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RESEARCH ARTICLE

Long-term legumes inclusion in basmati rice-based production systems improves soil physical and chemical properties in the Indo-Gangetic Plains

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Abstract

This field study was conducted at Sardar Vallabhbhai Patel University of Agriculture and Technology (SVPUAT), Meerut, India, to evaluate the long-term impact (7 years, 2016 -23) of legume inclusion on soil physical and chemical properties. The experiment employed a randomized block design (RBD) with four replications and tested 5 production systems: fallow, rice-wheat–dhaincha (*Sesbania*), rice-kabuli chickpea-mung bean, rice-chickpea–mung bean and rice-berseem–mung bean. Soil samples were collected at 3 depths (0–15 cm, 15–30 cm and 30–45 cm) and analyzed for key soil health indicators including porosity, water holding capacity (WHC), hydraulic conductivity (HC), bulk density (ρb), pH, electrical conductivity (EC), cation exchange capacity (CEC) and available nitrogen (N), phosphorus (P) and potassium (K). Among the production systems, the rice–berseem–mung bean system demonstrated the most significant improvements in soil health. At the 0–15 cm depth, porosity increased to 46.32 % , WHC to 48.65 % and HC to 1.94 cm hr^1, while ρb decreased to 1.323 mg m^{-3}, indicating enhanced soil structure and water retention over the fallow system. Chemical properties also improved, with CEC 26.75 C mol kg^1 and EC reduced to 0.12 dS m^{-1}, reflecting better nutrient retention and lower salinity under the legume embodied system over fallow. Nutrient availability was highest under this system, with available N at 240.75 kg ha^{-1}, P at 23.63 kg ha^{-1} and K at 279.50 kg ha^{-1}, followed by basmati rice-wheat- *Sesbania* system. These findings showed the potential of the rice–berseem–mung bean system to mitigate soil degradation by improving physical and chemical soil properties, enhancing nutrient availability and promoting sustainable rice farming in the Indo-Gangetic Plains (IGP).

Keywords: basmati rice; cropping systems; Indo-Gangetic Plains; nutrient availability; soil health

Introduction

Rice (*Oryza sativa* L.) is a staple crop in the Indo-Gangetic Plains (IGP), providing a primary source of food and livelihoods for millions. Despite its central role in food security, rice farming in the IGP is increasingly threatened by persistent soil degradation. This degradation is primarily driven by continuous monoculture practices, declining organic matter and imbalanced nutrient management, which collectively impair soil structure, reduce water retention, increase salinity and deplete essential nutrients, ultimately compromising crop productivity and long-term soil health (1). The conventional rice–wheat system, which dominates the IGP, has contributed to stagnating yields and deteriorating soil quality. Long-term reliance on this system has been shown to reduce microbial diversity, disrupt nutrient cycling and increase soil compaction. A study demonstrated that rice–legume–rice rotations not only increased cumulative grain yields by 7–16 % but also improved water-stable aggregation and organic carbon content in the 15–30 cm soil layer, highlighting the potential of diversified cropping systems to restore soil health (2). Crucial metrics for assessing soil health include physical properties such as porosity, water-holding capacity (WHC), hydraulic conductivity (HC) and bulk density (ρb), which are critical for root development, water movement and nutrient uptake. Earlier research found that soils under rice–chickpea and rice–lathyrus systems exhibited significantly better physical attributes than those under rice–wheat, with bulk density (ρb) reduced by 0.12 Mg m^{-3} and notable improvements in WHC and HC (3). Chemical features, including pH, electrical conductivity (EC) and cation exchange capacity (CEC), also respond positively to diversified cropping systems. A study observed that rice–vegetable pea–sorghum systems maintained stable EC and pH levels, suggesting improved nutrient retention and reduced salinity. Crops such as Dhaincha and Sunhemp have been shown to reduce fertilizer nitrogen (N) requirements by 30–100 kg ha^{-1} and to increase rice yield by up to 90 % when applied at 20 t ha^{-1} (4). It is further reported that the incorporation of such crops significantly increased soil available N, phosphorus (P) and potassium (K) after crop harvest, with dhaincha-treated plots showing the greatest increases (5). Nutrient availability is another vital component of soil health. An earlier study reported that the rice–legume system increased available N by 35.9 % , P by 14 % and K by 18 %

compared to rice–wheat (6). Despite these promising outcomes, there remains a critical need for site-specific evaluations of diversified rice-based cropping systems under varying agro-climatic conditions. The IGP, with its heterogeneous soil types and farming practices, demands tailored strategies to restore soil health and sustained productivity over time. In response to this need, the present research aimed to systematically analyze the consequences of legume-embedded rice-based cropping systems on soil health. The study aims to evaluate how different legume combinations influence soil physical properties such as porosity, water holding capacity, HC and ρb ; to examine changes in chemical properties, including pH, EC and CEC; and to quantify the availability of essential nutrients- N, P and K across the soil profile. Through this comprehensive assessment, the study seeks to identify the most effective legume-embedded basmati rice-based production system to foster healthier soil and promote sustainable agriculture in the IGP.

Materials and Methods

Site of experimentation and climatological conditions

The study was conducted at Sardar Vallabhbhai Patel University of Agriculture and Technology (SVPUAT), Meerut, situated in the IGP of western Uttar Pradesh, India. The geographical coordinates of the site are 29°40′ N and 77°42′ E, with an elevation of 237 m above sea level. This area has a subtropical, heat-prone climate with warm summers and cool winters and receives an average annual rainfall of approximately 750 mm. The study area's soil is grouped as Inceptisols (Typic Ustochrept), which are moderately developed alluvial soils typical of the Indo-Gangetic region.

Treatment details and layout

The experiment was laid out in a Randomized Block Design (RBD) with 5 production systems and 4 replications. The treatments consisted of different production systems designed to evaluate their impact on soil physical and chemical properties. The production systems included: fallow; basmati rice – wheat – dhaincha; basmati rice – kabuli chickpea – mung bean; basmati rice – chickpea – mung bean; and basmati rice – berseem – mung bean. Each treatment plot was managed according to standard agronomic practices and soil was sampled at 3 distinct layers: 0 – 15 cm, 15 – 30 cm and 30 – 45 cm. All treatment plots were managed as per the recommended package of practices. Fertilizers were applied according to standard crop recommendations and irrigation was uniformly provided based on crop requirements and prevailing weather conditions. Weed, pest and disease management were carried out as needed to minimize non-treatment-related variability in soil properties.

Soil sampling and analysis

To determine the influence of legumes on soil health, soil samples were collected from 3 depths (0 – 15, 15 – 30 and 30 – 45 cm) to represent the effective root zone of rice and legume-based cropping systems. Most root biomass, nutrient uptake and biological activity in rice occur within the upper 30 cm of soil, whereas legumes commonly develop deeper roots extending up to 45 cm. The 0 – 15 cm layer reflects surface soil processes and residue effects, the 15 – 30 cm layer captures active root growth and nutrient movement and the 30 – 45 cm layer represents deeper root influence and associated changes in soil properties. Thus, sampling up to 45 cm adequately captures the critical soil-root interactions relevant to all crops in the system. Within each replication, soil samples were collected from multiple places within each plot and composited for each depth. Accordingly, 4 independent composite samples per depth were obtained for each treatment, corresponding to the 4 replications. After collection, the samples were air-dried in shade, gently crushed using a wooden roller and passed through a 2.0 mm sieve to obtain uniform, representative samples suitable for laboratory analysis. The soil's physical properties were analyzed using established scientific protocols. Bulk density in mg m^{-3} was determined by core-based sampling, with oven-drying of soil samples at 105⊠ °C until a steady weight was reached, following a standardized procedure (7). From the ρb values, porosity was calculated using the standard formula:

$$\text{Porosity}\,(\%) = (1\text{-Bulk density} \div \text{Particle density}) \times 100 \qquad \text{(Eqn. 1)}$$

Soil sampling was carried out under near field-capacity conditions to minimize the influence of excessive moisture variability on ρb , WHC and HC measurements. To evaluate the soil's ability to retain moisture, the maximum water-holding capacity was measured using a standardized protocol (8). This method helped quantify the soil's capacity to hold water against gravity. Additionally, HC (cm h^{-1}), which reflects the ease with which water moves through soil pores, was estimated using the constant head method (9). The soil's chemical characteristics were also thoroughly examined. A glass electrode pH meter was used to measure soil pH in a 1:2.5 soil-water mixture (10). This helped determine the soil's acidity or alkalinity, which influences nutrient availability. Similarly, EC was assessed in the same suspension using a Wheatstone Conductivity Bridge, with results expressed in electrical conductivity per meter (11). Electrical conductivity values indicated the soluble salt content in the soil. The CEC, indicating how well the soil can retain and exchange essential nutrients, was determined using the ammonium acetate method (10). This parameter is vital for understanding the soil's fertility potential. For nutrient availability, available N was estimated using the alkaline potassium permanganate method (11), while available P and K were analyzed using standard procedures (10).

Statistical analysis

The experimental data were analyzed using Analysis of Variance (ANOVA) appropriate for a RBD, to assess the significance of treatment effects. Prior to analysis, data were tested for normality and homogeneity of variance to satisfy ANOVA assumptions. Treatment means were compared using the Least Significant Difference (LSD) test at $p = 0.05$. The standard error of the mean (SEm±) was calculated to assess the precision of the estimates. Correlation analysis of soil physical and chemical properties was performed and a correlation heat matrix was generated in R (version 4.5.1) for better visualization and interpretation of interrelationships.

Results and Discussion

Soil physical properties

The soil physical properties under different basmati rice-based production systems in the IGP revealed significant variations across soil depths and treatments. Soil porosity ranged from 42.61 % to 46.32 % at 0 – 15 cm, with the highest values observed in the basmati rice–berseem–mung bean system across soil depths (Table 1). This system showed a marked improvement in porosity compared to the fallow, which recorded the lowest values. The enhanced porosity under legume inclusive systems may be attributed to improved root architecture and organic matter input, which contribute to better soil structure (12). Other production systems also demonstrated notable effects on porosity over the fallow system. The basmati rice–kabuli chickpea–mung bean syestem recorded porosity of 46.15 % at 0–15 cm soil depth, while the basmati rice–chickpea–mung bean system showed 46.14 % at the same depth. These values, though slightly lower than those of the berseem embedded system, were still significantly higher than those of fallow (44.60 %), indicating that legume inclusion generally enhances soil aeration and structure. The WHC followed a similar trend. The basmati rice–berseem–mung bean system recorded the highest WHC at 48.65 % (0–15 cm), while the fallow had the lowest at 34.25 % (30–45 cm). The basmati rice–kabuli chickpea–mung bean and basmati rice–chickpea–mung bean systems showed intermediate WHC values of 46.23 % and 46.85 %, respectively, at the surface layer (0-15 cm depth). These results suggest that all legume-inclusive systems improve moisture retention, with berseem likely contributing most due to its deep roots and ability to enhance soil aggregation. Similar declines in WHC under fallow or less-diversified systems have been reported in recent long-term experiments in the IGP (13). The HC ranged from 1.35 to 1.94 cm hr^{1}, the highest value was observed in the basmati rice–berseem–mung bean system. This indicates superior water infiltration and reduced compaction, likely due to better root penetration and organic matter inputs. Similar improvements in HC under conservation agriculture and diversified production systems were reported in the Eastern IGP (12). Bulk density varied inversely with porosity and WHC, ranging from 1.323 to 1.532 mg m^{3}. The lowest pb was recorded at 0-15 cm soil depth under the basmati rice-berseem-mung bean system (1.323 mg m^{-3}), indicating a looser soil structure conducive to root growth and microbial activity. At 0-15 cm soil depth, basmati rice-kabuli chickpea–mung bean and basmati rice–chickpea–mung bean systems showed slightly higher pb of 1.334 and 1.336 mg m^{-3}, respectively, compared to the fallow (1.384 mg m^{-3}), which reflected compaction and poor soil aeration. These results are consistent with findings from a previous study, which reported reduced pb under conservation agriculture practices in rice–wheat–mung bean systems (14). Statistical analysis confirmed that differences among treatments were significant at $p = 0.05$. Overall, the inclusion of legumes such as berseem, kabuli chickpea and chickpea during the winter season and mung bean during the summer in rice-based cropping systems positively influenced soil physical properties. These improvements are likely due to enhanced organic matter input, better root dynamics and reduced soil disturbance, with the basmati rice–berseem–mung bean system consistently outperforming others in terms of soil structure and water-related parameters.

Soil chemical properties

The chemical characterization of soils under various basmati rice-based production systems in the IGP revealed distinct trends in EC, pH and CEC across soil depths and production systems (Table 2). These variations reflect the influence of crop diversity, organic inputs and root dynamics on soil chemical behavior. The EC indicates the concentration of soluble salts in the soil and consistently declined with increasing soil depth across all production systems. The fallow exhibited the highest EC values, reaching 0.24 dS m^{-1} at 0-15 cm depth, suggesting greater salt accumulation due to the absence of active nutrient uptake and organic cycling. In contrast, the basmati rice–wheat–dhaincha and basmati rice–berseem–mung bean systems recorded significantly lower EC values of 0.11 and 0.12 dS m^{-1}, respectively, at 30–45 cm soil depth. These reductions reflect improved salt management, likely facilitated by enhanced biological activity and root turnover. Similar improvements in EC through the incorporation of crops such as sunhemp, dhaincha and horse gram

Table 1. Effect of basmati rice-based production systems on soil physical properties

	Porosity (%)			WHC (%)			HC (cm hr^{-1})			Bulk density (Mg m^{-3})		
Soil depths (cm)	0-15	15-30	30-45	0-15	15-30	30-45	0-15	15-30	30-45	0-15	15-30	30-45
Production systems												
Fallow	44.60	43.98	42.61	43.25	40.63	34.25	1.53	1.46	1.35	1.384	1.449	1.532
Basmati rice-Wheat-Dhaincha	45.75	45.08	43.79	47.38	45.42	41.56	1.78	1.73	1.68	1.347	1.4171	1.494
Basmati rice-Kabuli chickpea-Mung bean	46.15	45.49	44.22	46.23	43.86	39.75	1.80	1.75	1.68	1.334	1.404	1.480
Basmati rice-Chickpea-Mung bean	46.14	45.48	44.19	46.85	43.55	40.50	1.77	1.71	1.66	1.336	1.405	1.4821
Basmati rice-Berseem-Mung bean	46.32	45.63	44.47	48.65	46.75	42.58	1.94	1.90	1.81	1.323	1.392	1.467
SEm±	0.53	0.47	0.56	0.38	0.59	0.63	0.04	0.05	0.06	0.020	0.021	0.015
LSD (p= 0.05)	1.56	1.38	1.66	1.12	1.75	1.89	0.11	0.13	0.18	0.059	0.064	0.043

Table 2. Effect of basmati rice-based production systems on soil chemical properties

	EC (dS m^{-1})			pH			CEC (C mol kg^{-1})		
Production systems									
Soil depths (cm)	0-15	15-30	30-45	0-15	15-30	30-45	0-15	15-30	30-45
Fallow	0.24	0.20	0.19	7.99	8.10	8.14	20.81	15.79	13.31
Basmati rice-Wheat-Dhaincha	0.17	0.14	0.11	7.71	7.81	7.88	25.03	19.58	17.78
Basmati rice-Kabuli chickpea-Mung bean	0.19	0.16	0.14	7.82	7.91	7.94	24.55	20.30	17.13
Basmati rice-Chickpea-Mung bean	0.20	0.17	0.15	7.84	7.89	7.91	24.10	19.39	17.16
Basmati rice-Berseem-Mung bean	0.18	0.15	0.12	7.65	7.75	7.78	26.75	22.39	18.75
SEm±	0.01	0.01	0.003	0.05	0.05	0.04	0.63	0.62	0.47
LSD (p= 0.05)	0.03	0.02	0.01	0.16	0.14	0.12	1.89	1.85	1.39

under regenerative farming systems in Karnataka, India (15). Soil pH values ranged from 7.65 to 8.14, indicating a slightly alkaline nature typical of alluvial soils in the IGP. The highest pH was observed in the fallow (8.14 at 30-45 cm depth), while the lowest was recorded in the basmati rice–berseem–mung bean system (7.78 at 30–45 cm soil depth). The reduction in pH under legume-based systems may be attributed to organic acid production during decomposition and root exudation, which buffers soil alkalinity. This trend is consistent with the findings of one study, who demonstrated that organic amendments and crop residue incorporation in rice–wheat–mung bean systems led to a gradual decline in soil pH, driven by enhanced microbial activity and carbon cycling (1).

The CEC, a key indicator of soil fertility and nutrient retention, showed marked improvement in diversified production systems. The basmati rice–berseem–mung bean system recorded the highest CEC value of 26.75 C mol kg^{1} at 0-15 cm soil depth, reflecting superior nutrient-holding capacity. The basmati rice-kabuli chickpea–mung bean and basmati rice-chickpea–mung bean systems also showed elevated CEC values of 24.55 and 24.10 C mol kg^{-1}, respectively, compared to the fallow, which had the lowest CEC of 20.81 C mol kg^{1} at 0-15 soil depth These improvements are likely due to increased organic matter inputs and better soil aggregation, which enhance the nutrient-holding and exchanging capability of the soil. The role of crop residues and organic amendments in enhancing nutrient buffering capacity in cereal–legume rotations was also earlier emphasized (16). Overall, the integration of legumes such as berseem, mung bean, kabuli chickpea and dhaincha into basmati rice-based systems significantly improved soil chemical properties. The observed reductions in EC and pH, coupled with enhanced CEC, suggest improved soil chemical health and greater resilience to nutrient depletion. These findings reinforce the conclusion that organic nutrient sources and residue management significantly influence the physicochemical properties of IGP soils (17).

Soil nutrient availability

The evaluation of soil nutrient status under various basmati rice-based production systems revealed substantial differences in the availability of N, P and K across treatments and soil depths (Table 3). These differences underscore the influence of cropping diversity and biological processes on soil fertility in the IGP. Among all systems studied, the basmati rice–berseem–mung bean combination consistently delivered the highest nutrient concentrations. At the surface layer (0–15 cm), available N in the soil reached 240.75 kg ha^{-1}, a notable increase over the fallow, which recorded only 184.25 kg ha^{-1}. This upward trend in N availability persisted through the deeper layers, indicating the system's capacity to enrich soil even beyond the root zone.

Soil P levels followed a similar pattern. The berseem embedded basmati rice-based system recorded 23.63 kg P ha^{-1} at 0–15 cm, soil depth, while the fallow lagged at 15.86 kg ha^{-1}. K availability was also highest in the berseem embedded basmati rice -based system, with 279.50 kg ha^{-1} at the surface, compared to 180.00 kg ha^{-1} under fallow. These differences were statistically significant, validating the effectiveness of diversified production systems in enhancing nutrient availability. The basmati rice–wheat–dhaincha system also showed strong performance, particularly in N enrichment, attributed to dhaincha' s well-documented ability to fix atmospheric N and contribute organic carbon to the soil (18, 19). Similarly, the basmati rice–kabuli chickpea–mung bean system demonstrated elevated nutrient levels, reinforcing the role of pulses in improving soil fertility through biological N fixation and residue decomposition. Berseem's deep rooting and high biomass production are likely associated with nutrient retention and translocation, while mung bean contributed to microbial stimulation and organic matter cycling. A study highlighted the importance of legumes in promoting nutrient mobilization and improving soil health through enhanced enzymatic activity (20). The inclusion of kabuli chickpea and chickpea also resulted in improved nutrient profiles, though not as pronounced as the berseem embedded basmati rice-based system. In contrast, the fallow system consistently recorded the lowest nutrient concentrations across all depths, underscoring the detrimental impact of leaving land uncultivated. Nutrient levels generally declined with depth across all treatments, as expected due to reduced biological activity and organic input in subsoil layers. However, systems involving legumes maintained relatively higher nutrient concentrations even at 30–45 cm, suggesting deeper nutrient movement and better root penetration. Taken together, these findings demonstrate that cropping systems integrating legumes significantly enhance soil nutrient availability in basmati rice cultivation. The basmati rice–berseem–mung bean system emerged as the most effective, followed closely by basmati rice–wheat–dhaincha, both of which suggest viable techniques to improve soil fertility and sustain agricultural productivity in the IGP. These results align with earlier studies emphasizing the value of organic amendments and pulse rotations in maintaining soil nutrient dynamics and long-term sustainability (18–21).

Correlation among soil properties

The correlation matrix heat map (Fig. 1) reveals key interrelationships among soil properties. Strong positive correlations are evident between CEC and porosity (0.94) and between WHC and porosity (0.94), suggesting that soils with higher

Table 3. Effect of basmati rice-based production systems on soil nutrient availability

	Available N (kg ha^{-1})			Available P (kg ha^{-1})			Available K (kg ha^{-1})		
Soil depths (cm)	0-15	15-30	30-45	0-15	15-30	30-45	0-15	15-30	30-45
Production systems									
Fallow	184.25	122.04	92.63	15.86	10.02	7.63	180.00	138.98	117.48
Basmati rice-Wheat-Dhaincha	226.25	151.22	113.69	22.63	14.79	11.36	259.75	200.54	167.73
Basmati rice-Kabuli chickpea-Mung bean	212.78	142.83	107.45	20.48	13.46	10.04	246.00	187.43	156.48
Basmati rice-Chickpea-Mung bean	211.13	142.02	105.27	20.22	13.43	9.91	243.33	180.87	157.32
Basmati rice-Berseem-Mung bean	240.75	161.31	115.91	23.63	15.71	11.86	279.50	213.16	185.71
SEm±	4.56	2.20	2.97	0.43	0.20	0.29	5.40	3.06	3.76
LSD (P= 0.05)	13.56	6.55	8.83	1.29	0.60	0.85	16.06	9.09	11.18

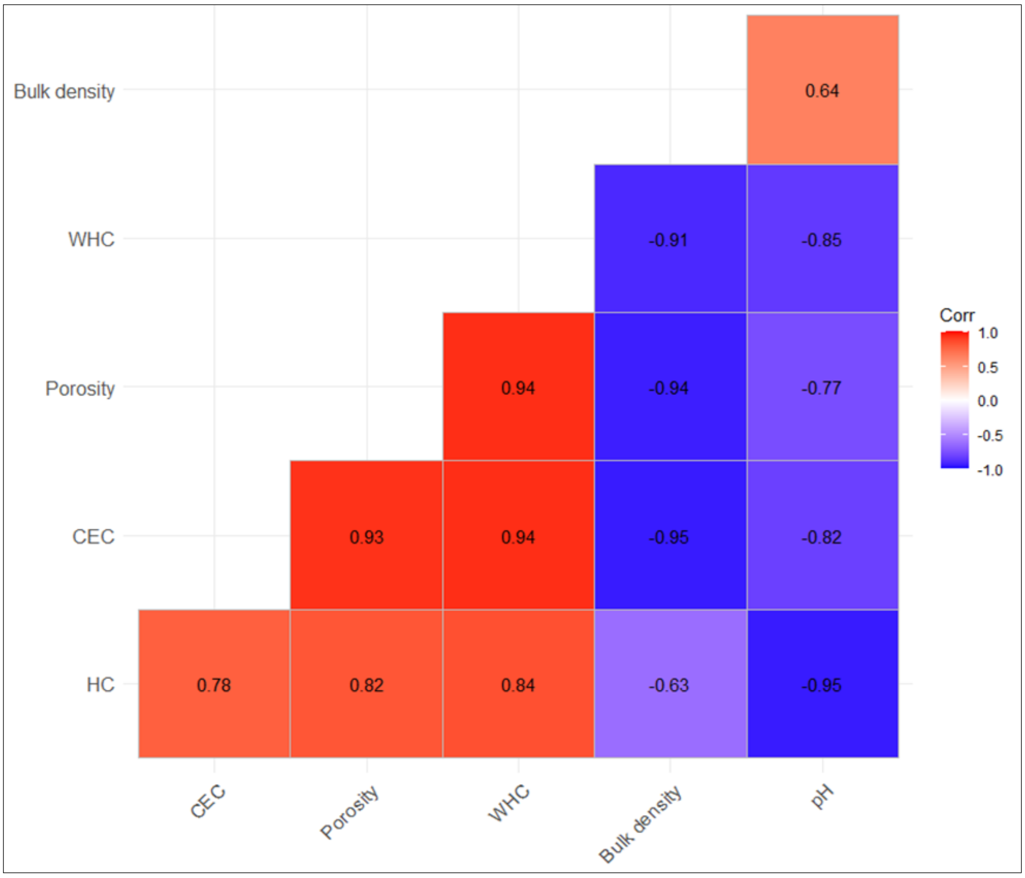

Fig. 1. The correlation matrix heatmap illustrates the relationships among soil properties: hydraulic conductivity (HC), cation exchange capacity (CEC), porosity, water holding capacity (WHC), bulk density and pH. Colour gradients range from red (strong positive correlation) to blue (strong negative correlation), with numerical values indicating the strength of the correlation.

CEC and WHC tend to be more porous. On the other hand, ρb shows strong negative correlations with WHC (-0.91) and porosity (-0.94), indicating that denser soils retain less water and have reduced pore space. Additionally, pH is negatively correlated with HC (-0.95), suggesting that higher hydrocarbon content is associated with lower pH. These findings show the interconnected nature of soil characteristics. For example, increased porosity enhances both nutrient retention, CEC and WHC, which are critical for plant growth. Conversely, high ρb may hinder root penetration and reduce soil aeration. Understanding these correlations is essential for soil management strategies, helping optimize conditions for agricultural productivity and environmental sustainability.

Conclusion

This study demonstrates that integrating legumes into basmati rice-based production systems can substantially strengthen soil health in the IGP. Among the systems evaluated, the rice-berseem-mung bean sequence proved most effective, consistently improving soil structure, nutrient availability and overall physico-chemical functioning of soil. These benefits highlight the capacity of legume-supported rotations to mitigate soil degradation and enhance long-term system resilience compared to conventional rice-wheat production systems. While the findings are promising, they reflect conditions specific to the experimental site and may vary with soil type, climate and management history. Potential interactions with factors such as microbial activity, residue quality and seasonal variability were beyond the scope of this study and require further investigation. Future research should explore multi-location trials, long-term monitoring of soil biological responses and the inclusion of additional legume species or diversified rotations to optimize system performance and support broader scalability across the region. The outcomes of this study offer valuable insights for shaping agricultural policy in the IGP, particularly regarding soil restoration and sustainable food production. The demonstrated effectiveness of the basmati rice-berseem–mung bean production system in improving soil physical properties and nutrient availability calls for strategic policy support to encourage its wider adoption. To begin with, national and regional agricultural programs should actively incentivize legume-based production systems through financial subsidies, input support. For wider promotion extension training modules should emphasize the agronomic and ecological benefits of integrating legumes into basmati rice-based production systems, supported by demonstration plots and farmer field schools.

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Authors' contributions

SK[1] investigated, curated data, performed formal analysis and wrote the original draft. UPS conceptualized and supervised the venture. SK[2] supervised, reviewed and edited the manuscript. YK, V and KK reviewed and edited the manuscript. All authors read and approved the final manuscript [SK[1] stands for Sanjeev Kumar and SK[2] stands for Satendra Kumar].

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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