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NUTRIENT UPTAKE, SOIL FERTILITY DYNAMICS AND SUSTAINABILITY OF DIVERSIFIED RICE-BASED CROPPING SYSTEMS IN EASTERN INDIA

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ABSTRACT

Diversification of rice–based cropping systems can substantially influence nutrient uptake, nutrient balance and soil fertility under irrigated conditions. A field experiment was conducted during 2021–22 and 2022–23 at the Central Research Station, Odisha University of Agriculture and Technology, Bhubaneswar. Ten diversified rice–based cropping systems were evaluated for nitrogen (N), phosphorus (P) and potassium (K) uptake, apparent nutrient balance, nutrient depletion, soil quality index (SQI) and changes in soil physicochemical properties. Total nitrogen uptake by the systems ranged from 113.6 to 212.3 kg ha^{-1}, while total phosphorus and potassium uptake varied from 22.3 to 37.5 kg ha^{-1} and 96.9 to 173.8 kg ha^{-1}, respectively. Total nutrient uptake was higher in legume- and fodder-based systems, whereas P and K removal was greater in vegetable-based systems. All the systems demonstrated a decrease in soil bulk density and an increase in organic carbon compared to starting values with the legume- and vegetable-based systems showing the highest improvement. Soil available N, P and K decreased in all agricultural systems although the magnitude of nutrient depletion was relatively smaller in systems with legumes and green manure. Based on apparent nutritional balance studies, fodder and high biomass generating systems had a higher level of nutrient mining, especially potassium, while legume-based systems had a more favourable nutrient balance. Soil quality index values indicated superior soil health under green manure- and legume-inclusive cropping systems. Principal component analysis identified soil organic carbon, water holding capacity and available nitrogen as the major contributors governing variability among diversified rice-based cropping systems. The study demonstrates that diversification of rice–based cropping systems significantly affects nutrient dynamics, enhances soil quality and sustainability, and improves soil physical condition under irrigated conditions in eastern India.
Keywords **:** Nutrient balance; Nutrient depletion; Soil quality index; Principal component analysis; Cropping system diversification; Sustainability

Introduction

Rice based cropping systems dominate the irrigated agro-ecosystems of eastern India and are vital for food and livelihood security (Tuti *et al*., 2018). However, continuous rice agriculture or less diverse rice-based sequences typically results in the nutrient imbalance, soil degradation and decreased system productivity (Shankar *et al*., 2021). Intensive nutrient mining and inadequate replenishment has become a serious constrain for maintaining of soil fertility and crop production in such systems. The integration of legumes, fodder and vegetable crops in rice-based farming systems has been promoted as a viable method for improving nutrient use efficiency, soil health and long-term sustainability (Srinivasan, 2025). Diversified cropping systems may alter biomass production, residue return and biological nutrient cycling, and thereby alter nutrient dynamics (Liu *et al*., 2024).

Legumes inclusion increases biological nitrogen fixation, augments soil organic carbon and increases nutrient availability for subsequent crops (Neda, 2021). Similarly fodder and vegetable crops also have a considerable impact on the uptake of nutrients and nutritional status of the soil because of their high biomass output and need for nutrients. understanding nutrient absorption pattern in various rice-based cropping systems is important for the optimisation of fertiliser management and reduction of soil nutrient depletion under intense irrigation condition. Assessment of apparent nutrient balance and nutrient depletion provides valuable information on nutrient mining and the long-term sustainability of cropping systems.

Long-term experiments provide good insights on the cumulative impact of cropping system diversity on soil physicochemical characteristics and nutrient dynamics. Changes in the bulk density, water holding capacity, organic carbon content and accessible nutrients of the soil are markers of soil quality and sustainability. Integration of these indicators through a Soil Quality Index (SQI) enables comprehensive evaluation of soil health under diversified cropping systems. Furthermore, multivariate approaches such as Principal Component Analysis (PCA) facilitate the identification of key soil and nutrient-related variables governing system performance and sustainability.

There is very little evidence available on the effect of diverse rice-based cropping systems on nitrogen absorption and soil fertility in irrigated ecosystems in eastern India. In this context, the current research was attempted to examine the absorption patterns of nitrogen, phosphorous and potassium and changes in soil physicochemical parameters under diverse rice–based cropping systems in irrigated eastern India. The experiment seeks to discover nutrient-efficient cropping systems to increase soil health and to provide sustainable intensification of rice-based cropping systems.

Despite the importance of diversified rice-based cropping systems, information on their influence on nutrient uptake, nutrient balance, nutrient depletion and soil quality under irrigated ecosystems of eastern India remains limited. Most previous studies have focused primarily on productivity and economics, while comprehensive assessments integrating nutrient dynamics, soil quality indicators and sustainability metrics are scarce.

In this context, the present investigation was undertaken to evaluate the uptake of nitrogen (N), phosphorus (P) and potassium (K), apparent nutrient balance, nutrient depletion, and changes in soil physicochemical properties under diversified rice-based cropping systems in irrigated eastern India. The study also aimed to assess soil quality through SQI and identify the major factors influencing system sustainability using PCA. The findings are expected to identify nutrient-efficient and sustainable cropping systems capable of improving soil health and supporting the sustainable intensification of rice-based agriculture.

Materials and Methods

Experimental Site

The experiment was conducted during 2021–22 and 2022–23 at the Central Research Station, Odisha University of Agriculture and Technology, Bhubaneswar, Odisha (20°26′ N, 85°81′ E, 25.9 m above mean sea level). Ten rice–based cropping systems were evaluated in a randomized block design with three replications under irrigated conditions. The data presented in tables are pooled mean values of two years. The region experiences a tropical humid climate characterized by hot summers and mild winters. The mean annual rainfall is approximately 1970.5 mm, most of which is received during the southwest monsoon season (June–September). Before initiation of the experiment, composite soil samples (0–15 cm depth) were collected and analysed. The soil was sandy loam in texture with pH 5.98, electrical conductivity (EC) 0.25 dS m^{-1}, organic carbon 6.8 g kg^{-1}, available nitrogen 290 kg ha^{-1}, available phosphorus 13.8 kg ha^{-1} and available potassium 196 kg ha^{-1}.

Experimental Design and Cropping Systems

The experiment was laid out in a randomized block design (RBD) with three replications. Ten diversified rice-based cropping systems were evaluated under irrigated conditions:

Table 1 : Treatment details

Treatment	*Kharif*	*Rabi*	Summer
T_1	Rice	Groundnut	Okra
T_2	Rice	Green gram	Sesame
T_3	Rice	Groundnut	Cowpea (vegetable)
T_4	Rice	Frenchbean	Greengram
T_5	Rice	Rapeseed	Greengram
T_6	Rice	Groundnut	Greengram
T_7	Rice	Oat (fodder)	Cowpea (fodder)
T_8	Rice	Maize (fodder)	Cowpea (fodder)
T_9	Scented rice	Potato	Okra
T_{10}	Scented rice	Sweetcorn	Bittergourd

The recommended package of practices for each crop was followed throughout the study period. Fertilizer application was carried out according to the recommended dose of fertilizers for individual component crops as detailed in Table 2.

Table 2 : Crop wise recommended fertilizer dose

Season	Crop	Fertilizer dose ($N:P_2O_5:K_2O$) (kg ha^{-1})
Kharif	Rice	80:40:40
Rabi	Groundnut	20:40:40
	Rapeseed	60:30:30
	*French bean	40:80:80
	Potato	120:80:120
	*Sweetcorn	80:40:40
	Greengram	20:40:20
	Oat (fodder)	60:30:30
	Maize (fodder)	60:30:30
Summer	*Okra	80:40:40
	Sesamum	60:30:30
	*Cowpea (vegetable)	25:50:50
	Greengram	20:40:20
	*Bittergourd	60:25:50
	Cowpea (fodder)	20:40:20

*Final plucking date

Crop Management Practices

Field preparation, sowing, transplanting, irrigation and plant protection measures were undertaken following the recommended agronomic practices of Odisha University of Agriculture and Technology. Rice was grown during the kharif season under irrigated conditions, followed by rabi and summer crops according to the respective cropping sequences. Recommended doses of nitrogen, phosphorus and potassium fertilizers were applied through urea, single superphosphate (SSP) and muriate of potash (MOP), respectively.

Soil Sampling and Analysis

After completion of each cropping cycle, soil samples were collected from the surface layer (0–15 cm depth) of each experimental plot. The samples were air-dried, ground and passed through a 2-mm sieve prior to laboratory analysis.

Soil pH and EC were determined in a 1:2.5 soil-water suspension using digital pH and EC meters. Organic carbon was estimated by the Walkley and Black wet oxidation method. Bulk density was determined using the core sampler method and water-holding capacity was estimated by the Keen box method. Available nitrogen was determined by the alkaline permanganate method, available phosphorus by Bray's extraction method and available potassium by neutral normal ammonium acetate extraction followed by flame photometric determination.

Estimation of Nutrient Uptake

Representative samples of grain/economic yield and straw/by-product yield from each crop were collected at harvest. The plant samples were oven dried at 65 ± 5°C until constant weight, ground and analyzed for nutrient content.

Nitrogen concentration was determined using the micro-Kjeldahl method. Phosphorus concentration was estimated by using a spectrophotometer, whereas potassium concentration was determined using a flame photometer.

Nutrient uptake was computed as:

Nutrient uptake (kg ha^{-1}) = Nutrient concentration (%) × Dry matter yield (kg ha^{-1}) / 100

Total nutrient uptake of each cropping system was obtained by summing nutrient uptake values of all component crops.

Apparent Nutrient Balance

Apparent nutrient balance was calculated to assess nutrient mining or accumulation under different cropping systems. The balance was estimated separately for nitrogen, phosphorus and potassium as:

Apparent Nutrient Balance = Total Nutrient Added − Total Nutrient Removed

where nutrient added refers to the total quantity of fertilizer nutrients applied to all crops in a cropping sequence and nutrient removed refers to the total nutrient uptake by the cropping system.

Positive values indicate nutrient accumulation, whereas negative values indicate nutrient depletion or nutrient mining.

Nutrient Depletion Percentage

Nutrient depletion percentage was calculated to quantify the extent of reduction in available soil nutrients after completion of the cropping sequence.

Percentage Nutrient Depletion = [(Initial Nutrient − Final Nutrient) / Initial Nutrient] × 100

where initial nutrient refers to the nutrient status of the soil before initiation of the experiment and final nutrient refers to post-harvest available nutrient status.

Soil Quality Index (SQI)

Soil quality was assessed using a Soil Quality Index (SQI) based on selected physical and chemical soil indicators, namely bulk density, water-holding capacity, organic carbon, available nitrogen, available phosphorus and available potassium.

The linear scoring technique was used for normalization of indicators. For indicators where higher values were desirable (organic carbon, water-holding capacity and available nutrients), scores were calculated by dividing the observed value by the maximum observed value. For indicators where lower values were desirable (bulk density), scores were calculated by dividing the minimum observed value by the observed value.

The normalized scores were integrated using the simple additive index approach:

$$SQI = \Sigma Si / n$$

where Si is the normalized score of the ith indicator and n is the total number of indicators used.

Higher SQI values indicate better soil quality and sustainability. The range of SQI is 0-1.

Principal Component Analysis

Principal component analysis (PCA) was performed using standardized data of soil physicochemical properties and nutrient uptake variables. The variables included bulk density, water-holding capacity, organic carbon, available nitrogen, available phosphorus, available potassium and total N, P and K uptake.

PCA was employed to identify major factors contributing to variability among diversified rice-based cropping systems and to determine relationships between soil quality indicators and nutrient dynamics. Components with eigenvalues greater than one were retained for interpretation.

Statistical Analysis

The experimental data were subjected to analysis of variance (ANOVA) appropriate for a randomized block design. Treatment means were compared using the least significant difference (LSD) test at the 5% level of significance. Standard error of mean (SEm±) and critical difference (CD) values were calculated wherever treatment effects were significant. All statistical analyses were performed using OPSTAT software, while principal component analysis was carried out using R software.

Results and Discussion

Nutrient Uptake by Crops under Diversified Rice-Based Cropping Systems

The uptake of nitrogen (N), phosphorous (P) and potassium (K) was significantly impacted by the various rice-based cropping systems (Table 3). Total nitrogen intake varied between 113.62 and 212.34 kg ha^{-1} across the systems. Maximum N uptake (212.34 kg ha^{-1}) was obtained in Rice-Groundnut-Greengram system followed by Rice-Oat-Cowpea (198.82 kg ha^{-1}) and Rice-Maize (fodder)-Cowpea (197.05 kg ha^{-1}) and minimum in Rice-Greengram-Sesame (113.62 kg ha^{-1}).

The phosphorus uptake ranged from 22.34 to 37.50 kg ha^{-1}. Maximum uptake was recorded in Scented Rice–Potato–Okra (37.50 kg ha^{-1}) followed by Rice–Groundnut–Okra (33.43 kg ha^{-1}). Higher P absorption in vegetable-based systems may be attributed to higher biomass accumulation, intense root growth and higher fertiliser responsiveness under high input farming systems.

Potassium intake varied from 96.89 to 173.78 kg ha^{-1} with maximum in Rice–Oat–Cowpea (173.78 kg ha^{-1}) and Scented Rice–Potato–Okra (173.24 kg ha^{-1}). The potassium absorption was higher in fodder and vegetable-based systems owing to larger biomass yields and better nutrient extraction from the soil-plant systems.

The total nutrient intake varied from 232.84 to 402.93 kg ha^{-1}. The maximum total nutrient intake was found in rice-oat-cowpea system (402.93 kg ha^{-1}) with higher system production and nutritional need followed by scented rice-potato-okra (379.03 kg ha^{-1}) and rice maize (fodder)-cowpea systems (366.72 kg ha^{-1}). The least overall uptake was in Rice–Greengram–Sesame system indicating relatively lower biomass output and nutrient requirement. Overall, diversity with fodder and vegetable crops significantly improved nutrient absorption, emphasising the necessity for balanced and better nutrient management techniques in intensive cropping systems. These findings have also been reported by Bastia (2008), Patra *et al.* (2019), Patra *et al.* (2021) and Srinivasan (2025).

Soil Physicochemical Properties

The effect of different rice–based cropping systems on soil physicochemical properties are presented in Table 4. Bulk density decreased in all cropping systems compared to the initial value (1.42 Mg m^{-3}), indicating improvement in soil structure due to continuous cropping and organic matter addition. The lowest bulk density (1.31 Mg m^{-3}) was recorded under the GM–rice–groundnut–cowpea (vegetable) system, likely due to greater root biomass and organic residue incorporation. Soil pH remained nearly stable across all systems. Electrical conductivity also remained within safe limits, suggesting no salinity build–up under irrigated conditions. Water holding capacity increased in all systems compared to the initial status, with the highest value (44%) observed in the GM–rice–groundnut–cowpea (vegetable) system, reflecting improved soil aggregation and organic matter content. Soil organic carbon increased in all cropping systems from the initial value of 6.8 g kg^{-1}. The highest organic carbon content was observed in the GM–rice–groundnut–cowpea (vegetable) system (7.33 g kg^{-1}), followed by GM–rice–frenchbean–greengram and scented rice–potato–okra systems (7.27 g kg^{-1}). The increase in organic carbon can be attributed to higher biomass addition, root residues and inclusion of legumes and vegetables. The results demonstrate that legume–, fodder– and vegetable–based diversified rice systems enhance improve soil physical properties and increase soil organic carbon under irrigated conditions. Similar results were also recorded by Cagna *et al.* (2026), Kachroo *et al.* (2014) and Patra *et al.* (2019).

Available Soil Nutrient Status

Available nitrogen, phosphorus and potassium status after completion of the cropping sequences are presented in Table 5. Although nutrient levels declined compared with the initial soil status, the extent of depletion varied among cropping systems.

Green manure- and legume-based systems maintained relatively higher available nitrogen levels due to biological nitrogen fixation and improved nutrient recycling. Similarly, these systems showed better retention of available phosphorus and potassium compared with fodder-based systems.

Fodder-based systems recorded comparatively lower available nutrient levels because of greater nutrient extraction through biomass removal. Vegetable-based systems also exhibited substantial nutrient removal owing to their high nutrient demand

Table 3 : Total N, P and K uptake by crops under diversified rice-based cropping systems

Cropping system	Total uptake (kg ha^{-1})			Total nutrient (N+P+K) uptake by the system (kg ha^{-1})
	N	p	K	
Rice–groundnut–okra	160.84	33.43	149.05	343.31
Rice–greengram–sesame	113.62	22.34	96.89	232.84
GM–rice–groundnut–cowpea (veg)	194.94	28.39	130.29	353.62
GM–rice–frenchbean–greengram	161.83	29.06	108.69	299.58
Rice–rapeseed–greengram	128.44	26.33	101.61	256.38
Rice–groundnut–greengram	212.34	27.44	103.00	342.78
Rice–oat–cowpea (fodder)	198.82	30.33	173.78	402.93
Rice–maize (fodder)–cowpea (fodder)	197.05	30.84	138.83	366.72
Scented rice–potato–okra	168.29	37.50	173.24	379.03
Scented rice–sweetcorn–bittergourd	145.14	26.62	107.48	279.24
SEM (±)	4.8	0.85	5.3	7.20
CD (P=0.05)	14.1	2.5	15.6	21.20

Table 4 : Soil physicochemical properties and organic carbon after completion of cropping cycles

Cropping system	Bulk density (Mg m^{-3})	WHC (%)	Soil pH	EC (dS/m^{-1})	Organic carbon (g kg^{-1})
Rice–groundnut–okra	1.33	39	6.0	0.31	6.93
Rice–greengram–sesame	1.34	40	6.0	0.30	7.00
GM–rice–groundnut–cowpea (veg)	1.31	44	5.9	0.32	7.33
GM–rice–frenchbean–greengram	1.32	41	6.4	0.32	7.27
Rice–rapeseed–greengram	1.33	40	6.1	0.29	7.20
Rice–groundnut–greengram	1.34	39	5.5	0.31	7.13
Rice–oat–cowpea (fodder)	1.34	39	6.1	0.30	7.00
Rice–maize (fodder)–cowpea (fodder)	1.35	39	6.0	0.30	6.87
Scented rice–potato–okra	1.35	41	6.0	0.30	7.27
Scented rice – sweetcorn–bittergourd	1.36	40	6.1	0.31	7.07
SEM (±)	0.010	0.65	0.15	0.007	0.10
CD (P=0.05)	0.029	1.92	0.44	0.021	0.30
Initial values of soil physicochemical properties	1.42	38.4	5.98	0.25	6.8

Table 5 : Post-harvest available N, P and K status of soil

Cropping system	Available nutrient (kg ha^{-1})		
	N	P	K
Rice–groundnut–okra	267	11.1	168.0
Rice–greengram–sesame	267	11.5	172.0
GM–rice–groundnut–cowpea (veg)	289	12.2	177.3
GM–rice–frenchbean–greengram	288	12.5	174.7
Rice–rapeseed–greengram	273	12.3	172.0

Rice–groundnut–greengram	264	11.6	175.3
Rice–oat–cowpea (fodder)	263	11.7	177.3
Rice–maize (fodder)–cowpea (fodder)	263	11.8	164.7
Scented rice–potato–okra	283	11.9	178.0
Scented rice – sweetcorn–bittergourd	271	11.6	172.7
SEM (±)	5.8	0.30	3.8
CD (P=0.05)	17.1	0.89	11.2
Initial values of soil physicochemical properties	290	13.8	196

Apparent Nutrient Balance

Apparent nutrient balance differed markedly among the diversified rice-based cropping systems (Table 6), reflecting variations in fertilizer inputs and nutrient removal through crop uptake. Positive balance values indicate nutrient accumulation in the soil, whereas negative values indicate nutrient depletion or mining.

The apparent nitrogen balance ranged from +111.71 to −92.34 kg ha^{-1}. The highest positive nitrogen balance was recorded in Scented Rice–Potato–Okra (+111.71 kg ha^{-1}), followed by Scented Rice–Sweetcorn–Bittergourd (+74.86 kg ha^{-1}), Rice–Greengram–Sesame (+46.38 kg ha^{-1}) and Rice–Rapeseed–Greengram (+31.56 kg ha^{-1}). In contrast, Rice–Groundnut–Greengram recorded the most negative nitrogen balance (−92.34 kg ha^{-1}), followed by GM–Rice–Groundnut–Cowpea (veg) (−69.94 kg ha^{-1}). The negative nitrogen balance in these systems was mainly due to higher nitrogen uptake exceeding the quantity of nitrogen applied.

All cropping systems exhibited a positive phosphorus balance, ranging from +78.38 to +130.94 kg ha^{-1}. The maximum phosphorus balance was observed in GM–Rice–Frenchbean–Greengram (+130.94 kg ha^{-1}), followed by Scented Rice–Potato–Okra (+122.50 kg ha^{-1}) and GM–Rice–Groundnut–Cowpea (veg) (+101.61 kg ha^{-1}). The consistently positive phosphorus balance across systems indicates that phosphorus application exceeded crop removal, resulting in phosphorus accumulation in the soil.

Potassium balance varied from −53.78 to +31.31 kg ha^{-1}. The highest positive potassium balance was recorded in GM–Rice–Frenchbean–Greengram (+31.31 kg ha^{-1}), followed by Scented Rice–Potato–Okra (+26.76 kg ha^{-1}) and Scented Rice–Sweetcorn–Bittergourd (+22.52 kg ha^{-1}). However, several systems showed negative potassium balances, with the greatest depletion observed in Rice–Oat–Cowpea (fodder) (−53.78 kg ha^{-1}), followed by Rice–Groundnut–Okra (−29.05 kg ha^{-1}) and Rice–Maize (fodder)–Cowpea (fodder) (−18.83 kg ha^{-1}). The negative potassium balance in fodder-based systems can be attributed to their high biomass production and consequent removal of large quantities of potassium.

Overall, the results indicate that while phosphorus accumulated in all cropping systems, nitrogen and potassium balances varied considerably depending on crop composition and nutrient uptake patterns. Systems involving fodder crops and high-yielding legumes tended to mine nitrogen and potassium, whereas vegetable-based systems with higher fertilizer inputs maintained positive nutrient balances. These findings highlight the importance of nutrient balance assessment for developing sustainable nutrient management strategies in diversified rice-based cropping systems.

Table 6 : Apparent N, P and K balance under diversified rice-based cropping systems in kg ha^{-1}

Cropping system	Total N applied	Total P_2O_5 applied	Total K_2O applied	Total N uptake	Total P uptake	Total K uptake	Apparent N balance	Apparent P balance	Apparent K balance
Rice–Groundnut–Okra	180	120	120	160.84	33.43	149.05	+19.16	+86.57	-29.05
Rice–Greengram–Sesame	160	110	90	113.62	22.34	96.89	+46.38	+87.66	-6.89
GM–Rice–Groundnut–Cowpea (veg)	125	130	130	194.94	28.39	130.29	-69.94	+101.61	-0.29
GM–Rice–Frenchbean–Greengram	140	160	140	161.83	29.06	108.69	-21.83	+130.94	+31.31
Rice–Rapeseed–Greengram	160	110	90	128.44	26.33	101.61	+31.56	+83.67	-11.61
Rice–Groundnut–Greengram	120	120	100	212.34	27.44	103.00	-92.34	+92.56	-3.00
Rice–Oat–Cowpea (fodder)	165	120	120	198.82	30.33	173.78	-33.82	+89.67	-53.78
Rice–Maize (fodder)–Cowpea (fodder)	165	120	120	197.05	30.84	138.83	-32.05	+89.16	-18.83
Scented Rice–Potato–Okra	280	160	200	168.29	37.50	173.24	+111.71	+122.50	+26.76
Scented Rice–Sweetcorn–Bittergourd	220	105	130	145.14	26.62	107.48	+74.86	+78.38	+22.52

Table 7 : Nutrient depletion (%) from soil under diversified rice-based cropping systems

Cropping system	Final N (kg ha^{-1})	N depletion (%)	Final P (kg ha^{-1})	P depletion (%)	Final K (kg ha^{-1})	K depletion (%)
Rice–Groundnut–Okra	267	7.93	11.1	19.57	168.0	14.29
Rice–Greengram–Sesame	267	7.93	11.5	16.67	172.0	12.24
GM–Rice–Groundnut–Cowpea (veg)	289	0.34	12.2	11.59	177.3	9.54
GM–Rice–Frenchbean–Greengram	288	0.69	12.5	9.42	174.7	10.87
Rice–Rapeseed–Greengram	273	5.86	12.3	10.87	172.0	12.24
Rice–Groundnut–Greengram	264	8.97	11.6	15.94	175.3	10.56
Rice–Oat–Cowpea (fodder)	263	9.31	11.7	15.22	177.3	9.54
Rice–Maize (fodder)–Cowpea (fodder)	263	9.31	11.8	14.49	164.7	15.97
Scented Rice–Potato–Okra	283	2.41	11.9	13.77	178.0	9.18
Scented Rice–Sweetcorn–Bittergourd	271	6.55	11.6	15.94	172.7	11.89

Soil Quality Index (SQI)

The Soil Quality Index (SQI) effectively integrated various soil indicators into a single sustainability metric (Table 8). SQI values ranged from lower values in fodder-dominated systems to higher values in green manure- and legume-inclusive systems.

The highest SQI was recorded in Green Manure–Rice–Groundnut–Cowpea, followed by Green Manure–Rice–Frenchbean–Greengram and Scented Rice–Potato–Okra. These systems exhibited favourable soil physical properties, higher organic carbon content and better nutrient availability.

The lower SQI observed in fodder-based systems may be attributed to greater nutrient depletion and comparatively lower improvement in soil quality parameters.

The findings indicate that diversified cropping systems involving legumes and green manure contribute substantially to soil quality improvement and long-term sustainability.

Table 8 : Soil Quality Index of diversified rice-based cropping systems

Cropping system	SQI
Rice–Groundnut–Okra	0.924
Rice–Greengram–Sesame	0.938
GM–Rice–Groundnut–Cowpea (veg)	0.995
GM–Rice–Frenchbean–Greengram	0.976
Rice–Rapeseed–Greengram	0.951
Rice–Groundnut–Greengram	0.936
Rice–Oat–Cowpea (fodder)	0.939
Rice–Maize (fodder)–Cowpea (fodder)	0.911
Scented Rice–Potato–Okra	0.969
Scented Rice–Sweetcorn–Bittergourd	0.935

Principal Component Analysis (PCA)

Principal Component Analysis (PCA) explained 70.2% of the total variation, with PC1 and PC2 contributing 45.4% and 24.8%, respectively. The biplot showed a strong positive association among organic carbon (OC), water holding capacity (WHC), and available N, P, and K, indicating improved soil fertility under diversified cropping systems. Bulk density (BD) was negatively associated with these parameters, suggesting that lower soil compaction favoured better soil health. Nutrient uptake traits (N, P, and K uptake) were positively correlated and clustered together. The GM–Rice–Groundnut–Cowpea (veg) system was closely associated with higher soil fertility attributes, whereas the Scented Rice–Potato–Okra system was linked with greater nutrient uptake. Overall, legume- and vegetable-based cropping systems exhibited superior soil quality and nutrient dynamics compared to other systems.

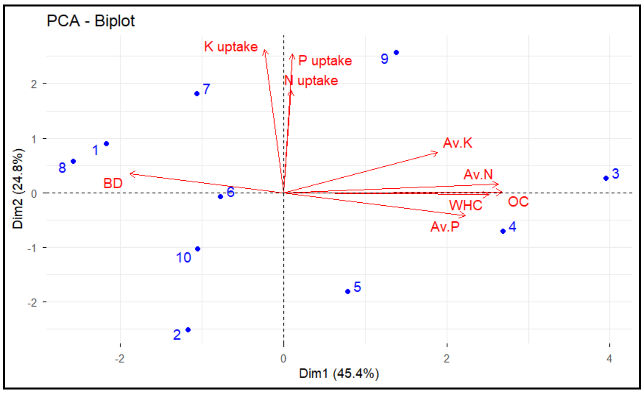

Fig. 1 : PCA biplot showing association among soil properties, nutrient uptake and cropping systems

Sustainability Ranking of Cropping Systems

Based on nutrient balance, nutrient depletion, soil quality index and PCA interpretation, the cropping systems were ranked for sustainability (Table 9).

Green Manure–Rice–Groundnut–Cowpea emerged as the most sustainable system owing to its superior soil quality, favourable nutrient balance and lower nutrient depletion. Green Manure–Rice–Frenchbean–Greengram and Scented Rice–Potato–Okra also performed well. In contrast, fodder-based systems ranked lower because of greater nutrient mining and potassium depletion.

Table 9 : Sustainability ranking of diversified rice-based cropping systems

Rank	Cropping system	Sustainability status
1	GM–Rice–Groundnut–Cowpea (vegetable)	Very High
2	GM–Rice–Frenchbean–Greengram	Very High
3	Scented Rice–Potato–Okra	High
4	Rice–Rapeseed–Greengram	High
5	Rice–Groundnut–Greengram	Moderately High
6	Rice–Greengram–Sesame	Moderate
7	Rice–Groundnut–Okra	Moderate
8	Scented Rice–Sweetcorn–Bittergourd	Moderate
9	Rice–Oat–Cowpea (fodder)	Low
10	Rice–Maize (fodder)–Cowpea (fodder)	Very Low

Conclusion

The present study demonstrated that diversification of rice-based cropping systems significantly influenced nutrient uptake, soil fertility and soil physical properties under irrigated conditions of eastern India. Total N, P and K uptake varied considerably among the systems, with legume-, fodder- and vegetable-based sequences exhibiting greater nutrient acquisition than conventional systems. Inclusion of legumes and green manure crops improved nutrient cycling, enhanced soil organic carbon and contributed to better maintenance of soil fertility.

All diversified systems reduced soil bulk density and improved water-holding capacity and organic carbon content compared to the initial soil status, indicating improvement in soil physical health. Although available N, P and K declined across all systems due to continuous cropping, the extent of nutrient depletion was lower in systems involving legumes and green manure. Soil Quality Index (SQI) and PCA further confirmed the superiority of these systems in sustaining soil health and nutrient availability.

Among the evaluated systems, GM–Rice–Groundnut–Cowpea (vegetable) emerged as the most sustainable cropping sequence, followed by GM–Rice–Frenchbean–Greengram and Scented Rice–Potato–Okra, owing to their higher soil quality, better nutrient balance and lower nutrient depletion. In contrast, fodder-based systems exhibited greater nutrient mining, particularly of potassium, which may compromise long-term sustainability if nutrient replenishment is not ensured.

Overall, the study highlights that incorporation of green manure and legume crops into rice-based cropping systems is an effective strategy for improving nutrient use efficiency, maintaining soil fertility and enhancing the sustainability of irrigated agriculture in eastern India. These systems can be recommended for sustainable intensification and long-term productivity of rice-based farming systems in the region.

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