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Decoding Resource Efficient Strategies to Enhance Ecosystem Services in Aerobic Rice-blackgram Cropping System

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ABSTRACT

Background: Monocropping of rice, widely practiced in many regions of India, has resulted in declining yield and soil health degradation due to continuous nutrient depletion, disrupted nutrient cycling and adverse changes in soil physicochemical properties. This unsustainable practice also reduces biodiversity and increases the vulnerability of food production systems to biotic and abiotic stresses. In view of these constraints, crop diversification through the inclusion of legumes and the adoption of sustainable production strategies are essential.

Methods: The experiment was laid out in a split-plot design (SPD) with three replications. Main plots included sole rice and rice + *dhaincha*, while sub-plots had six nutrient management treatments combining inorganic fertilizers, enriched farm yard manure (EFYM), vermicompost, AM fungi and foliar nutrients.

Result: The results revealed that incorporation of *daincha* (M_2) along with half dose of recommended nitrogen from inorganic fertilizer + quarter dose of recommended nitrogen from enriched farmyard manure + quarter dose of recommended nitrogen from vermicompost + AM fungi and foliar nutrients of 0.5% urea, 1% $FeSO_4$ and 0.5% $ZnSO_4$ (S_6) increased the system productivity by 42.5%, system profitability by 49.0%compared to application of inorganic fertilizer alone. This integrated approach enhances yield, boosts productivity and profitability and ensures environmental sustainability in aerobic rice-blackgram cropping system. The aerobic rice-blackgram cropping system offers a sustainable alternative to traditional rice cultivation, addressing issues like climate resilience and declining soil fertility.

Key words: AM fungi, Crop rotation, Green manure, Sustainability, System productivity.

INTRODUCTION

Rice-based cropping systems play crucial role in global food production (Samant *et al.,* 2021). In India, rice is the major crop during the *kharif* season, but the land left fallow after rice cultivation is underutilized. There is significant potential to make productive use of this fallow land, offering an opportunity to address food and nutritional insecurity (Gumma *et al.,* 2024). Pulses are sown under rice fallow conditions on about 2.6 lakh hectares in Tamil Nadu, which accounts for 30.8% of the total area under pulses in the state (Rathika and Ramesh, 2023). However, conventional flooded rice cultivation, which requires continuous submergence of field, lead to high water demand and creates anaerobic soil condition responsible for significant methane emission. With increasing concerns over water scarcity, declining groundwater level and the environmental impacts of methane release, there is a growing interest in alternative rice production systems that require less water and reduce greenhouse gas emission. Among these, aerobic rice cultivation has emerged as a promising option. Aerobic rice cultivation has been shown to reduce irrigation water use by 5-70% (Zhang *et al.,* 2016) and decrease methane emissions by >90% (Sharma *et al.,* 2016) compared to traditional anaerobic systems. Continuous cultivation of the cereal-cereal cropping system can be exhaustive and leads to the deterioration of the rhizosphere environment. This degradation could result in reduced nutrient availability and hinder root growth of the crops. To overcome this issue, the existing cropping systems is to be diversified by incorporating various leguminous crops into the rotation. The integration of pulses into rotations is a widely practiced strategy to improve system productivity (Sangothari and Radhamani, 2025).

The tropical climate prevailing in India results in low organic carbon content in the soil. Furthermore, unbalanced nutrient application lead to the degradation of soil health. Prolonged application of chemical fertilizers can substantially reduce crop yield potential and degrade the physico-chemical properties of the soil (Pahalvi *et al.,* 2021). In the absence of organic fertilizers and biofertilizers, deficiencies in secondary nutrients and micronutrients lead to reduced soil productivity (Howe *et al.,* 2024 and Rajitha *et al.,* 2024). Consequently, there is a need to shift towards

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sustainable nutrient management as a crucial measure to sustain the productivity of cropping systems in the long term. Integration of AM fungi into sustainable nutrient management practices improve nutrient acquisition efficiency in rice cultivation and help maintain nutrient availability for subsequent crop within the cropping system (Wang *et al.,* 2023). Incorporation of green manure into cropping systems improves soil health through multiple mechanisms *viz.,* regulates soil pH, improves soil structure, increases water retention and contributes to nitrogen enrichment. The combined use of organic, inorganic, green manure and biofertilizer sources in nutrient management represents a highly effective strategy for reducing dependence on non-renewable energy resources, sustain soil fertility, enhance crop yield, improve farm profitability and minimize environmental pollution (Kharlukhi *et al.,* 2024 and Saikia *et al.,* 2018).

Based on the above concerns, the present investigation hypothesised that the integrated application of inorganic fertilizer, vermicompost, EFYM, AM fungi, green manure along with foliar supplementation of urea, zinc and iron in an aerobic rice-blackgram cropping system would prove to be a viable strategy to enhance production sustainability and optimize resource utilization.

MATERIALS AND METHODS

The present investigation on sustainable nutrient management in aerobic rice-blackgram cropping system was carried out during 2022 to 2023 at the wetland farm, Tamil Nadu Agricultural University, Coimbatore (11°01′06″ N latitude, 76°58′21″E longitude and 426.7 m above mean sea level). The region of study comes under the western agro-climatic zone of Tamil Nadu. The average annual rainfall was 403 mm and 392 mm, received over 31 and 29 rainy days during 2022 and 2023, respectively. The top soil (0-15 cm) of the site belongs to the clay loam class (clay 45.45%, silt 16.82%, fine sand 15.81% and coarse sand 26.84%). Soil analysis at a depth of 0-15 cm revealed low organic carbon content (0.66 and 0.68 g ha^{-1}) and available nitrogen (210 and 222 kg ha^{-1}), moderate level of available phosphorus (20.2 and 21.7 kg ha^{-1}), high level of potassium (690 and 699 kg ha^{-1}) and pH values of 8.10 and 8.00, respectively during the two year study period. The experiment was conducted in a split-plot design (SPD) with and without green manure intercropping in the main plots and six nutrient management strategies in the sub-plots and replicated thrice. Details of the treatments imposed in the experiment are furnished in Table 1. Paddy seeds were sown directly in dry soil at a spacing of 20 × 10 cm. *Dhaincha* was sown simultaneously using an additive series (1:1 ratio) as per the treatment plan and the green manure was manually incorporated 25 days after sowing. The recommended dose of nitrogen (RDN) (150:50:50 kg/ha of N:P:K) was applied in four splits: 20% at 15 DAS, 30% at tillering and panicle initiation and the remaining 20% at flowering. Potassium was applied in two equal splits, with half at the basal stage and the rest at panicle initiation stage. After rice crop harvest, blackgram was directly sown into the rice stubble without any field preparation. No additional nutrients were applied and the succeeding crop solely depended on the residual nutrients from the fertilizers applied to the preceding rice crop.

Cropping system analysis

To compare the effectiveness of *dhaincha* incorporation and nutrient management practices, the economic yield of all treatments were converted into rice equivalent yield (REY) based on the prevailing market price. The following formulae were employed to work out the system productivity and profitability under aerobic rice-blackgram cropping sequence.

Rice equivalent yield (REY)

$$\text{Rice equivalent yield} = \frac{\text{Yield of blackgram (kg)} \times \text{Price of blackgram (kg)}}{\text{Price of rice (kg)}}$$

System productivity

$$\text{System productivity} = \frac{\text{Total ecomomical yield (kg ha}^{-1})}{\text{Crop duration (Days)}}$$

System profitability analysis

Based on current market price of inputs such seeds, organic manures, fertilisers, pesticides and crop outputs, the cost of cultivation, gross return, net return and cost benefit ratio were calculated.

System profitability

$$\text{System profitability} = \frac{\text{Net returns (Rs. ha}^{-1})}{\text{Crop duration (Days)}}$$

Nitrogen balance

The nitrogen balance was computed as the difference between total nitrogen input and total nitrogen output, with a positive balance indicating a net nitrogen gain and a negative balance reflecting a deficit in the system (Raghuwanshi *et al.,* 1991).

Statistical analysis

In the study, the normality of the parameters was assessed using R software (Version 4.2.0), revealing that all parameters exhibited a normal distribution. The means were distinguished through least significant difference (LSD) method with a significance level of $P \leq 0.05$.

RESULTS AND DISCUSSION

Response on rice equivalent yield and system productivity

Rice intercropping with *dhaincha* (M_2) significantly increased rice equivalent yield (12.5, 12.6 and 12.6%) and system productivity (12.5, 11.9 and 13.1%) in the first, second year and pooled results, respectively compared to sole rice (M_1). In nutrient management strategies, plots treated with half dose of RDN from inorganic fertilizer,

quarter dose of RDN from EFYM, quarter dose of RDN from vermicompost, AM fungi and foliar application of 0.5% urea, 1% $FeSO_4$ and 0.5% $ZnSO_4$ (S_6) recorded significantly higher rice equivalent yield (43.8, 41.8 and 42.7%) and system productivity (43.4, 41.7 and 42.5%) in the first, second year and pooled results, respectively compared to sole application of chemical fertilizer (S_2) (Fig 1). This might be due to a balanced supply of nutrients through organic and inorganic sources that contribute to providing the crop with the required elements for optimal growth and development. This balanced supply of nutrients might have played a crucial role in enhancing the grain yield of the crop as already reported by Dash *et al*. (2025). The presence of AM fungi extend their hyphal network into the soil, increasing the surface area for nutrient absorption and facilitating the uptake of phosphorus and other nutrients essential for rice and blackgram growth. They also might have improved the soil structure by binding soil particles, enhancing aeration, water retention capacity and root penetration, which benefit crop growth. By promoting a healthy environment surrounding the root system and maintaining soil fertility, AM fungi support the sustainability and productivity of the aerobic rice-blackgram cropping system over time (Panneerselvam *et al.,* 2023). The incorporation of green manure in aerobic rice and its residue retention in blackgram improved soil fertility by enhancing nutrient availability, microbial activity and moisture retention. This facilitated better nutrient uptake and increased yield, thereby improving overall system productivity (Park and Lee, 2025). With regard to interaction effect *dhaincha* intercropping and nutrient management strategies on rice equivalent yield and system productivity was non-significant in both the years of study and pooled analysis results.

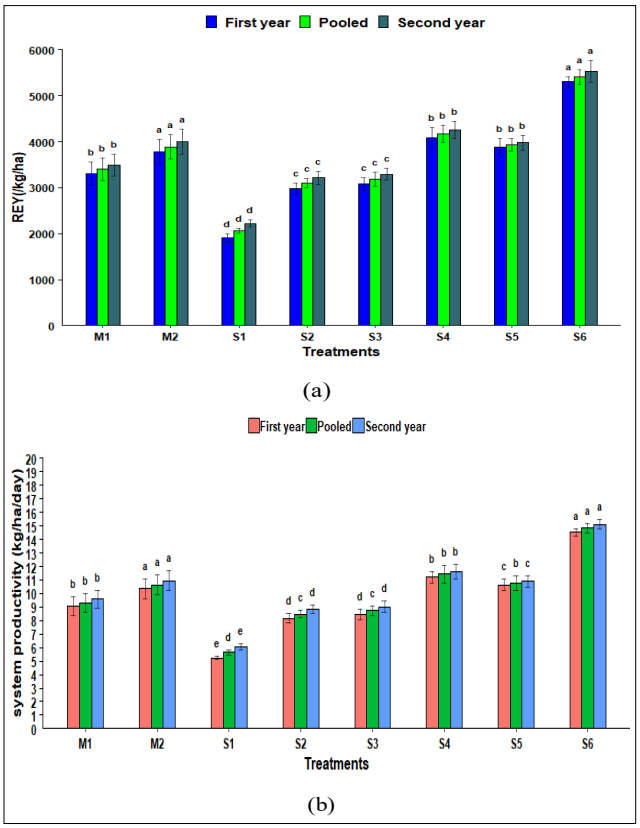


Fig 1: Response of sustainable nutrient management strategies on REY and system productivity of aerobic-blackgram cropping system.

Response on system profitability

Rice intercropped with *dhaincha* recorded higher system profitability (28.6, 26.8 and 27.6 %) in the first, second year and pooled results, respectively compared to sole rice. Regarding, nutrient management strategies, plot received with half dose of RDN from inorganic fertilizer, quarter dose from EFYM, quarter dose from vermicompost, AM fungi and foliar nutrients of 0.5% urea, 1% $FeSO_4$ and 0.5% $ZnSO_4$ (S_6) resulted higher system profitability (51.2, 46.9 and 49.0%) across the first, second year and pooled results, respectively compared to sole application of chemical fertilizer (S_2) (Fig 2). The higher grain and straw yields attained in the aerobic rice-blackgram cropping system contributed to increased system profitability. This could be attributed to the improved productivity of both rice and blackgram crop and enhanced

Table 1: Treatment details.

Main plot: Intercropping

M_1- Sole rice

M_2- Rice + *Dhaincha*intercropping (1:1)

Sub plot: Nutrient management strategies

S_1- Control (Without fertilizer)

S_2- Full dose of RDN (Recommended dose of nitrogen) from inorganic fertilizer

S_3- Half dose RDN from inorganic fertilizer + half dose of RDN from enriched farmyard manure (EFYM)

S_4- Half dose of RDN from inorganic fertilizer + half dose of RDN from EFYM + AM fungi + foliar nutrients (0.5% urea + 1% $FeSO_4$ + 0.5% $ZnSO_4$ at 25 and 45 DAS)

S_5- Half dose of RDN from inorganic fertilizer + quarter dose of RDN from EFYM + quarter dose of RDN from vermicompost (VC), top-dressed at 25 DAS

S_6- Half dose of RDN from inorganic fertilizer + quarter dose of RDN from EFYM + quarter dose of RDN from VC + AM fungi + foliar nutrients (0.5% urea + 1% $FeSO_4$ + 0.5% $ZnSO_4$ at 25 and 45 DAS)

profitability (Nagarjuna *et al.,* 2023). The judicious application of fertilizers along with organic manures not only enhances farm profitability but also lowers cultivation expenses through efficient residue recycling, ultimately improving net returns (Mangaraj *et al*., 2023b). The interaction effect between *dhaincha* intercropping and nutrient management strategies on system profitability was significant in both years and pooled results.

Response on economics

Rice intercropping with *dhaincha* and application of combined application of inorganic fertilizer, enriched FYM, vermicompost, AM fungi and foliar application of nutrients (M_2S_6) registered higher total cost of cultivation (71,868, 71,443 and 71,656 Rs. ha^{-1}, respectively), gross returns (133,085, 137,655 and 135,370 Rs. ha^{-1}, respectively), net returns (71,868, 62,212 and 63,715 Rs. ha^{-1}, respectively) and benefit cost ratio (BCR) (1.85, 1.93 and 1.89 respectively) under aerobic rice-blackgram cropping sequence during first, second year and pooled results. The lowest total cost of cultivation, gross returns, net returns and BCR were recorded in control plot (M_1S_1) during both the years and pooled results. Economics of aerobic rice-blackgram cropping system increased with sustainable nutrient management strategies as compared to application of recommended dose of fertilizer alone (Table 2). This might be due to higher grain and straw yield obtained from sustainable nutrient management strategies in turn increased the economics of aerobic rice-blackgram cropping system (Mangaraj *et al.,* 2023a).

Nitrogen balance in soil

Sustainable nutrient management practices to aerobic rice-blackgram cropping sequence positively influenced the net balance of nitrogen in soil at the end of the cropping system in both the years (Table 3 and 3a).

During first and second year, net gain of soil nitrogen (22 and 24 kg ha^{-1}, respectively) was maximum by *dhaincha* intercropping along with combined application of half dose

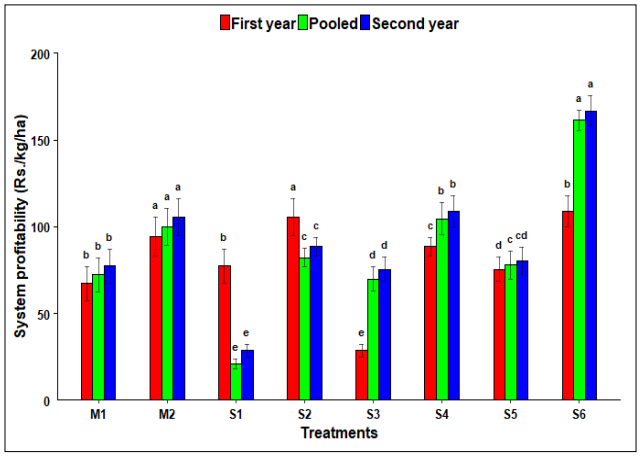


Fig 2: Response of sustainable nutrient management strategies on system profitability of aerobic-blackgram cropping system.

Table 2: Response of sustainable nutrient management strategies on economics of aerobic-blackgram cropping system.

Treatments	Total cost of cultivation (Rs. ha^{-1})			Total gross return (Rs. ha^{-1})			Total net return (Rs. ha^{-1})			B:C ratio		
	2022	2023	Pooled	2022	2023	Pooled	2022	2023	Pooled	2022	2023	Pooled
M_1S_1	44895	44470	44683	48290	51840	50065	3395	7370	5383	1.08	1.17	1.13
M_1S_2	46688	46263	46476	70115	74495	72305	23427	28232	25830	1.50	1.61	1.56
M_1S_3	52870	52445	52658	70630	74470	72550	17761	22026	19894	1.34	1.42	1.38
M_1S_4	61518	61093	61306	90780	94020	92400	29262	32927	31095	1.48	1.54	1.51
M_1S_5	65607	65182	65395	86500	88500	87500	20894	23319	22107	1.32	1.36	1.34
M_1S_6	70868	70443	70656	123385	125945	124665	52517	55502	54010	1.74	1.79	1.77
M_2S_1	45895	45470	45683	51870	58990	55430	5975	13520	9748	1.13	1.30	1.22
M_2S_2	47688	47263	47476	79750	83650	81700	32062	36387	34225	1.67	1.77	1.72
M_2S_3	53870	53445	53658	82930	86430	84680	29061	32986	31024	1.54	1.62	1.58
M_2S_4	62518	62093	62306	106370	108820	107595	43852	46727	45290	1.70	1.75	1.73
M_2S_5	66607	66182	66395	100940	101540	101240	34334	35359	34847	1.52	1.53	1.53
M_2S_6	71868	71443	71656	133085	137655	135370	61217	66212	63715	1.85	1.93	1.89

Table 3: Response of sustainable nutrient management strategies on nitrogen balance under aerobic rice-blackgram cropping system (2022).

Treatments	Rice initial (A)	Applied N (B)	Total N (A+B =C)	Rice N uptake (D)	Expected balance (C-D =E)	Actual balance (F)	Net gain (+) or loss (-) (F-E=G)	Blackgram initial (A)	Blackgram uptake N (B)	Expected balance (A-B=C)	Actual balance (D)	Net gain (+) or loss (-) (D-C=E)
M_1S_1	210	0	210	65	145	110	-35	110	16	94	97	3
M_1S_2	210	150	360	89	271	138	-133	138	24	114	118	4
M_1S_3	210	150	360	86	274	149	-125	149	26	123	132	9
M_1S_4	210	150	360	94	266	178	-88	178	30	148	159	11
M_1S_5	210	150	360	90	270	164	-106	164	28	136	146	10
M_1S_6	210	150	360	100	261	189	-72	189	32	157	170	13
M_2S_1	210	0	210	83	127	118	-9	118	21	97	101	4
M_2S_2	210	150	360	93	267	145	-122	145	25	120	127	7
M_2S_3	210	150	360	92	268	161	-107	161	30	131	143	12
M_2S_4	210	150	360	97	263	189	-74	189	32	157	170	13
M_2S_5	210	150	360	95	265	180	-85	180	31	149	163	14
M_2S_6	210	150	360	107	253	191	-62	191	39	152	174	22

Table 3a: Response of sustainable nutrient management strategies on nitrogen balance under aerobic rice - blackgram cropping system (2023).

Treatments	Rice initial (A)	Applied N (B)	Total N (A+B =C)	Rice N uptake (D)	Expected balance (C-D =E)	Actual balance (F)	Net gain (+) or loss (-) (F-E=G)	Blackgram initial (A)	Blackgram uptake N (B)	Expected balance (A-B=C)	Actual balance (D)	Net gain (+) or loss (-) (D-C=E)
M_1S_1	221	0	221	63	158	116	-42	116	22	94	100	6
M_1S_2	221	150	371	87	284	149	-135	149	29	120	126	7
M_1S_3	221	150	371	85	286	209	-77	209	32	177	187	10
M_1S_4	221	150	371	93	279	243	-36	243	36	207	221	14
M_1S_5	221	150	371	90	281	230	-51	230	34	196	209	13
M_1S_6	221	150	371	98	273	252	-21	252	37	215	230	15
M_2S_1	221	0	221	82	139	125	-14	125	28	97	103	6
M_2S_2	221	150	371	93	278	173	-105	173	31	142	151	9
M_2S_3	221	150	371	90	281	246	-35	246	34	212	222	11
M_2S_4	221	150	371	95	276	259	-17	259	38	222	239	18
M_2S_5	221	150	371	92	279	244	-35	244	36	208	224	16
M_2S_6	221	150	371	105	266	264	-2	264	44	220	244	24

of RDN by inorganic fertilizer + quarter dose of RDN by EFYM + quarter dose of RDN by VC + AM fungi + foliar nutrients of 0.5% Urea +1% $FeSO_4$ + 0.5% $ZnSO_4$ (M_2S_6) than all other nutrient management practices. The lowest net gain of soil nitrogen (3.0 and 6.0 kg ha^{-1}, respectively) was recorded in treatment M_1S_1. Sustainable nutrient management strategies and rotation with legume increased the net gain of soil nitrogen status under aerobic rice- blackgram cropping sequence. This might be due to crop rotation with legume and the integration of various nutrient sources could have a positive impact on the multiplication of beneficial microbes in the soil. These microbes might have played a crucial role in converting organically bound nitrogen from organic residues, such as crop residues and organic manures, into inorganic forms of nitrogen that are readily available for plant uptake. As a result of this microbial activity, higher net gain was observed in available nitrogen in the soil, making it more accessible to the subsequent crops in the rotation (Midya *et al.,* 2021).

CONCLUSION

In accordance with the results of the present investigation, adoption of sustainable nutrient management strategies *viz.,* green manure, organic manures, inorganic fertilizers, micronutrients and biofertilizer increased the system productivity by 42.5 per cent and profitability by 49.0 per cent compared to the recommended dose of fertilizer in aerobic rice-blackgram cropping system. Therefore, the shift from exclusive reliance on inorganic fertilizers to the integrated use of diverse nutrient sources in the aerobic rice-blackgram cropping system can be considered as a sustainable alternative, particularly under the conditions of the Western Zone of Tamil Nadu, India. However, further investigations are necessary to evaluate the broader effects of sustainable nutrient management strategies on ecosystem services, resource use efficiency and system performance under varying crop diversification practices.

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Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Informed consent

Nil.

Conflict of interest

All authors declare that they have no conflicts of interest.

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