and Dwivedi (1991) reported a significant increase in colonization of vesicular-arbuscular mycorrhiza (VAM), nodules plant^{-1}, dry weight of nodules, and nitrogenase activity of chickpea with *Glomus versiforme* inoculation.

Legume species not only differ in nodulation but cultivars within species also differ significantly, suggesting that host factors are important determinants of nodulation. Besides the specificity for root infection, the development of root nodules is influenced by both bacterial and plant genes. Patel et al. (1986) found significant interaction between *Rhizobium* strains and genotypes of chickpea. In chickpea cv BG 209, strain KG 31 was most effective whereas strain F 75 in cvs Dohad yellow and JG 315, and strain F 6 in cv Chafa were more effecive (Table 11). Studies on effectiveness of single and multi-strains of *Rhizobium* on chickpea cv BDN 9-3 did not show any advantage of multi-strain inoculation over single strain (Pedgaonkar and Raut 1985). Bhattacharya and Sengupta (1984) evaluated 21 genotypes of lentil and observed that genotypes with high coralloid nodules had better nodulation. Further, they found that genotypes with pink nodules gave higher yield than other genotypes.

The symbiotic association between plant roots and mycorrhizal fungi has received greater attention in recent years. The VAM enhances plant growth by improved mineral nutrition particularly P and water uptake on account of the hyphal network originating from mycorrhizal roots which make close contact with the soil mass. Rao et al. (1986) observed higher N and P concentration in shoots of chickpea due to *Glomus fasciculatum* inoculation which was almost equivalent to the effect of seed inoculation with *Rhizobium*. Reddy (1992) reported that both *Rhizobium* and VAM inoculation improved number of nodules, dry weight of nodules, and seed yield in lentil and were

Table 11: Effect of *Rhizobium* inoculation on the grain yield of four genotypes of chickpea at Dohad (Gujarat) during 1978/79 to 1980/81.

	Grain yield (t ha^{-1})				Increase in yield
Rhizobium strain	BG 209	Dohad yellow	JG 315	Chafa	over control (%)
F 6	3.02	3.10	3.49	2.93	49
Ca 181	2.78	3.02	3.49	2.62	42
KG 31	3.17	2.54	4.24	1.89	41
F 75	3.10	3.17	4.44	2.54	58
H 45	2.54	2.94	3.41	2.41	41
Uninoculated control	1.91	1.91	2.62	1.98	–
	Genotypes (G)	*Rhizobium* strains (S)		G × S	
SE	± 0.34	± 0.14		± 0.29	
LSD (P = 0.05)	NS[1]	0.41		NS	

[1] NS = not significant.

Source: Patel et al. (1986).

at par with each other (Table 12). Dual inoculation with *Rhizobium* and VAM further increased nodulation and yield.

Table 12: Effect of biofertilizers on root nodulation at 80 days after sowing and grain yield of lentil during 1989/90.

Biofertilizer[1]	Nodules (number $plant^{-1}$)	Dry weight of nodules (mg $plant^{-1}$)	Grain yield (t ha^{-1})
Uninoculated control	17.4	4.2	0.84
Rhizobium	26.1	5.4	1.03
VAM	20.5	6.3	1.09
Rhizobium + VAM	29.8	7.2	1.19
LSD (P = 0.05)	NA[2]	NA	0.04

[1] VAM = Vesicular arbuscular mycorrhiza.

[2] NA = LSD values not available.

Source: Reddy (1992).

Irrigation Management

Drought and excess moisture are deterimental to BNF and growth of legumes (Smith 1987; Kirda et al. 1989). The ability of these crops to survive under low soil moisture conditions/drought is, however, only at the cost of biological and economic yields. There is evidence that cytokinins induce tolerance in plants to moisture stress (Sharma et al. 1995). *Rhizobium* strains are capable of producing cytokinins. Therefore, it is likely that nodules impart some tolerance to legumes against drought. Once nodules disintegrate, this mechanism may cease to operate and plants would become more susceptible to moisture stress.

Drought of different intensities is experienced in rainfed areas of the IGP at seedling, vegetative, and terminal growth stages of legumes and causes irrepairable damage to crops and also vitiates plant stand. *Rhizobium* bacteria are less severely affected by drought than host plants. Sprent et al. (1988) viewed that while the soil may be sufficiently dry to prevent plant growth, it may still contain enough wet microsites to allow the survival and even growth of rhizobial inoculum. The ability of rhizobia to survive under dry conditions varies with species, soil type, and other factors. When enough moisture becomes available to permit plant growth, pockets of rhizobia multiply, and spread in soil pores which have become wet. Efforts to develop short-duration cultivars, having drought tolerance characteristics is a long-term strategy. The immediate solution lies in diverting some irrigation water to legumes which do comparatively better at low levels of irrigation than cereals.

Response to limited irrigation has been observed in most of the grain legumes in India (Ali 1994b). Among various crops, common bean (*Phaseolus vulgaris*) was found to be more responsive to irrigation, followed by pea. The success of mung bean as a catch crop in the rice-wheat system is solely dependent upon adequate supply of irrigation. Late-sown chickpea in sequence with rice also needs more irrigation than the normal planted crop probably due to restricted root growth.

Various approaches, e.g., crop growth stage, frequency, and cumulative pan evaporation, have been adopted for scheduling irrigation. Pod initiation has been found to be the most critical stage in most of the legumes. However, the initial profile moisture and soil type largely determine the requirement of subsequent irrigation. Pal and Jana (1991) found that in summer mung bean, irrigation at vegetative stage was most critical. Nodulation was also severely affected by delayed irrigation (Table 13). In pea, moisture stress at an early stage (vegetative) considerably reduced nodulation, nitrogenase activity, and seed yield (Kasturi 1995). The nitrogenase activity of plants subjected to moisture stress at the vegetative stage was 3.96 μmoles C_2H_4 plant^{-1} h^{-1} as compared with 4.95 μmoles C_2H_4 plant^{-1} h^{-1} when stress was imposed at pod development (Table 8).

Table 13: Effect of irrigation on nodulation and yield of mung bean[1].

Irrigation level	Nodules (number plant^{-1})	Fresh weight of nodules (mg plant^{-1})	Grain yield (t ha^{-1}) 1982	Grain yield (t ha^{-1}) 1984
Rainfed (Control)	10.3	26	1.20	1.56
One at vegetative (V)	27.0	55	1.48	1.80
One at pod development (P)	41.0	27	1.72	1.90
Two, at V P	27.2	58	1.92	2.02

[1] Statistical analysis values are not available in the original publication.
Source: Pal and Jana (1991).

Using a climatological basis for calculating irrigation requirement, irrigation at an irrigation water/cumulative pan evaporation (IW/CPE) ratio of 0.25 in medium-duration pigeonpea (180–200 days) on clayey soils of

Navsari, Gujarat (Patel and Patel 1995), 0.4 in chickpea on sandy loam soils of Delhi (Prabhakar and Saraf 1991), and 0.7 in soybean on clay loam soils of Raipur, Madhya Pradesh (Pandey et al. 1995) in India have been found to be most efficient. A higher number of nodules and their dry weight were recorded both at 45 and 55 DAS in soybean with irrigation scheduled at IW/CPE ratio of a 0.07 as compared with 0.5 (Table 14). At 70 DAS, the nodule formation was reduced at all the levels of irrigation. Pal and Lal (1993) at Pantnagar, Uttar Pradesh observed higher nodulation in summer planted mung bean when irrigation was scheduled at 10 cm cumulative pan evaporation (CPE) as compared with that at 15 and 20 cm CPE thereby indicating a positive interaction between soil moisture and root nodules.

Table 14: Effect of irrigation on nodulation and grain yield of soybean at Raipur, Madhya Pradesh, India during 1990/91.

	Nodules at DAS[1] (number plant^{-1})			Dry weight of nodules at DAS (mg plant^{-1})			Grain yield
Irrigation treatment[2]	45	55	70	45	55	70	(t ha^{-1})
I_1	18	25	19	95	173	143	1.52
I_2	13	16	14	75	130	113	1.21
I_3	17	18	14	91	139	130	1.27
I_4	18	24	14	93	169	129	1.17
I_5	15	21	16	77	144	131	1.44
I_6	14	17	11	18	140	109	1.15
LSD (P = 0.05)	2	1	2	5	16	11	0.13

[1] DAS = days after sowing.

[2] I_1 - 0.07 irrigation water/cumulative pan evaporation (IW/CPE) at all stages; I_2 - 0.03 IW/CPE at vegetative stage and 0.7 at flowering stage; I_3 - 0.7 IW/CPE at vegetative and podding stages and no irrigation at flowering stage; I_4 - 0.7 IW/CPE at vegetative and flowering stages and 0.3 at podding stage; I_5 - 0.5 IW/CPE at vegetative and podding stages and 0.7 at flowering stage; and I_6 - 0.5 IW/CPE at all stages.

Source: Pandey et al. (1995).

The effect of excess moisture or waterlogging could be direct by reducing O_2 concentration in the rhizosphere or indirect by reducing availability of photosynthates. Waterlogging affects BNF due to anoxia. Singh et al. (1988) noted that flooding decreased leaf area index (LAI), nodulation, and seed yield of mung bean. Plants at seedling stage were more susceptible to flooding than those at flowering stage. Rainy season legumes, particularly short-season pigeonpea grown in sequence with wheat, do experience excess moisture conditions during early stages of their growth and consequently suffer loss of plant stand resulting in low productivity. It is therefore imperative to provide appropriate drainage (surface or subsurface) especially in low lying areas. Raised bed and ridge-furrow seed beds are quite effective in draining out the excess water, ensure better plant stand, and enhance yield of legumes.

Weed Management

In early stages of crop growth, legumes are poor competitors to weeds and consequently suffer heavy yield losses. Studies under the AICPIP during 1983–85 revealed yield losses (due to unchecked weeds) of 0.65 t ha^{-1} (44%) in pigeonpea, 0.29 t ha^{-1} (36%) in mung bean, 0.62 t ha^{-1} (50%) in black gram, and 0.78 t ha^{-1} (42%) in chickpea over weed-free plots (Table 15).

Table 15: Effect of weed control measures on productivity of grain legumes under rainfed conditions during 1983–1985.[1]

	Grain yield (t ha^{-1})			
Treatment	Pigeonpea (9)[2]	Mung bean (15)	Black gram (12)	Chickpea (18)
Weedy control	0.81	0.52	0.64	1.04
Weed free	1.46	0.81	1.26	1.82
One hand weeding (25–30 days after sowing)	1.17	0.71	0.98	1.34
One intercultivation	1.04	0.64	0.81	NT[3]
Fluchloralin (1.0 kg ha^{-1})	1.13	0.79	0.93	1.43
Pendimethalin (0.75 kg ha^{-1})	1.21	0.76	0.91	NT
Oxadiazon (0.75 kg ha^{-1})	1.19	0.77	0.91	1.23
Yield loss due to weeds (%)	44	36	50	42

[1] All India Coordinated Pulses Improvement Project trials.
[2] Figures in parentheses denote number of locations.
[3] NT = not tested.

The nature and magnitude of crop-weed competition is influenced by several factors such as crop species, cropping system, planting time, plant population, moisture availability, and fertility conditions. Since weeds compete with crop plants for moisture, nutrients, light, and space, their adverse effect on BNF is obvious.

Among various management practices, pre-emergence application of pendimethalin at 1.0–1.5 kg ha^{-1} and metolachlor at 1.0–1.5 kg ha^{-1}, and pre-plant incorporation of 1.0 kg ha^{-1} fluchloralin were effective in controlling seasonal weeds in chickpea, lentil, pea, common bean, pigeonpea, black gram, and mung bean in northern India (Ali 1994b). Adverse effects of high doses of herbicides on plant growth, yield, and nodulation in legumes have also been observed (Goyal et al. 1991). In a field experiment at Faizabad, Uttar Pradesh, Vaishya et al. (1995) studied relative efficacy of cultural and chemical methods of weed management in chickpea. They found that use of herbicide (1.0 kg ha^{-1} fluchloralin) appreciably decreased number of nodules as compared with the weedy check and hand weeding (Table 16). The grain yield was, however, significantly high with herbicide use due to control of weeds. Sandhu et al. (1991) at Ludhiana, Punjab, India also found that number of nodules, dry weight of nodules, and nitrogenase activity in chickpea decreased with application of herbicides (oxyfluorfen, linuron, oxadiazon, and metribuzin) as compared with hand weeding.

Table 16: Effect of weed management practices on nodulation and yield of chickpea at Faizabad in Uttar Pradesh, India during 1987/88.

Weed control measure	Nodules (number plant^{-1})	Grain yield (t ha^{-1})
Hand weeding (25 and 45 DAS)[1]	27.3	2.20
Fluchloralin (1.0 kg ha^{-1})	17.0	1.72
Fluchloralin (1.0 kg ha^{-1}) and hand weeding at 20 DAS	20.3	1.67
Weedy control	24.0	1.16
LSD (P = 0.05)	1.6	0.10

[1] DAS = days after sowing.
Source: Vaishya et al. (1995).

Intercropping of short-statured legumes such as black gram, mung bean, cowpea, and soybean helps in smothering weeds and enhancing crop productivity (Ahlawat and Venkateshwarlu 1987; Ali 1988). Among various legumes, cowpea has been found to be more efficient in smothering weeds, followed by mung bean and soybean. It would, therefore, be imperative to grow dense canopy legumes both as sole crops and intercrops to suppress weeds besides improving physical and biological conditions of soil and high economic returns.

FUTURE RESEARCH PRIORITIES

Even though legumes have a major role to play in the N cycle of rice-wheat cropping systems (RWCS), their primary purpose for cultivation is for grain. Good conditions for crop growth are required for both optimal fixation of N_2 and grain yield. Most of the agronomic and genotypic improvements for legumes in the past have been done for optimal growing conditions. Introduction of legumes in RWCS would be an opportunity cropping, largely under conditions of unfavourable soil moisture, soil texture, nutrients, and weather. There is a need to develop genotypes and agronomic practices to overcome constraints faced by the genotypes to reduce the opportunity costs involved in this cropping.

Development of simulation models would allow identification of crop characteristics that are needed to optimize resource utilization in RWCS. Already simulation models of most legumes, e.g., groundnut, soybean, and chickpea, that can be potentially used in such systems have been developed. But there is an urgent need to develop these models for other legumes. However, adequate simulation of N_2-fixation, especially under adverse conditons is still unsuccessful. Successful simulation of crop growth and N_2-fixation would permit better conceptualization of constraints and opportunities for growing legumes in RWCS.

More multilocational testing of agronomic packages of legumes with critical observation should be done as soil conditions for the rice-wheat systems vary greatly from location to location. These would allow validation of models and permit generalizations that may be useful for other locations with different environmental conditions.

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