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Enhancing productivity of rice (*Oryza sativa*)-rice-fallow system through balanced fertilization: A farmer participatory approach in Kerala's southern coastal plains

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ABSTRACT

A farmer participatory approach captures diverse farming practices in their environmental context, generating locally appropriate solutions to address challenges. The present experiment, conducted during rainy (*kharif*) and winter (*rabi*) seasons from 2017–18 to 2022–23 in six panchayats of Thiruvananthapuram, Kerala was aimed to evaluate the effects of balanced NPK fertilization, including $ZnSO_4$, on the productivity and profitability of the rice (*Oryza sativa* L.)-rice-fallow system in Kerala's southern coastal plains, with a focus on farmer participation and site specific nutrient management. The experiment was laid out in a randomized block design (RBD) with 7 treatments, viz. T_1, Control (no fertilization); T_2, N; T_3, NP; T_4, NK; T_5, NPK; T_6, NPK + $ZnSO_4$; and T_7, Conventional farmers' practice (FP), with rice (*Oryza sativa* L.) grown in both rainy (*kharif*) and winter (*rabi*) seasons. The application of balanced fertilization NPK + $ZnSO_4$ (NPK 90:45:45 kg/ha + $ZnSO_4$ 20 kg/ha in *kharif* and NPK 90:45:45 kg/ha in *rabi*) to medium duration rice significantly increased system rice equivalent yield (5.25 t/ha and 5.20 t/ha) in both seasons. The highest system rice equivalent yield (10.46 t/ha), gross return (₹2.92 lakh/ha), net return (₹0.89 lakh/ha) and benefit cost ratio (1.44) were recorded with NPK+ $ZnSO_4$. In addition to improved nutrient response (26.28 kg yield/kg nutrient), higher sustainable value index (0.71) was observed with NPK + $ZnSO_4$. The farmer participatory study concluded that balanced fertilization with NPK + $ZnSO_4$ is essential for increased rice yield, system productivity, and economic profitability in the rice-rice-fallow system. The successful farmer adoption of this balanced fertilization highlights the need for policy support to promote development of location specific sustainable agricultural systems.

Keywords: Balanced fertilization, Micronutrient, Net returns, Participatory evaluation, Rice yield, Zinc sulphate

The rice (*Oryza sativa* L.)-rice-fallow cropping system, prevalent across 56,782 ha in the southern coastal plains agroecological unit of Kerala, plays a pivotal role in regional food security and livelihoods. This system, which alternates two rice crops with a fallow period, has been highly productive due to the widespread adoption of high-yielding rice varieties and the intensive use of chemical fertilizers. These advances have significantly contributed to the agricultural output of Kerala and supported the food supply chain in India. However, this success comes with challenges to sustainability, as the long-term economic viability of food production systems in India is increasingly undermined by declining fertilizer response (Singh *et al.* 2017). The annual consumption of nitrogenous fertilizers in Kerala during six-year period 2017–2023 increased from 73.11 kt in 2018–19 to a peak of 88.06 kt in 2020–21 before declining to 73.83 kt in 2022–23 (FAI 2021, 2022, 2024). Similarly, the use of potassium (K_2O) fertilizers also peaked in 2020–21 at 75.10 kt. In contrast, phosphorus (P_2O_5) fertilizer consumption exhibited a consistent decline (40.80 kt–29.16 kt) throughout the period. While nitrogen use remains relatively high, the decreasing trend in phosphatic and potassic fertilizers suggests a nutrient imbalance, which raises concerns for soil health, crop productivity, environmental pollution, and greenhouse gas emissions. The declining fertilizer response in rice-based systems is symptomatic of a larger issue of imbalanced nutrient management. While macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) have been prioritized due to subsidies and their direct impact on yields, the essential role of micronutrients like zinc

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(Zn) has been largely overlooked. This imbalance has led to widespread soil fertility degradation and micronutrient deficiencies, particularly Zn, which is crucial for rice growth and development (Bhabani *et al.* 2022). Zn deficiency is further exacerbated by minimal Zn fertilization practices, a trend that is common in rice systems reliant on chemical fertilizers (Saha *et al.* 2015). Over time, the excessive use of NPK fertilizers has not only intensified nutrient imbalances but has also reduced soil organic matter, negatively affecting soil productivity and resilience (Benbi *et al.* 2006). These deficiencies pose a direct threat to agricultural sustainability, as soil health is a critical determinant of crop yields and the overall success of cropping systems.

Addressing these challenges requires a paradigm shift towards balanced nutrient management practices that integrate macronutrients with adequate micronutrient application. Fertilizer strategies must be grounded in scientific evidence and tailored to site-specific soil and crop requirements. Effective nutrient management can restore soil fertility, enhance productivity, and mitigate environmental degradation, thereby improving the sustainability of rice-based systems (Patra *et al.* 2019). Moreover, this approach aligns with the global agenda for the sustainable intensification of agriculture, which seeks to increase food production while minimizing ecological footprints. This study hypothesizes that balanced nutrient application, incorporating both macronutrients NPK and micronutrient Zn, can enhance productivity, improve economic viability, and increase the sustainability of the rice-rice-fallow system. In this context, the study explores various nutrient treatment combinations, incorporating both macro and micronutrients, to identify optimal strategies for improving yields and economic returns. By situating this experiment directly in farmers' fields, the research bridges the gap between theoretical knowledge and practical application, fostering a deeper understanding of balanced fertilization in the unique agroecological context of Kerala. This farmer-participatory research emphasizes the importance of engaging farmers in the co-creation of knowledge to ensure the practical relevance and adoption of sustainable practices. The central research question addressed is how site-specific nutrient management treatments, including Zn application, influence the productivity, economic returns, and long-term sustainability of the rice-rice-fallow cropping system. The findings of this research are expected to contribute significantly to the body of knowledge on nutrient management in rice systems. They hold the potential to inform policy reforms, particularly regarding the rationalization of fertilizer subsidies and the promotion of integrated nutrient management practices. Furthermore, the study highlights the necessity of adopting a systems-based approach to agricultural research, which integrates soil health, crop productivity, and profitability into a cohesive framework for sustainable development. As such, this work aligns with the broader goals of ensuring food security, farmer livelihood, reducing environmental impacts, and promoting resilience in agricultural systems.

MATERIALS AND METHODS

The present experiments were conducted during rainy (*kharif*) and winter (*rabi*) seasons from 2017–18 to 2022–23 in six panchayats of Thiruvananthapuram, Kerala, in 24 farmers' fields India. These study sites located in the Southern Coastal Plains agroecological unit were Chemmaruthy, Ottur, Cherunniyur panchayats of Varkala block, and Kadakkavoor, Keezhuvilam, Chirayinkeezhu panchayats of Chirayinkeezhu block. The initial physical and chemical properties of soils indicated that the clay loam textured soil was strongly acid in reaction (*p*H 5.27), and non-saline (EC 0.16 dS/m). Fertility status indicated that the soils were medium in organic carbon (0.63%), medium in available N (293 kg/ ha), P (18.3 kg/ ha), and K (161 kg/ha), and deficient in HCl-extractable Zn (0.89 mg/kg). Acidic soils in Kerala having Zn lower than 1.00 mg/kg are considered to be deficient in Zn (KAU 2024).

The experiment was laid out in a randomized block design (RBD), with each farmer's field serving as a replication. The seven treatments included, T_1, Control (no fertilization); T_2, N; T_3, NP; T_4, NK; T_5, NPK; T_6, NPK + $ZnSO_4$; and T_7, Conventional farmers' practice (FP). Farmers applied an average of nitrogen 106 ± 15 kg/ha, phosphorus 49 ± 7 kg/ha, and potassium 57 ± 31 kg/ha. From the 3rd year onwards, farmers voluntarily incorporated application of $ZnSO_4$ @20 kg/ha into their practice, inspired by the significant yield improvements observed in the NPK + $ZnSO_4$ treatment. The NPK + $ZnSO_4$ treatment was application of NPK 90:45:45 kg/ha along with $ZnSO_4$ 20 kg/ha in *kharif* and NPK 90:45:45 kg/ha in *rabi* seasons (KAU 2024). Urea, rock phosphate, muriate of potash, and zinc sulphate were used as source for N, P, K, and Zn, respectively. Nitrogen was applied in three equal splits at the basal, active tillering and panicle initiation stages. Phosphorus was applied as a single basal dose, while potassium was applied in two equal splits, one at the basal stage and the other at the panicle initiation stage and zinc was applied as a single basal dose.

The widely cultivated medium duration rice variety Uma, was grown during both *kharif* and *rabi* seasons. The experimental site was puddled, levelled, and small bunds were formed around each plot. The gross and net plot areas were 100 m^2 and 81 m^2, respectively. The nursery raised seedlings were transplanted 18 days after sowing (DAS) into treatment plots. Irrigation, weed, pest and disease management practices were carried out following the recommendations of Kerala Agricultural University (KAU 2024). During each season, the data on grain and straw yields were recorded at harvest. Subsequently, the data were statistically analysed using procedure outlined by Gomez and Gomez (1984).

RESULTS AND DISCUSSION

Yield during kharif *and* rabi *seasons*: In the *kharif* season, yield of NPK+$ZnSO_4$ treatment ranged between 4.39 t/ha and 5.64 t/ha, while unfertilized control yielded only 1.30–1.58 t/ha (Table 1). On average, the NPK+$ZnSO_4$

treatment yielded 5.25 t/ha, significantly outperforming all other treatments. Farmers' practice, which yielded 4.83 t/ha, was comparable to NPK (4.79 t/ha), and both were superior to other treatments. The application of NPK+$ZnSO_4$ led to a significant increase in yield, 72.0%, 62.7%, 40.2%, 45.3%, 8.8%, and 8.0% over the control, N, NP, NK, NPK, and farmers' practice, respectively. The yield increase in NPK+$ZnSO_4$ confirms the necessity of balanced fertilization.

During the *rabi* season, the NPK+$ZnSO_4$ treatment similarly outperformed all other treatments, resulting in significantly higher yield (5.20 t/ha) (Table 1). This yield ranged from 4.90–5.58 t/ha across the years. In contrast, unfertilized control yielded between 1.28 t/ha and 1.55 t/ha. The farmers' practice (4.87 t/ha) yielded on par with NPK (4.78 t/ha), and both were superior to other treatments. The application of NPK+$ZnSO_4$ resulted in a significant yield increase of 72.1%, 58.8%, 39.8%, 42.3%, 8.1%, and 6.3% over the control, N, NP, NK, NPK, and farmers' practice, respectively. The enhanced yield observed with NPK+$ZnSO_4$ highlights the importance of balanced fertilization.

Productivity of rice-rice-fallow system: The study revealed that the productivity of the rice-rice-fallow system was significantly influenced by the application of balanced fertilizers, with the NPK + $ZnSO_4$ treatment achieving the highest system productivity of 10.46 t/ha (Table 2). This yield outperformed both the farmers' practice (9.70 t/ha) and the NPK treatment (9.57 t/ha). Comparative analyses indicated that the application of NPK + $ZnSO_4$ resulted in productivity improvements of 72.2%, 60.8%, 40.1%, 44.0%, 8.5%, and 7.3% over control, N, NP, NK, NPK, and farmers' practice, respectively. The study showed that the annual rice productivity of each treatment from high to low was as follows: NPK+Zn>NPK>NP>NK>N. The increased productivity in NPK + $ZnSO_4$ confirms the necessity of balanced fertilization.

The results showed that, NP treatment (6.27 t/ha) yielded more compared to NK treatment (5.86 t/ha) (Table 2). The application of phosphorous had a greater impact on increasing rice yields than the application of potassium. Previous studies have shown that nitrogen and phosphorus in soil are the key elements limiting rice yield (Kong *et al*. 2014, Zhang *et al*. 2018, Maaz *et al*. 2021, Liu *et al*. 2022). To ensure high crop yields, farmers tend to apply large amounts of N fertilizers. However, in the paddy fields of Kerala, high temperature and rainfall accelerate the conversion of nitrogen into ammonium and nitrate, leading to significant losses through ammonia volatilization and nitrate leaching. The excessive application of N fertilizers lowers both Nitrogen Use Efficiency (NUE) and Nitrogen Recovery Efficiency (NRE) in rice to below 30% (Liu *et al.* 2008, Yang *et al.* 2013) without contributing to an increase in rice yield.

The nutrient response was notably higher with the NPK + $ZnSO_4$ treatment, yielding 26.28 kg of grain per kg of

Table 1 Yield of rice-rice-fallow cropping system as influenced by different nutrient treatment combinations

Treatment	Rice equivalent yield (t/ha)						
	2017–18	2018–19	2019–20	2020–21	2021–22	2022–23	Pooled mean
				Kharif yield			
T_1	1.41	1.30	1.54	1.57	1.58	1.41	1.47
T_2	1.81	1.70	2.04	1.98	2.09	2.13	1.96
T_3	3.30	2.55	3.31	3.20	3.18	3.28	3.14
T_4	2.89	2.35	3.03	3.17	3.20	2.55	2.87
T_5	5.26	4.02	4.99	4.85	4.84	4.79	4.79
T_6	5.19	4.39	5.64	5.56	5.60	5.12	5.25
T_7	5.20	4.00	5.36	5.45	5.32	3.65	4.83
SEm (±)	0.144	0.081	0.091	0.06	0.142	0.109	0.108
CD (*P*=0.05)	0.416	0.237	0.255	0.168	0.419	0.314	0.316
				Rabi yield			
T_1	1.28	1.54	1.55	1.49	1.49	1.32	1.45
T_2	1.87	2.41	2.20	2.25	2.30	1.82	2.14
T_3	3.21	3.33	3.24	3.32	3.24	2.44	3.13
T_4	2.53	3.09	3.01	3.29	3.24	2.83	3.00
T_5	4.96	4.84	4.59	4.79	4.78	4.72	4.78
T_6	4.90	5.09	5.12	5.58	5.42	5.11	5.20
T_7	4.89	4.65	4.98	5.44	5.30	3.96	4.87
SEm (±)	0.103	0.043	0.049	0.062	0.148	0.116	0.101
CD (*P*=0.05)	0.297	0.127	0.139	0.174	0.415	0.342	0.296

Treatment details are given under Materials and Methods.

Table 2 Productivity and profitability of rice-rice-fallow cropping system as influenced by various nutrient treatment combinations

Treatment	System rice equivalent yield (t/ha)	Nutrient response (kg yield/kg nutrient)	Cost of cultivation (× 10^5 ₹/ha)	Gross return (× 10^5 ₹/ha)	Sustainable value index	Benefit cost ratio
T_1	2.91	–	1.87	0.82	0.61	0.44
T_2	4.10	16.19	1.94	1.15	0.60	0.60
T_3	6.27	15.18	1.99	1.74	0.65	0.89
T_4	5.86	23.21	1.98	1.65	0.63	0.84
T_5	9.57	16.29	2.01	2.66	0.69	1.32
T_6	10.46	26.28	2.03	2.92	0.71	1.44
T_7	9.70	24.42	2.08	2.71	0.66	1.30

Treatment details are given under Materials and Methods.

nutrient applied, compared to farmers' practice (24.42 kg/kg) and NPK treatment (16.29 kg/kg) (Table 2). Regmi *et al*. (2003) observed consistently higher rice yields in NPK treated plots compared to those where one or more nutrients were omitted over a 20-year-long experiment. Combined application of NPK in a 38-year-long fertilization experiment resulted in the highest average year-round rice grain yield (Gao *et al.* 2023). Their findings showed that applying a balanced ratio of NPK fertilizers while maintaining the N application rate constant can enhance rice growth, improve N uptake, and thereby reduce N surplus in soil. The balanced application of NPK nutrients ensured optimal input utilization, enhancing productivity of rice-rice-fallow system. The present study demonstrates that, in addition to balanced NPK application, the supplementation of micronutrient Zn which was identified as deficient in the soil can further enhance rice yield in Southern Coastal Plains of Kerala. Baishya *et al*. (2017) reported increased productivity in the rice-rice cropping system when NPK fertilizers were applied in combination with $ZnSO_4$ in the Lower Brahmaputra Valley Zone of Assam.

The enhanced yields observed in the NPK + $ZnSO_4$ treatment can be attributed to the synergistic roles of the applied nutrients. Tuiwong *et al*. (2024) reported a synergistic interaction between N and Zn mediated by N and Zn transporter related genes. Their findings confirmed that the application of nitrogen and zinc significantly enhanced rice productivity. Nawaz *et al.* (2015) reported that the highest rice yield was obtained when NPK + $ZnSO_4$ was applied to the soil at the time of puddling. This increase in yield was attributed to the role of Zn in activating enzymes involved in biosynthesis and translocation of carbohydrates during grain filling, as well as the role of Zn in improving pollination that eventually resulted in an increased grain filling (Baishya *et al*. 2017). N is the main component of protein and promotes stem and leaf growth, as well as the development of tiller primordia, maintains and regulates the physiological functions of rice, thus improving the yield and quality of rice (Gao *et al.* 2023). P promotes improved root development, facilitating efficient nutrient uptake, while K supports N metabolism, translocation of photo-assimilates, and stomatal regulation. These mechanisms collectively enhanced the productivity of cropping system, underscoring the importance of balanced fertilization. The experimental sites in the present study exhibited a baseline deficiency in HCl-extractable Zn (0.89 mg/kg) before planting the *kharif* crop, emphasizing the need for Zn supplementation.

The application of $ZnSO_4$ at 20 kg/ha alongside NPK significantly enhanced system productivity (10.46 t/ha), particularly in the rice-rice-fallow system (Table 2). Over the study period, farmers increasingly recognized the benefits of balanced nutrient application, with many voluntarily adopting $ZnSO_4$ application (20 kg/ha) from the third year onwards as part of their standard practice, leading to an increase in system productivity (9.70 t/ha). This transition reflects the effectiveness of the participatory research approach in promoting sustainable agricultural practices and farmer-led innovation. The voluntary adoption of the $ZnSO_4$ application highlights the practical relevance and impact of on-farm research in improving nutrient management practices. Singh *et al*. (2017) emphasized that on-farm participatory research plays a critical role in fostering the adoption of improved nutrient management strategies. They highlighted that achieving higher productivity in India's major cropping systems requires not only the application of NPK but also the inclusion of cropping system and location-specific micronutrients. This study further underscores the importance of tailoring nutrient management practices to address site-specific deficiencies for sustainable productivity gains. The results clearly demonstrate that balanced fertilization with NPK + $ZnSO_4$ is a superior nutrient management strategy for enhancing the productivity of the rice-rice-fallow system. The findings highlight the critical role of micronutrients like Zn in addressing soil deficiencies and improving crop yields. The widespread adoption of $ZnSO_4$ by farmers, facilitated through participatory research, underscores the potential of collaborative approaches to drive sustainable agricultural transformation. Future efforts should focus on scaling these practices, supported by targeted policy interventions and farmer education programs, to ensure widespread benefits across similar agroecological systems.

Profitability of rice-rice-fallow system: The profitability of the rice-rice-fallow system was significantly influenced by the choice of fertilization treatments, with the NPK + $ZnSO_4$ treatment emerging as the most economically viable option. This treatment achieved the highest gross return of ₹2.92 × 10^5/ha and net return of ₹0.89 × 10^5/ha, outperforming all other treatments, including farmers' practice (Table 2). The profitability was further underscored by the highest sustainable value index (0.71) and benefit-cost ratio (1.44) observed in this treatment, reflecting its superior economic efficiency. Farmers' practice incurred the highest system cost of cultivation at ₹2.08 × 10^5/ha, driven by excessive and imbalanced fertilization during the first two years of the study. This approach not only escalated input costs but also resulted in relatively lower system productivity (9.70 t/ha) compared to the NPK + $ZnSO_4$ treatment (10.46 t/ha). The imbalance in nutrient application led to inefficient resource use, underscoring the economic disadvantage of such practices. In contrast, the NPK + $ZnSO_4$ treatment maintained a lower cost of cultivation (₹2.03 × 10^5/ha) while delivering higher productivity, resulting in greater profitability. The balanced application of nutrients enhanced both productivity and economic returns.

The higher profitability of the NPK + $ZnSO_4$ treatment can be attributed to its integrated approach to nutrient management. By addressing both macronutrient and micronutrient deficiencies, this treatment optimized plant growth and productivity, translating into higher economic returns. Previous studies support these findings. Singh *et al*. (2017) highlighted that the inclusion of location-specific micronutrients alongside NPK significantly increased returns in cereal-based systems. Pasha *et al*. (2018) and Patra *et al*. (2019) also demonstrated that balanced fertilization with NPK + $ZnSO_4$ resulted in higher profitability compared to treatments involving imbalanced fertilization, such as N, NP, NK, and farmers' practices. The results suggested that, the sustainable value index (0.71) for the NPK + $ZnSO_4$ treatment indicates a high probability that the minimum guaranteed monetary net returns would exceed 71% of the potential net returns in the rice-rice-fallow system. Additionally, the observed benefit-cost ratio of 1.44 for the NPK + $ZnSO_4$ treatment demonstrates that the benefits surpass the costs by 44%, confirming the profitability of this system. These findings highlight not only the immediate economic viability but also the long-term sustainability of the rice-rice-fallow system. The findings highlight the critical importance of balanced fertilization in enhancing the economic viability of rice-based systems. The significant reduction in input costs and increase in productivity achieved through NPK + $ZnSO_4$ application demonstrate its potential as a sustainable practice for resource-constrained farmers. Encouragingly, these benefits were not limited to short-term gains, as the higher sustainable value index indicates that balanced fertilization contributes to the long-term sustainability of the rice-rice-fallow system.

The voluntary adoption of NPK + $ZnSO_4$ application by farmers from the third year of the study highlights its practical relevance and cost-effectiveness. The participatory research approach played a pivotal role in demonstrating the economic advantages of balanced fertilization, fostering farmer confidence in the practice. Scaling such practices through targeted extension programs and policy interventions can further enhance adoption rates. Subsidy structures should also be revisited to incentivize balanced fertilization, including the use of micronutrients like Zn, to ensure economic and environmental sustainability. Investments in farmer education and support for location-specific nutrient recommendations can maximize the profitability and resilience of cropping systems.

The six year-long fertilization experiment performed under this study demonstrated that balanced fertilization, specifically NPK 90:45:45 kg/ha with $ZnSO_4$ 20 kg/ha in *kharif* and NPK 90:45:45 kg/ha in *rabi*, significantly enhances the productivity (10.46 t/ha), profitability (net return ₹0.89 × 10^5/ha), and sustainability (benefit-cost ratio 1.44) of the rice-rice-fallow system in Kerala's Southern Coastal Plains. The inclusion of zinc sulphate addressed critical micronutrient deficiencies, improving nutrient uptake, nitrogen metabolism, and overall crop performance. The voluntary adoption of zinc sulphate application by farmers highlights its practical relevance and scalability. This research underscores the need for site-specific nutrient strategies and policy reforms to promote balanced fertilization, ensuring sustainable agricultural intensification and long-term food security. Future efforts should integrate advanced precision tools to optimize nutrient management further.

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