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EFFECT OF PHOSPHORUS LEVELS ON YIELD, ECONOMICS, ENERGETICS AND CARBON FOOTPRINT OF FORAGE RICE BEAN GENOTYPES

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SUMMARY

A field experiment was conducted to study the effect of graded phosphorus levels on the growth, yield, quality, economics, energetics, and carbon footprint of promising forage rice bean [*Vigna umbellata* (Thunb.) Ohwi and Ohashi] genotypes. The experiment was laid out in a factorial randomized block design with three genotypes (JOR-21-1, Bidhan-2 and Bidhan-3 and three phosphorus levels (40, 60 and 80 kg P_2O_5 ha^{-1}), replicated thrice. Phosphorus application significantly and progressively improved plant height, leaf:stem ratio, dry matter content and crude protein content, with the highest values recorded at 80 kg P_2O_5 ha^{-1}. Green fodder yield, dry matter yield, and crude protein yield followed the same trend, increasing by about 18-58% from 40 to 80 kg P_2O_5 ha^{-1}. Among genotypes, Bidhan-3 and Bidhan-2 significantly outperformed JOR-21-1 across all growth and yield parameters. Economic analysis showed that gross and net income rose steadily with phosphorus level, but the benefit-cost ratio plateaued beyond 60 kg P_2O_5 ha^{-1} (2.50 at 60 kg *vs*. 2.51 at 80 kg P_2O_5 ha^{-1}), indicating diminishing marginal returns at the highest dose. Energy-use efficiency and energy productivity increased consistently with phosphorus level, reflecting the near-constant energy input and rising biomass output. Carbon budgeting revealed that although total carbon footprint increased with phosphorus dose, the carbon footprint per unit yield (CFy) was lowest at 60 kg P_2O_5 ha^{-1}, after which it rose again, identifying this level as the environmentally optimal dose. Bidhan-3 also recorded the highest eco-efficiency and carbon efficiency and the lowest carbon footprint per unit yield among genotypes. Fertilization with 60 kg P_2O_5 ha^{-1} combined with high-yielding genotypes such as Bidhan-3 or Bidhan-2 offers the best balance of productivity, profitability, and environmental sustainability for forage rice bean cultivation with particular relevance to fodder-deficit regions such as North Bihar.

Key words: Carbon footprint, eco-efficiency, economics, energetics, forage yield, phosphorus, rice bean

Rice bean [*Vigna umbellata* (Thunb.) Ohwi and Ohashi] is an underutilized legume with strong potential as a fodder crop,especiallyto overcome green-forage deficit during the lean periods. As a legume, it fixes atmospheric nitrogen, produces palatable, nutrient-dense biomass and tolerates marginal growing conditions.However, its agronomic management, especially phosphorus nutrition for forage-specific production, is comparatively under-researched relative to major fodder legumes such as cowpea and berseem.

Phosphorus is one of the most important macronutrients for plants and has a critical function in root growth, affecting nutrient absorption, plant growth and development (Nanda *et al*., 2023). Being a legume, rice bean has a particularly high phosphorus requirement, since the nutrient is needed for nodule formation as well as for the transfer of energy via ATP and ADP (Nanda, 2024). Therefore, phosphorus management is predicted to influence nitrogen fixation and, consequently, the crude protein level of leguminous pasture crops (Nanda, 2024). However, phosphorus deficiency is common in agricultural soils. As Bilal *et al*. (2021) highlighted, the availability of phosphorus (P) to crops is still constrained in two-thirds of the soils, limiting the yield potential unless applied through fertilization. This constraint is especially relevant for legumes, since adequate

phosphorus supply in legumes directly supports nodulation and biological nitrogen fixation.

Field evidence from rice bean and its related Vigna species is a strong argument for a P response. Khanda *et al*. (1999) reported that phosphorus application at 60 kg ha^{-1}markedly influenced the growth, yield attributes and seed yield over the unfertilized control. Similarly, Maiti *et al*. (2005) working on rice bean as a grain legume, specifically showed that seed yield rose progressively with phosphorus application, reaching a maximum at 80 kg P_2O_5/ha. This pattern has been validated in recent agronomic trials on rice bean fodder and grain production in Nepal and Karnataka, where both vegetative growth and yield parameters responded strongly to graded phosphorus and NPK combinations (Sabar *et al*., 2024; Bhattarai *et al*., 2022). Related work on rangeland and cowpea fodder systems indicates that phosphorus fertilization increases forage yield and quality and also increases the economic optimum benefit of the input (Polat *et al*., 2007) highlighting the need to evaluate the economics of phosphorus use alongside its agronomic effects.

Beyond yield and profitability, fertilizer decisions increasingly need to be assessed through energy and environmental lenses. Fertilizer manufacture and application are energy-intensive and constitute a major share of the carbon footprint of cropping systems (Plaza-Bonilla *et al*., 2018). Legumes reduce dependence on nitrogen fertilizers through biological nitrogen fixation, and their inclusion in cropping systems has been shown to reduce energy use and greenhouse gas emissions. Hoeppner *et al*. (2000) reported that rotations containing 50% perennial forage legumes decreased energy use by 85% and increased energy use efficiency by 409% relative to continuous grain rotations. In a similar vein, Manoj *et al*. (2022) demonstrated that legume-based forage cropping systems in semi-arid India were among the most carbon- and energy-efficient options for climate-smart livestock feed production. However, phosphatic fertilizers themselves carry an embedded energy and emissions cost from mining and processing, so the environmental benefit of a legume forage crop can be eroded by excessive or poorly calibrated phosphorus application. An integrated assessment of energetics and carbon footprint alongside yield and economics is therefore necessary to identify a phosphorus dose that is both agronomically and environmentally optimal.

Bihar is predominantly an agrarian state where nearly three-fourths of the population depends on agriculture and allied sectors including livestock rearing, for its livelihood. According to the 20th Livestock Census, Bihar held a total livestock population of about 36.45 million, comprising roughly 15.31 million cattle, 7.72 million buffaloes and 12.82 million goats, making animal husbandry a major component of the rural economy (DAHD, 2019). Livestock and dairying in particular function as a critical secondary income source for millions of smallholders and landless households in the state. However, this substantial livestock population depends heavily on crop residues, particularly wheat and rice straw, as well as natural grazing, while access to nutritious green fodder remains limited (Nilanjaya and Nanda, 2019). Singh *et al*. (2013) highlighted that inadequate feed and fodder availability continues to be a major constraint to improving livestock productivity in the state. A wide and persistent gap exists between the demand and supply of both dry and green fodder for Bihar. This deficit is not uniform across the state: south Bihar, with assured irrigation and paddy-wheat cropping systems, tends to be fodder-surplus, whereas north Bihar is chronically fodder-deficit and depends on fodder transported from surplus regions (Singh *et al*., 2012). The problem is compounded during the monsoon season, when recurrent flooding destroys standing fodder crops and forces farmers into distress sale of cattle due to the resulting feed shortage. The fodder deficit is further compounded by soil fertility constraints, particularly in the calcareous soils of Bihar, where limited phosphorus availability is an important factor restricting crop productivity (Nanda *et al*., 2022 and Chandravanshi *et al.* 2026). Therefore, efficient phosphorus management is essential for ensuring adequate growth, productivity, and nutritional quality of forage crops introduced into these cropping systems. Given this scenario, there is an urgent need to identify short-duration, nutrient-efficient legume fodder crops such as rice bean that can be fitted into existing cropping windows to help bridge the green-fodder gap, improve household dairy income, and reduce dependence on purchased feed, while also being agronomically optimized through balanced phosphorus nutrition.

Despite this evidence from related legumes and preliminary agronomic work on rice bean, no study has comprehensively examined the combined effects of phosphorus fertilization on the yield, economics, energetics, and carbon footprint of forage rice bean under a single, integrated experimental framework, particularly in the fodder-deficit agro-climatic

conditions of North Bihar. The present investigation was therefore undertaken to address this gap.

MATERIALS AND METHODS

The present experiment was carried out at Forage Research Block (Plot no. 12) of Cattle Farm, Animal Production Research Institute, Dr. Rajendra Prasad Central Agricultural University, Pusa, Samastipur, Bihar, under AICRP on Forage Crops and Utilization during the *Kharif* season, 2024. Three forage rice bean genotypes (JOR-21-1, Bidhan-2 and Bidhan-3) and three phosphorus levels (40, 60 and 80 kg P_2O_5 ha^{-1}) were accommodated in a factorial randomized complete block design with three replications. The crop was sown on 25.07.2024 at a row spacing of 30 cm using a seed rate of 35 kg ha^{-1}. A recommended dose of 20 kg of N and 40 kg of K_2O was applied at the time of sowing. Application of phosphorus was done as per the treatments. The sources for nitrogen, phosphorus and potassium were urea, single superphosphate (SSP), and muriate of potash (MOP), respectively. All other cultural operations were done as per the recommended package of practices. Harvesting of green fodder was done at 50% flowering and the green forage yield (GFY) of the plot was recorded and converted to q ha^{-1}. To measure dry matter yield (DMY), dry matter content was determined by taking 500 g of green fodder samples from each plot and placing them in a hot air oven at 70 ± 2°C temperature till constant weight was attained, and multiplied by GFY (Nanda and Nilanjaya, 2022). The nitrogen content in dry matter was multiplied by a factor of 6.25 to get crude protein (CP) content (Jackson, 1973). CP content (%) was multiplied by DMY to get crude protein yield (CPY) (Samal *et al.*, 2023). The economics of forage rice bean was calculated using prevailing market prices of the inputs and output i.e. green forage (Rs. 250/q). Energy budgeting and eco-efficiency were calculated as per Nanda *et al.* (2025). Carbon budgeting was done using carbon co-efficients as suggested by Lal (2004) and Benbi (2018). Data were subjected to Analysis of Variance for a factorial experiment in randomized block design (Gomez and Gomez, 1984).

RESULTS AND DISCUSSION

Growth parameters and crude protein content

Among the three genotypes evaluated plant height (146.1-151.7 cm) and dry matter content (19.8-20.5%) did not differ significantly, indicating that these traits were relatively stable across genotypes under the prevailing agro-climatic conditions (Table 1). However, leaf:stem (L:S) ratio and crude protein (CP) content varied significantly. Bidhan-3 recorded the highest L:S ratio (0.68), followed by JOR-21-1 (0.61) and Bidhan-2 (0.59), while CP content was highest in Bidhan-2 (14.33%), statistically at par with Bidhan-3 (14.28%) and significantly higher than JOR-21-1 (13.25%). The higher L:S ratio in Bidhan-3 reflects a greater proportion of leafy biomass relative to stem, which is agronomically desirable in a forage crop since leaves are more digestible and nutrient-dense than stems.

Phosphorus application had a pronounced and consistent effect on all four parameters. Plant height increased significantly from 138.7 cm at 40 kg P_2O_5/ha to 156.1 cm at 80 kg P_2O_5/ha, while L:S ratio, dry matter content and CP content followed the same increasing trend (0.57 to 0.66, 18.1 to 21.6%, and 13.21 to 14.49%, respectively). This progressive improvement with increasing phosphorus supply is consistent with the established physiological role of phosphorus in meristematic activity, cell division and elongation, and in enhancing root proliferation, which together improve nutrient and water uptake and translate into greater vegetative growth (Khanda *et al.*, 1999). The steady rise in CP content with phosphorus level further corroborates the role of phosphorus in nitrogen metabolism, since adequate P nutrition promotes nodulation and biological nitrogen fixation in legumes, thereby enhancing protein synthesis in plant tissue (Bilal *et al.*, 2021).

TABLE 1
Effect of different P levels on growth parameters, L:S ratio, dry matter (%) and crude protein (%) of promising genotypes of forage rice bean

Treatments	Plant height (cm)	L:S ratio	DM (%)	CP (%)
Genotypes				
JOR-21-1	146.1	0.61	20.1	13.25
Bidhan-2	150.0	0.59	20.5	14.33
Bidhan-3	151.7	0.68	19.8	14.28
SEm ±	2.6	0.03	0.9	0.13
CD (P=0.05)	NS	0.08	NS	0.40
P_2O_5 levels (kg/ha)				
40	138.7	0.57	18.1	13.21
60	153.0	0.65	20.7	14.16
80	156.1	0.66	21.6	14.49
SEm ±	2.6	0.03	0.9	0.13
CD (P=0.05)	7.9	0.08	2.7	0.40

Fodder yield

Bidhan-3 produced the highest green fodder yield (GFY, 315.7 q/ha), dry matter yield (DMY, 62.5 q ha^{-1}) and crude protein yield (CPY, 9.0 q/ha), statistically at par with Bidhan-2 (303.0, 61.8 and 8.9 q/ha, respectively) but significantly superior to JOR-21-1 (217.5, 43.7 and 5.8 q/ha) (Table 2). This yield advantage of Bidhan-2 and Bidhan-3 is consistent with their superior growth attributes and CP content noted in Table 1 confirming that genotypes with a higher leaf proportion and better nutrient assimilation capacity translate vegetative vigor more efficiently into forage and protein yield.

All yield parameters (GFY, DFY and CPY) increased significantly and progressively with increasing phosphorus dose: GFY rose from 251.5 q ha^{-1} (40 kg P_2O_5 ha^{-1}) to 297.8 q ha^{-1} (80 kg P_2O_5 ha^{-1}), an increase of nearly 18%, while DMY and CPY rose by about 42% and 58%, respectively, over the same range. This is in agreement with earlier reports in rice bean where increasing phosphorus supply markedly improved yield-contributing characters and overall biomass production (Khanda *et al*., 1999; Maiti *et al*., 2005), and with similar dose-dependent forage yield responses reported in other *Vigna* and legume fodder crops under comparable phosphorus gradients (Polat *et al*., 2007). The proportionally larger gains in DMY and CPY relative to GFY reflect the concurrent rise in dry matter and CP percentage (Table 1), indicating that phosphorus improved not just the quantity but also the nutritive quality of the herbage.

TABLE 2
Effect of different P levels on fodder yield and quality of promising genotypes of forage rice bean

Treatments	GFY (q/ha)	DMY (q/ha)	CPY (q/ha)
Genotypes			
JOR-21-1	217.5	43.7	5.8
Bidhan-2	303.0	61.8	8.9
Bidhan-3	315.7	62.5	9.0
SEm ±	8.0	2.5	0.3
P_2O_5 levels (kg/ha)			
CD (P=0.05)	24.0	7.6	1.0
40	251.5	44.8	5.9
60	286.8	59.5	8.4
80	297.8	63.8	9.3
SEm ±	8.0	2.5	0.3
CD (P=0.05)	24.0	7.6	1.0

GFY-green fodder yield; DMY-dry matter yield; CPY-crude protein yield.

Production economics and energetics

The data on production economics and energy indices are presented in Table 3. Despite an identical cost of cultivation (Rs. 28,640/ha) across genotypes, Bidhan-3 generated the highest gross income (Rs. 78,925/ha), net income (Rs. 50,285/ha) and B:C ratio (2.75), followed closely by Bidhan-2 (2.64), both significantly outperforming JOR-21-1 (1.90). A similar trend was evident for energetics: energy input (Ei) was essentially uniform across genotypes (4,090 MJ/ha), while energy output (Eo), net energy (NE), energy-use efficiency (EUE) and energy productivity (EP) were all significantly higher in Bidhan-3 and Bidhan-2 than in JOR-21-1 (Table 3). Because the energy and monetary inputs were essentially constant across genotypes, these differences are attributable almost entirely to the higher biomass output of Bidhan-2 and Bidhan-3, reaffirming that genotype selection alone, independent of input cost is a powerful lever for improving both farm profitability and energy-use efficiency in forage rice bean.

Cost of cultivation rose only marginally with phosphorus dose (Rs. 27,590 to Rs. 29,690 ha^{-1} from 40 to 80 kg P_2O_5/ha), reflecting the comparatively low-cost share of phosphatic fertilizer in the overall input basket. Gross and net income increased significantly with phosphorus level, rising from Rs. 62,886 and Rs. 35,296/ha at 40 kg P_2O_5/ha to Rs. 74,450 and Rs. 44,760/ha at 80 kg P_2O_5/ha. Notably, the B:C ratio did not differ significantly between the 60 kg (2.50) and 80 kg (2.51) P_2O_5/ha levels, indicating that the marginal economic return diminished beyond 60 kg P_2O_5/ha even though absolute income continued to rise. This trend is consistent with earlier economic assessments of phosphorus response in forage legumes, which reported that profitability tends to plateau once phosphorus application reaches an agronomically effective level (Polat *et al*., 2007). Energy output, net energy, energy-use efficiency (EUE) and energy productivity (EP) increased progressively with increasing phosphorus application. EUE increased from 19.81 to 27.92, while EP increased from 1.10 to 1.55 as phosphorus application increased from 40 to 80 kg P_2O_5/ha. This improvement was primarily attributed to the relatively stable energy inputs across the treatments coupled with a substantial increase in biomass output under higher phosphorus levels, thereby enhancing the output-based energy indices. This aligns with the broader observation that legume-based forage systems, by virtue of biological nitrogen

fixation, tend to achieve high energy-use efficiency when other yield-limiting nutrients such as phosphorus are adequately supplied (Hoeppner *et al*., 2000; Manoj *et al*., 2022).

Eco-efficiency and carbon budgeting

Bidhan-3 recorded the highest eco-efficiency (12.3 Rs/MJ) and carbon efficiency (10.8), statistically at par with Bidhan-2 (11.5 and 10.7, respectively) and significantly higher than JOR-21-1 (6.3 and 7.7). Because carbon input was identical across genotypes (252 kg CO_2 equivalent (CE), driven by the common input package rather than genotype), the higher carbon output, carbon efficiency, carbon sustainability index and eco-efficiency of Bidhan-2 and Bidhan-3 aroused directly from their higher biomass productivity. A similar trend was observed for carbon footprint per unit yield (CFy). JOR-21-1 showed the highest CFy (77.6 kg CE Mg^{-1}), whereas Bidhan-3 recorded the lowest value (55.5). The lower CFy under Bidhan-3 suggests that its carbon emissions were spread over a larger quantity of forage produced, resulting in fewer emissions per unit of yield. This also indicates that selecting a suitable genotype can improve carbon efficiency without requiring any additional fertilizer input.

Carbon input rose with phosphorus dose (225.0 to 279.0 kg CE/ha from 40 to 80 kg P_2O_5/ha), reflecting the embedded energy and emissions costs of phosphatic fertilizer manufacture and application

TABLE 3

Effect of different P levels on production economics and energetics of promising genotypes of forage rice bean.

Treatments	Cost of cultivation (Rs./ha)	Gross income (Rs./ha)	Net income (Rs./ha)	B:C ratio	Ei (MJ/ha)	Eo (MJ/ha)	NE (MJ/ha)	EUE	EP (kg DMY/MJ)
Genotypes									
JOR-21-1	28640	54378	25737	1.90	4090	78622	74532	19.22	1.07
Bidhan-2	28640	75739	47099	2.64	4090	111328	107238	27.20	1.51
Bidhan-3	28640	78925	50285	2.75	4090	112511	108421	27.49	1.53
SEm ±	-	2003	2003	0.07	0	4557	4557	1.11	0.06
CD (P=0.05)	-	6004	6004	0.21	0	13661	13661	3.34	0.19
P_2O_5 levels (kg/ha)									
40	27590	62886	35296	2.28	4068	80597	76529	19.81	1.10
60	28640	71706	43065	2.50	4090	107070	102980	26.18	1.45
80	29690	74450	44760	2.51	4112	114794	110682	27.92	1.55
SEm ±	-	2003	2003	0.07	0	4557	4557	1.11	0.06
CD (P=0.05)	-	6004	6004	NS	0	13661	13661	3.34	0.19

Ei-energy input; Eo-energy output; NE-net energy; EUE-energy-use efficiency; EP-energy productivity.

TABLE 4

Effect of different P levels on eco-efficiency and carbon budgeting of promising genotypes of forage rice bean

Treatments	Eco-efficiency (Rs./MJ)	Carbon input (kg CE/ha)	Carbon output (kg CE/ha)	Carbon efficiency	Carbon sustainability index	Carbon footprint (kg CE/ha)	CFy (kg (CE/Mg)
Genotypes							
JOR-21-1	6.3	252.0	1922	7.7	6.7	335.3	77.6
Bidhan-2	11.5	252.0	2721	10.7	9.7	335.3	55.9
Bidhan-3	12.3	252.0	2750	10.8	9.8	335.3	55.5
SEm ±	0.5	-	111	0.4	0.4	-	2.7
CD (P=0.05)	1.5	-	334	1.3	1.3	-	8.1
P_2O_5 levels (kg/ha)							
40	8.7	225.0	1970	8.8	7.8	308.3	70.0
60	10.5	252.0	2617	10.4	9.4	335.3	58.5
80	10.9	279.0	2806	10.1	9.1	362.3	60.4
SEm ±	0.5	-	111	0.4	0.4	-	2.7
CD (P=0.05)	1.5	-	334	1.3	1.3	-	8.1

CFy-carbon footprint per unit yield.

(Plaza-Bonilla *et al.*, 2018). Carbon output and eco-efficiency increased correspondingly, but carbon efficiency and the carbon sustainability index peaked at 60 kg P_2O_5 ha^{-1} (10.4 and 9.4) rather than at 80 kg P_2O_5/ha (10.1 and 9.1) and total carbon footprint rose steadily with dose (308.3 to 362.3 kg CE/ha. Most importantly, the carbon footprint per Mg of biomass produced (CFy) declined from 70.0 kg CO_2-eq Mg^{-1} at 40 kg P_2O_5/ha to 58.5 kg CO_2-eq Mg^{-1} at 60 kg P_2O_5/ha, indicating improved carbon efficiency with the increase in phosphorus level. However, CFy increased slightly to 60.4 kg CO_2-eq Mg^{-1} at 80 kg P_2O_5/ha. This indicates that although 80 kg P_2O_5/ha maximized absolute yield and income, the environmentally optimal dose was 60 kg P_2O_5/ha, above which the extra carbon cost of fertilizer input outweighed the incremental biomass output, a trade-off consistent with findings that excessive fertilizer application in cropping systems can reduce the carbon-efficiency advantage otherwise provided by legumes (Manoj *et al.*, 2022; Plaza-Bonilla *et al.*, 2018).

CONCLUSION

The present study demonstrated that phosphorus nutrition is a key determinant of productivity, profitability, and environmental performance in forage rice bean. Results indicate that phosphorus application at 80 kg P_2O_5/ha maximized growth, forage yield, quality, net income and energy output, but the incremental economic return (B:C ratio) and carbon efficiency both plateaued or declined beyond 60 kg P_2O_5/ha, suggesting that this level offers the best balance between productivity, profitability and environmental sustainability. Among genotypes, Bidhan-3, closely followed by Bidhan-2, consistently outperformed JOR-21-1 in terms of yield, economic returns, energetics and carbon-related parameters. These improvements were achieved without any additional resource input, highlighting genotype selection as a practical and cost-effective approach for improving the sustainability of forage rice bean production, alongside appropriate phosphorus management.

REFERENCES

Bhattarai, S., S. Rai, N. Adhikari and G. Yadav, 2022 : Efficacy of different doses of NPK on growth and yield of rice bean (*Vigna umbellata*) in Khadbari, Sankhuwasabha, Nepal. *Archives of Agriculture and Environmental Science*, **7**(4): 488-494.

Bilal, S., Hazafa, A., Ashraf, I., Alamri, S., Siddiqui, M. H., Ramzan, A., Qamar, N., Sher, F. and Naeem, M. 2021 : Comparative effect of inoculation of phosphorus-solubilizing bacteria and phosphorus as sustainable fertilizer on yield and quality of mung bean (*Vigna radiata* L.). *Plants*, **10**(10): 2079.

Chandavanshi, M., M. Kumar, B. Pramanick, G. Nanda, S. K. Singh, and S. Kumar, 2026 : Legume intercropping and phosphorus management enhance the productivity and profitability of winter maize in calcareous soil. Plant Science Today, **13**(special): 1-8. https://doi.org.10.14719/pst.12955.

Department of Animal Husbandry and Dairying 2019 : *20th livestock census: All India report*. Ministry of Fisheries, Animal Husbandry and Dairying, Government of India.

Gomez, K.A. and A.A. Gomez, 1984 : Statistical Procedures for Agricultural Research. John Willey and Sons, New York.

Hoeppner, J. W., M. H. Entz, B. G. McConkey, G. P. Lafond and R. P. Zentner, 2000 : The role of forage legumes in reducing on-farm non-renewable energy use [Poster presentation]. *Soils and Crops Workshop*.

Jackson, M.I., 1973 : Soil Chemical Analysis. Prentice Hall of India Pvt. Ltd., New Delhi.

Khanda, C. M., A. K. Mohapatra and P. K. Misra, 1999 : Effect of nitrogen and phosphorus fertilization on growth, yield and nutrient uptake of winter rice bean (*Vigna umbellata*). *Indian Journal of Agronomy*, **44**(4): 791-794.

Maiti, S., A. K. Mukherjee, M. K. Nanda and S. Bhattacharya, 2005 : Effect of levels of phosphorus and dates of sowing on the productivity of ricebean when grown as a grain legume. *Crop and Weed*, **2**(2): 37-39.

Manoj, K. N., Shekara, B. G., Sridhara, S., Mudalagiriyappa, Chikkarugi, N. M., Gopakkali, P., Jha, P. K. and Prasad, P. V. V. 2022 : Carbon footprint assessment and energy budgeting of different annual and perennial forage cropping systems: A study from the semi-arid region of Karnataka, India. *Agronomy*, **12**(8): 1783.

Nanda, G., 2024 : Optimizing phosphorus fertilizer rates for maximizing forage yield and phosphorus use efficiency in Berseem (*Trifolium alexandrinum* L.) genotypes. *Forage Research*, **50**(2): 165-169.

Nanda, G. and Nilanjaya, 2022 : Yield, nitrogen use efficiency and economics of forage pearl millet as affected by genotypes and nitrogen levels. *Forage Research*, **48**(2):214-219.

Nanda, G., Agrawal, R. K. and Nilanjaya, 2024 : Production potential, profitability and nitrogen use efficiency of forage pearl millet varieties with nitrogen doses. Indian Journal of Ecology **51**(3): 537-541.

Nanda, G., Jha, S. K., Agrawal, R. K., Soni, J. K., Chand, S. and Yadav, V. K. 2025 : Enhancing forage efficiency: Insights from cultivar, nitrogen and cutting strategies in Pearl millet. Grass and Forage Science. 80(4): e70005.

Nanda, G., Nilanjaya. and A. K. S. Yadav, 2022 : Response of berseem genotypes to graded phosphorus levels. *Forage Research,* **48**(3): 215-220.

Nanda, G., Nilanjaya. and A. K. S. Yadav, 2023 : Response of forage cowpea genotypes to graded doses ofphosphorus application. *Forage Research,* **48**(4): 470- 473.

Nilanjaya and Nanda, G. 2019. Fodder and livestock scenario in Bihar. In: Indian Fodder Scenario: Redefining State Wise Status (Roy AK, Agrawal, RK and Bhardaj, NR Eds). All India Coordinated Research Project on Forage Crops and Utilization, Jhansi-284 003, India. Technical publication no. 06/2019 pp. 31-32.

Plaza-Bonilla, D., Nogué-Serra, I., Raffaillac, D., Cantero-Martínez, C. andJustes, É. 2018 : Carbon footprint of cropping systems with grain legumes and cover crops: A case-study in SW France. *Agricultural Systems,* **167**: 92-102.

Polat, T., Bükün, B. andOkant, M. (2007). Dose response effect of nitrogen and phosphorus on forage quality, yield and economic return of rangelands. *Pakistan Journal of Botany* **39**(1): 151-160.

Sabar, J., S. R. Anand, K. N. Kalyana Murthy, A. Rehaman and K. Murali, 2024 : Response of rice bean (*Vigna umbellata*) to different spacing and fertilizer levels under eastern dry zone of Karnataka. *Mysore Journal of Agricultural Sciences,* **58**(2): 131-142.

Samal, R. P., G. Nanda, M. Kumar and A. Sattar, 2023 ; Yield, quality and profitability of fodder oat varieties in response to different dates of sowing. *Forage Res.,* **48**(4): 43-47.

Singh, K. M., R. K. P. Singh, A. K. Jha and A. Kumar, 2012 : Understanding the fodder markets for sustainable development of livestock sector in Bihar- a rapid appraisal approach (MPRA Paper No. 47059). Munich Personal RePEc Archive. https://mpra.ub.uni-muenchen.de/47059/

Singh, K. M., Singh, R. K. P., Jha, A. K. and Kumar, Abhay. 2013 : Fodder market in Bihar: An exploratory study. *Economic Affairs,* **58**(4): 355-364.