



RESEARCH ARTICLE

Residual effect of foliar applied nanofertilisers on rice fallow green gram for sustainable rice intensification

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Abstract

Sustainable crop intensification through rice-green gram cropping system utilises the residual benefits of fertilisers, particularly through foliar application of nanofertilisers. Therefore, the present study aimed to assess the residual effects of foliar-applied nanofertilisers especially nitrogen (N), zinc (Zn) and copper (Cu) on rice fallow green gram. The field trial was conducted using a randomised block design with 12 treatments and 3 replications, integrating soil and nano foliar applied fertilisers. The results indicated that in experiment I, 100 % nitrogen, phosphorus and potassium (NPK) + nano N, Zn and Cu at active tillering, each at 4 mL L⁻¹ of water showed significantly higher green gram yield by 12.69 %, nitrogen uptake by 8.45 % and net returns by 23 % compared to conventional fertilisation (100 % NPK). In experiment II, foliar application of nano N at active tillering at 8 mL L⁻¹ of water, combined with either 100 % NPK or 75 % N + 100 % PK, significantly enhanced yield by 13.05 %, nitrogen uptake by 15.6 % and net returns by 28.5 %. System indices also showed similar trend with respect to rice equivalent yield, system productivity and profitability. In conclusion, application of either 100 % NPK or 75 % N + 100 % PK along with foliar application of nano N at 8 mL L⁻¹ during active tillering proved effective in enhancing green gram performance and sustaining soil and environmental health in rice-fallow systems.

Keywords: foliar nanofertilisers; green gram; integrated nutrient management; residual effect; rice based cropping systems

Introduction

The global as well as country's population is anticipated to increase, intensifying the demand for increased food production further aggravated by the adverse effects of climate change through innovative technological solutions in agriculture sector, while simultaneously safeguarding environmental health to sustain long-term global food security. A paradigm shift towards sustainable crop intensification is imperative, emphasising enhanced productivity per unit input alongside reduced environmental impact through conservation of natural resources (1). Horizontal intensification of legumes in rice based cropping systems improves crop productivity by 2–4 times (2), soil health through carbon sequestration and nitrogen fixation (3, 4) and further reduces greenhouse gases by 45 % (5) compared to cereal-cereal cropping system. Green gram (*Vigna radiata* (L.) R. Wilczek), a short-duration and climate-resilient legume crop is capable for cultivation during the rice fallow period due to its adaptability, nitrogen-fixing capacity and nutritional value (6).

The residual benefit of fertilisers from the current crop is often ignored and full recommended dose of fertilisers are applied to the succeeding crop in the cropping system contributing to soil deterioration and environmental health. Thus, in recent years, the integration of advanced nutrient delivery systems such as nanotechnology in agriculture has garnered significant attention for enhancing crop productivity and nutrient use efficiency (7, 8).

Foliar application of nano nutrients offers the advantage of enhanced solubility, targeted delivery, better absorption and translocation of nutrients within plant tissues and prolonged availability of applied soil nutrients in the system (9, 10), thus facilitating the residual crop to be taken up on rice fallows. Several studies have demonstrated that foliar application of nano nutrients significantly improved yield and nutrient content in cereals (11–14), millets (15–17), pulses (18, 19), oilseeds (20–22) and horticulture crops (23–25). However, the studies on residual effects of foliar nanofertilisers on succeeding crops in a cropping system, especially in rice fallow scenarios, remain limited. A previous study (26) indicated that the residual effects of foliar applied nanofertilisers to rice along with 50 % recommended dose of nitrogen via synthetic fertiliser + 50 % via farmyard manure (FYM) showed better growth, yield, nutrient uptake, microbial population and dehydrogenase activity in succeeding lentil. Previous research indicates that (27) the residual effect of foliar nano nitrogen, phosphorus and potassium (NPK) application in rice enhanced the performance of succeeding green pea.

Understanding the concept of residual fertility is crucial for designing integrated nutrient management strategies that optimise input use, reduce costs, increase yields and promote sustainable crop intensification. Modern agricultural strategies emphasise integrated nutrient application to bring trade-off between high crop productivity and ecological safety and long-term soil sustainability. Keeping in view the above-mentioned

background, the present study was undertaken to evaluate the residual effect of foliar-applied nano nutrients (nitrogen (N), zinc (Zn) and copper (Cu)) to preceding rice on performance of succeeding green gram grown under rice fallows.

Materials and Methods

Experimental site

The field experiments were conducted in two different fields during rabi 2020–2021 and summer 2021 respectively after rice crop located at the wetland farms of Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore, India (11° N latitude, 77° E longitude). The soils of the experimental site are classified under Typic Haplustalf subgroup, Noyyal series and clayey loam in texture. The initial soil conditions of the experimental site including the respective range values, rating criteria and methodology is presented in Supplementary Table 1. After harvest and before green gram sowing, the available soil N, P and K were in the range of 127.3–288.5 kg ha⁻¹, 12.2–23.3 kg ha⁻¹ and 597.2–742.0 kg ha⁻¹ in experiment I and 113.5–278.9 kg ha⁻¹, 7.9–17.2 kg ha⁻¹ and 713.5–903.1 kg ha⁻¹ respectively across various treatments. The weather conditions prevailing during the experimental period are provided in Supplementary Table 2.

Experimental design and treatments

The residual effect of twelve treatments in each of the two experiments comprising of various levels of fertiliser application along with foliar application of nano N, Zn and Cu at different doses in rice fallow green gram was evaluated (Table 1) using randomised complete block design with three replications (Supplementary Fig. 1). Nano N, Zn and Cu procured from Indian Farmers Fertiliser Cooperative Limited (IFFCO) were each applied at 4 mL L⁻¹ of water in Experiment I and 8 mL L⁻¹ of water in Experiment II to rice and the residual effect of treatments was studied on succeeding green gram in both the experiments. The recommended dose of IFFCO nano-fertilisers were used in Experiment I and double the recommended dose was tried in Experiment II.

Crop management

Green gram (CO 8) seeds were sown during November 2020 and April 2021 in Experiment I and II respectively. After rice harvest, weeds in the irrigation channels were clipped up to the ground level using sickles and no field preparation was done. Pre-sowing irrigation was given in each of the two years. The seed rate of 30 kg ha⁻¹ was adopted and two seeds were dibbled between the rice

stubbles adopting a spacing of 25 × 10 cm. Thinning and gap filling were done at 10 days after sowing (DAS). Flood irrigation was provided immediately after sowing and later irrigated at an interval of 7–10 days depending on the environmental conditions. Paraquat dichloride 24 % SL at 8 mL L⁻¹ of water was sprayed immediately after the harvest of rice crop. Later, two hand weedings were done on 15 and 30 DAS. Harvesting was done after the pods were dried completely.

Nutrient management

As referred in a previous study (33) the recommended dose of fertiliser for rice CO-51 variety was 150:50:50 kg N: P₂O₅: K₂O ha⁻¹. Nitrogen, phosphorus and potassium were supplied in the form of urea, single super phosphate and muriate of potash respectively. The proposed quantity of phosphorus was supplied basally to the soil in both experiments. According to the treatments scheduled, entire recommended quantity of nitrogen and potassium were soil applied in four equal splits i.e., at basal, active tillering (25 days after transplanting (DAT)), panicle initiation (35 DAT) and heading stage (55 DAT) during Experiment I, whereas in three equal splits (basal, active tillering and panicle initiation stage) during Experiment II.

Nano N, Zn and Cu were foliar applied to the preceding rice crop at 4 mL L⁻¹ of water in Experiment I and 8 mL L⁻¹ of water in Experiment II using hand operated knapsack sprayer with flat fan nozzles to ensure optimal foliage coverage. In both the experiments, nano nutrients were applied as foliar at active tillering stage on 30 DAT and panicle emergence stage on 60 DAT. With respect to combination treatments (T₆ to T₈), all the 3 nano liquid fertilisers were tank mixed and applied as foliar spray. The liquid nano N, Zn and Cu contained 40000 ppm of N, 10000 ppm of Zn and 8000 ppm of Cu respectively. To evaluate the residual effect of fertilisers on succeeding green gram, neither soil application of fertilisers nor foliar spray of nano nutrients was done.

Data collection

The growth parameters of rice fallow green gram such as plant height and dry matter production were measured at 30 DAS and harvest stages of crop growth from the five tagged plants in each net plot and the mean value was documented. The border two rows in each of the treatments are avoided for sampling. The yield attributing characteristics such as number of pods per plant and seeds per pod were recorded at harvest from the tagged plants and the mean value was arrived. The grain and haulm yield were recorded from the entire net plot area and expressed as kg ha⁻¹.

Table 1. Treatment details

Treatment No.	Treatment details	Treatment abbreviation
T ₁	100 % NPK (150:50:50 kg NPK ha ⁻¹)	100 _{NPK}
T ₂	0 % N + 100 % RD PK	0 _N + 100 _{PK}
T ₃	100 % RD N + 100 % RD PK + Nano N at active tillering	100 _{NPK} + nFN at AT
T ₄	75 % RD N + 100 % RD PK + Nano N at active tillering	75 _N + 100 _{PK} + nFN at AT
T ₅	50 % RD N + 100 % RD PK + Nano N at active tillering	50 _N + 100 _{PK} + nFN at AT
T ₆	100 % RD N + 100 % RD PK + Nano N + Nano Zn + Nano Cu at active tillering	100 _{NPK} + nFNZnCu at AT
T ₇	75 % RD N + 100 % RD PK + Nano N + Nano Zn + Nano Cu at active tillering	75 _N + 100 _{PK} + nFNZnCu at AT
T ₈	50 % RD N + 100 % RD PK + Nano N + Nano Zn + Nano Cu at active tillering	50 _N + 100 _{PK} + nFNZnCu at AT
T ₉	100 % NPK + Nano Zn at active tillering	100 _{NPK} + nFZn at AT
T ₁₀	100 % NPK + Nano Zn at active tillering and panicle emergence	100 _{NPK} + nFZn at AT and PE
T ₁₁	100 % NPK + Nano Cu at active tillering	100 _{NPK} + nFCu at AT
T ₁₂	100 % NPK + Nano Cu at active tillering and panicle emergence	100 _{NPK} + nFCu at AT and PE

Nano N, Nano Zn and Nano Cu were applied each at the rate of 4 mL L⁻¹ of water in experiment I and 8 mL L⁻¹ of water in experiment II to rice and the residual effect of above treatments was studied on succeeding green gram in both the experiments. RD: recommended dose; AT: active tillering; PE: panicle emergence; N: nitrogen; P: phosphorus; K: potassium; Zn: zinc; Cu: copper.

Soil and plant analysis

The post-harvest soil samples from rice as well as green gram were collected from each individual treatment plot up to a depth of 30 cm and analysed for available N, P and K. The plant samples at maturity of green gram were uprooted and grinded into fine powder using Willey mill. One gram of the powdered samples was kept for overnight pre-digestion and analysed for total N content using micro-Kjeldahl distillation using a Kelplus N Analyser (34), P content using vanadomolybdate yellow tri-acid extract method with spectrophotometer at 420 nm (35) and K content using tri-acid extract with flame photometer (36). The nutrient uptake was calculated by multiplying the nutrient content with dry matter production at harvest.

Economic evaluation

The cost of cultivation (₹ ha⁻¹) for green gram was calculated based on the input quantity and market price prevailing during the experiment period. The gross income was computed as the product of economic yield and market price. Net income was estimated by subtracting the cultivation cost from the gross income. The benefit cost ratio was obtained by dividing the gross income with cultivation cost.

Cropping system evaluation

The rice equivalent yield (REY, kg ha⁻¹) was calculated based on the yield and price of rice and green gram (37). System production efficiency (SPE, kg ha⁻¹ day⁻¹) was calculated by dividing the REY with total duration of crops in the cropping system. System economic efficiency (SEE, ₹ ha⁻¹ day⁻¹) was worked out by dividing the net income obtained from the cropping system with total duration of crops in the cropping system (38).

Statistical analysis

The recorded data on various parameters were statistically analysed according to the mathematical methodology for randomised block design (39) using Microsoft Excel 2019. Where the F-test showed significant treatment differences, critical difference was calculated at 5 % probability level using least significant difference (LSD)

to draw valid conclusions.

Results

Growth parameters

Among different treatments, the combined application of 100 % recommended NPK along with foliar nano nutrients showed consistently superior performance in terms of plant height and dry matter production in both the experiments (Table 2). In Experiment I, the treatment involving 100 % NPK with foliar application of nano N, Zn and Cu at active tillering stage (T₆) recorded significantly higher crop growth in terms of plant height and dry matter accumulation, followed closely by 100 % NPK and nano N at active tillering (T₃). However, in Experiment II, 100 % NPK combined with foliar nano N at active tillering showed significantly higher growth performance when compared with T₁ and was on par with the treatment receiving reduced nitrogen (75 % N + 100 % PK) along with nano N at active tillering (T₄). In contrast, the treatment without nitrogen application (100 % PK only) consistently resulted in the significantly lower growth parameters at all stages in both the experiments.

Yield attributing characteristics

In Experiment I, plants supplied with 100 % NPK along with foliar application of nano nutrients containing N, Zn and Cu at active tillering stage exhibited significant improvement in yield attributes, particularly in terms of pods per plant and seeds per pod. This treatment outperformed the control and remained statistically comparable with the application of 100 % NPK combined with nano N alone. A slightly different trend was observed in Experiment II, where the application of 100 % NPK with foliar nano N at active tillering showed significantly higher yield attributing characteristics and was on par with the treatment with reduced nitrogen (75 % N + 100 % PK) supplemented with nano N, suggesting that partial substitution of nitrogen, when supported by nano nutrient application, can still sustain better reproductive performance. The treatment with no nitrogen and only 100 % PK

Table 2. Effect of foliar nano nutrients (N, Zn and Cu) application on growth parameters of rice fallow green gram

Treatments	Plant height (cm)				Dry matter production (kg ha ⁻¹)			
	Experiment I (4 mL L ⁻¹)		Experiment II (8 mL L ⁻¹)		Experiment I (4 mL L ⁻¹)		Experiment II (8 mL L ⁻¹)	
	30 DAS	Harvest	30 DAS	Harvest	30 DAS	Harvest	30 DAS	Harvest
T ₁ : 100 _{NPK}	17.2	43.1	16.5	41.7	703	2745	677	2499
T ₂ : 0 _N + 100 _{PK}	11.5	22.0	11.3	25.9	529	2118	511	2043
T ₃ : 100 _{NPK} + nFN at AT	20.1	47.6	21.7	50.3	752	3018	807	3205
T ₄ : 75 _N + 100 _{PK} + nFN at AT	14.2	38.3	19.5	47.2	681	2604	755	2942
T ₅ : 50 _N + 100 _{PK} + nFN at AT	12.5	26.6	14.1	32.5	624	2272	601	2236
T ₆ : 100 _{NPK} + nFNZnCu at AT	21.2	48.7	16.2	44.4	786	3198	658	2574
T ₇ : 75 _N + 100 _{PK} + nFNZnCu at AT	15.0	41.6	13.8	34.8	693	2683	612	2388
T ₈ : 50 _N + 100 _{PK} + nFNZnCu at AT	12.7	30.8	12.4	31.6	667	2319	595	2195
T ₉ : 100 _{NPK} + nFZn at AT	17.8	43.5	18.1	44.1	705	2909	716	2811
T ₁₀ : 100 _{NPK} + nFZn at AT and PE	19.2	44.2	19.0	44.8	727	2998	738	2916
T ₁₁ : 100 _{NPK} + nFCu at AT	14.1	32.7	15.5	38.8	699	2544	632	2406
T ₁₂ : 100 _{NPK} + nFCu at AT and PE	13.2	32.1	14.8	37.7	685	2429	619	2395
SEd	1.1	2.3	1.1	2.5	32	132	36	144
SEm (±)	0.78	1.63	0.77	1.77	23	93	25	102
CD (p = 0.05)	2.2	4.8	2.3	5.2	67	271	75	295

DAS: days after sowing; RD: recommended dose; AT: active tillering; PE: panicle emergence; N: nitrogen; P: phosphorus; K: potassium; Zn: zinc; Cu: copper; Sed: standard error of difference; SEm (±): standard error of mean; CD (p = 0.05): critical difference at 5 % level of significance.

Table 3. Effect of foliar nano nutrients (N, Zn and Cu) application on yield attributing characteristics of rice fallow green gram

Treatments	Pods plant ⁻¹		Seeds pod ⁻¹	
	Experiment I (4 mL L ⁻¹)	Experiment II (8 mL L ⁻¹)	Experiment I (4 mL L ⁻¹)	Experiment II (8 mL L ⁻¹)
T ₁ : 100 _{NPK}	24.3	21.9	11.40	11.31
T ₂ : 0 _N + 100 _{PK}	15.2	14.1	8.98	8.69
T ₃ : 100 _{NPK} + nFN at AT	29.1	30.2	11.87	12.13
T ₄ : 75 _N + 100 _{PK} + nFN at AT	22.8	28.5	10.95	11.95
T ₅ : 50 _N + 100 _{PK} + nFN at AT	17.5	18.7	9.48	9.78
T ₆ : 100 _{NPK} + nFNZnCu at AT	30.5	22.1	12.02	11.59
T ₇ : 75 _N + 100 _{PK} + nFNZnCu at AT	23.8	19.9	11.14	10.84
T ₈ : 50 _N + 100 _{PK} + nFNZnCu at AT	18.0	16.1	9.87	9.67
T ₉ : 100 _{NPK} + nFZn at AT	25.9	27.5	11.61	11.73
T ₁₀ : 100 _{NPK} + nFZn at AT and PE	28.4	27.8	11.79	11.81
T ₁₁ : 100 _{NPK} + nFCu at AT	21.7	21.1	10.43	11.21
T ₁₂ : 100 _{NPK} + nFCu at AT and PE	20.9	19.8	10.01	10.90
SEd	1.3	1.5	0.41	0.43
SEm (±)	0.92	1.1	0.29	0.30
CD (p = 0.05)	2.6	3.1	0.84	0.88

DAS: days after sowing; AT: active tillering; PE: panicle emergence; N: nitrogen; P: phosphorus; K: potassium; Zn: zinc; Cu: copper; Sed: standard error of difference; SEm (±): standard error of mean; CD (p = 0.05): critical difference at 5 % level of significance.

showed significantly lower performance (Table 3).

Yield

The grain (Fig. 1) and haulm yield (Fig. 2) of green gram were markedly affected by the residual influence of imposed treatments in both the experiments. In Experiment I, significantly higher grain yield of 693 kg ha⁻¹ and haulm yield of 2252 kg ha⁻¹ was recorded in 100 % NPK + nFNZnCu at active tillering (T₆) and was on par with 100 % NPK + nFN at active tillering (T₃), which produced 665 kg ha⁻¹ grain and 2062 kg ha⁻¹ haulm yield. In Experiment II, relatively higher yield levels were observed. The treatment 100 % NPK + nFN at active tillering (T₃) recorded significantly higher grain yield of 728 kg ha⁻¹ and haulm yield of 2353 kg ha⁻¹ and was on par with 75 % N + 100 % PK + nFN at active tillering (T₄). In contrast, the omission of nitrogen (T₂: 0 % N + 100 % PK) consistently resulted in significantly lower grain and haulm yields in both the experiments, highlighting the critical role of nitrogen in improving green gram productivity.

Nutrient uptake

The uptake of major nutrients (N, P and K) by green gram at harvest (Table 4) varied significantly due to the residual influence of different treatments in both the experiments.

In Experiment I, the highest uptake values were recorded under the residual effect of 100 % NPK + nFNZnCu applied at active tillering (T₆), registering 45.1 kg N ha⁻¹, 12.6 kg P ha⁻¹ and 49.5 kg K ha⁻¹. This was closely followed by 100 % NPK + nFN at active tillering (T₃), which resulted in nutrient uptake of 43.6, 12.2 and 47.8 kg ha⁻¹ of N, P and K respectively. Comparable uptake levels were also observed with 100 % NPK + nFZn at active tillering (T₉) and its split application at active tillering and panicle emergence (T₁₀). In Experiment II, a general increase in nutrient uptake was evident. Significantly higher uptake was achieved with 100 % NPK + nFN at active tillering (T₃), recording 47.3 kg N ha⁻¹, 13.1 kg P ha⁻¹ and 50.1 kg K ha⁻¹, which was followed by 75 % N + 100 % PK + nFN at active tillering (T₄) and 100 % NPK + nFZn applied at both active tillering and panicle emergence (T₁₀), exhibiting statistically similar performance. In contrast, the

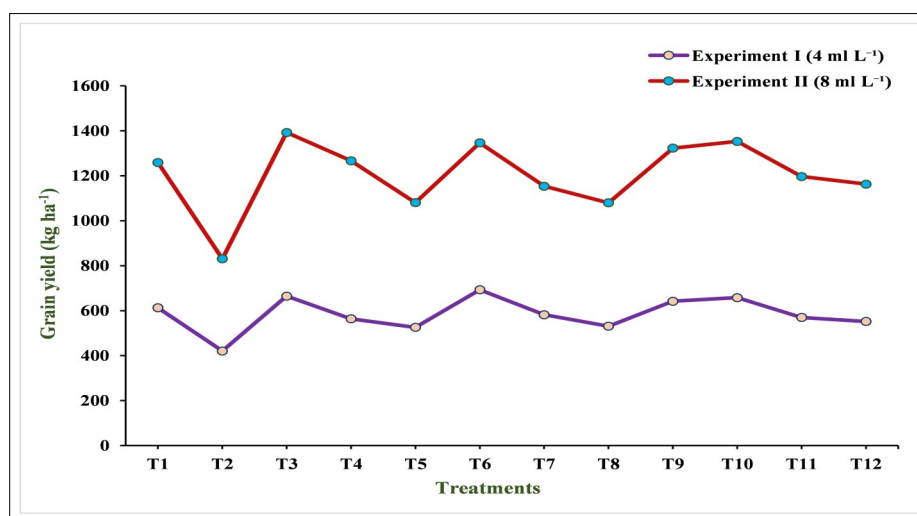


Fig. 1. Effect of foliar nano nutrients (N, Zn and Cu) application on grain yield of rice fallow green gram. Nano N, Nano Zn and Nano Cu were applied each at the rate of 4 mL L⁻¹ of water in experiment I and 8 mL L⁻¹ of water in experiment II to rice and the residual effect of above treatments was studied on succeeding green gram in both the experiments. T₁: 100 % NPK (150:50:50 kg NPK ha⁻¹), T₂: 0 % N + 100 % RD PK, T₃: 100 % RD N + 100 % RD PK + Nano N at active tillering, T₄: 75 % RD N + 100 % RD PK + Nano N at active tillering, T₅: 50 % RD N + 100 % RD PK + Nano N at active tillering, T₆: 100 % RD N + 100 % RD PK + Nano N + Nano Zn + Nano Cu at active tillering, T₇: 75 % RD N + 100 % RD PK + Nano N + Nano Zn + Nano Cu at active tillering, T₈: 50 % RD N + 100 % RD PK + Nano N + Nano Zn + Nano Cu at active tillering, T₉: 100 % NPK + Nano Zn at active tillering, T₁₀: 100 % NPK + Nano Zn at active tillering and panicle emergence, T₁₁: 100 % NPK + Nano Cu at active tillering, T₁₂: 100 % NPK + Nano Cu at active tillering and panicle emergence.

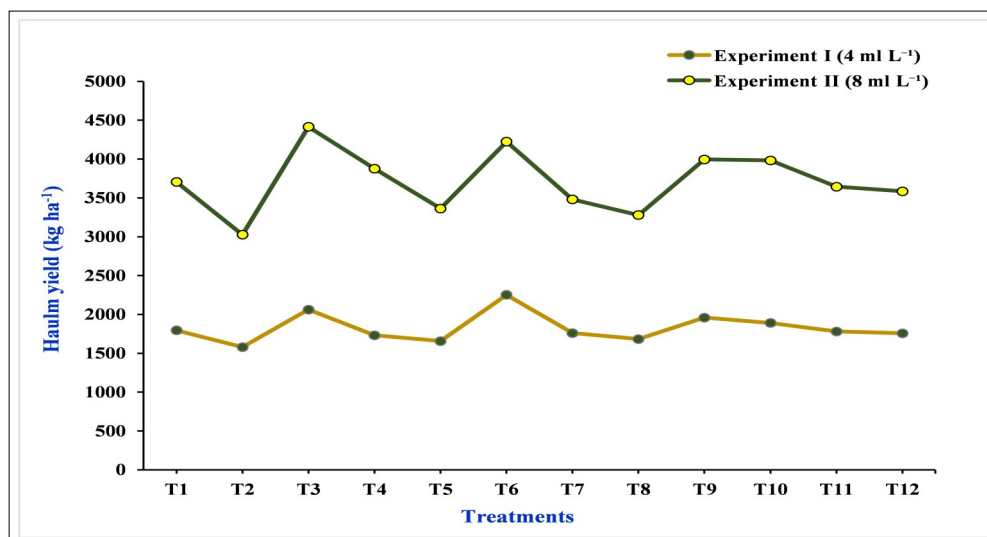


Fig. 2. Effect of foliar nano nutrients (N, Zn and Cu) application on haulm yield of rice fallow green gram. Nano N, Nano Zn and Nano Cu were applied each at the rate of 4 mL L⁻¹ of water in experiment I and 8 mL L⁻¹ of water in experiment II to rice and the residual effect of above treatments was studied on succeeding green gram in both the experiments. T₁: 100 % NPK (150:50:50 kg NPK ha⁻¹), T₂: 0 % N + 100 % RD PK, T₃: 100 % RD N + 100 % RD PK + Nano N at active tillering, T₄: 75 % RD N + 100 % RD PK + Nano N at active tillering, T₅: 50 % RD N + 100 % RD PK + Nano N at active tillering, T₆: 100 % RD N + 100 % RD PK + Nano N + Nano Zn + Nano Cu at active tillering, T₇: 75 % RD N + 100 % RD PK + Nano N + Nano Zn + Nano Cu at active tillering, T₈: 50 % RD N + 100 % RD PK + Nano N + Nano Zn + Nano Cu at active tillering, T₉: 100 % NPK + Nano Zn at active tillering and panicle emergence, T₁₀: 100 % NPK + Nano Zn at active tillering and panicle emergence, T₁₁: 100 % NPK + Nano Cu at active tillering, T₁₂: 100 % NPK + Nano Cu at active tillering and panicle emergence.

Table 4. Effect of foliar nano nutrients (N, Zn and Cu) application on nutrient uptake (kg ha⁻¹) of rice fallow green gram

Treatments	Nitrogen		Phosphorus		Potassium	
	Experiment I (4 mL L ⁻¹)	Experiment II (8 mL L ⁻¹)	Experiment I (4 mL L ⁻¹)	Experiment II (8 mL L ⁻¹)	Experiment I (4 mL L ⁻¹)	Experiment II (8 mL L ⁻¹)
T ₁ : 100 _{NPK}	40.2	40.9	11.1	10.9	43.7	43.8
T ₂ : 0 _N + 100 _{PK}	27.9	26.1	8.0	8.2	35.4	34.6
T ₃ : 100 _{NPK} + nFN at AT	43.6	47.3	12.2	13.1	47.8	50.1
T ₄ : 75 _N + 100 _{PK} + nFN at AT	37.1	45.2	9.6	12.7	39.3	48.6
T ₅ : 50 _N + 100 _{PK} + nFN at AT	31.4	32.6	8.5	9.3	36.0	38.4
T ₆ : 100 _{NPK} + nFNZnCu at AT	45.1	41.5	12.6	11.2	49.5	43.8
T ₇ : 75 _N + 100 _{PK} + nFNZnCu at AT	39.6	34.8	9.9	9.6	40.4	39.5
T ₈ : 50 _N + 100 _{PK} + nFNZnCu at AT	32.9	30.7	8.7	8.3	37.2	37.9
T ₉ : 100 _{NPK} + nFZn at AT	42.3	43.9	11.9	11.8	46.7	47.3
T ₁₀ : 100 _{NPK} + nFZn at AT and PE	41.8	44.4	11.5	12.2	45.1	48.0
T ₁₁ : 100 _{NPK} + nFCu at AT	38.7	39.1	10.8	10.6	41.2	42.9
T ₁₂ : 100 _{NPK} + nFCu at AT and PE	36.5	38.3	10.3	10.5	40.6	41.2
SEd	1.8	2.1	0.6	0.7	2.4	2.7
SEm (±)	1.3	1.5	0.42	0.49	1.7	1.9
CD (p = 0.05)	3.7	4.3	1.2	1.4	4.9	5.2

AT: active tillering; PE: panicle emergence; N: nitrogen; P: phosphorus; K: potassium; Zn: zinc; Cu: copper; Sed: standard error of difference; SEm (±): standard error of mean; CD (p = 0.05): critical difference at 5 % level of significance.

treatment without nitrogen (T₂: 0 % N + 100 % PK) consistently resulted in significantly lower uptake of N, P and K in both the experiments, underscoring the importance of nitrogen in enhancing nutrient absorption by green gram.

Available soil nutrients after green gram harvest

The residual nutrient management practices significantly influenced the post-harvest availability of soil N, P and K (Table 5) in both the experiments. In Experiment I, treatments receiving a balanced combination of macronutrients along with nano formulations maintained relatively higher soil nutrient status. Among these, the application of 100 % NPK integrated with nFNZnCu at active tillering (T₆) recorded significantly higher available N, P and K, though it remained statistically comparable with treatments receiving 100 % NPK + nFN and 100 % NPK + nFZn. Overall, integrated nutrient approaches were effective in sustaining soil fertility compared to other treatments. In Experiment II, a similar trend was observed, where treatments involving 100 % NPK combined with nano N at active tillering resulted in significantly higher residual soil nutrient

availability and was on par with the 75 % N along with full PK and nano N at active tillering (T₄), indicating that partial substitution of nitrogen did not adversely affect soil fertility. In contrast, the omission of nitrogen consistently resulted in significantly lower availability of N, P and K after harvest in both the experiments, highlighting the essential role of nitrogen in maintaining soil nutrient balance in the cropping system.

Economics of green gram

The cost of cultivation for rice fallow green gram remained uniform across all treatments in both experiments (Table 6), as only residual effect was studied. Economic analysis clearly demonstrated the advantage of integrating recommended fertiliser doses with nanofertilisers. In Experiment I, the combined application of 100 % NPK along with nano N, Zn and Cu at active tillering resulted in highest gross and net returns as well as benefit-cost ratio. This was closely followed by the treatment receiving 100 % NPK in combination with nano N at active tillering, with both the treatments showing comparable economic superiority

Table 5. Effect of foliar nano nutrients (N, Zn and Cu) application on available soil nutrients (kg ha⁻¹) after harvest of green gram

Treatments	Nitrogen		Phosphorus		Potassium	
	Experiment I (4 mL L ⁻¹)	Experiment II (8 mL L ⁻¹)	Experiment I (4 mL L ⁻¹)	Experiment II (8 mL L ⁻¹)	Experiment I (4 mL L ⁻¹)	Experiment II (8 mL L ⁻¹)
T ₁ : 100 _{NPK}	220.2	234.3	11.8	9.2	649.1	724.9
T ₂ : 0 _N + 100 _{PK}	117.0	104.4	10.9	6.9	612.2	698.5
T ₃ : 100 _{NPK} + nFN at AT	275.7	289.9	21.6	16.2	692.8	870.1
T ₄ : 75 _N + 100 _{PK} + nFN at AT	205.1	266.4	14.5	15.1	681.4	797.5
T ₅ : 50 _N + 100 _{PK} + nFN at AT	175.5	179.1	12.2	7.6	625.3	702.8
T ₆ : 100 _{NPK} + nFNZnCu at AT	282.5	255.5	22.1	11.5	714.0	754.4
T ₇ : 75 _N + 100 _{PK} + nFNZnCu at AT	215.6	207.7	13.4	8.4	672.1	719.6
T ₈ : 50 _N + 100 _{PK} + nFNZnCu at AT	191.9	148.4	12.7	7.7	634.5	702.2
T ₉ : 100 _{NPK} + nFZn at AT	256.1	237.1	20.8	10.7	654.5	720.0
T ₁₀ : 100 _{NPK} + nFZn at AT and PE	258.4	257.9	21.0	14.3	653.2	776.2
T ₁₁ : 100 _{NPK} + nFCu at AT	244.3	245.8	18.6	9.4	616.7	736.3
T ₁₂ : 100 _{NPK} + nFCu at AT and PE	254.8	248.2	20.4	10.2	627.4	748.7
SEd	14.1	15.3	1.0	0.6	32.2	43.5
SEm (±)	9.9	10.8	0.71	0.42	22.8	30.7
CD (p = 0.05)	28.9	29.2	2.1	1.2	66.7	87.7

AT: active tillering; PE: panicle emergence; N: nitrogen; P: phosphorus; K: potassium; Zn: zinc; Cu: copper; Sed: standard error of difference; SEm (±): standard error of mean; CD (p = 0.05): critical difference at 5 % level of significance.

Table 6. Effect of foliar nano nutrients (N, Zn and Cu) application on economics of rice fallow green gram

Treatments	Gross return (₹ ha ⁻¹)		Net return (₹ ha ⁻¹)		B:C ratio	
	Experiment I (4 mL L ⁻¹)	Experiment II (8 mL L ⁻¹)	Experiment I (4 mL L ⁻¹)	Experiment II (8 mL L ⁻¹)	Experiment I (4 mL L ⁻¹)	Experiment II (8 mL L ⁻¹)
T ₁ : 100 _{NPK}	38006	40052	15771	17817	1.71	1.80
T ₂ : 0 _N + 100 _{PK}	26102	25420	3867	3185	1.17	1.14
T ₃ : 100 _{NPK} + nFN at AT	41230	45136	18995	22901	1.85	2.03
T ₄ : 75 _N + 100 _{PK} + nFN at AT	34968	43586	12733	21351	1.57	1.96
T ₅ : 50 _N + 100 _{PK} + nFN at AT	32612	34410	10377	12175	1.47	1.55
T ₆ : 100 _{NPK} + nFNZnCu at AT	42966	40548	20731	18313	1.93	1.82
T ₇ : 75 _N + 100 _{PK} + nFNZnCu at AT	36084	35464	13849	13229	1.62	1.59
T ₈ : 50 _N + 100 _{PK} + nFNZnCu at AT	32922	34038	10687	11803	1.48	1.53
T ₉ : 100 _{NPK} + nFZn at AT	39804	42222	17569	19987	1.79	1.90
T ₁₀ : 100 _{NPK} + nFZn at AT and PE	40796	43090	18561	20855	1.83	1.94
T ₁₁ : 100 _{NPK} + nFCu at AT	35340	38874	13105	16639	1.59	1.75
T ₁₂ : 100 _{NPK} + nFCu at AT and PE	34224	37882	11989	15647	1.54	1.70

Cost of cultivation of rice fallow green gram was ₹ 22235 ha⁻¹ AT: active tillering; PE: panicle emergence; B ratio: benefit-cost ratio.

over the rest of the treatments. A similar trend was evident in Experiment II, where the application of 100 % NPK integrated with nano N at active tillering recorded the best economic performance. Treatments involving partial substitution of N along with nano N, as well as those integrating nano Zn at different growth stages, also performed well and remained competitive in terms of profitability. In contrast, the omission of N consistently resulted in poor economic returns in both the experiments, reflecting lower productivity and reduced profitability. Overall, the results highlight that the integration of conventional fertilisers with nanofertilisers is an economically viable strategy for enhancing returns in rice fallow green gram.

Cropping system evaluation

System economics

The economic performance of rice–green gram cropping system was markedly influenced by the integration of nanofertilisers with soil-applied nutrients in both the experiments (Table 7). The cost of cultivation varied slightly among treatments depending on the type, combination and concentration of nano foliar applications. In Experiment I, treatments involving combined nano applications at active tillering and panicle emergence incurred relatively higher production costs, particularly those supplemented with nano Zn (T₁₀) and nano Cu (T₁₂), followed by the integrated application of nano N, Zn and Cu at active tillering alone (T₆). Despite the marginal increase in cultivation cost, treatments integrating 100 % NPK with nanofertilisers produced substantially higher economic returns. Treatments involving nano Zn and its split applications also

demonstrated competitive performance, indicating the economic advantage of micronutrient supplementation.

In Experiment II, a similar pattern was observed, where treatments receiving higher concentrations of combined nanofertilisers recorded comparatively greater cultivation costs, while the lowest cost was consistently associated with the treatment lacking nitrogen application. The economic superiority shifted slightly towards the application of 100 % NPK in combination with nano N at active tillering (T₃), which recorded the highest returns and benefit-cost ratio. Treatments involving partial substitution of N along with nano N at active tillering (T₄) also maintained favourable economic outcomes, reflecting efficient nutrient use without compromising profitability. Conversely, the omission of nitrogen consistently resulted in the lowest gross income, net returns and benefit-cost ratio across both experiments. Overall, the findings emphasise that the integration of nanofertilisers with recommended fertiliser practices enhance the economic viability of the rice–green gram system, in spite of slight increase in the cultivation cost.

System indices

The system productivity and profitability of rice–green gram cropping system were significantly influenced by the integration of nanofertilisers with soil-applied nutrients in both the experiments (Table 8), with consistent treatment effects observed across key performance indicators. In Experiment I, the application of 100 % NPK in combination with nano N, Zn and Cu at active tillering (T₆) resulted in the highest rice equivalent yield, system production efficiency and system profitability. However, its performance

Table 7. Effect of foliar nano nutrients (N, Zn and Cu) application on economics of rice-green gram cropping system

Treatments	Gross return (₹ ha ⁻¹)		Net return (₹ ha ⁻¹)		B:C ratio	
	Experiment I (4 mL L ⁻¹)	Experiment II (8 mL L ⁻¹)	Experiment I (4 mL L ⁻¹)	Experiment II (8 mL L ⁻¹)	Experiment I (4 mL L ⁻¹)	Experiment II (8 mL L ⁻¹)
T ₁ : 100 _{NPK}	131561	137711	65874	72024	2.00	2.10
T ₂ : 0 _N + 100 _{PK}	106127	101620	42373	37866	1.66	1.59
T ₃ : 100 _{NPK} + nFN at AT	133840	154645	66578	86658	1.99	2.27
T ₄ : 75 _N + 100 _{PK} + nFN at AT	129168	148597	62386	79090	1.93	2.20
T ₅ : 50 _N + 100 _{PK} + nFN at AT	120812	124050	54517	57030	1.82	1.85
T ₆ : 100 _{NPK} + nFNZnCu at AT	141441	138192	72729	68882	2.06	1.95
T ₇ : 75 _N + 100 _{PK} + nFNZnCu at AT	126114	126649	57882	57819	1.85	1.80
T ₈ : 50 _N + 100 _{PK} + nFNZnCu at AT	121317	121989	53572	53646	1.79	1.74
T ₉ : 100 _{NPK} + nFZn at AT	134904	140854	67642	72867	2.01	2.07
T ₁₀ : 100 _{NPK} + nFZn at AT and PE	137171	141413	68334	71126	1.99	2.01
T ₁₁ : 100 _{NPK} + nFCu at AT	127140	131307	59878	63320	1.89	1.93
T ₁₂ : 100 _{NPK} + nFCu at AT and PE	126549	128857	57712	58570	1.84	1.83

AT: active tillering; PE: panicle emergence; B ratio: benefit-cost ratio.

Table 8. Effect of foliar nano nutrients (N, Zn and Cu) application on rice-green gram cropping system indices

Treatments	Rice equivalent yield (kg ha ⁻¹)		System production efficiency (kg ha ⁻¹ day ⁻¹)		System profitability (₹ ha ⁻¹ day ⁻¹)	
	Experiment I (4 mL L ⁻¹)	Experiment II (8 mL L ⁻¹)	Experiment I (4 mL L ⁻¹)	Experiment II (8 mL L ⁻¹)	Experiment I (4 mL L ⁻¹)	Experiment II (8 mL L ⁻¹)
T ₁ : 100 _{NPK}	6814	7069	33.6	35.3	319.4	360.1
T ₂ : 0 _N + 100 _{PK}	5375	5186	26.9	25.8	211.0	189.3
T ₃ : 100 _{NPK} + nFN at AT	7084	8121	35.4	40.6	332.9	433.3
T ₄ : 75 _N + 100 _{PK} + nFN at AT	6531	7969	32.7	39.8	311.5	395.5
T ₅ : 50 _N + 100 _{PK} + nFN at AT	6274	6626	31.4	33.1	272.6	285.1
T ₆ : 100 _{NPK} + nFNZnCu at AT	7539	7338	37.7	36.4	363.3	344.4
T ₇ : 75 _N + 100 _{PK} + nFNZnCu at AT	6621	6819	33.1	34.1	289.4	289.1
T ₈ : 50 _N + 100 _{PK} + nFNZnCu at AT	6275	6294	31.4	31.5	267.9	268.2
T ₉ : 100 _{NPK} + nFZn at AT	7064	7471	35.3	37.4	338.2	364.3
T ₁₀ : 100 _{NPK} + nFZn at AT and PE	7085	7643	35.4	38.2	341.7	355.6
T ₁₁ : 100 _{NPK} + nFCu at AT	6646	6889	33.2	34.4	299.4	316.6
T ₁₂ : 100 _{NPK} + nFCu at AT and PE	6517	6734	32.6	33.7	288.6	292.8
SEd	343	347	1.8	2.1	21.5	22.6
SEm (±)	243	245	1.27	1.48	15.2	15.9
CD (p = 0.05)	707	716	3.6	3.9	43.2	45.4

AT: active tillering; PE: panicle emergence; Sed: standard error of difference; SEm (±): standard error of mean; CD (p = 0.05): critical difference at 5 % level of significance.

remained statistically comparable with treatments involving nano Zn supplementation and nano N application at similar or multiple growth stages, indicating that these integrated nutrient strategies were equally effective in enhancing system performance. In Experiment II, the superiority of integrated nutrient management was again evident, with the treatment receiving 100 % NPK along with nano N at active tillering (T₃) achieving the highest system productivity and profitability. This treatment was found to be on par with the treatment involving partial substitution of N along with nano N at active tillering (T₄), demonstrating that reduced N levels, when supplemented with nanofertilisers, can sustain overall system efficiency. In contrast, the treatment without N consistently recorded significantly lower rice equivalent yield, system production efficiency and profitability across both the experiments, underscoring the essential role of N in maintaining productivity and economic viability of the rice-based cropping system.

Discussion

Rice fallow green gram exhibited significant impact of the treatments applied to rice with respect to growth, yield, nutrient uptake and available NPK as it depends entirely on the residual fertility of preceding crop. The residual effect of fertilisers applied to preceding rice on green gram was the highest in experiment I with 100 % NPK + nFZnCu at 4 mL L⁻¹ at active tillering and was at par with 100 % NPK + nFN at 4 mL L⁻¹ at active tillering in terms of all the observed and analysed parameters. In Experiment II, nano

N at 8 mL L⁻¹ at active tillering with either 100 % NPK or 75 % N + 100 % PK recorded the highest growth, yield, nutrient uptake and available soil nutrients. This is due to the highest available soil NPK observed in the present study after harvest of rice and before the start of green gram that formed basis for the nutrients to be more available to green gram even without application of fertilisers to green gram. Application of foliar nanofertilisers might have reduced the leaching of nutrients into the soil and improved nutrient use efficiency by gradually releasing the nutrients into the plant over a longer period of time that helps conserve nutrients in the soil for succeeding crops as reported in the recent studies by previous researchers (26, 27, 40). Also, significant effect of soil microbial activity and dehydrogenase enzyme action was observed in the early growth stages of lentil due to residual soil status of preceding rice (27). Spraying of foliar nanofertilisers at critical crop growth stages fulfils its nutritional requirement and comparatively reduces the competition for soil nutrients which resulted in increased available nutrients in the rhizosphere even after the harvest of rice crop and were made available to the succeeding green gram which might have resulted in increased performance of rice fallow green gram. Similar results were attained by (27, 41). Rice fallow green gram treated with 100 % PK alone showed significantly lower growth and yield, which might be due to residual nitrogen deficiency that affected the slow initial growth nature of green gram making it highly sensitive to nitrogen in the early vegetative stage and delayed the functional establishment

of nodulation and nitrogen fixation as reported by previous researchers (42, 43).

Foliar nanofertilisers improved plant growth and yield while also enhancing soil fertility, resulting in higher available NPK at the end of the cropping system compared to the initial status in both field trials. This illustrates the improvements in green gram yield and soil health achieved through foliar nanofertiliser application. Similar findings were observed in rice-green pea cropping sequence and in maize-wheat and pearl millet-mustard systems (27, 44). The net loss of soil available N and P was observed at the end of rice-green gram cropping system when no nano nitrogen was applied in either 0 % N (control) or 100 % NPK. This might be due to lack of foliar spray of nanofertilisers and the available soil nutrients that were taken up by the crop leaving lesser nitrogen and phosphorus in the soil. Whereas positive balance of potassium was noticed at the end of both the experiments even in the treatment 0 % N + 100 % PK, which is due to very high initial available potassium and also application of full rate of potassium increased soil K. This may also be attributed to the release of fixed K into the available soil K pool, as reported in the rice-blackgram system (42). In Experiment II, green gram showed lower residual performance when treated with all three nano-nutrients (T_6) compared to nano-N alone (T_3) which might be attributed to antagonistic or zero interaction of nano Zn and Cu at high dosages, leading to phytotoxic accumulation in roots and shoots that negatively impacted overall crop growth and development (44, 45).

The economics of rice fallow green gram also followed the similar trend of growth and yield of green gram. But, in contrast to economics of rice in Experiment I, the highest benefit-cost (B:C) ratio was attained in the treatment imposed with 100 % NPK + nano N, Zn and Cu at 4 mL L⁻¹ at active tillering in rice fallow green gram. This is due to significant increase in the green gram yield with the residual effect of nanofertilisers compared to 100 % NPK alone or no nanofertiliser spray. These treatments demonstrated the positive residual effect of integrated nutrient management, especially involving foliar-applied nano nutrients on overall productivity and profitability in rice-based cropping systems.

Economic evaluation of rice-green gram cropping system revealed that the highest cultivation cost was observed in the treatments receiving nano Zn and Cu separately at active tillering and panicle emergence with 4 mL L⁻¹. This is because of increase in the number of sprays resulting in increased fertiliser and spraying cost apart from common cost of cultivation. This treatment was followed by 100 % NPK + nFNZnCu at 4 mL L⁻¹ during active tillering alone. This increase is due to fertiliser cost and not due to spraying cost, since N, Zn and Cu were tank mixed and sprayed at once. The fertiliser and spraying cost of various treatments in both the experiments are presented in Supplementary Table 3 & 4. In Experiment I, the highest gross, net income and B:C ratio were observed in 100 % NPK + nFNZnCu at 4 mL L⁻¹ at active tillering followed by 100 % NPK + nFZn at 4 mL L⁻¹ at active tillering. This is due to the lower cultivation cost and comparable gross and net income in the former. In Experiment II, foliar spray of nano nitrogen at 8 mL L⁻¹ with 100 % NPK recorded the highest gross, net income and B:C ratio followed by 75 % N + 100 % PK, which is due to higher yield in rice-green gram cropping system. Hence, application of

nano nitrogen at 8 mL L⁻¹ at active tillering combined with either 100 % soil NPK or 75 % N + 100 % PK was found beneficial with respect to yield, net income and B:C ratio.

Rice equivalent yield was higher in experiment I, when 100 % NPK + nFNZnCu at 4 mL L⁻¹ at active tillering was applied and in Experiment II, when 100 % NPK + nFN at 8 mL L⁻¹ at active tillering was treated. The combination of foliar spray of nano nutrients to rice and biological nitrogen fixation capacity of green gram increased the soil and plant available nutrients, thus the growth and rice equivalent yield. System production and economic efficiency also showed similar trend of rice equivalent yield as system production efficiency is directly dependent on the yield of rice-green gram cropping system (46). The trade-off between yield and greenhouse gas (GHG) emission reduction was observed due to foliar application of nano-urea and nano-diammonium phosphate (DAP) in combination with conventional fertilisers in maize by (47–49), highlighting the potential of nano-fertilisers in enhancing the soil sustainability and reducing the carbon footprint and environmental impact of the fertilisers. Furthermore, the present study of residual effect of foliar nano-fertilisers demonstrates its potential for sustainable intensification of rice-based cropping system.

Conclusion

The study demonstrated that residual effect of integrating foliar-applied nano nitrogen at 8 mL L⁻¹ of water during active tillering, along with either 100 % NPK or 75 % N + 100 % PK, significantly increased the yield by 12.69 %, nitrogen uptake by 15.6 % and net returns by 28.5 % compared to conventional fertilisation with 100 % NPK in rice fallow green gram. The results highlight that foliar nanofertilisers exert not only direct impact on rice but also substantial residual impact on the succeeding green gram. The integration of nano nitrogen contributes to closing nutrient loops, reducing fertiliser input costs and lowering energy use, thereby safeguarding environmental quality.

From an application perspective, this approach offers a viable nutrient management strategy that can be promoted through targeted extension programs, including farmer field schools, on-farm demonstrations and capacity-building initiatives to enhance awareness and adoption. However, its scalability across diverse agro-climatic conditions requires location-specific validation, particularly with respect to soil types, rainfall regimes and cropping intensities. Future research and adaptive trials across regions will be essential to refine recommendations and ensure consistent performance under varying field conditions. Overall, this nutrient-efficient strategy supports resource conservation and aligns with the principles of sustainable intensification of rice-based cropping systems, while offering practical pathways for policy support and farmer-level adoption. Policy support in the form of inclusion of nanofertilisers in subsidy frameworks, standardisation of application protocols and strengthening supply chains will further facilitate large-scale adoption.

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Authors' contributions

PC carried out material preparation, data collection and data analysis. CRC and KRL performed project administration and data validation. JP conducted data analysis. YL carried out data collection and data analysis. All authors read and approved the final manuscript.

Compliance with ethical standards

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