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RESEARCH ARTICLE

Crop diversification and intensification improve productivity, profitability and nutrient recycling in rice-based cropping systems

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Abstract

Crop diversification is a key component of sustainable agriculture, as it improves system resilience, enhances resource-use efficiency and minimises the risk of crop failure. A three-year field experiment was conducted at the Agricultural Research Station, Kattuthottam, Thanjavur, India, under randomised block design (RBD) to evaluate the effects of diversified rice-based cropping systems on productivity, profitability and soil fertility. About 10 different cropping systems were evaluated in the study, incorporating a range of crops such as legumes, vegetables, oilseeds, millets, green manures and fodder crops. Among these systems, the maize-rice (Seeraga samba)-bhendi + black gram (5 : 1) system significantly increased ($p \leq 0.05$) rice equivalent yield (REY) (23.04 t $ha^{-1}yr^{-1}$), system productivity (58.5 kg ha^{-1} day^{-1}), net returns (Rs 399206 $ha^{-1}yr^{-1}$) and benefit–cost ratio (3.13), indicating enhanced productivity and economic return. Also, this system recorded an 83 % higher net return when compared with the conventional rice–rice–black gram cropping sequence and achieved the highest sustainable yield index (0.880) and sustainable value index (0.874). In terms of nutrient recycling potential, the highest soil organic carbon (SOC) content (0.60 %) and available nitrogen (270 kg ha^{-1}) were observed in green manure (GM) sunnhemp - rice + daincha (10 : 1) - green gram system. Ragi - rice (Navara) - cluster bean + black gram (5 : 1) system significantly improved ($p < 0.05$) field water use efficiency of 11.62 kg ha^{-1} mm^{-1} and nutrient use efficiency of 50.09 kg kg^{-1}. Overall, the findings indicated that rice-based systems diversified with high-value crops such as maize and vegetables outperform existing rice monocropping or rice-pulses system in terms of productivity and income enhancement. Furthermore, the inclusion of legumes and green manure crops were more effective in terms of soil restoration.

Keywords: Cauvery Delta Zone; crop diversification; cropping system; productivity; rice; sustainability

Introduction

Rice (*Oryza sativa* L.) is one of the world's most important staple food crops, feeding more than half of the global population and has grown in a variety of cropping systems across the world for millennia (1, 2). Within Asia, rice contributes between 35 % and 60 % of the total caloric consumption for three billion people (3). India ranks as the world's second-largest rice producer, accounting for roughly 24 % of total global production (4). As the most extensive and productive cropping system in India, the rice-cereals based systems occupy approximately 10.5 million hectares (5). Following the rice-wheat system, the rice-rice cropping system is the second most prevalent cropping system in India. It is extensively practiced in the southern and northeastern regions of the country, including in the states of Andhra Pradesh, Tamil Nadu, West Bengal, Odisha, Kerala and Karnataka (6). However, continuous monocropping of rice has resulted in declining soil fertility, reduced biodiversity and unsustainable production, mainly due to poor diversification and excessive use of chemical fertilisers (7). Therefore, there is a pressing need to shift toward diversified rice-based systems that integrate legumes, oilseeds and high-value vegetables to enhance resource-use efficiency and ensure long-term environmental and economic sustainability (8).

Crop diversification involves cultivating different crops through crop rotation, multiple cropping or intercropping at farm or regional scales (9, 10). It is widely recognised as a key component of sustainable agriculture and acts as an alternative to monoculture-based production systems (11). During the rainy season, rice cannot be replaced by other crops due to heavy rainfall, flooding and unsuitable terrain. Hence, crop diversification is accomplished by introducing suitable crops in the post-rainy (November–February) and summer (March–May) seasons (12). In rice-based systems, the inclusion of legumes fixes atmospheric nitrogen and lowers the

usage of chemical fertilisers. Crop rotation with legumes can increase the yield of succeeding cereal crops by 40 % and enriches soil organic carbon (SOC) and stimulates microbial activity (13).

In diversified farming systems, groundnut and sesame offer significant agronomic and economic benefits (8, 14). Groundnut achieves biological nitrogen fixation of 552 mg N plant^{-1}, boosts rice-system productivity around 10.14 t ha^{-1} thereby enriching SOC content (15). Fodder crops are essential for integrating livestock, enhancing soil health and income. In rice-based systems, annual fodder crops like cowpea, maize and sugar beet can raise productivity up to 177 % in rice equivalent yield (REY) compared to fallow, while reducing soil and nutrient loss by up to 51 %. They provide a steady feed supply but require balanced nutrient management to offset high biomass removal (16, 17). Crops like sunnhemp and sesbania, cultivated as green manure, are typically incorporated into soil during early flowering, acting as natural conditioners (17). They improve soil structure, increase organic matter and enhance available nitrogen (18). Functioning as a "biological pump," they retrieve nutrients from deeper soil horizons and enhance both soil pH and moisture retention (17, 18). The integration of vegetable crops into conventional farming systems provides two complementary benefits of enhanced income and better nutrition (15). Millets are climate-resilient, nutrient-rich crops that grow well under low-input conditions (11). They enhance soil health by promoting microbial activity and leveraging intercropping advantages, while simultaneously lowering greenhouse gas emissions and improving energy efficiency (14).

While previous studies have examined rice-based crop rotations, most have focused on specific crop combinations or individual diversification components, rather than systematically comparing a wide range of cereals, legumes, vegetables, fodder crops and green manure sequences under identical conditions. There is also limited information on how these diversified systems affect productivity, profitability, soil health and resource-use efficiency in the Cauvery Delta Zone. This study addresses these gaps by systematically evaluating diverse rice-based cropping sequences within a common experimental environment. This approach allows for direct comparison of agronomic, economic and resource-use performance and helps identify effective diversification strategies to enhance the sustainability of rice-based systems. The study specifically aims to assess the impact of rice-based crop diversification on system productivity, profitability, soil health, nutrient recycling and water and nitrogen use efficiency.

Materials and Methods

Study area

Field experiments were conducted under All India Coordinated Research Project (AICRP)-Integrated Farming System for three consecutive years (2021–22 to 2023–24) at Tamil Nadu Agricultural University, Agricultural Research Station, Kattuthottam, Thanjavur. The site is located in the Cauvery New Delta Zone of Tamil Nadu, India at 10°45′ N latitude and 79°00′ E longitude, with an elevation of 50 m above mean sea level. The study area is shown in Fig. 1. Weather parameters such as maximum and minimum temperature, relative humidity and rainfall during the study periods were obtained from the meterological observatory of Agricultural Research Station, Thanjavur (Fig. 2). The region is characterised by a tropical climate and well known for its fertile alluvial soil. During the study period, maximum temperature ranged from 29.1 to 38.5 °C, while minimum temperature varied from 18.0 to 28.3 °C. The average annual rainfall of the area is 976.8 mm, nearly two-thirds of which is received during the northeast monsoon. The maximum amount of rainfall (538.0 mm) was recorded in November 2021, whereas no rainfall

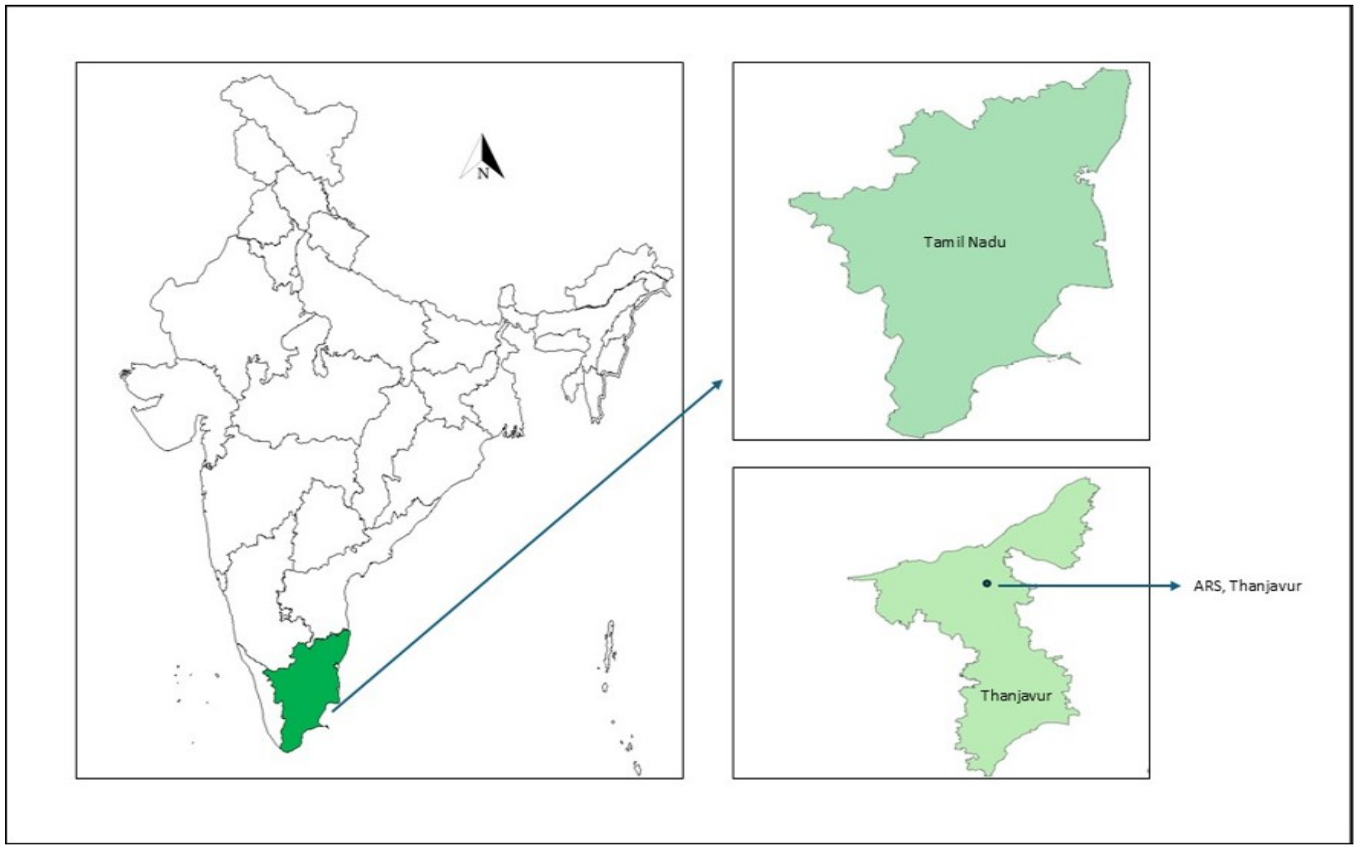
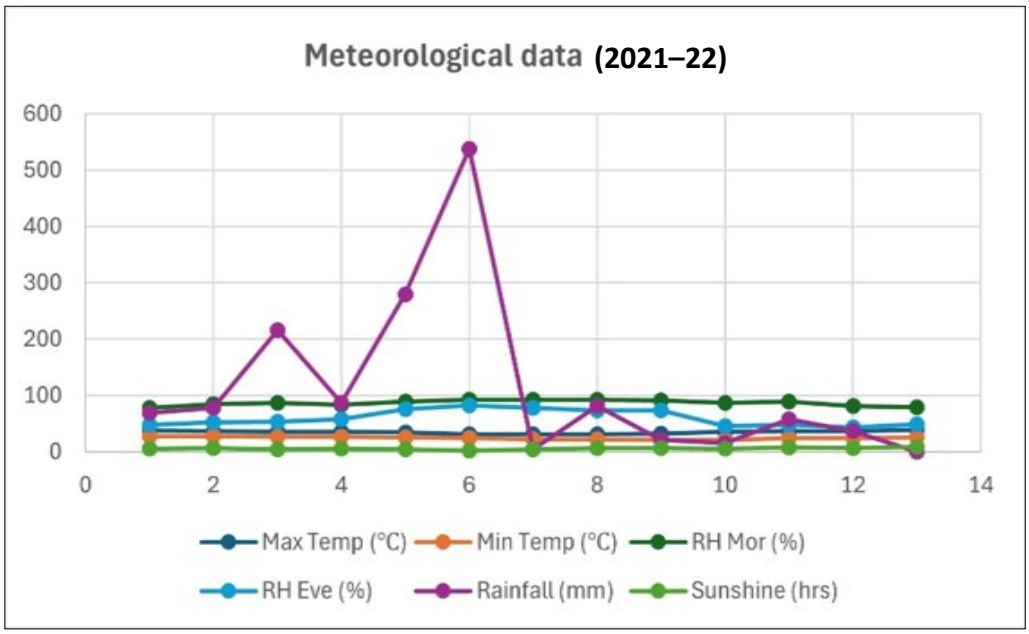
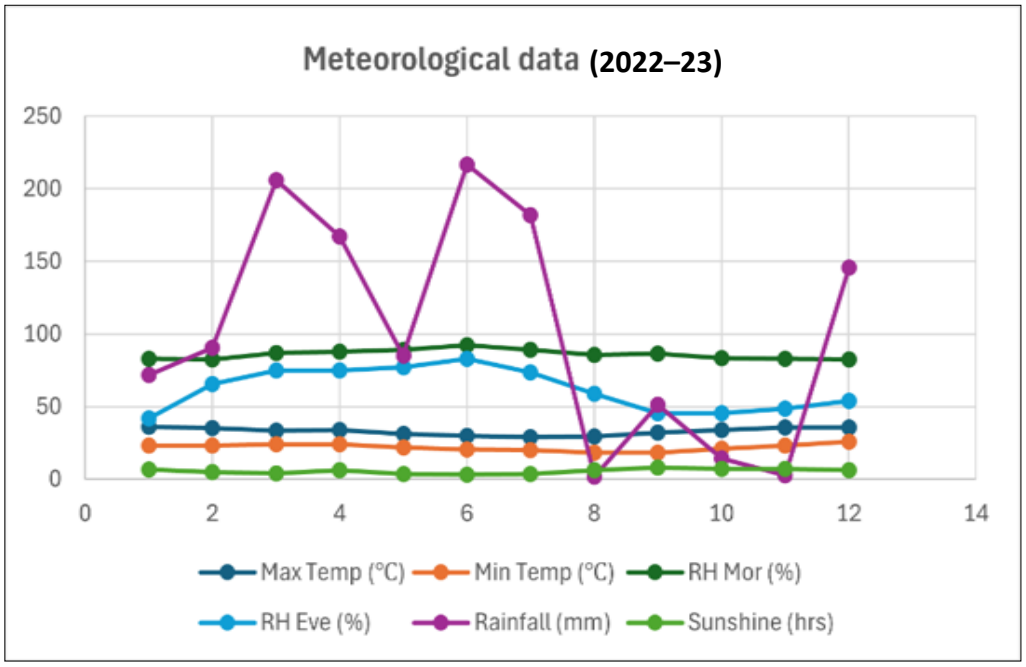


Fig. 1. Geographical location of the experimental site: Agricultural Research Station, Kattuthottam, Thanjavur, Tamil Nadu, India [Source: Maps generated by the authors in Microsoft Excel using geographic coordinates and assembled and annotated using Microsoft PowerPoint].





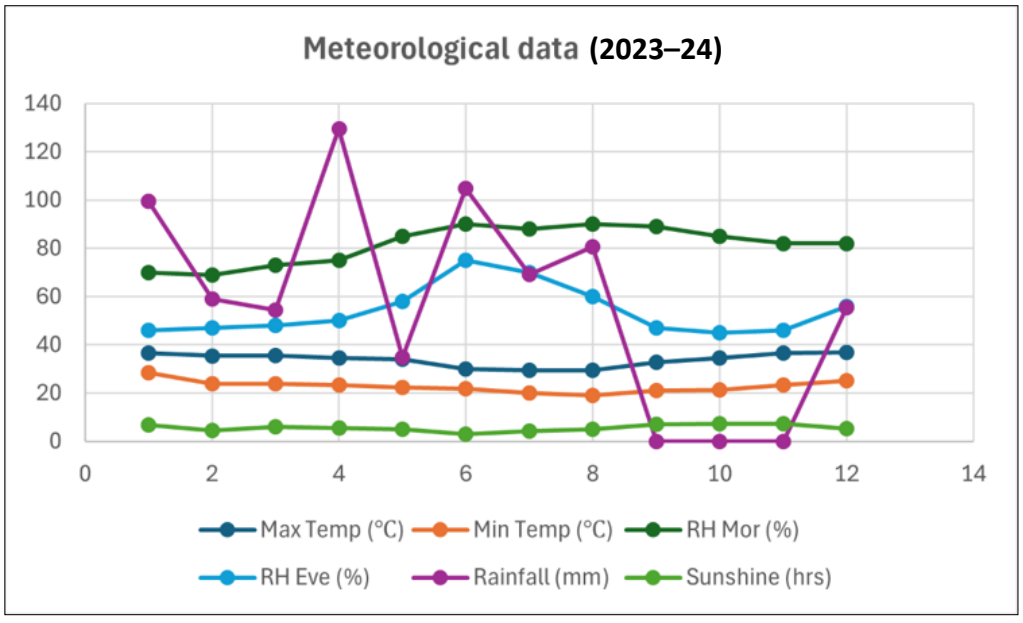


Fig. 2. Weather data during three years of study, Thanjavur, India (2021-24).

was recorded during February-April 2024. The soil in the experimental area was well-drained sandy clay loam, classified taxonomically as a Typic Haplustalf. Prior to the beginning of the experiment, the soil with a pH of 6.7 (slightly acidic), EC of 0.12 dS m^{-1} and SOC of 0.48 % (which is considered low).

Treatment details

The experiment consisted of 10 different rice-based cropping systems with multiple crop components that complemented each other (Table 1). The system was practiced across three seasons (Kharif, rabi and summer) under a randomised block design (RBD) with 3 replications. The area allocated for each plot was 8 m × 5 m. Crops were selected based on their specific roles in rice-based systems. Black gram and green gram were included for N fixation, while sesame and groundnut served as short-duration oilseed crops. Dhaincha and sunnhemp were used as green manure to increase biomass and nitrogen. Fodder cowpea, maize and sorghum provided high biomass and fodder value. Maize and ragi were included as alternative cereals with distinct resource needs. Bhendi was chosen for its high market value as a vegetable.

Table 1. Treatments details of the experiment

Treatments	**Cropping sequence** (Kharif – rabi – summer)
T_1	Rice – rice – black gram
T_2	Rice – rice – sesame
T_3	Dhaincha – rice + dhaincha (5 : 1) – black gram
T_4	Sunnhemp – rice + dhaincha (10 : 1) – greengram
T_5	Blackgram – rice – groundnut
T_6	Greengram – rice – sesame
T_7	Fodder cowpea – rice – fodder maize
T_8	Fodder sorghum – rice – fodder cowpea
T_9	Maize – rice – bhendi + black gram (5 : 1)
T_{10}	Ragi – rice – cluster bean + black gram (5 : 1)

The kharif season (June–September) had diversified cropping base including rice, green manure crops (Sesbania and sunnhemp), pulses and high-value cereals including maize and sown in the second and third week of June. Due to the erratic rainfall pattern, rice predominated during the rabi season (October–February). Various varieties were utilised, including the medium-duration rice variety (ADT 46), traditional rice varieties (Seeraga samba and Navara) and biofortified rice (DRR Dhan 45). For rabi crops, sowing operations were carried out in the third week of September. During summer (February–May), variety of crops were introduced such as pulses, oilseeds, vegetables and fodder crops. All the summer crops were sown in the second and third week of February. A green manure crop like dhaincha at different ratios (5 : 1 and 10 : 1) was adopted during the rabi season as an intercrop to enhance soil fertility and ensure efficient resource utilisation. The spacing adopted, varieties used and seed rate required for each treatment are described in Table 2.

Weed, pest and disease management practices were implemented, according to need-based chemical and mechanical measures. Fertiliser application was made as per crop-specific recommendations described in Table 2. The recommended nitrogen, phosphorus and potassium (NPK) fertiliser applications for the kharif, rabi and summer seasons were supplied by using urea, single superphosphate and muriate of potash. Green manure crops were grown without any additional chemical fertiliser. In transplanted rice, weed control included pre-emergence application of pretilachlor 50 emulsifiable concentrate (EC) at 0.75 kg a.i. ha^{-1} at 3 days after transplanting (DAT), followed by bispyribac-sodium 10 suspension concentrate (SC) at 25 g a.i. ha^{-1} at 20–25 DAT and hand weeding at 40 DAT as needed. For upland crops, pendimethalin 30 EC at 1.0 kg a.i. ha^{-1} was applied pre-emergence herbicide in black gram, green gram, groundnut, sesame, bhendi and cluster bean

Table 2. Crop cultivation details of the experiment

Season	Treatment	Crop	Variety	Duration (days)	Spacing (cm)	Seed rate (kg ha^{-1})	Fertiliser (N : P: K kg ha^{-1})
Kharif	T_1, T_2	Rice	CO 51	107	15 × 10	60	150:50:50
	T_3	Green manure (Dhaincha)	–	45	Direct sown	25	–
	T_4	Green manure (Sunnhemp)	–	45	Direct sown	25	–
	T_5	Black gram	VBN 8	75	30 × 10	20	25 : 50 : 25
	T_6	Greengram	CO 7	75	30 × 10	20	25 : 50 : 25
	T_7	Fodder cowpea	CO 9	84	45 × 15	25	25 : 40 : 20
	T_8	Fodder sorghum	CO 31	84	30 × 15	5	135 : 40 : 40
	T_9	Maize	CO 6	100	60 × 25	20	250 : 75 : 75
	T_{10}	Ragi	CO 15	110	30 × 10	15	60 : 30 : 30
Rabi	T_1, T_2, T_5, T_7, T_8	Rice	ADT 46	135	20 × 10	40	150 : 50 : 50
	T_3	Rice + Dhaincha (5 : 1)	ADT 46	135	20 × 10	40	150 : 50 : 50
	T_4	Rice + Dhaincha (10 : 1)	ADT 46	135	20 × 10	40	150 : 50 : 50
	T_6	Biofortified rice	DRR Dhan 45	131	20 × 10	40	150 : 50 : 50
	T_9	Rice	Seeraga samba	119	20 × 10	30	100 : 50 : 50
	T_{10}	Rice	Navara	110	20 × 10	30	100 : 50 : 50
Summer	T_1, T_3	Black gram	VBN 8	74	30 × 10	20	25 : 50 : 25
	T_2, T_6	Sesame	VRI 4	100	30 × 30	5	35 : 23 : 23
	T_4	Green gram	CO 7	74	30 × 10	20	25 : 50 : 25
	T_5	Groundnut	VRI 10	95	30 × 10	125	25 : 50 : 75
	T_7	Fodder maize	African tall	71	30 × 15	20	25 : 40 : 20
	T_8	Fodder cowpea	CO 9	75	45 × 15	25	25 : 40 : 20
	T_9	Bhendi + Black gram (5 : 1)	Arka Anamika + VBN 8	102	45 × 30	2.5 + 20	200 : 100 : 100
	T_{10}	Cluster bean + Black gram (5 : 1)	MDU 1 + VBN 8	102	45 × 15	10 + 20	50 : 50 : 25

within 2-3 DAS. Atrazine 50 WP at 0.5 kg a.i. ha^{-1} was applied as a pre-emergence herbicide in maize and fodder maize at 3 DAS. In ragi and fodder sorghum, weed management involved timely intercultivation and hand weeding at critical crop growth stages. Pest and disease control was based on integrated pest management (IPM) principles, with recommended insecticides and fungicides applied when pest or disease incidence reached the economic threshold level (ETL). Irrigation in transplanted rice was scheduled by maintaining a water depth of 2.5 cm from transplanting to active tillering, 5 cm from panicle initiation to flowering and 2.5 cm during grain filling and stopped 10 days before harvest. Upland, fodder and green manure crops were irrigated at critical growth stages based on crop water requirements. Green manure crops (dhaincha and sunnhemp) were incorporated into the soil at 45 DAS before flowering using a tractor-operated rotavator to support biomass decomposition and nutrient recycling. Other crops were harvested at physiological maturity to avoid yield losses. Grain crops were harvested manually, bundled, sun-dried and threshed separately for each plot to determine grain and straw yields. Vegetable crops were harvested through successive pickings, with cumulative yields recorded. Fodder crops were harvested manually at the pre-flowering stage by cutting the plants close to the ground surface and fresh biomass yield was recorded on a plot basis.

Soil chemical properties

At the beginning and end of each year, soil samples were collected from the 0–15 cm depth at 3 locations within each plot throughout the experiment. The mean values of soil analysis were computed from three years of data. Soil pH was measured by using a glass electrode pH meter and electrical conductivity (EC) by conductivity bridge, expressed in deciSiemens per meter (dSm^{-1}) (19). The Walkley and Black's rapid titration method was used to determine SOC (20). The available N in the soil was estimated using alkaline potassium permanganate method (21), available P by sodium bicarbonate extraction method (22) and available K by using the flame photometer / neutral normal ammonium acetate extraction method (23). The available N, P and K were expressed as kg ha^{-1}.

Yield and economics

Yield was recorded individually for each treatment at the harvest time across three seasons, average was calculated and expressed in kg ha^{-1}. To compare the overall productivity of various crops in a single unit, REY was used to convert the yield of different crops into rice yield equivalents based on the prevailing market price of rice (24).

$$\text{REY (t ha}^{-1}\text{)} = \frac{\text{Yield of non - rice crop x Price of non - rice crop}}{\text{Price of rice crop}}$$

The cost of cultivation was calculated by including variable costs such as operational, input and labour costs incurred during crop production. Fixed costs were not considered in the analysis. Gross returns were derived from yield of main and by-products multiplied with their respective market value. Net returns were determined by deducting the cost of cultivation from the gross returns. All these parameters were expressed in terms of Rs. ha^{-1}. The benefit cost ratio (B : C) was derived by using the formula (25):

$$\text{Benefit cost ratio (BCR)} = \frac{\text{Gross return}}{\text{Cost of cultivation}}$$

System productivity and profitability

These indices were calculated using the formulas described by Upadhaya et al. (18):

$$\text{System productivity (kg ha}^{-1}\text{ day}^{-1}\text{)} = \frac{\text{System REY}}{365 \text{ days}}$$

$$\text{System profitability (Rs ha}^{-1}\text{ day}^{-1}\text{)} = \frac{\text{Net return}}{365 \text{ days}}$$

Sustainability indices

It was calculated by using the formula cited by previous researchers (18):

$$\text{Sustainable yield index (SYI)} = \frac{Y - \sigma}{Ymax}$$

(Where Y - average yield over the experimental year, σ - standard deviation and Y_{max} - maximum yield recorded among all the treatment during the study period)

$$\text{Sustainable value index (SVI)} = \frac{Y - \sigma}{Vmax}$$

(Where Y - average net income over the experimental year, σ - standard deviation and V_{max} - maximum net income recorded among all the treatment during the study period)

Resource use efficiency

Field water use efficiency (kg ha^{-1} mm^{-1}) was worked out based on the ratio of rice equivalent yield to total quantity of water required for the crop during entire cropping period. The quantity of irrigation water applied was estimated from the discharge rate and irrigation duration, while rainfall data was obtained from the agrometeorological observatory. Total water use was expressed in mm as the sum of irrigation water and rainfall. Nutrient use efficiency was expressed in kg kg^{-1} and derived from the formula dividing REY by the total nutrient applied to each cropping system.

Statistical methods

Prior to statistical analysis, the data were examined for normality using the Shapiro–Wilk test and for homogeneity of variances using Levene's test. As both assumptions were satisfied, data transformation was not required. Individual data sets were statistically analysed using ANOVA at a critical difference (CD) of 0.05 level of probability (26). Treatment means were compared using Duncan's multiple range test (DMRT) at the 5 % level of significance ($p \leq 0.05$) and significant differences among treatment means were denoted by different alphabetical letters. All data were analysed using R software (version 4.6.0; Foundation for Statistical Computing, Vienna, Austria) with the agricolae package.

Results

Rice equivalent yield and system productivity of diversified cropping systems

Among the cropping systems, T_9 (Maize - rice - bhendi + black gram (5 : 1)) exhibited the highest REY (23.04 t ha^{-1} yr^{-1}) with maximum system productivity (58.5 kg ha^{-1} day^{-1}) (Table 3) indicating the superior performance of the system due to the inclusion of maize and high-value vegetable crop. This was followed by T_5 (Black gram - rice - groundnut) with a REY of 16.18 t ha^{-1} yr^{-1} and system productivity of 42.9 kg ha^{-1} day^{-1}, while T_{10} also recorded higher productivity. In comparison with other cropping system, rice-rice system (T_1 and T_2) showed similar REY values (15.22–15.36 t ha^{-1} yr^{-1}) on par with T_{10} (Ragi - rice - cluster bean + black gram (5 : 1)). Although T_{10} had lower production, the traditional variety Navara along with cluster bean contributed to higher equivalent yield due to their high economic value. The lowest REY and system productivity were observed in T_4 (8.98 t ha^{-1} yr^{-1} and 23.9 kg ha^{-1} day^{-1}), followed closely by T_3 (9.03 t ha^{-1} yr^{-1} and 24.6 kg ha^{-1} day^{-1}) (Fig. 3).

Economics

The cost of cultivation varied significantly among the treatments, ranging from Rs. 88046 to Rs. 189648 ha^{-1} yr^{-1}, with the corresponding B : C ratios of 2.13 to 3.13. The highest gross return of Rs. 588854 ha^{-1} yr^{-1}, net return of Rs. 399206 ha^{-1} yr^{-1}, B : C ratio of 3.13 and maximum system profitability of Rs. 1094 ha^{-1} day^{-1} was observed in the cropping system T_9 (Table 4). When compared with the traditional rice-rice-black gram sequence (T_1), T_9 showed greater net returns of about 83 %. Despite moderate gross and net returns, T_8 recorded a relatively high B : C ratio (2.63), due to lower cultivation costs. System profitability across cropping systems ranged from Rs. 334 to Rs. 1094 ha^{-1} day^{-1}. The highest profitability was achieved in T_9 followed by T_{10} and T_5. The lowest system profitability was recorded in T_3 and T_4 (Table 4). Gross return, net return, B : C ratio and system profitability differed significantly among cropping systems ($p \leq 0.05$).

Table 3. Rice equivalent yield (REY) and system productivity of all systems

Treatment	Rice equivalent yield (t ha^{-1} yr^{-1})	System productivity (kg ha^{-1} day^{-1})
T_1	15.22^{b}	41.80^{b}
T_2	15.36^{b}	42.80^{b}
T_3	9.03^{d}	24.60^{e}
T_4	8.98^{d}	23.90^{e}
T_5	16.18^{b}	45.60^{b}
T_6	10.84^{c}	30.60^{d}
T_7	10.52^{c}	31.20^{cd}
T_8	11.64^{c}	34.93^{c}
T_9	23.04^{a}	58.50^{a}
T_{10}	15.58^{b}	42.90^{b}
SE.d	0.61	1.92
S.Em. ±	0.44	1.36
CD	1.30	4.05

Mean of the three years.

Sustainability indices

The sustainability indices varied among the different rice-based cropping systems (Fig. 4). Based on the mean data of 3 years, T_9 recorded the highest sustainability value index (SVI) value of 0.87 along with a higher sustainability yield index (SYI) value of 0.88, indicating stable economic return and reduced variability in productivity over the study period (Table 5). This was followed by T_{10}, which recorded an SVI of 0.84 and an SYI of 0.75. Among the other treatments, SVI values of 0.81 and 0.80 were recorded in T_8 and T_1, respectively, followed by T_4 (0.77) and T_3 (0.76). The lowest SVI (0.67) and SYI (0.65) were recorded in T_5.

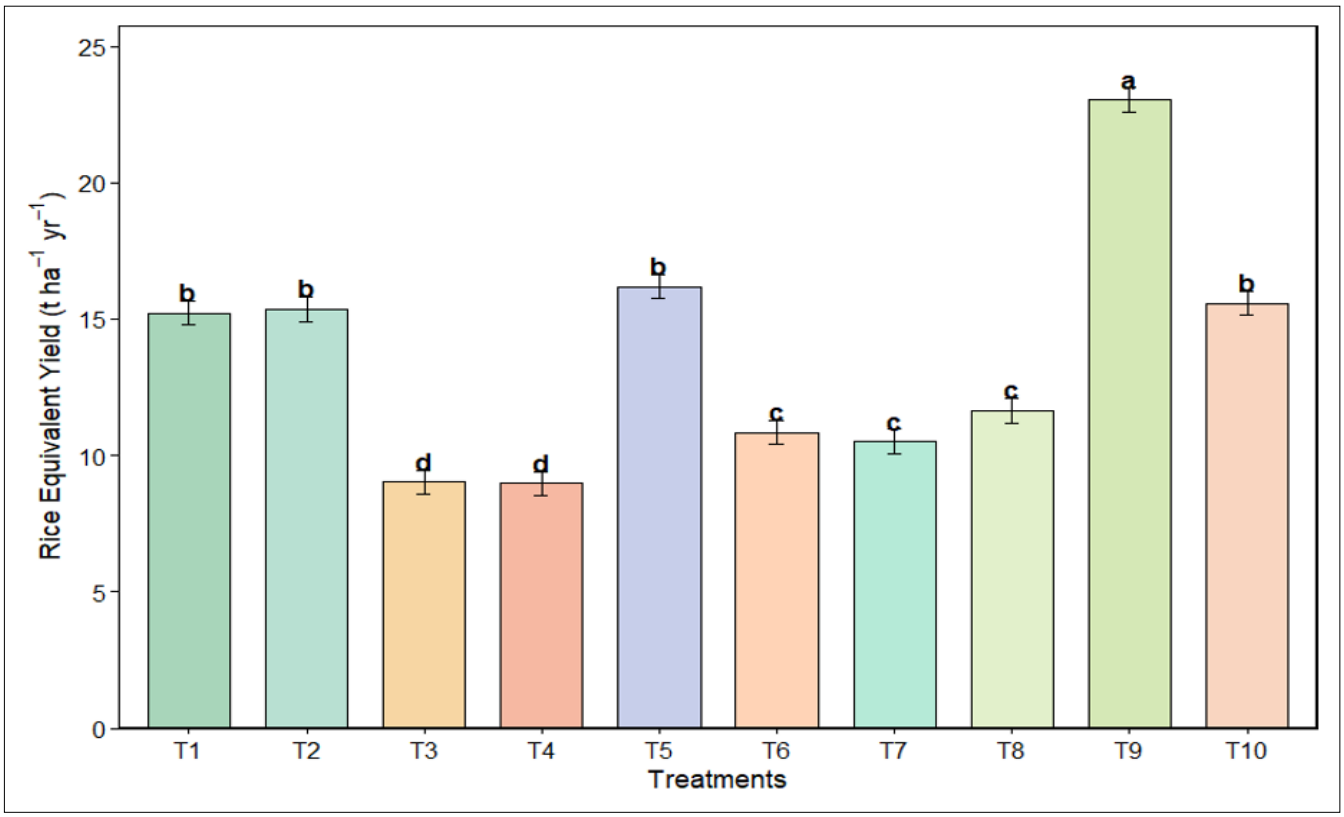


Fig. 3. Comparison of mean rice equivalent yield (REY) among different rice-based cropping systems during the experimental period.

Table 4. Economic analysis of different rice-based production systems

Treatment	Gross return (Rs. ha^{-1} yr^{-1})	Total cost (Rs. ha^{-1} yr^{-1})	Net return (Rs. ha^{-1} yr^{-1})	B : C ratio	System profitability (Rs. ha^{-1} day^{-1})
T_1	366745	148589	218155	2.46	598
T_2	360778	153858	206919	2.30	567
T_3	215330	93520	121809	2.13	334
T_4	215792	88046	127746	2.30	350
T_5	378644	151674	226969	2.56	622
T_6	249896	116167	133729	2.20	366
T_7	255499	116768	133837	2.13	367
T_8	293225	112768	179891	2.63	493
T_9	588854	189648	399206	3.13	1094
T_{10}	469845	179735	290110	2.56	795

Mean of the three years.

Table 5. Sustainable yield index and sustainable value index of different cropping systems

Treatment	SVI	SYI
T_1	0.80	0.81
T_2	0.74	0.86
T_3	0.76	0.82
T_4	0.77	0.84
T_5	0.67	0.65
T_6	0.72	0.81
T_7	0.67	0.85
T_8	0.81	0.77
T_9	0.87	0.88
T_{10}	0.84	0.75

Mean of the three years.

Post-harvest analysis

Soil organic carbon, a key indicator of soil health and fertility, increased across most cropping systems compared with the initial value (0.48 %) (Fig. 5). Based on the 3 years mean data, T_4 (Sunnhemp - rice + dhaincha (10 : 1) - green gram) recorded the highest SOC content (0.60 %), followed by T_3 (0.58 %) and T_8(0.56 %) (Fig. 5). In contrast, the lowest SOC content was observed in T_2 (0.46 %) shows lower organic matter addition. Significant differences in available N, P and K were observed among treatments. Highest available N was found in T_4 (270 kg ha^{-1}), followed by T_3 (260 kg ha^{-1}) and T_{10} (254 kg ha^{-1}) (Fig. 6). $T_2$and T_9 were recorded with lower available N in soil due to the exhaustive nutrient removal of the crops included in the system (Table 6). Similar trend was observed for available P and K with T_3 and T_4 showing higher values. Almost all other treatments were on par with each other for available P, except T_7.

Resource use efficiency

Among the treatments, T_{10} (Ragi - rice - cluster bean + black gram (5 : 1)) recorded the highest field water use efficiency (FWUE) (11.62 kg ha^{-1} mm^{-1}) and nitrogen use efficiency (NUE) (50.09 kg kg^{-1}) attributed to better utilisation of water and nutrients applied, which led to greater yield per unit of input. T_9 system (maize - rice - bhendi + black gram (5 : 1)) achieved high WUE of 11.23 kg ha^{-1} mm^{-1} indicating efficient use of applied water resources (Table 7). However, the system's NUE remained low (26.87 kg kg^{-1}), revealing that nutrients were not utilised with the same efficiency as water. Incorporating green manure and leguminous crops in the cropping system which improved NUE ranged between 45.3 and 48.3 kg kg^{-1}. In contrast, the lowest water use efficiency was observed in T_4 recorded 5.04 kg ha^{-1} mm^{-1} and T_7 with 5.32 kg ha^{-1} mm^{-1}, while T_8 exhibited the lowest NUE across all treatments at 20.36 kg kg^{-1}.

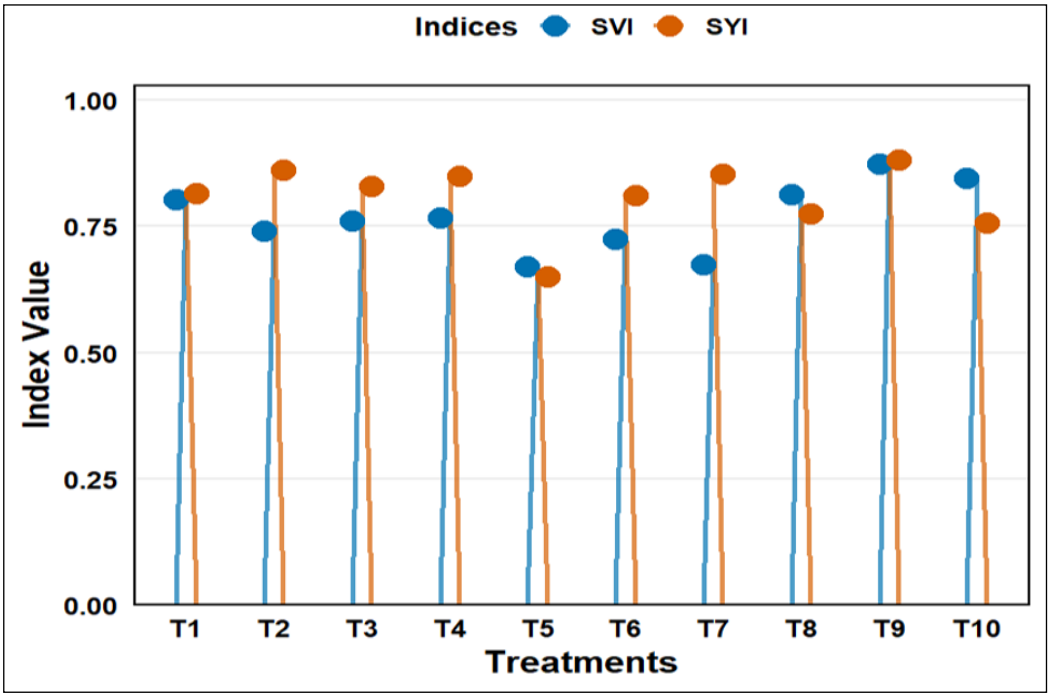


Fig. 4. Sustainable value index (SVI) and sustainable yield index (SYI) of different cropping systems.

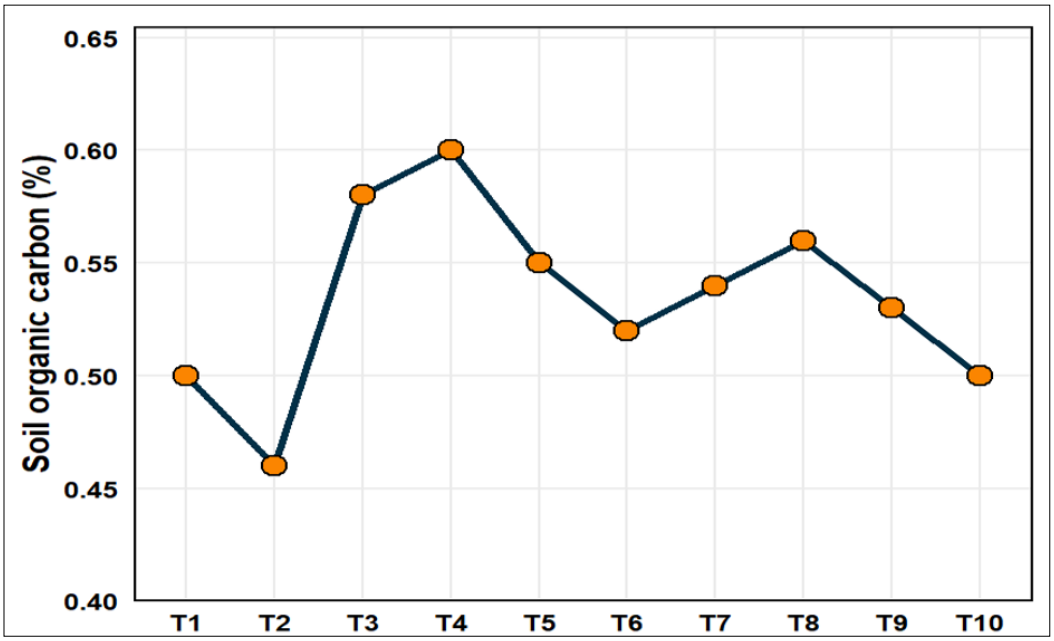


Fig. 5. Effect of different cropping systems on soil organic carbon content during study period.

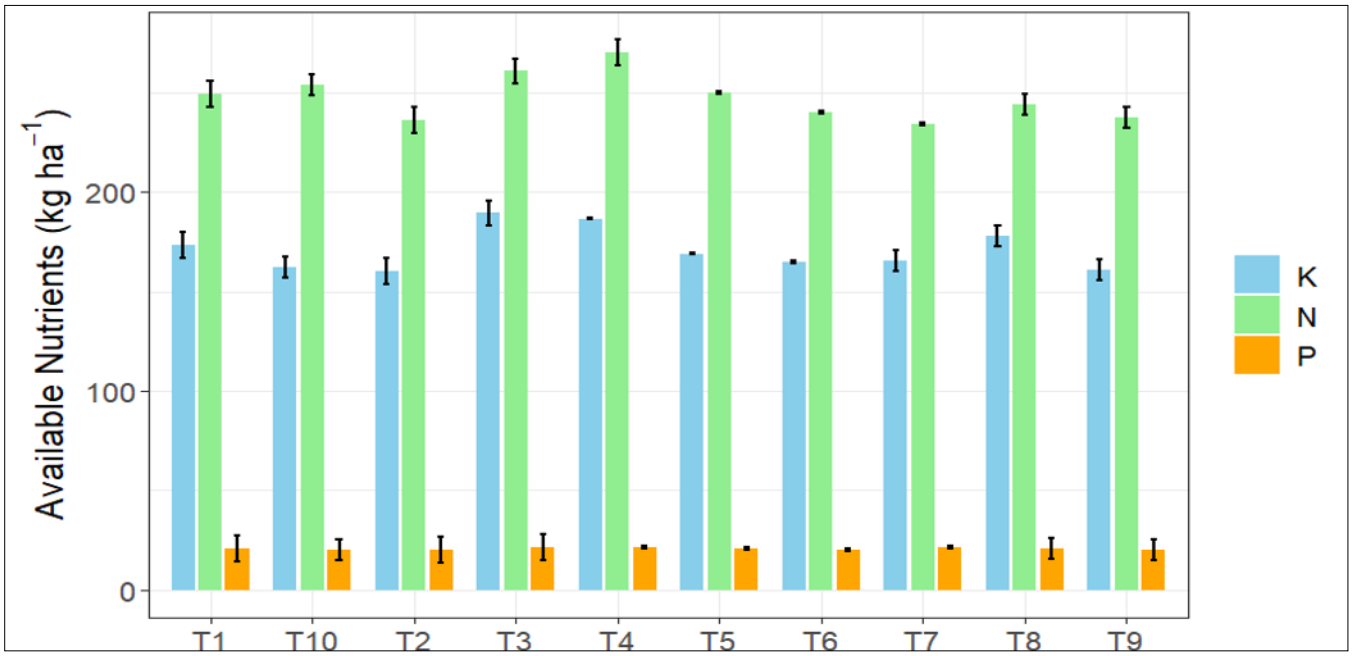


Fig. 6. Available soil nitrogen (N), phosphorus (P) and potassium (K) status as influenced by different rice-based cropping systems.

Table 6. Post-harvest soil analysis of different cropping systems

Treatment	Soil organic carbon (%)	Available N (kg ha^{-1})	Available P (kg ha^{-1})	Available K (kg ha^{-1})
T_1	0.50	249.33^{abc}	20.73^{a}	173.33^{abc}
T_2	0.46	236.00^{c}	20.20^{a}	160.00^{c}
T_3	0.58	260.67^{ab}	21.67^{a}	189.33^{a}
T_4	0.60	270.00^{a}	21.40^{a}	186.67^{a}
T_5	0.55	250.00^{abc}	20.77^{a}	169.00^{bc}
T_6	0.52	240.00^{bc}	20.30^{a}	164.67^{bc}
T_7	0.54	234.00^{c}	21.20^{a}	165.33^{bc}
T_8	0.56	244.00^{bc}	20.93^{a}	178.00^{ab}
T_9	0.53	237.33^{c}	20.07^{a}	160.67^{bc}
T_{10}	0.50	254.00^{abc}	20.17^{a}	162.00^{bc}
SE.d	-	9.17	0.85	7.46
S.Em.±	-	6.49	0.61	5.28
CD	-	19.29	1.80	15.67

FWUE: field water use efficiency; NUE: Nitrogen use efficiency. Mean of the three years.

Table 7. Resource use efficiency of different rice-based cropping systems

Treatment	FWUE (kg ha^{-1} mm^{-1})	NUE (kg kg^{-1})
T_1	6.31	29.68
T_2	6.40	27.30
T_3	5.45	46.36
T_4	5.04	45.36
T_5	8.66	48.25
T_6	6.07	32.29
T_7	5.32	35.46
T_8	6.15	20.36
T_9	11.23	26.87
T_{10}	11.62	50.09

FWUE: field water use efficiency; NUE: Nitrogen use efficiency. Mean of the three years.

Discussion

Rice equivalent yield and system productivity of diversified cropping systems

In diversified cropping systems, REY is a key indicator that helps to directly compare overall productivity on a common basis across different cropping systems (27, 28). Compared to the conventional system (T_1), T_9 (Maize - rice - bhendi + black gram (5 : 1) recorded a 51.38 % increase in REY and 39.95 % increase in system productivity, indicating a substantial improvement in overall system performance. This can be attributed to the combined effect of crops with high yield potential and their market value. Bhendi is classified as a high-value vegetable crop owing to its high market price compared to staple cereals (15). The inclusion of okra enhances REY and overall system profitability. Maize, a C_4 crop, possesses a CO_2-concentrating mechanism that enables high photosynthetic rates and efficient carbon assimilation under high light and temperature conditions, thereby supporting greater biomass accumulation and yield potential than many C_3 crops (29). Additionally, maize develops a vigorous and extensive root system that enhances the uptake of water and nutrients from different soil depths, while its high biomass production contributes substantially to overall system productivity (11, 16, 17). Legumes such as black gram form symbiotic relationships with rhizobia, converting atmospheric N_2 into plant-available N (11, 17). A portion of this fixed N returns to the soil through root exudation, rhizodeposition, nodule turnover and residue decomposition, which increases N availability for subsequent crops (17, 18, 25). Their narrow carbon-to-N ratio supports rapid decomposition and nitrogen mineralisation, while root-derived carbon further stimulates microbial activity and nutrient cycling (4, 18). Thus, the combination of a C_4 cereal with a high-value vegetable and legume provides both biological and economic advantages, which are reflected in the greater REY and system productivity of T_9. Research from the Philippines indicates that cultivating special rice varieties fetches higher economic value due to their premium quality compared to ordinary rice varieties (30). Seeraga samba and Navara generally have lower yield potential, but their premium market prices contribute to higher REY. Leguminous crops play a crucial role in enhancing the performance of cropping systems, as reflected in T_5 which recorded higher REY next to T_9. Also, it showed a 9.09 % increase in system productivity over T_1, highlighting the "legume effect", which enriches the system through biological N fixation and efficient nutrient recycling. This result aligns with findings from the Indo-Gangetic Plains, where summer legumes increased rice grain yield by 4.7–13.9 % compared to conventional rice-wheat systems (12). Differences in improvement may result from variations in companion crops and the prevailing agro-climatic conditions of the Cauvery Delta Zone, indicating that the benefits of legumes are influenced by site-specific conditions and crop management practices. According to previous researchers, the maize–peas–spring groundnut system recorded a REY of 19.98 t ha^{-1} over a six-year study in Punjab (25). The lower REY and system productivity observed in green manure-based systems (T_3 and T_4) and decline around 41 % compared to traditional rice-rice systems due to the inclusion of crops like dhaincha and sunnhemp which possess little or no market value, because it was incorporated and utilised for improving soil fertility. Similar findings support that rice–sunnhemp–green gram system recorded a lower REY (8.98 t ha^{-1}) than the rice-green gram–pearl millet system (10.42 t ha^{-1} over a four year study (17). These findings demonstrate that integrating high-value cereals and vegetables into rice-based systems can substantially improve system productivity while maintaining production sustainability.

Economics

Among the treatments, T_9 followed by T_{10} had higher cost of cultivation due to the inclusion of vegetables, which require more labour for multiple harvesting, higher seed costs and better management practices. Similar findings were reported by previous researchers (31). Also, similar trend was observed for net returns, with both T_9 and T_{10} recording the highest net returns, gross returns and system profitability among all treatments. This could be due to higher productivity of maize and bhendi which fetch better market price. Previous researchers found that vegetables offer quick and higher returns per unit of land despite their high cost of cultivation and their findings revealed that cropping systems which included such as cabbage and radish achieved the highest system profitability (Rs. 775 ha^{-1} day^{-1}) and outperformed traditional rice-wheat rotations (8). Also, the production cost of traditional rice varieties is generally lower than that of modern varieties (32). Moreover, the inclusion of legumes offers additional advantages, with the rice-cowpea system achieving a 32 % higher net return (33). Next to T_9, the fodder-based system T_8 recorded a higher B : C ratio (2.63), even though it had lower net returns compared to other systems. This may be attributed to its lower cost of cultivation, as it requires less maintenance along with minimal post-harvest losses and processing costs compared to rice-based systems, thereby improving overall economic efficiency (17, 29). These findings highlight the suitability of fodder-based systems for mixed crop-livestock farming, where economic returns are complemented by a reliable supply of quality fodder. The lowest net returns were recorded in the green manure-based systems T_3 and T_4, although they still exhibited reasonable profitability, with B : C ratios of 2.13 –2.30. This was due to their low cost of cultivation, which represented a reduction of approximately 37 % to 41 % compared to T_1. Although these crops have no direct market value, they require fewer inputs and are beneficial for improving soil fertility and restoration. Incorporation of *Sesbania* in cropping systems in the Eastern Gangetic Plains recorded B : C ratios ranging from 1.49 to 1.75, which aligns with the present findings (18). These findings demonstrate that diversified rice-based systems integrating high-value vegetables can substantially enhance farm profitability, whereas fodder and green manure-based systems offer alternative economic benefits depending on farm objectives and resource

availability.

Sustainability indices

The sustainability yield index (SYI) is a quantitative parameter that helps to measure the stability and sustainability crop yield across varying climatic conditions. A higher SYI value signifies that crop productivity remains stable despite varying environmental conditions, thereby lowering the risk of crop failure over time (4). On the other hand, SVI indicates sustainability based on the consistency of monetary returns over time, rather than crop yield (34, 35). The high SVI (0.87) and SYI (0.88) observed in T_9 confirm that the system maintains stable yields and consistent returns over the years followed by T_{10}(Fig. 4). Evidence indicates that the inclusion of vegetables and legumes in cereal-based cropping systems outperforms traditional sequences, recording SYI and SVI around 84 % and 96 % (17,35). Green manure-based systems ($T_3$and T_4) exhibited higher SYI values, which is aligns with findings from study in western India that also reported improved yield stability under such systems (17). T_5 (Black gram–rice–groundnut) recorded the lowest SVI (0.67) and SYI (0.65) in the study, which may be attributed to yield instability associated with groundnut under variable monsoon.

Post-harvest analysis

Of all the cropping sequences, T_4 (Sunnhemp-based) and T_3 (Dhaincha-based) exhibited 16–20 % increase in SOC and 4–8 % increase in available N. Leguminous and green manure crops positively influenced the SOC and available N level owing to their higher biomass addition and residue incorporation. This superior performance may be attributed to the incorporation of high biomass, which enhances soil organic matter buildup, along with the ability of these crops to fix atmospheric N (36). Additionally, their low C : N ratio facilitates faster decomposition and efficient nutrient release (18). Findings shown that groundnut can fix about 21 to 102 kg N ha^{-1}, while cowpea fix as much as 337 kg N ha^{-1}(37) and these crops act as slow-release N sources, supplying nutrients gradually for succeeding crops (5). The fodder-based system T_8 (Fodder sorghum-rice-fodder cowpea) sustained a high SOC level of 0.56 % due to the dual role of fodder cowpea as fixing atmospheric nitrogen in soil besides fodder crop. According to previous studies, incorporation of fodder cowpea offers high biomass turnover and N fixation (12). In contrast, T_2 (Rice-rice-sesame) recorded comparatively lower SOC and nutrient levels because sesame is a nutrient-exhaustive crop that reduces soil nutrient availability and consequently lowers the yield of the succeeding crop (30).

Resource use efficiency

In this study, T_{10} and T_9 exhibited the highest FWUE, reflecting better water productivity because ragi and black gram are highly water efficient crops. They require significantly less water compared to rice cultivation and thus contribute to improved water use efficiency in diversified cropping systems (38). T_9 recorded lowest NUE due to the inclusion of maize and bhendi, which are exhaustive crops with high nutrient demand. These crops require heavy fertiliser inputs, often exceeding plant uptake efficiency, leading to reduced NUE (34). T_3 and T_4 required around 1700 mm of water, due to the inclusion of green manure crops, which have no marketable value, reduced the overall FWUE. But they achieved higher NUE due to the lower fertiliser requirement, as green manure crops supply nitrogen through biological fixation and reduce dependence on external inputs (3, 17). The results suggest that the choice of cropping system should consider not only productivity but also resource-use efficiency to ensure long-term sustainability under conditions of limited water and fertiliser availability.

Conclusion

The study clearly demonstrates that crop diversification is a highly effective strategy for increasing productivity, profitability and soil health in rice-based farming systems. Although the traditional rice-rice-pulse system remains predominant, it was comparatively less productive and economically weaker than the diversified cropping systems evaluated. Cereal–vegetable integration significantly improved overall productivity, enhanced farm income and indicated stable yield and economic performance over 3 years. Addition of legumes strengthened the soil nitrogen (N) availability through the capability of fixing atmospheric N. Fodder-based system produced high biomass for livestock integration and green manure rotations played a crucial role in building soil organic carbon (SOC) and maintaining soil fertility. Also, millets and traditional rice varieties exhibited higher field water use efficiency (FWUE) and nutrient use efficiency (NUE) while maintaining better productivity, thereby enhancing overall resource-use efficiency of the cropping system. Overall, this study recommends that farmers in the Cauvery Delta Zone gradually transition from conventional rice-based monocropping and adopt diversified, rice-based systems aligned with their specific farming goals. Therefore, crop diversification emerges as a sustainable approach for strengthening rice-based agriculture and ensuring economic stability in the region. This study provides comprehensive evidence from a three-year field experiment comparing ten diversified rice-based cropping systems, offering practical guidance for designing sustainable production systems in irrigated rice-growing regions.

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Authors' contributions

TP carried out the experiment, analysed the data and prepared the original draft. KS, PMS and NR contributed to the conceptualisation of the study and supervised the work. RV contributed to data curation and visualisation. NS, SKN, SS and SPS contributed to summarising and revising the manuscript. All the authors read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

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