Plant Archives Vol. 26, Supplement 2, 2026 pp.613-618 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org

DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2026.v26.supplement-2.069

SUSTAINABLE INTENSIFICATION THROUGH CROPPING SYSTEM DIVERSIFICATION: IMPACTS ON NUTRIENT DYNAMICS AND SOIL HEALTH IN THE INDO-GANGETIC PLAINS

Vaibhav Pandey[1*], M. Z. Siddiqui[1], Aalok Kumar[2], Abhishek Mishra[1], and Deepak Kumar Dwivedi[2]

[1]Department of Agronomy, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur-208002, Uttar Pradesh, India.

[2]SNRM, College of PG Studies in Agricultural Sciences, (Central Agricultural University-Imphal), Umiam, 793 103, Meghalaya, India

*Corresponding author E-mail: vaibhavagroofficial@gmail.com

(Date of Receiving : 04-03-2026; Date of Revision : 16-04-2026; Date of Acceptance : 10-05-2026)

ABSTRACT

Cropping system diversification plays a crucial role in sustaining soil health and enhancing nutrient availability in the Indo-Gangetic Plains. A field experiment was conducted during 2023–24 and 2024–25 at the Student's Instructional Farm of Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, under the All India Coordinated Research Project on Integrated Farming Systems. In order to determine the effects of ten different cropping systems on the chemical characteristics of the soil and the availability of nutrients, the study used a randomized block design with four replications. The findings showed that cropping systems had a moderate impact on the electrical conductivity and pH of the soil, both of which stayed within safe bounds for all treatments. Nonetheless, under legume-based systems, notable gains in soil organic carbon and nutrient availability were noted. In addition to having the best available nitrogen (239.02 kg ha^{-1}), phosphorus (16.22 kg ha^{-1}), and potassium (227.90 kg ha^{-1}), the Blackgram–Chickpea + Mustard system (CSSc3) also had the greatest organic carbon (0.52%). These gains were ascribed to rhizosphere acidification, improved biomass addition, biological nitrogen fixation, and effective nutrient recycling. The traditional rice-wheat system, on the other hand, showed comparatively poorer soil fertility. The results show that adding legumes to cropping systems greatly enhances soil health and nutrient dynamics, providing the Indo-Gangetic Plains with a viable substitute for conventional cereal-based systems.

***Keywords*:** Sustainable Intensification, Cropping System, Diversification, Nutrient Dynamics, Soil Health, Indo-Gangetic Plains.

Introduction

India's agriculture is currently struggling to maintain output while protecting natural resources in the face of growing population pressure and unpredictable weather. One of the most vital agricultural areas is the Indo-Gangetic Plain (IGP), where intensive cereal-based cropping systems, especially rice-wheat, greatly contribute to the nation's food security. While the rice-wheat system was instrumental in increasing food grain production during the Green Revolution, decades of continuous cultivation have resulted in a number of agronomic, environmental, and economic challenges, such as yield stagnation, declining soil fertility, groundwater depletion, and growing cultivation costs. The stability and resilience of ecosystems have been negatively impacted by agricultural intensification, which has led to simplified production systems with less crop diversity and more genetic uniformity (Abdulkadir, 2023). These monoculture-based systems are more susceptible to nutrient imbalances, insect outbreaks, and climate stress. Cropping system diversity has become a viable tactic to boost output, increase resource efficiency, and preserve ecological equilibrium in this setting. By adding legumes, oilseeds, fodder crops, and high-value crops to cereal-based systems, diversification improves soil health, boosts nutrient cycling, and strengthens system resilience. Numerous studies have shown how varied cropping systems improve crop productivity and growth. Legumes increase soil fertility and crop performance by improving biological nitrogen fixing and lowering reliance on chemical fertilizers. Because of the complementary interactions between component crops, diversified systems also encourage effective use of water, nutrients, and solar radiation. Because of this, these systems frequently show greater yield stability and system productivity than traditional monocropping systems.

Diversification of rice-wheat systems has demonstrated encouraging outcomes in increasing production and profitability in the Indo-Gangetic Plain. According to Banjara *et al.* (2022), when compared to the conventional rice–wheat system, rice-based diversified systems including rice–berseem–cowpea and rice–potato–green gram considerably improved growth metrics, yield attributes, nutrient uptake, and economic returns. Higher grain yields and more effective resource use resulted from the addition of legumes and fodder crops, which enhanced soil fertility and system efficiency. Additionally, varied systems showed increased economic returns and energy productivity, suggesting that they are suitable for sustainable intensification. Cropping systems have a significant impact on nutrient dynamics because various crops have varied patterns of nutrient uptake and contributions to soil fertility. While diverse systems increase nutrient availability and uptake through improved biological processes and the addition of organic matter, continuous cereal cultivation frequently results in nutrient mining and imbalance. Increased agricultural output and decreased environmental concerns from excessive fertilizer usage are two benefits of improved nutrient-use efficiency.

Another essential element of sustainable agriculture is soil health, which is greatly impacted by cropping system management. By raising soil organic carbon, boosting microbial activity, and strengthening soil structure, diversified cropping systems improve the physical, chemical, and biological characteristics of soil. These enhancements support improved nutrient availability, water retention, and the production system's long-term viability. From an economic standpoint, diversification presents chances to lower production risks and increase farm profitability. Due to resource limitations and rising input costs, traditional rice-wheat systems are losing money. Diversified systems, on the other hand, offer greater returns due to improved productivity, lower input costs, and a variety of revenue streams. Incorporating high-value and short-duration crops increases overall profitability and cropping intensity, making diversification a financially feasible choice for farmers in the IGP. Adoption of diverse cropping systems is still restricted despite their well-established advantages because of factors like ignorance, market volatility, and management difficulties unique to a given area. Therefore, in order to find profitable and sustainable alternatives to traditional systems, a thorough assessment of several agricultural systems under the agro-ecological conditions of the Indo-Gangetic Plain is crucial.

Materials and Methods

Experimental Site and Climatic Conditions

The field experiment was conducted during two consecutive years (2023–24 and 2024–25) at the Student's Instructional Farm, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, Uttar Pradesh, India. The study was carried out under the All India Coordinated Research Project (AICRP) on Integrated Farming Systems, focusing on need-based cropping system diversification in the Indo-Gangetic Plains. The experimental site is in the central part of the Indo-Gangetic alluvial plains of Uttar Pradesh and is characterized by a subtropical climate with distinct seasonal variations. The region experiences hot summers, cold winters, and a monsoon season with variable rainfall distribution. The mean annual rainfall of the region ranges from 850 to 900 mm, of which approximately 85–90% is received during the southwest monsoon period from June to September. The onset of monsoon generally occurs during the third week of June. Winters are typically cold and dry, with occasional frost events affecting crop growth during December and January. The experimental field was well leveled with uniform topography and had adequate irrigation and drainage facilities to ensure proper crop establishment and growth. The soil of the experimental site was alluvial in nature with characteristics suitable for medium land cropping. The mean morning RH ranged from 36% to 96% with an average of 81.50%, whereas afternoon relative humidity varied from 16% to 81% with a mean of 53.33%. A total rainfall of 1118.90 mm was received during the study period. The total evaporation recorded during the experimental period was 1237.20 mm, while bright sunshine hours totaled 279.90 hours.

Experimental design and Treatment Allocation

A randomized block design with ten different cropping system treatments with four replications (Table 1).

Table 1 : Evaluation of Ten cropping system treatments

Treatment	Symbol	Treatments details
T_1	CSSc1	Hybrid rice – Wheat
T_2	CSSc2	Hybrid maize – Wheat
T_3	CSSc3	Blackgram – chickpea + Mustard
T_4	CSSc4	Hybrid Maize + Black gram – Chickpea + Linseed
T_5	CSSc5	Hybrid Rice – Veg. Pea + Mustard
T_6	CSSc6	Hybrid Maize – Chickpea + Mustard
T_7	CSSc7	Maize + Cow pea (Fodder) – Berseem
T_8	CSSc8	Maize + Cow pea (Fodder) – Oat
T_9	CSSc9	Maize (Cob) – Potato + Mustard
T_{10}	CSSc10	Okra – Veg. Pea + Mustard

Agronomic Management

The established agronomic guidelines for the region were adhered to for all crops in the diverse sequences. Fertilizers were applied to the plants at optimal rates for each crop, both at the base and as a top dressing. Irrigation timing was enhanced to satisfy the crops physiological requirements during critical growth phases. To mitigate biotic stress, all experimental plots employed identical integrated weed management strategies, encompassing mechanical methods, pre- and post-emergence chemical treatments, and preventive plant protection measures.

Soil Sampling and Analytical Protocols

Following the conclusion of the 2023–24 and 2024–25 cropping cycles, representative post-harvest soil samples were taken from the active rhizosphere (0–15 cm depth) across all treatment plots in order to quantitatively evaluate the impact of cropping system variety on soil health indices. The composite soil samples were shade-dried at room temperature, gently mashed with a wooden mortar and pestle, and then sieved through a 2-mm stainless steel screen before being examined in the lab.

The pH and electrical conductivity (EC), has been measured at a 1:2.5 (w/v) soil to water aqueous suspension. A digital glass electrode pH meter was utilized to measure the pH, and a conductivity bridge was used to measure the EC. The conventional Walkley and Black wet oxidation method was employed to determine the soil's organic carbon content which utilizes wet oxidation of organic matter with potassium dichromate ($K_2Cr_2O_7$) and sulfuric acid (H_2SO_4). The alkaline potassium permanganate method was employed to determine the amount of nitrogen (N) present in the ground wherein the liberated ammonia was captured in boric acid during distillation followed by back titration against standard sulfuric acid. Olsen's reagent (0.5 M $NaHCO_3$ at pH 8.5) was used to determine the sample's phosphorus (P) content. To determine the amount, we employed both a spectrophotometer and the ascorbic acid method. To measure the amount of potassium (K) Neutral normal ammonium acetate (1 N NH_4OAc at pH 7.0) was used to extract exchangeable and water-soluble potassium and subsequent quantification was performed using flame photometer.

Statistical Analysis

We used Analysis of Variance for a Randomized Block Design to examine all soil analysis. To observe how the treatment performed, we separated the variance components. The Standard Error of the Mean (SEm) was utilized to determine the degree of agreement between the estimated and actual means. The significance of the mean differences between the cropping system treatments was thoroughly examined using the Least Significant Difference (LSD) post-hoc test with a 95% confidence interval (< 0.05).

Results and Discussion

Soil Chemical Properties

The soil chemical properties (Tab. 2 and Fig. 1) were moderately influenced by cropping systems. Soil pH remained slightly alkaline across treatments, indicating minimal effect of cropping systems on soil reaction. Electrical conductivity remained within the safe range, suggesting no salinity hazard. However, organic carbon content showed noticeable variation, with higher values recorded under CSSc3 (0.52%) followed by CSSc4 and CSSc6. The increase in organic carbon under these systems may be attributed to the inclusion of legumes and greater biomass addition, which enhances soil organic matter. The response of the soil was statistically significantly affected by the various crop varieties. This demonstrates how pulse-based systems can alter the rhizosphere. In the 2023–2024 and 2024–2025 seasons, the pH of the baseline Hybrid rice–Wheat sequence (CSSc1). This was consistently elevated. Conversely, adding rotations that included a lot of legumes significantly reduced the soil's alkalinity. At 8.12, the Blackgram – Chickpea + Mustard system (CSSc3) had the lowest soil pH. Hybrid Maize + Black Gram – Chickpea + Linseed (CSSc4), the system in second place, received an 8.15. From 0.31 dS/m in CSSc2 to 0.43 dS/m in CSSc6, the electrical conductivity (EC) decreased somewhat but not significantly. The Indo-Gangetic Plains (IGP) soils have been negatively impacted by the traditional rice-wheat cropping system (RWCS) because it maintains excessively high pH levels, which hinders the availability of nutrients (Yadav *et al.*, 2025). Because the same legumes were repeatedly cultivated in the same location, the pH of the soil significantly decreased in the CSSc3 and CSSc4 treatments. The soil surrounding the roots becomes slightly more acidic due to the active release of organic acids by pulse crops, such as citric and malic acids (Upadhaya *et al.*, 2022; Alekhya *et al.*, 2025). Unlike continuous production of the same cereal type, this localized acidification improves the micro-environment for microbial activity and nutrient solubilization.

When different crops were planted, the amount of Soil Organic Carbon that accumulated varied significantly. With an OC level of 0.52%, the CSSc3 treatment maintained the highest carbon content throughout the investigation. The CSSc4 system's OC was 0.50%, which was extremely similar to the CSSc1 system's OC. The organic carbon content of the okra-based CSSc10 sequence was significantly lower, at just 0.45%. Puddling and compacting the soil exacerbate carbon loss in conventional grain systems (Yadav *et al.*, 2025). Conversely, pulse-based systems produce waste with a low C:N ratio and a high carbon content (Alekhya *et al.*, 2025). This composition makes it easier for microbes to consume carbon, which accelerates the process of converting wastes into stable organic matter rather than losing them as carbon dioxide (Upadhaya *et al.*, 2022). When the roots of pulses and other plants cooperate, a glycoprotein known as glomalin is produced. It aids in the retention of carbon in systems like CSSc3. Small soil particles are adhered to create stable macro-aggregates that stop carbon from oxidizing quickly over time (Singh *et al.*, 2019; Alekhya *et al.*, 2025).

Table 2: Effect of cropping system diversification on soil pH, EC, and organic carbon (%).

Treatment	pH		EC		Organic carbon (%)	
	2023-24	2024-25	2023-24	2024-25	2023-24	2024-25
CSSc1	8.22	8.22	0.32	0.32	0.45	0.45
CSSc2	8.21	8.21	0.31	0.31	0.47	0.47
CSSc3	8.12	8.12	0.40	0.40	0.52	0.52
CSSc4	8.15	8.15	0.41	0.41	0.50	0.50
CSSc5	8.18	8.18	0.31	0.31	0.46	0.46
CSSc6	8.17	8.17	0.43	0.43	0.49	0.49
CSSc7	8.19	8.19	0.33	0.33	0.46	0.46
CSSc8	8.21	8.21	0.37	0.37	0.46	0.46
CSSc9	8.20	8.20	0.32	0.32	0.48	0.48
CSSc10	8.19	8.19	0.34	0.34	0.45	0.45
LSD ($p \leq 0.05$)	0.046	0.046	0.013	0.013	0.023	0.023
SE (m)	0.015	0.015	0.004	0.004	0.007	0.007

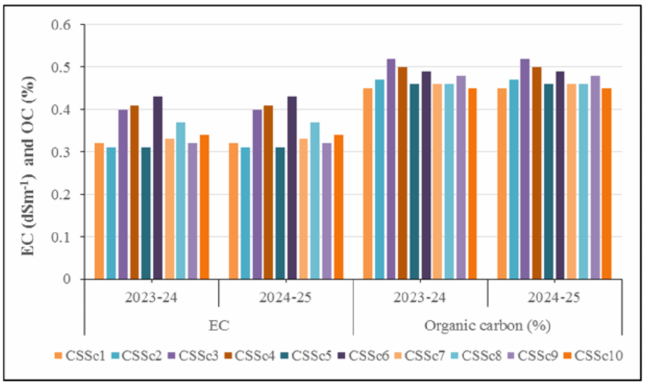

Fig. 1 : Effect of cropping system diversification on EC, and Organic Carbon (%).

Available Nutrient Status

The amount of nitrogen accessible for all treatments (Tab. 3 and Fig. 2), with the exception of CSSc8, increased briefly between 2023–2024 and 2024–2025. The CSSc3 system performed better statistically. At 234.02 kg/ha in 2023–2024 and 239.02 kg/ha in 2024–2025, it provided the most nitrogen. At 205.20 kg/ha and 206.20 kg/ha, the CSSc1 baseline values were significantly below average. The remarkable increase in nitrogen availability highlights the benefits of biological nitrogen fixing for the ecosystem. Traditional rice-wheat rotations frequently transfer nitrate below the active root zone and deplete soil nitrogen (Singh *et al.*, 2019). You can also retain nitrogen in the soil for a brief period of time if you store a lot of C:N rice straw (Yadav *et al.*, 2025). By combining blackgram with chickpea, the CSSc3 sequence fixes nitrogen from the atmosphere using Rhizobium, which is found in plant roots. This preserves a lot of nitrogen in the topsoil and satisfies the natural needs of the pulses (Upadhaya *et al.*, 2022; Ghosh *et al.*, 2025). Because of their deep roots, these pulses also function as a biological net. Nitrate that would otherwise leak out is captured by them and returned to the top layer (Singh *et al.*, 2019). Phosphorus was highest in the CSSc3 system (15.12 kg/ha; 16.22 kg/ha) and CSSc4 system (14.42 kg/ha and 14.98 kg/ha). With only 12.50 kg/ha and 13.10 kg/ha of P available, the CSSc1 system had the least amount. The acidity of the rhizosphere brought on by legumes is directly related to the significant increase in accessible phosphorus. When pulse roots emit organic acids, calcium phosphates, which are prevalent in the calcareous soils of the IGP and difficult to dissolve, decompose. These orthophosphates can be utilized by the body (Upadhaya *et al.*, 2022; Alekhya *et al.*, 2025). The highest amount of potassium was 224.90 kg/ha in 2023–2024 and 227.90 in 2024–2025. In contrast, the CSSc1 system only achieved 201.25 kg/ha and 205.50 kg/ha. The negative consequences of potassium mining associated with standard RWCS are effectively mitigated by the CSSc3 and CSSc4 systems. Both wheat and rice require a lot of potassium to grow. The potassium that is accessible for exchange is rapidly depleted when they are constantly grown (Singh *et al.*, 2019). This is exacerbated by burning crop debris, which can lose up to 85% of the absorbed potassium (Yadav *et al.*, 2021). In order to obtain potassium, the pulses in CSSc3 have deep taproots that penetrate lower soil strata (Alekhya *et al.*, 2023). Potassium is added to the soil by these plants' frequent leaf loss. Without relying solely on synthetic fertilizers, this is a natural method of replenishing the active topsoil zone with nutrients (Singh *et al.*, 2019; Alekhya *et al.*, 2025).

Table 3: Effect of cropping system diversification on nutrient dynamics

Treatment	Available N (kg/ha)		Available P (kg/ha)		Available K (kg/ha)	
	2023-24	2024-25	2023-24	2024-25	2023-24	2024-25
CSSc1	205.20	206.20	12.50	13.10	201.25	205.50
CSSc2	212.40	216.40	12.60	13.80	206.57	208.65
CSSc3	234.02	239.02	15.12	16.22	224.90	227.90
CSSc4	225.92	229.92	14.42	14.98	218.20	222.62
CSSc5	220.55	226.55	14.03	15.03	200.45	204.87
CSSc6	218.95	224.95	13.88	14.38	214.30	217.89
CSSc7	212.70	216.70	13.76	14.56	204.47	208.67
CSSc8	207.55	2012.55	13.67	14.67	198.92	200.89
CSSc9	201.40	208.40	13.47	14.33	210.85	216.07
CSSc10	215.82	221.82	13.77	14.37	197.27	200.75
LSD ($p \leq 0.05$)	**4.53**	**4.59**	**0.56**	**0.58**	**0.65**	**0.68**
SE (m)	**1.51**	**1.53**	**0.18**	**0.18**	**0.21**	**0.22**

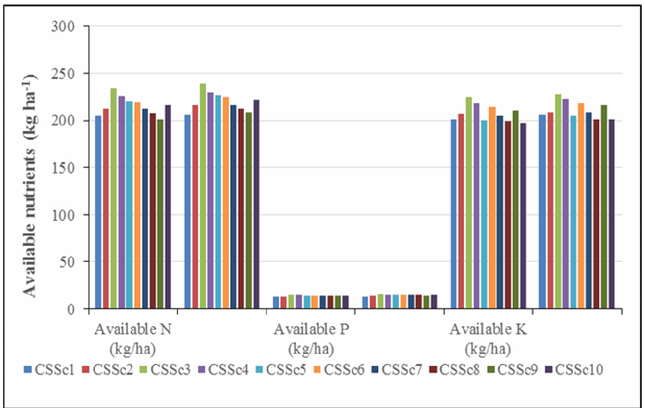

Fig. 2: Effect of cropping system diversification on nutrient dynamics

Conclusion

The study clearly demonstrates that cropping system diversification, particularly through the inclusion of legume-based sequences, substantially enhances soil health and nutrient availability compared to conventional cereal-based systems. The Blackgram–Chickpea + Mustard (CSSc3) and Hybrid Maize + Blackgram–Chickpea + Linseed (CSSc4) systems outperformed the other treatments in terms of enhancing soil organic carbon, lowering soil alkalinity, and raising nitrogen, phosphate, and potassium availability. Improved nutrient recycling processes, rhizosphere changes, organic matter addition, and biological nitrogen fixation are the main drivers of these advantages. The conventional rice-wheat system, on the other hand, demonstrated somewhat reduced soil fertility and little change in soil characteristics, suggesting that it is not long-term sustainable under intense cultivation. The findings highlight how including pulses into cropping systems improves soil quality and supports sustainable agricultural production in the Indo-Gangetic Plains. Adopting diverse, legume-based cropping systems can therefore be a practical way to preserve soil productivity, enhance nitrogen balance, and guarantee the region's long-term agricultural viability.

References

Abdulkadir, A. (2023). Agricultural intensification and crop diversification: Implications for productivity, environmental sustainability, and resilience of agro-ecosystems. *Agricultural Systems*, **210**, 103680.

Banjara, T. R., Singh, V., Kumar, R., & Singh, A. (2022). Diversification of rice–wheat cropping system for enhancing productivity, nutrient uptake, and economic efficiency under Indo-Gangetic Plains. *International Journal of Plant & Soil Science*, **34**(20), 1–12.

Ghosh, S., Das, T. K., Raj, R., Sudhishri, S., Mishra, A. K., Biswas, D. R., Bandyopadhyay, K. K., Ghosh, S., Susha, V. S., Roy, A., Alekhya, G., Saha, P., & Sharma, T. (2025). Long-term conservation agriculture improves water-nutrient-energy nexus in maize-wheat-greengram system of South Asia. *Frontiers in Sustainable Food Systems*, **9**, 1470188. https://doi.org/10.3389/fsufs.2025.1470188

Gora, M. K., Kumar, S., Jat, H. S., Kakraliya, S. K., Choudhary, M., Dhaka, A. K., Jat, R. D., Kakraliya, M., Sharma, P. C., & Jat, M. L. (2022). Scalable diversification options deliver sustainable and nutritious food in Indo-Gangetic Plains. *Scientific Reports*, **12**, 14371.

Hobbs, P. R., Sayre, K., & Gupta, R. (2008). The role of conservation agriculture in sustainable agriculture. *Philosophical Transactions of the Royal Society B*, **363**, 543–555.

Ladha, J. K., Pathak, H., Krupnik, T. J., Six, J., & van Kessel, C. (2005). Efficiency of fertilizer nitrogen in cereal production: Retrospects and prospects. *Advances in Agronomy*, **87**, 85–156.

Scopel, E., Triomphe, B., Affholder, F. *et al.* (2012). Conservation agriculture cropping systems in temperate and tropical conditions: Performances and impacts. *Agronomy for Sustainable Development*, **33**, 113–130.

Alekhya, G., Darjee, S., Rajareddy, G., Reddy, A. J., & Reddy, K. S. (2025). Crop diversification with pulses for enhancing soil nutrient dynamics in conservation agriculture. *Current Science*, **129**(5), 425–433. https://doi.org/10.18520/cs/v129/i5/425-433

Shahane, A. A., & Shivay, Y. S. (2019). Viable options for diversification of rice in Indo-Gangetic Plains. *International Journal of Bio-resource and Stress Management*, **10**(4), 352–363.

Singh, R. K., Bohra, J. S., Nath, T., Singh, Y., & Singh, K. (2011). Diversification of rice–wheat cropping system for sustainable productivity in Indo-Gangetic Plains. *Journal of Crop Improvement*, **25**(4), 371–385.

Singh, V. K., Dwivedi, B. S., Mishra, R. P., Shukla, A. K., Timsina, J., Upadhyay, P. K., Shekhawat, K., Majumdar, K., & Panwar, A. S. (2019). Yields, soil health and farm profits under a rice-wheat system: Long-term effect of fertilizers and organic manures applied alone and in combination. *Agronomy*, **9**(1), 1. https://doi.org/10.3390/agronomy9010001

Tilman, D., Reich, P. B., & Knops, J. (2006). Biodiversity and ecosystem stability in grasslands. *Nature*, **441**, 629–632.

Upadhaya, B., Kishor, K., Kumar, V., Kumar, N., Kumar, S., Yadav, V. K., Kumar, R., Gaber, A., Laing, A. M., Brestic, M., & Hossain, A. (2022). Diversification of rice-based cropping system for improving system productivity and soil health in Eastern Gangetic Plains of India. *Agronomy*, **12**(10), 2393. https://doi.org/10.3390/agronomy12102393

Yadav, R., Yadav, S., Krishna, Devi, G., Jyoti, & Rubal. (2025). Sustainable intensification and climate resilience in the rice-wheat cropping system of North-Western India: Challenges and strategies. *Journal of Experimental Agriculture International*, **47**(1), 171–185. https://doi.org/10.9734/jeai/2025/v47i13215.