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RESEARCH ARTICLE

Advancing the growth and yield of transplanted puddled rice (TPR) through nanofertilization

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Abstract

The study's main purpose was to evaluate the impact of foliar application of nano nitrogen, phosphorous and potassium (nano NPK) on key growth stages of TPR, including tillering, panicle initiation (PI) and flowering. The field experiment was conducted from December 2023 to April 2024 during the late *rabi* season at the Department of Agronomy, V.O.C Agricultural College and Research Institute, Killikulam, Tamil Nadu, India. The experiment utilized a randomized block design with 14 treatments and 3 replications. Results showed that the 100% RDF (Recommended dose of fertilizers) applied as a soil treatment achieved the highest dry matter production (DMP) and crop growth rate (CGR), followed closely by 3 foliar applications of nano NPK. The control treatment, with no fertilizer application, recorded the lowest values on DMP and CGR. A similar trend was observed for plant height, number of tillers, leaf area index (LAI) and chlorophyll content. For grain yield, straw yield and harvest index, both 100% RDF soil application and 3 foliar applications of nano NPK recorded the highest results. The benefit-cost ratio was found to be higher in RDF as a soil application. The study concluded that both 100% RDF soil application and 3 foliar applications of nano NPK performed equally well in enhancing growth and yield.

Keywords

foliar application; growth; nano NPK fertilizers; TPR; yield

Introduction

Rice cultivation is highly significant, predominantly concentrated in Asia. India and China are the leading rice-producing nations in this region and rice serves as the primary staple food for about half of the global population (1). India is the second-largest rice producer globally and holds a crucial position in agricultural and economic domains (2). In 2021, rice production in India reached 129.66 million tons from cultivation across 464 lakh ha of land, surpassing all other food crops in yield (3). In Tamil Nadu, rice is cultivated across 22.05 lakh ha (37%), making it the leading cereal crop in terms of both area and production (4).

Rice requires large amounts of inorganic fertilizers for optimal growth and output. Rice production is influenced by the soil's conditions and the availability of nutrients such as nitrogen, phosphorus, potassium, sulphur and zinc (5). Therefore, fertilizers play a crucial role in improving food productivity and quality and are an essential part of any agricultural production system (6). The average percentage of the yield attributed to NPK fertilizers in rice was around 38, 12 and 8% respectively (7). Research on improving nutrient use efficiency has become increasingly crucial and challenging. Providing nutrients to crops and cropping systems is essential for achieving optimal production and enhancing crop and soil health (8). Intensive use of inorganic fertilizers for crop cultivation depletes soil fertility over time, creating a deficit in soil nutrients that poses significant challenges for sustainable crop production in the future (9). The depletion of soil fertility not only reduces soil quality but also poses significant challenges for maintaining consistent crop yields over time. As traditional methods struggle to provide long-term solutions, innovative approaches are increasingly needed to preserve soil health and enhance agricultural productivity sustainably.

In response to these challenges, nanotechnology has emerged as an innovative approach to address agricultural challenges more effectively than conventional methods. "Nanofertilizers" refer to a new category of plant nutrients engineered at the nanoscale. Nanofertilizers are nutrients encapsulated in nanomaterials that may possess beneficial properties for crops, including on-demand nutrient release and controlled delivery of chemical fertilizers that regulate plant growth and improve targeted activity (8). Their smaller particle size increases the specific surface area and the number of particles per unit area of fertilizer, enhancing the likelihood of maximum contact between nanofertilizers and the applied plant surface (9). Utilizing nanotechnologies and nanoparticles can enhance rice production by reducing nutrient losses during fertilizer application as a foliar spray. Nanofertilizers, with their unique physicochemical properties, have the potential to augment plant metabolism. Considering these facts, this experiment was set up to apply nanofertilizers as a foliar spray to investigate their effect on enhanced productivity and nutrient utilization efficiency in TPR.

Materials and Methods

Site specification and characteristics

The present study was performed during the late *rabi* season from December 2023 to April 2024 at the Department of Agronomy, V.O.C Agricultural College and Research Institute, Tamil Nadu Agricultural University, Killikulam, Thoothukudi, Tamil Nadu, India. The experimental field is located in the southern agro-climatic zone of Tamil Nadu with a latitude of 8.705372°N and a longitude of 77.857498°E, at an elevation of 40 m above mean sea level (MSL). The soil of the experimental plot was sandy clay loam with a pH of 7.73, which is slightly salinity in nature. The soil contains organic carbon of 6.41 g/kg, with available nitrogen at 287.42 kg/ha, available phosphorus at 25.15 kg/ha and available potassium at 152.37 kg/ha. The climate in the region is tropical, generally hot and humid and benefited from more rainfall during the northeast monsoon (NEM) season. The mean monthly temperature from December to April ranges from 29 °C to 35 °C. The average rainfall during the NEM in this region is 680 nm. For the experiment, seeds of the TNAU rice variety ASD 16 were sourced from Agricultural Research Station (ARS) in Ambasamudram.

Experimental design and nutrient application

The experiment was laid out in a randomized block design (RBD) with 3 replications and 14 treatments. The treatments were as follows: T_1 - Foliar application of nano N and P at 2 times; T_2- Foliar application of nano N and P at 3 times; T_3- Foliar application of nano N and P at 4 times; T_4- Foliar application of nano N and K at 2 times; T_5- Foliar application of nano N and K at 3 times; T_6- Foliar application of nano N and K at 4 times; T_7- Foliar application of nano P and K at 2 times; T_8- Foliar application of nano P and K at 3 times; T_9- Foliar application of nano P and K at 4 times; T_{10}- Foliar application of nano NPK at 2 times; T_{11}- Foliar application of nano NPK at 3 times; T_{12}- Foliar application of nano NPK at 4 times. These treatments were compared with T_{13}- 100% RDF as soil application and T_{14}- Absolute control. The foliar application of nanofertilizers was performed at varying intervals depending on the treatment. The treatments included 2 applications at the active tillering (AT) and panicle initiation (PI) stages; 3 applications at the tillering, AT and PI stages; 4 applications at the tillering, AT, PI and flowering stages. Nano urea, nano DAP and nano potash were sprayed at a concentration of 4.0 mL/L according to the treatment structure. Fig. 1 provides an aerial perspective of the research field.

A statistical analysis was conducted using R software to analyze and interpret data collected from field observations. This analysis involved processing and examining the recorded data and applying various statistical techniques to identify patterns, trends and relationships within the field data. The use of R software allowed for detailed visualization and interpretation, providing valuable insights into the observations and supporting data-driven conclusions.

Fig. 1. Aerial view of research field.

Results

Effect of foliar nanofertilizers application on plant height of TPR

Plant height is one of the most important features in the growth and yield of rice affecting all parts of its development and productivity. An optimal height supports efficient grain production and ensures greater stability (10). Foliar application of nanofertilizers and soil application of recommended fertilizers notably affected plant height at the active tillering, panicle initiation and harvest stages, with height increasing steadily and reaching its maximum at harvest. The 100% RDF (T_{13}) recorded the highest plant heights: 42.7 cm, 83.6 cm and 109.5 cm at the active tillering, panicle initiation and harvest stages respectively. The foliar application of nano NPK 4 times (T_{12}) achieved the next highest plant heights of 40.6 cm, 80.3 cm and 104.8 cm. These measurements were statistically similar to those from the foliar application of nano P and K 4 times (T_9), which recorded 40.3 cm, 80.1 cm and 103.5 cm and the foliar application of nano N and P 4 times (T_3), which had heights of 40.1 cm, 79.9 cm and 102.9 cm at AT, PI and harvest stages. The lowest height was recorded in the absolute control (T_{14}). Table 1 shows the effect of nanofertilizers foliar spray on plant height (cm) of TPR.

Table 1. Effect of nanofertilizers foliar spray on plant height (cm) of TPR

Treatments	Active tillering stage	Panicle initiation stage	Harvest stage
T_1	34.8^d	72.4^d	91.9^d
T_2	37.4^c	76.2^c	97.1^c
T_3	40.1^b	79.9^b	102.9^b
T_4	31.2^e	68.4^e	86.7^e
T_5	31.9^e	68.8^e	87.0^e
T_6	32.4^e	69.1^e	87.2^e
T_7	35.0^d	72.7^d	92.0^d
T_8	37.7^c	76.4^c	97.8^c
T_9	40.3^b	80.1^b	103.5^b
T_{10}	35.3^d	72.9^d	92.4^d
T_{11}	38.0^c	76.6^c	98.2^c
T_{12}	40.6^b	80.3^b	104.8^b
T_{13}	42.7^a	83.6^a	109.5^a
T_{14}	27.1^f	64.7^f	82.0^f
SE d	0.94	1.56	2.17
CD (p=0.05)	1.93	3.20	4.46

Effect of foliar nanofertilizers application on the number of tillers of TPR

The use of RDF applied to the soil and foliar sprays of nanofertilizers containing nitrogen, phosphorus and potassium at different growth stages had a notable impact on the number of tillers throughout the development of TPR. The application of 100% RDF (T_{13}) in 3 split doses significantly impacted tiller production, resulting in 288 tillers at active tillering, 311 at panicle initiation and 326 at harvest. The foliar application of nano NPK 3 times (T_{11}) was the second most effective treatment, yielding 272, 292 and 307 tillers/m^2 at the active tillering, panicle initiation and harvest stages respectively. The absolute control (T_{14}) showed the lowest number of tillers, with counts of 151 at active tillering, 171 at panicle initiation and 182 at harvest. Fig. 2 illustrates how nano NPK influences the number of tillers in TPR plants.

Effect of foliar nanofertilizers application on LAI of TPR

The LAI throughout the growing season significantly impacts crop production. Continuous monitoring of LAI can offer valuable insights into understanding crop growth in response to environmental conditions, thereby evaluating its ultimate yield (11). The results show that the LAI ranges between 1.93 to 5.71, which was measured at the active tillering, panicle initiation and harvest stages. The peak LAI was measured in 100% RDF as a soil application (T_{13}), with readings of 3.79, 4.14 and 5.71 respectively. This was followed by the foliar application of nano NPK applied 3 times (T_{11}), which recorded values at 3.50, 3.93 and 5.43 at the respective stages. The minimum LAI was observed in absolute control (T_{14}), with values of 1.93, 2.41 and 3.24 at all stages. Fig. 3 shows the effect of nano NPK on the LAI of TPR.

Effect of foliar nanofertilizers application on chlorophyll content of TPR

Higher SPAD values indicate more chlorophyll, suggesting better plant growth and nutrient status. They are crucial for optimizing nitrogen fertilization and monitoring plant health efficiently. The improved nutrient uptake in nanofertilizers boosts chlorophyll content, leading to better photosynthesis and overall plant health. By optimizing nutrient availability and reducing waste, nano nutrients support more robust plant growth and stress resilience (12). There was a slight increase in SPAD values from the active tillering stage to the panicle initiation stage, followed by a decline leading up to the harvest stage. The RDF (T_{13}) applied in 3 split doses through soil application achieved significantly higher SPAD values of 44.70 at active tillering, 46.37 at panicle initiation and 41.47 at harvest. The foliar application of nano NPK 3 times (T_{11}) recorded the next highest SPAD values of 42.80, 43.97 and 39.72 at the respective stages. The absolute control (T_{14}) had the lowest SPAD values, with measurements of 31.02 at active tillering, 31.12 at panicle initiation and 29.14 at harvest. Fig. 4 depicts the effect of nano NPK on the chlorophyll levels in TPR.

Effect of foliar nanofertilizers application on DMP of TPR

DMP has a direct relationship with plant nitrogen content and plays a major role in the grain and straw yield of any crop (13). The results indicate that various treatments of nanofertilizer foliar application and 100% RDF had a significant impact on dry matter accumulation in TPR. During AT, PI and harvest stages, a maximum DMP of 2391, 7984 and 15794 kg ha^{-1} was recorded in the treatment of 100% RDF as soil application (T_{13}). However, except during the rice active tillering stage, the next highest DMP was recorded by foliar application of nano NPK at 3 times

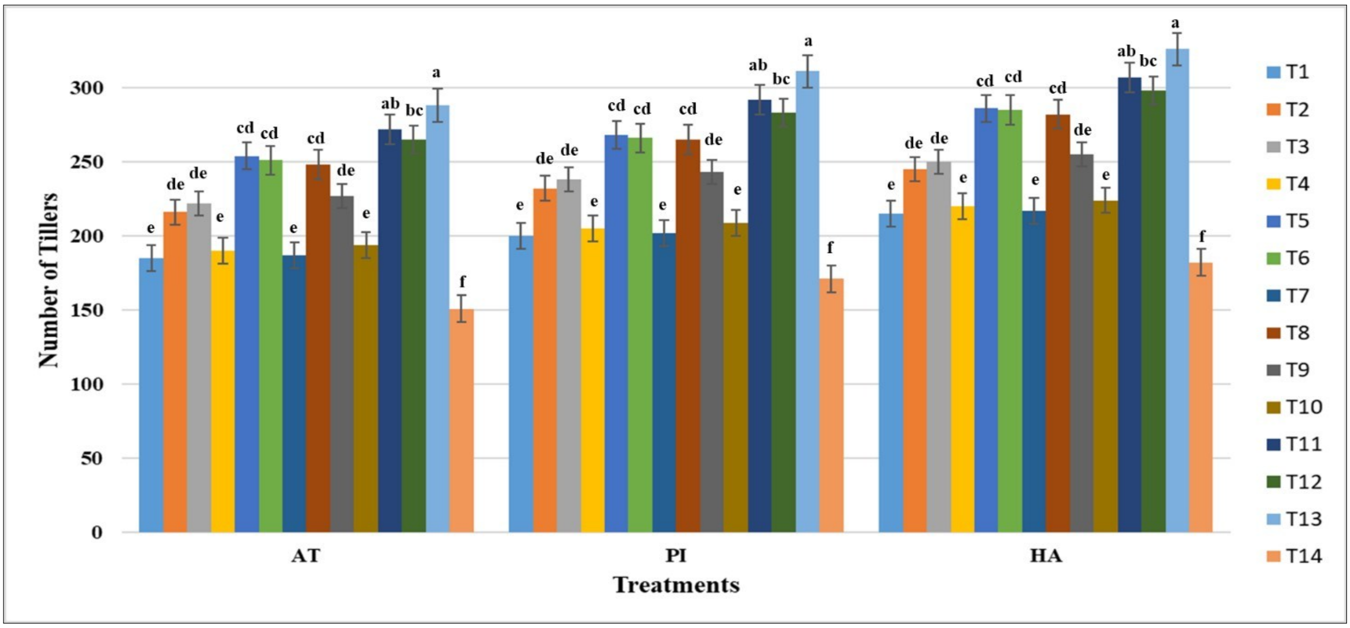

Fig. 2. Effect of nano NPK on the number of tillers of TPR.

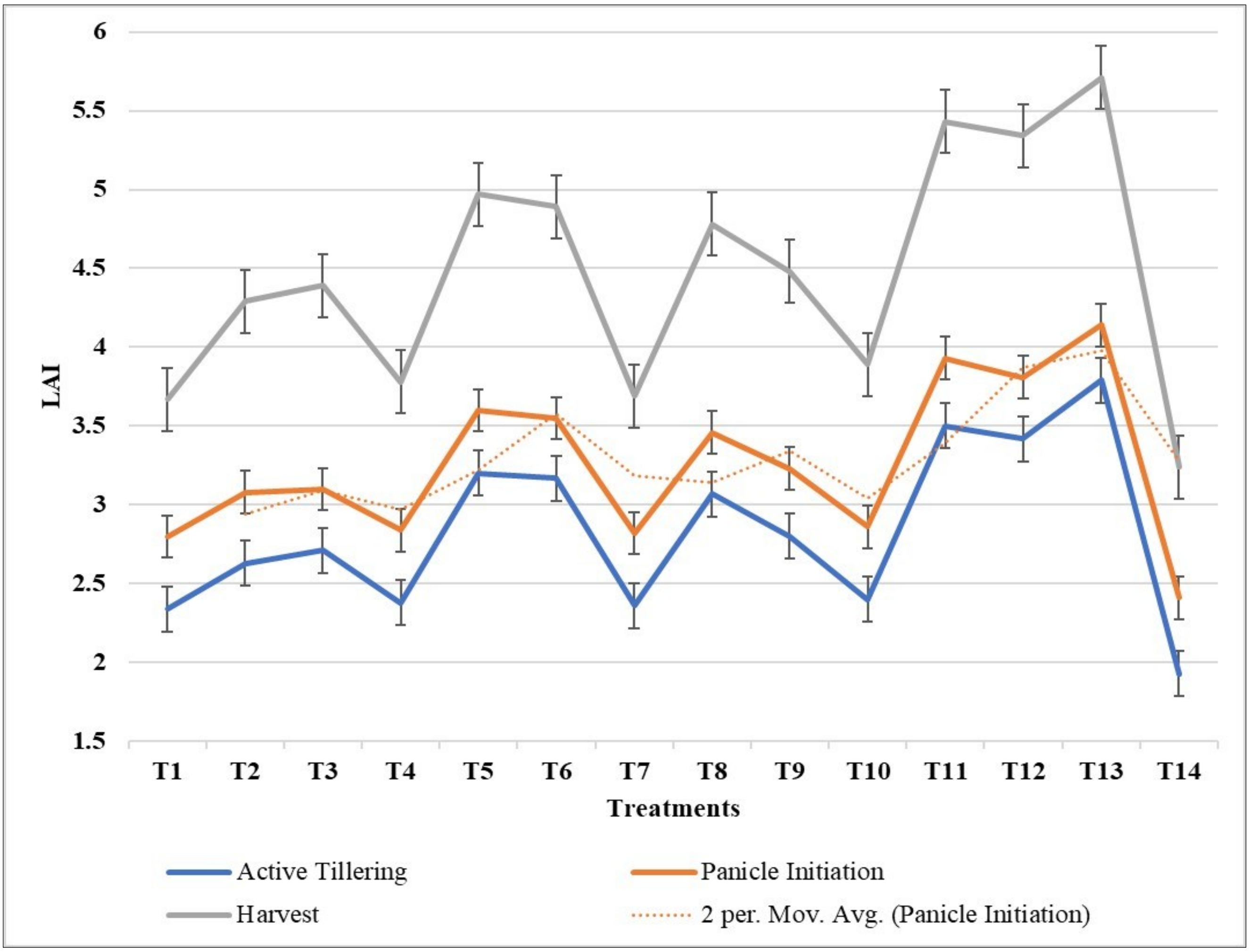

Fig. 3. Influence of nano NPK on LAI of TPR.

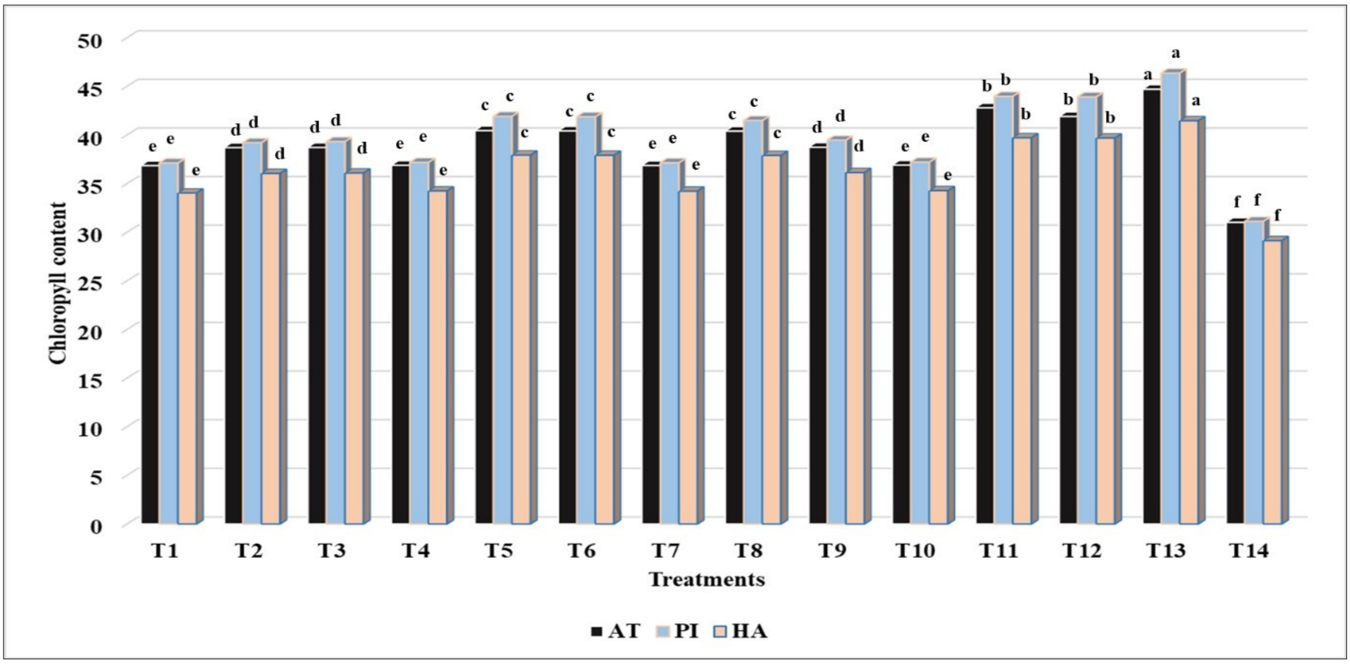

Fig. 4. Impact of nano NPK on chlorophyll content of TPR.

(T_{11}), with DMP values of 7544 and 14934 kg ha^{-1} during PI and harvest stages. At the AT stage, foliar application of nano NPK at 4 different stages of rice (T_{12}) recorded a DMP of 2292 kg ha^{-1}. The absolute control plot (T_{14}) recorded the minimum DMP of 1301, 3360 and 7802 kg ha^{-1} at all stages.

Effect of foliar nanofertilizers application on CGR of TPR

CGR refers to the rate at which dry matter is produced per unit area per unit of time. Dry matter production increases the growth parameters along with yield attributes (14). The results indicated that the CGR was significantly impacted by the foliar application of nanofertilizers at different growth stages of transplanted rice. CGR rose from sowing to active tillering and from active tillering to the panicle initiation stage; thereafter, it fell from the PI to the harvest stage. At sowing - AT, AT - PI and PI - harvest stages, 100% RDF as soil application (T_{13}) significantly recorded a higher CGR with values of 53.13, 372.9 and 142.0 kg $ha^{-1}day^{-1}$. At the sowing to AT stages, foliar application of nano NPK at 4 times (T_{12}) was found to be the next best treatment with a CGR value of 50.93 kg ha^{-1} day^{-1}, which was on par with foliar application of nano NPK at 3 times (T_{11}), with a CGR value of 49.58 kg $ha^{-1}day^{-1}$. The peak vegetative and reproductive stages, such as AT - PI and PI - harvest, along with the foliar application of nano NPK at 3 times (T_{11}), produced CGR values of 354.2 and 134.4 kg ha^{-1} day^{-1} respectively. In contrast, the lowest CGR values of 28.91, 137.3 and 80.8 kg ha^{-1} day^{-1} was recorded in the absolute control (T_{14}) at the respective stages. Table 2 presents the effect of foliar spray with nanofertilizers on the DMP and CGR of TPR.

Effect of foliar nanofertilizers application on grain yield (kg ha^{-1}) of TPR

The contribution to grain yield in cereal crops has been evaluated through various yield attributes. Differences observed in growth and yield parameters resulting from different treatments ultimately influence the attainment of the final harvestable yield (15). From the findings of the study, the application of RDF (T_{13}) in 3 splits resulted in a significantly higher grain yield of 6884 kg ha^{-1}. At the same time, the foliar application of nano NPK 3 times (tillering, active tillering and panicle initiation stages) (T_{11}) recorded the next best grain yield of 6281 kg ha^{-1} and it was equally performed with foliar application of nano NPK at 4 times (T_{12}), which recorded a yield of 6151 kg ha^{-1}. Considering the nanofertilizer treatments, foliar application of nano NPK 2 times (T_{10}), nano N and K 2 times (T_4), nano P and K 2 times (T_7) and nano N and P 2 times (T_1) (active tillering and panicle initiation stage) recorded lower grain yields ranging from 3080 to 3284 kg ha^{-1}. A minimum grain yield of 2330 kg ha^{-1} was recorded in the absolute control (T_{14}).

Effect of foliar nanofertilizers application on straw yield (kg ha^{-1}) of TPR

In comparison to the other treatments, the RDF (T_{13}) in 3 splits resulted in a significantly higher straw yield of 7855 kg ha^{-1}. The foliar application of nano NPK at 3 times (T_{11}) performed as the next best treatment, recording 7175 kg ha^{-1}, which was comparable to the foliar application of nano NPK at 4 times (T_{12}). Following these treatments, the foliar application of nano N and K at 3 times (T_5), nano N and K at 4 times (T_6) and nano P and K at 3 times (T_8) recorded statistically equivalent straw yields. A lower straw yield of 3051 kg ha^{-1} was recorded in the absolute control (T_{14}). Fig. 5 depicts the impact of nano NPK on the grain and straw yield of TPR.

Effect of foliar nanofertilizers application on harvest index (HI) of TPR

The HI serves as a metric to gauge biological efficiency in producing harvestable products. Foliar applications of nanofertilizers of nitrogen, phosphorus and potassium, along with soil application of RDF, had a significant influence on the HI of transplanted rice, which ranged from 0.43 to 0.47. The RDF applied in 3 splits (T_{13}), foliar application of nano NPK at 3 times (T_{11}) and foliar application of nano NPK at 4 times (T_{12}) recorded the HI of 0.47. Foliar application of nano P and K at 4 times (T_9), nano N and P at 4 times (T_3) and nano N and P at 3 times recorded the HI of 0.46. The absolute control (T_{14}) recorded the lowest HI of 0.43. Fig. 6 demonstrates how nano NPK affects the HI of TPR.

Effect of foliar nanofertilizers application on economics of TPR

The main outcomes of crop yield include financial effectiveness and the sustainability of crop cultivation. The quantity used and the number of applications have a direct relationship with the cost of cultivation. Foliar application of nano NPK at 4 different stages of rice (T_{12}) resulted in a higher cultivation cost of ₹62261 ha^{-1}. Following foliar application of nano P and K 4 times (T_9) incured a cost of ₹58261 ha^{-1}. The cost of cultivation for the recommended dose of NPK recorded at ₹40487 ha^{-1}, which is a difference of ₹21774 ha^{-1} (34%) lesser than that for foliar application of nano NPK at 4 different stages of rice (T_{12}) and ₹13389 ha^{-1} (24%) lesser than that for 3 application. The absolute control (T_{14}) showed a lower cultivation cost of ₹33890 ha^{-1}. The gross income varied across the treatments, ranging from ₹46433 ha^{-1} to ₹133709 ha^{-1}. The higher gross income of ₹133709 ha^{-1} was recorded in 100% RDF as soil application (T_{13}), followed by (T_{11}) foliar application of nano NPK 3 times with a gross income of ₹122021 ha^{-1}. A lower gross income of ₹46433 ha^{-1} was observed with absolute control (T_{14}).

Table 2. Influence of nanofertilizers foliar spray on DMP and CGR of TPR

Treatments	DMP (kg ha^{-1})			CGR		
	Active tillering	Panicle initiation	At harvest	Sowing -AT	AT-PI	PI-HA
T_1	1450	4780	10565	32.22	222.0	105.2
T_2	1674	5617	11786	37.20	262.9	112.2
T_3	1796	5797	12067	39.91	266.7	114.0
T_4	1514	4994	10884	33.64	232.0	107.1
T_5	2043	6824	13790	45.40	318.7	126.7
T_6	2018	6626	13538	44.84	307.2	125.7
T_7	1456	4866	10721	32.36	227.3	106.5
T_8	1950	6474	13366	43.33	301.6	125.3
T_9	1801	5982	12316	40.02	278.7	115.2
T_{10}	1525	5096	10996	33.89	238.1	107.3
T_{11}	2231	7544	14934	49.58	354.2	134.4
T_{12}	2292	7373	14540	50.93	338.7	130.3
T_{13}	2391	7984	15794	53.13	372.9	142.0
T_{14}	1301	3360	7802	28.91	137.3	80.8
SE d	45.75	194.60	272.92	3.63	29.54	7.31
CD (p=0.05)	94.04	400.00	561.00	7.47	60.72	15.03

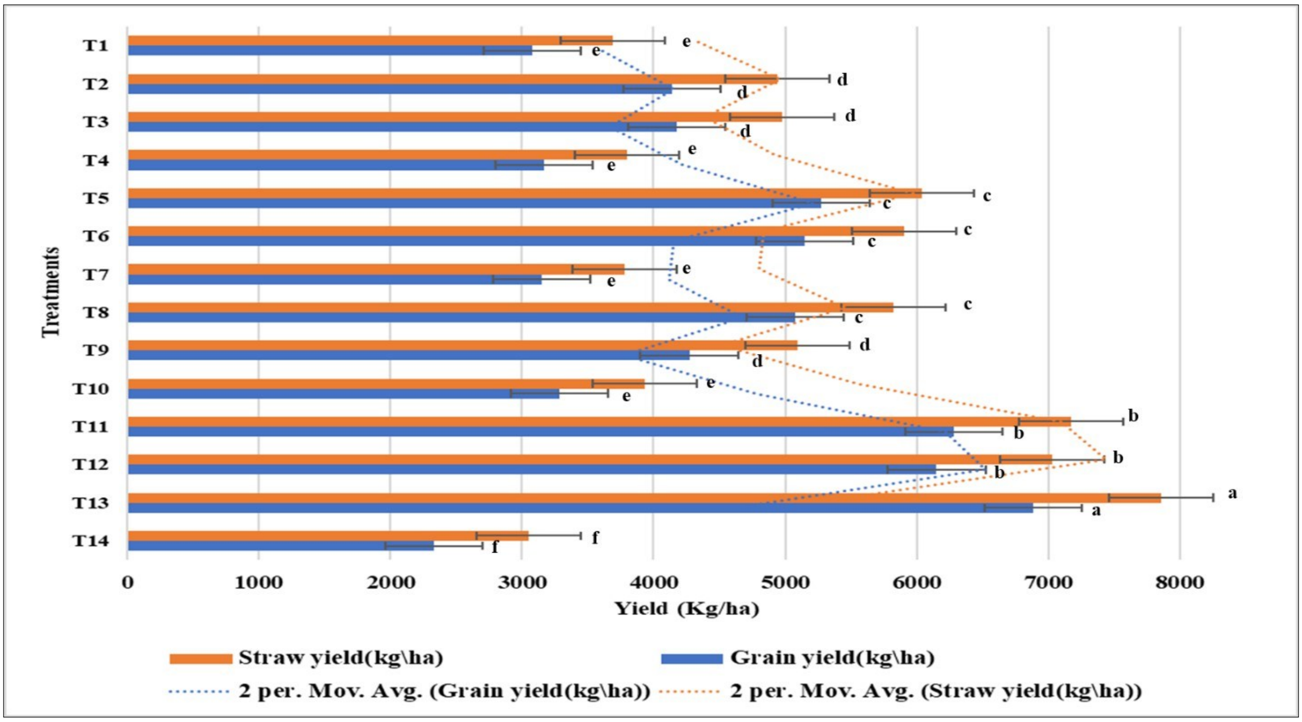

Fig. 5. Effect of nano NPK on grain and straw yield of TPR.

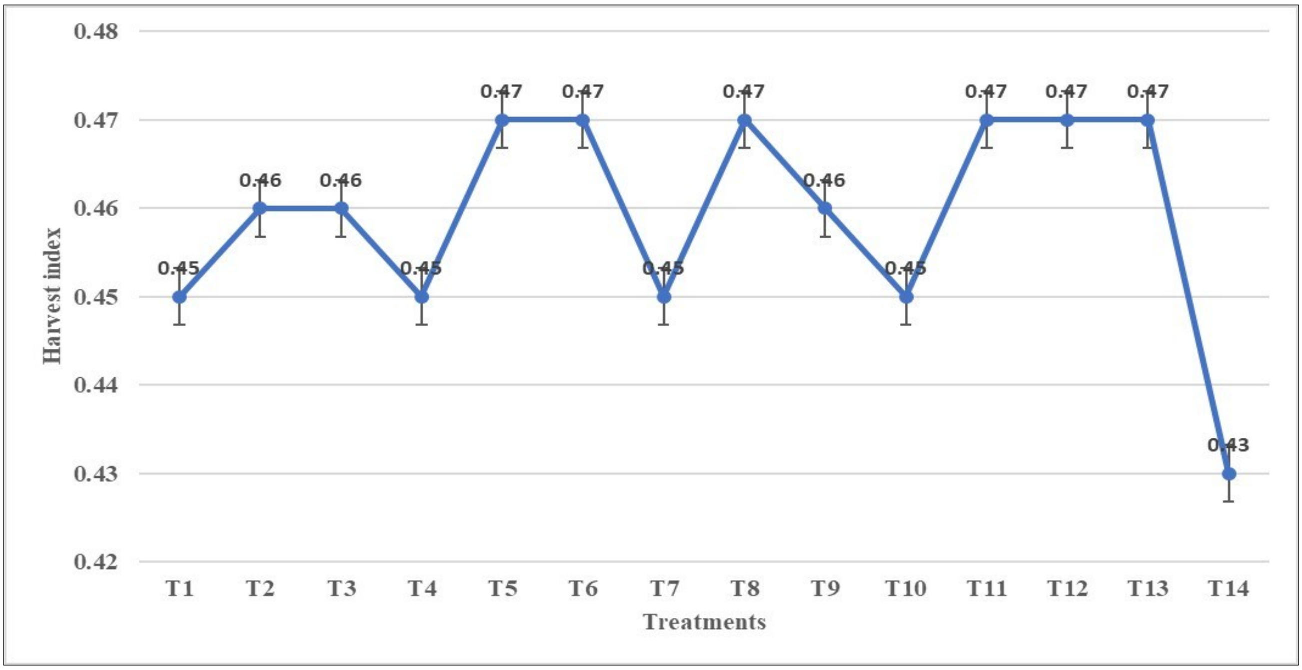

Fig. 6. Influence of nano NPK on harvest index of TPR.

Likewise, 100% RDF as a soil application accounted for a higher net return of ₹93222 ha^{-1}, followed by the application of nano NPK 3 times, which resulted in a net return of ₹68145 ha^{-1}. The absolute control (T_{14}) showed a lower net return of ₹12543 ha^{-1} compared to other treatments.

The B:C ratio varied between 1.37 and 3.30 due to various treatments. The higher B:C ratio of 3.30 was noted in treatment T_{13}, where 100% RDF was applied as a soil application. Following this, the foliar application of nano NPK 3 times (T_{11}) resulted in the next best B:C ratio of 2.26. The treatments, including absolute control (T_{14}), nano NPK applied 2 times (T_{10}) and nano P and K applied 2 times (T_7), accounted for a lower B:C ratio of 1.37. Table 3 details the impact of nanofertilizer foliar spray on the economic aspects of TPR.

Discussion

Plant height is a crucial factor influencing the growth and yield of rice, impacting all aspects of its development and productivity. Achieving an optimal height promotes efficient grain production and enhances stability. An increase in plant height in RDF as a soil application treatment may account for the continuous availability of plant nutrients in the soil. This is due to the increased uptake of soluble nutrients, which helps build new cell components, stimulating better plant growth and subsequently leading to greater plant height (15). The nanofertilizer treatment, owing to its efficient absorption and translocation properties, has contributed to greater plant height. The increased nutrient use efficiency, particularly nitrogen makes it more available on the plant surface. This, in turn, positively impacts growth and plant height (10). Similar research findings were also reported in rice (10).

Table 3. Influence of nanofertilizer foliar spray on economics of TPR

Treatments	Cost of cultivation (Rs ha^{-1})	Gross return (Rs ha^{-1})	Net return (Rs ha^{-1})	B:C ratio
T_1	42298	60353	18055	1.43
T_2	46676	81006	34330	1.74
T_3	52661	81727	29066	1.55
T_4	42298	62069	19771	1.47
T_5	46676	102485	55809	2.20
T_6	52661	100119	47458	1.90
T_7	45098	61718	16620	1.37
T_8	50876	98708	47832	1.94
T_9	58261	83621	25360	1.44
T_{10}	47098	64352	17254	1.37
T_{11}	53876	122021	68145	2.26
T_{12}	62261	119503	57242	1.92
T_{13}	40487	133709	93222	3.30
T_{14}	33890	46433	12543	1.37

The 100% RDF as a split application in soil provides balanced fertilization and continuous availability, which has led to an increase in the number of tillers. The nano NPK encourages plants to take up more water and nutrients from the soil, leading to improved photosynthesis efficiency. This enhancement in photosynthesis, in turn, promotes plant growth and development, ultimately resulting in a higher number of tillers (16).

The increase in LAI in nanofertilizer treatments is likely due to improved nutrient uptake efficiency, which supports greater leaf expansion and light capture during critical growth stages (17). Therefore, the use of conventional and nanofertilizers at various growth stages notably impacted the LAI throughout the growth stages of rice. Fig. 4 shows the effect of nano NPK on the LAI of TPR.

Nitrogen is vital for chlorophyll production and leaf expansion, both of which directly contribute to higher photosynthetic activity and plant growth. The application of nanofertilizers, with their enhanced nutrient delivery properties, likely boosts nitrogen availability during key growth phases, leading to higher chlorophyll content and improved photosynthesis efficiency (12). Additionally, the split application of RDF improves nitrogen uptake and consequently, chlorophyll production and leaf surface area (18). Comparable research results were also observed in rice (2024).

The increase in DMP in RDF is due to the enhanced nitrogen supply, which promotes the accumulation of dry matter by facilitating the synthesis of photo-assimilates in leaves. These photo-assimilates are later allocated to reproductive organs (19). Additionally, the use of nanofertilizers increases nitrogen absorption in plants, resulting in greater dry matter production due to improved nitrogen availability and reduced ammonia loss (6, 20). These results align with findings of previous research (21).

The increase in crop growth rate in RDF as a soil application is due to extending the availability of nutrients to align with the absorption patterns of rice plants, thereby enhancing growth parameters (22). Likewise, the increase in CGR observed with the foliar application of nanofertilizers could be attributed to improved nutrient availability. This promotes greater assimilation and translocation of photosynthates from the source to the sink (23).

The increased yield associated with the application of the nanofertilizers can be explained by their greater absorbance and enhanced dissolution in water compared to bulk fertilizers (24). Similar outcomes were also recorded (18). Additionally, applying 100% RDF to the soil in 3 split doses may lead to better nutrient uptake and use efficiency, thereby increased grain yield.

Applying RDF through the soil in 3 splits resulted in a greater number of productive tillers, which ultimately increased the straw yield (15). Nano-spray applied to plants stores nitrogen in plant cells, where it can be gradually released. This slow release mitigates both biotic and abiotic stresses on plants, leading to higher straw yields in the long term (25). The results agree with findings from previous research (26).

The enhanced HI may be caused by leaf maturation, which involves substantial functional and anatomical changes leading to a reversal in transport to the export position. This shift may improve the plant's ability to translocate materials within its system and result in greater biological yield, ultimately achieving a higher harvest index (25).

The higher B:C ratio in RDF might be the reason for the low cost of conventional inorganic fertilizers and the recorded higher yield. The treatment involving foliar application of nanofertilizer, whether applied 3 times or 4 times, resulted ina low B:C ratio due to its high material cost and application charges.

Conclusion

Based on the study findings, it can be concluded that the application of RDF in 3 split and foliar applications of nano NPK at 3 times (tillering, active tillering and panicle initiation stages) led to substantial enhancements in the growth and yield of rice, which recorded 307 tillers, 14934 kg ha^{-1} of DMP and 39.72 SPAD values at the harvest stage. Similarly, there were 6281 kg ha^{-1} of grain yield, 7175 kg $ha^{-1}$of straw yield, HI of 0.47 and B:C ratio of 2.26, which leads to higher economic returns from rice production. The use of nanofertilizers improved nutrient use efficiency, leading to increased overall productivity. Moreover, nanofertilizers offer the potential for more sustainable agriculture by reducing nutrient waste and enhancing nutrient absorption. Nanofertilizers lower the environmental impact by targeting the release of nutrients, which helps decrease the environmental footprint of conventional fertilizers by reducing the leaching of nitrogen and phosphorus. By improving fertilizer efficiency and reducing the number of chemical inputs required, nanofertilizers can contribute to a lower carbon footprint for agricultural practices, aligning with global goals for reducing greenhouse gas emissions in farming. A major limitation is the high cost of nanofertilizers, which increases the cost of cultivation. Further research is encouraged to explore the long-term environmental and economic benefits of using nanofertilizers under varying agricultural conditions to reduce cultivation costs and increase net returns for farmers.

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Authors' contributions

RSB was involved in the research activities and field establishment and writing of the research article. MJ and MH corrected and proofread the research article. JB, SS and DL were involved in statistical analysis work of the data collected during the research. NV and SS assisted during the analysis work and participated in the sequence alignment. All authors read and approved the final manuscript.

Compliance with ethical standards

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During the preparation of this work, the authors used Paperpal to improve language and readability only. After using this tool, the authors carefully reviewed and edited the content and took full responsibility for the content of the publication.

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