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RESEARCH ARTICLE

Foliar nanofertilizers: Effects on crop uptake, yield and soil health in puddled transplanted rice

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Abstract

The primary aim of the study was to investigate the impact of foliar application of nano-formulated nutrients-specifically nano nitrogen, nano phosphorus and nano potash-on the growth, development and yield performance of transplanted rice cultivated under puddled soil conditions. A field experiment took place from December 2023 to April 2024 during the late *Rabi* season at the Department of Agronomy, V.O.Chidambaranar Agricultural College and Research Institute, Killikulam, Tamil Nadu, India. The experiment used a randomized block design with fourteen treatments, consisting of various combinations of nano NPK with different times of foliar application and three replications. The soil of the experimental plot was sandy clay loam with a pH of 7.73, which is slightly saline 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 results showed that the 100 % recommended dose of fertilizer (RDF) in rice treatment achieved the highest nutrient uptake (N, P, K) and, in turn, the grain yield, while foliar application of nano N, P and K fertilizers, particularly when applied four times, closely matched with the performance of RDF. Nanofertilizers enhanced nutrient absorption due to their smaller particle size and better leaf penetration. However, both RDF and nano foliar fertilization had minimal impact on soil chemical properties (pH, EC and organic carbon) and microbial activity, indicating that nutrient delivery primarily occurred through the foliage rather than altering the soil environment. In terms of economics, foliar application of nano N, P and K at three times was more cost-effective and profitable than four times in puddled transplanted rice.

Keywords: crop uptake; economics; nano fertilization; soil health; transplanted puddled rice; yield

Introduction

Rice cultivation plays a vital role in global agriculture, with the majority of production concentrated in Asia. India and China are the top rice-producing countries in this region and rice serves as the staple food for nearly half of the world's population (1). India ranks as the second-largest rice producer globally, holding a significant position in both agriculture and the economy (2). In 2021, India produced 129.66 million tons of rice, cultivated over 464 lakh hectares, making it the highest-yielding food crop (3).

In Tamil Nadu, rice is the most important cereal crop, grown on 22.05 lakh hectares (37 % of the total cereal area) (4). To achieve optimal growth and yield, rice requires substantial amounts of inorganic fertilizers, as its production is influenced by soil conditions and the availability of essential nutrients such as nitrogen, phosphorus, potassium, sulphur and zinc (5). Fertilizers are therefore key to enhance food productivity and quality and are a critical component of agricultural production systems. On average, N, P and K fertilizers contribute approximately 38 %, 12 % and 8 % to rice yields respectively (6). With the growing need to improve nutrient use efficiency, research has focused on optimizing nutrient supply to crops and cropping systems to maximize production and maintain soil health (7). However, the intensive use of inorganic fertilizers can deplete soil fertility over time, leading to nutrient deficiencies that present challenges for sustainable crop production in the future (8).

Nanotechnology has emerged as a promising solution to tackle agricultural challenges more effectively than traditional methods. "Nanofertilizers" represent a new class of plant nutrients developed at the nanoscale. These fertilizers consist of nutrients encapsulated within nanomaterials, offering several advantages for crops, such as controlled nutrient release and precise delivery of chemical fertilizers, which can regulate plant growth and enhance targeted effectiveness (7). Due to their smaller particle size, nanofertilizers have a larger specific surface area and a higher number of particles per unit area, increasing the chances of better contact with the plant surface (8). The use of nanotechnology and nanoparticles in agriculture can boost rice production by minimizing nutrient losses when applied as a foliar spray. With their distinctive physicochemical properties, nanofertilizers have the potential to enhance plant metabolism. In light of these benefits, the experiment was designed to apply nanofertilizers as a foliar spray to assess their impact on improving productivity and nutrient utilization efficiency in transplanted puddled rice.

The significance of the research is to improve the fertilizer use efficiency of rice through nanofertilizers as compared to conventional fertilizers. The truth behind it is that, in general, it is claimed that nanoscale fertilizers lowering the size of the input, lead to improved absorption and higher total release efficiency, delivering better efficacy with a smaller amount required. One of the key benefits of applying nanofertilizers through foliar spraying is the faster nutrient uptake compared to soil-based methods, which helps decrease nutrient loss and improves overall efficiency. Additionally, nanofertilizers enable a slow and steady nutrient release, reducing leaching and ensuring a continuous supply to the plants (9). The research was essential to assess the soil's nutrient levels and other properties by using foliar application of nano-nutrient fertilizers in rice cultivation.

Materials and Methods

This study was conducted during the late *Rabi* season from December 2023 to April 2024 at the Department of Agronomy, V.O.Chidambaranar Agricultural College and Research Institute, Tamil Nadu Agricultural University, Killikulam, Thoothukudi, Tamil Nadu, India. The experimental site is situated in the southern agro-climatic zone of Tamil Nadu, at a latitude of 8.705372° N and a longitude of 77.857498° E with an elevation of 40 m above mean sea level (AMSL). The soil in the experimental plot was sandy clay loam with a pH of 7.73, indicating slight salinity. It contained 6.41 g/kg of organic carbon, with available nutrients including 287.42 kg/ha of nitrogen, 25.15 kg/ha of phosphorus and 152.37 kg/ha of potassium. The region experiences a tropical climate that is generally hot and humid, receiving most of its rainfall during the North East Monsoon (NEM) season. The average monthly temperature between December and April ranges from 29 °C to 35 °C and the typical rainfall during the NEM season is about 680 mm. For this experiment, seeds of the TNAU rice variety ASD 16 were obtained from the Agricultural Research Station (ARS) in Ambasamudram.

The experimental design was arranged in a randomized block design with three replications and a total of fourteen treatments viz., T_1 - Foliar application of nano N & P at two times, T_2 - Foliar application of Nano N & P at three times, T_3 - Foliar application of nano N & P at four times, T_4 - Foliar application of nano N & K at two times, T_5 - Foliar application of nano N & K at three times, T_6 - Foliar application of nano N & K at four times, T_7 - Foliar application of nano P & K at two times, T_8 - Foliar application of nano P & K at three times, T_9 - Foliar application of nano P & K at four times, T_{10} - Foliar application of nano N, P & K at two times, T_{11} - Foliar application of nano N, P & K at three times, T_{12} - Foliar application of nano N, P & K at four times and these treatments were compared with T_{13} - 100 % RDF as soil application and T_{14} - Absolute Control. The foliar application of nanofertilizers was scheduled based on the growth stages of the rice crop. For treatments with two applications, sprays were conducted at the Active Tillering (AT) and Panicle Initiation (PI) stages. For treatments with three applications, sprays were administered at the Tillering, AT and PI stages. For four applications, the sprays were given at the Tillering, AT, PI and Flowering stages. Nano urea, nano DAP and nano potash were applied to the rice crop at a concentration of 4 mL/L.

Statistical analysis

R, a programming language designed for statistical computation and visualisation and supported by the R Core Team and the R Foundation for Statistical Computing, was used to statistically analyse all of the data that was collected. While the significant treatments were evaluated at a 5 % probability level, the non-significant treatments were denoted by NS.

Results and Discussion

Effect of foliar nanofertilizers application on plant N, P and K uptake of puddled transplanted rice

Nitrogen (N) boosts vegetative growth and chlorophyll content, Phosphorus (P) supports root and seed development and Potassium (K) improves water use efficiency and stress tolerance in transplanted rice. Adequate N, P and K uptake ensures better grain quality and enhances the plant's resistance to abiotic stresses (10). The application of 100 % RDF in three splits substantially increased the nitrogen uptake of 122.5 kg/ha and it was followed by foliar application of nano N, P & K four times recorded 117.4 kg/ha of N uptake. Absolute control has recorded the lowest N uptake of 79.1 kg/ha. Likewise, application of 100 % RDF in three splits significantly increased the P uptake of 43 kg/ha and it was followed by foliar application of nano N, P & K at four times, recorded 40.9 kg/ha of P uptake and it was statistically on par with foliar application of nano N, P & K at three times with 39.8 kg/ha. Absolute control has recorded the lower P uptake of 19.5 kg/ha. Similarly, application of 100 % RDF in three splits registered the maximum K uptake of 106.5 kg/ha,while it was followed by foliar application of nano N, P & K at four times with K uptake of 100.5 kg/ha which was on par with foliar application of nano N, P & K at three times with 98.4 kg/ha of K uptake. Lower K uptake of 51.0 kg/ha was recorded in the absolute control. With soil application of RDF in three split doses, the uptake of nutrients was high in the rice owing to the increase in the dose of nutrients and in turn increased the nutrient uptake (11). This could be due to the split application, which ensured that nutrient availability aligned with the plant's requirements during its active growth phases. Furthermore, foliar spray of nano N, P & K at four times or at three times was the next best treatment. The increased nutrient uptake by rice plants can likely be attributed to the unique properties of nanofertilizers. Due to their extremely small particle size, smaller than the pores (stomata or cuticular openings) on the surface of plant leaves, they can penetrate the leaf tissue more effectively when applied foliarly. Additionally, their large surface area enhances the interaction between the nutrient particles and the leaf surface, facilitating faster and more efficient absorption. This improved penetration and absorption lead to higher nutrient availability within the plant system, ultimately increasing the internal nutrient content (12). A lesser amount of NPK uptake was recorded in the foliar application of nano N & P at two times and the lowest uptake of nutrients was observed in the absolute control plot. It might be due to the limited availability of nutrients to the crop (13). Fig. 1 represents the influence of foliar application of nanofertilizers on N, P and K uptake of puddled transplanted rice.

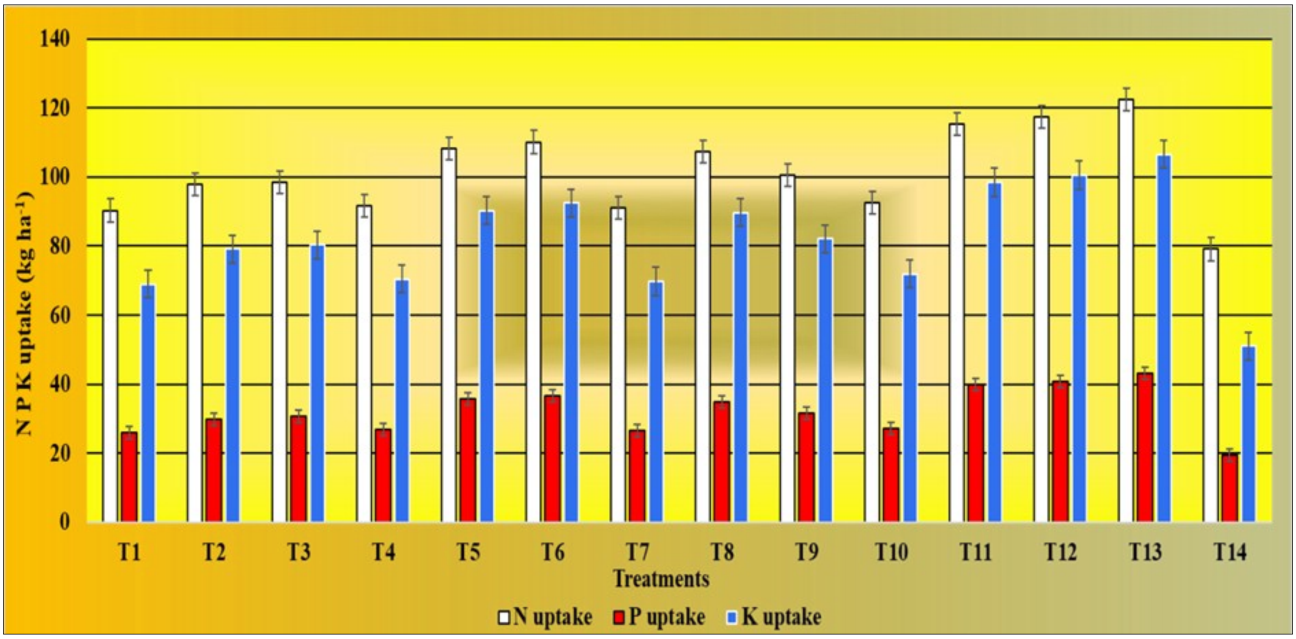

Fig. 1. Influence of foliar application of nanofertilizers on N, P and K uptake of puddled transplanted rice. T_1- foliar application of nano N & P at two times, T_2- foliar application of Nano N & P at three times, T_3- foliar application of nano N & P at four times, T_4- foliar application of nano N & K at two times, T_5- foliar application of nano N & K at three times, T_6- foliar application of nano N & K at four times, T_7- foliar application of nano P & K at two times, T_8- foliar application of nano P & K at three times, T_9- foliar application of nano P & K at four times, T_{10}- foliar application of nano N, P & K at two times, T_{11}- foliar application of nano N, P & K at three times, T_{12}- foliar application of nano N, P & K at four times and these treatments were compared with T_{13}- 100 % RDF as soil application and T_{14}- absolute control.

Effect of foliar nanofertilizers application on soil pH, Electrical Conductivity (EC) and organic carbon of puddled transplanted rice

Foliar nanofertilizers help to maintain stable soil pH and lower EC by reducing direct fertilizer input, minimizing risks of soil acidification and salinity. They also preserve soil organic carbon by preventing nutrient leaching and minimizing disturbance to soil microbial activity (14). After the harvest of the rice crop, the pH of the soil in each treatment plot was measured. The pH of the soil ranges between 6.93 to 7.26. The foliar application of nanofertilizers and 100 % RDF as soil application does not significantly affect the pH of the soil after crop harvest. Nevertheless, the highest soil pH of 7.26 was found in foliar application of nano N, P & K at two times and the lowest pH of 6.93 was found in 100 % recommended dose of fertilizers as soil application. Similarly, EC of the soil was also calculated and it ranges from 0.18 to 0.29 irrespective of the various treatments. EC is also not significantly affected by either foliar application of nanofertilizers or RDF as soil application. The higher EC of 0.29 was recorded in 100 % RDF and the lower EC of 0.18 was found in foliar application of nano N, P & K at two times.

Soil organic carbon was estimated at AT, PI and harvest stages of the crop and it was found that various treatments of nanofertilizers, as foliar application and the recommended dose of fertilizers as soil application, do not significantly alter the soil organic carbon. At the AT stage, the soil organic carbon content was recorded between 5.5 and 5.4 g/kg irrespective of the treatments. During the PI stage, the organic carbon value ranged from 5.2 to 5.4 g/kg and at the harvest stage, it ranged from 5.2 to 5.4 g/kg, which was found non-significant in all the stages of the crop. Soil pH, EC and organic carbon were not significantly influenced by the treatments of RDF as soil application and foliar application of nanofertilizers at different stages of transplanted rice. Soil application of RDF, the non-significant difference in soil pH, EC and organic carbon have been observed and it could be because the fertilizers were applied in amounts that the soil can buffer effectively. The fertilizers may not be concentrated enough to cause notable changes in these soil chemical parameters. Additionally, the nutrients are often absorbed by plants relatively quickly, preventing excessive accumulation in the soil that could otherwise alter its pH, EC or organic carbon levels (15). In contrast to conventional soil-applied fertilizers, foliar application of nanofertilizers involves delivering nutrients directly to the plant leaves rather than the soil. Since the nutrients are absorbed through the foliage, their contact and interaction with the soil are minimal. As a result, there is little to no influence on key soil properties such as pH (acidity/alkalinity), EC and organic carbon content. This mode of application effectively bypasses the soil, thereby preventing any significant alterations to its chemical composition or overall fertility status (16). The impact of foliar application of nano sources of nitrogen, phosphorus and potassium on pH, EC and soil organic carbon (g/kg) in transplanted rice is presented in Table 1.

Effect of foliar nanofertilizers application on Available soil N, P and K of puddled transplanted rice

Foliar nanofertilizers enhance nutrient use efficiency in transplanted rice by directly supplying N, P and K to leaves, reducing soil nutrient depletion and minimizing losses from leaching or fixation, thus helping to maintain higher levels of available soil N, P and K throughout the growing season (17). The various nutrient management of rice, either by foliar application of nanofertilizers and RDF, did not cause any significant effect on available nitrogen in the soil. Among the various treatments, 100 % RDF as soil application recorded higher available soil nitrogen with 267 kg/ha followed by foliar application of nano N, P & K at four times with 250 kg/ha. Even though the foliar application of nano N, P & K at three times also recorded 243 kg/ha. The lowest available nitrogen (230 kg/ha) was observed in the absolute control. Similarly, RDF as soil application recorded the highest available soil phosphorus (18 kg/ha) and it was followed by foliar application of nano N, P & K at four times, foliar application of

Table 1. Effect of foliar application of nano source of N, P and K on pH, EC and soil organic carbon of transplanted rice

Treatments	Post-harvest soil pH	Post-harvest soil EC	soil organic carbon (g/kg)		
			AT	PI	Post-harvest
T_1	7.14	0.21	5.5	5.3	5.2
T_2	7.16	0.23	5.4	5.3	5.2
T_3	7.19	0.20	5.4	5.2	5.2
T_4	7.17	0.24	5.5	5.3	5.2
T_5	7.20	0.19	5.4	5.3	5.2
T_6	7.20	0.24	5.4	5.2	5.2
T_7	7.14	0.21	5.5	5.3	5.2
T_8	7.20	0.20	5.4	5.2	5.2
T_9	7.18	0.22	5.4	5.3	5.2
T_{10}	7.26	0.18	5.5	5.3	5.3
T_{11}	7.22	0.24	5.4	5.3	5.3
T_{12}	7.25	0.23	5.4	5.3	5.3
T_{13}	6.93	0.29	5.5	5.4	5.4
T_{14}	7.22	0.21	5.4	5.3	5.2
SEd	0.44	0.03	0.11	0.08	0.07
CD (p=0.05)	NS	NS	NS	NS	NS

T_1- foliar application of nano N & P at two times, T_2- foliar application of nano N & P at three times, T_3- foliar application of nano N & P at four times, T_4- foliar application of nano N & K at two times, T_5- foliar application of nano N & K at three times, T_6- foliar application of nano N & K at four times, T_7- foliar application of nano P & K at two times, T_8- foliar application of nano P & K at three times, T_9- foliar application of nano P & K at four times, T_{10}- foliar application of nano N, P & K at two times, T_{11}- foliar application of nano N, P & K at three times, T_{12}- foliar application of nano N, P & K at four times and these treatments were compared with T_{13}- 100 % RDF as soil application and T_{14}- absolute control.

nano P & K at four times and foliar application of N & P at four times with 16.8 kg/ha. The foliar application of nano N, P & K at three times recorded a value of 16.7 kg/ha. Absolute control recorded the lowest available phosphorus of 14 kg/ha. Likewise, application of RDF in three splits recorded the highest available potassium of 209 kg/ha followed by foliar application of nano N, P & K at four times with 189 kg/ha. The lowest available potassium was recorded in absolute control with 158 kg/ha.

The post-harvest soil N, P & K were also not significantly influenced by the treatments of 100 % RDF as soil application and foliar application of nanofertilizers at different stages. However, the values are higher in RDF as compared to the nanofertilizer foliar application. The non-significant difference in NPK in soil levels by the recommended dose of fertilizers can be attributed to the efficient uptake of these nutrients by plants. When applied at appropriate levels, the nutrients are rapidly utilized by the crops, minimizing their residual concentration in the soil. Thus, the recommended dosage is balanced to meet crop needs without excessively altering the soil nutrient content. Research reported similar results from the previous study (18). Furthermore, the non-significant differences observed in post-harvest soil-available nitrogen (N), phosphorus (P) and potassium (K) levels can be attributed to the nature of foliar application of nanofertilizers, where nutrients are absorbed directly through the leaves, effectively bypassing the soil. This targeted delivery system ensures that only minimal quantities of N, P and K come into contact with the soil. As a result, there is little to no alteration in soil nutrient levels, since the soil does not serve as the primary medium for nutrient uptake in this method. Consequently, foliar nano fertilizer application has a negligible impact on soil fertility parameters related to N, P and K. Research indicates similar findings from the previous studies (16). Fig. 2 illustrates the effect of foliar application of nanofertilizers on the available nitrogen, phosphorus and potassium content in the soil of puddled transplanted rice.

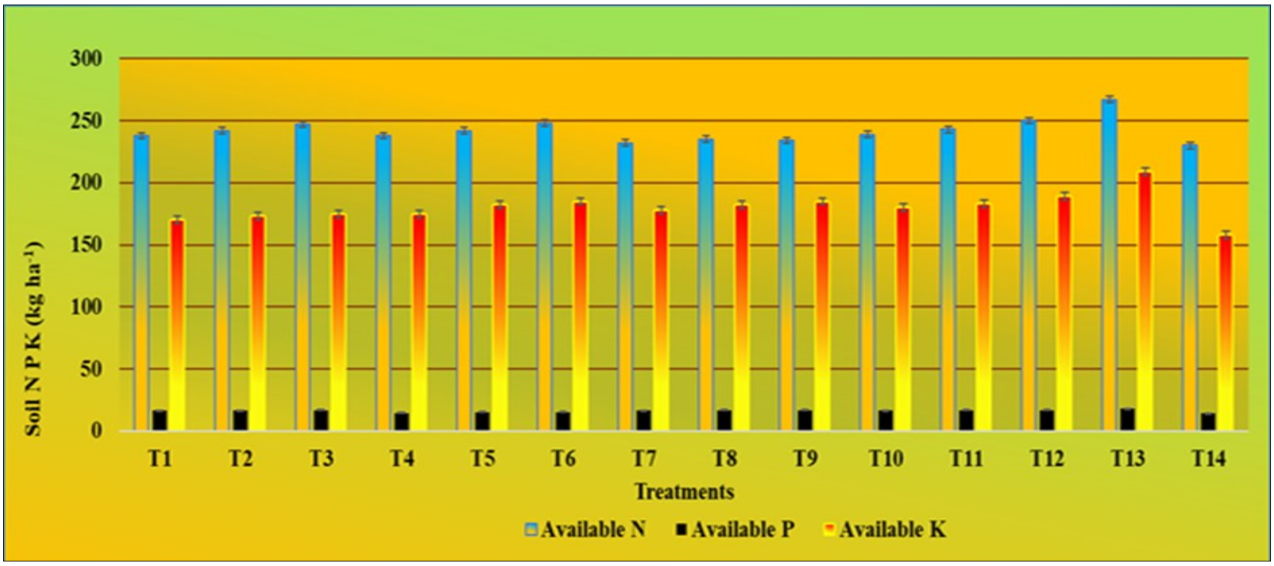

Fig. 2. Influence of foliar application of nanofertilizers on available soil N, P and K of puddled transplanted rice. T_1- foliar application of nano N & P at two times, T_2- foliar application of Nano N & P at three times, T_3- foliar application of nano N & P at four times, T_4- foliar application of nano N & K at two times, T_5- foliar application of nano N & K at three times, T_6- foliar application of nano N & K at four times, T_7- foliar application of nano P & K at two times, T_8- foliar application of nano P & K at three times, T_9- foliar application of nano P & K at four times, T_{10}- foliar application of nano N, P & K at two times, T_{11}- foliar application of nano N, P & K at three times, T_{12}- foliar application of nano N, P & K at four times and these treatments were compared with T_{13}- 100 % RDF as soil application and T_{14}- absolute control.

Effect of foliar nanofertilizers application on microbial population and enzymatic activity of puddled transplanted rice

Foliar nanofertilizers reduce soil nutrient input, minimizing disruptions to microbial habitats, thereby helping maintain healthy populations of bacteria, fungi and actinomycetes. This also supports soil enzymatic activities like dehydrogenase (19). Application of RDF and foliar application of nanofertilizers do not significantly affect the soil microbial population in this experiment. The bacterial population ranges from 30.3×10^6 to 68.7×10^6 cfu/g, the fungal population ranges from 9.7×10^4 to 21.5×10^4 cfu/g and the actinomycetes ranged from 13.3×10^3 to 7.0×10^3 cfu/g. 100 % RDF as soil application has higher soil microbial count of 68.7×10^6 of bacteria, 21.5×10^4 of fungi and 13.3×10^3 of actinomycetes. However, foliar application of nano N, P & K at four times has observed the next higher microbial count of 49.1×10^6 of bacteria, 14.8×10^4 of fungi, 10.0×10^3 of actinomycetes and foliar application of nano N, P & K at three times. Lower microbial count of 30.3×10^6 of bacteria, 9.7×10^4 of fungi, 7.0×10^3 of actinomycetes was recorded in the absolute control. The dehydrogenase activity ranges from 13.6 to 7.1 µg TPF/g soil/h. The recommended dose of fertilizers has recorded the maximum dehydrogenase activity of 13.6 µg TPF/g soil/h. Similar dehydrogenase activity was recorded in foliar application of nano N, P & K at four times and foliar application of nano N, P & K at three times with 9.6 and 9.4 µg TPF/g soil/h respectively. Lower dehydrogenase activity was observed in the absolute control with 7.1 µg TPF/g soil/h.

With regard to microbial population and enzymatic activity in the soil, the observed non-significant differences following the foliar application of nanofertilizers can be attributed to the method of application itself. Unlike conventional fertilizers that are applied to the soil, nanofertilizers in foliar form are sprayed directly onto the plant leaves, thereby minimizing direct nutrient input into the soil. As a result, the soil microbial communities and associated enzyme activities remain largely unaffected, since there is no substantial alteration in the soil's nutrient environment. Consequently, the biological processes governed by soil microbes and enzymes do not experience significant changes, which explains the lack of measurable impact from foliar nano fertilizer application (20). In RDF, since the fertilizers are applied at recommended levels, they do not excessively alter the soil's microbial balance and enzymatic processes, allowing these biological activities to remain stable and unaffected (21). Fig. 3 shows the impact of foliar application of nanofertilizers on the microbial population in puddled transplanted rice.

Effect of foliar nanofertilizers application on grain yield of puddled transplanted rice

The contribution of yield attributes to grain yield in cereal crops has been assessed through various parameters. (22). Variations in growth and yield characteristics under different treatments significantly impact the final harvestable yield. The study revealed that applying the recommended dose of fertilizers (T_{13}) in three splits resulted in a significantly higher grain yield of 6884 kg/ha. Similarly, the foliar application of nano N, P and K at three stages (tillering, active tillering and panicle initiation) (T_{11}) achieved the next highest grain yield of 6281 kg/ha, comparable to the yield from four foliar applications of nano N, P and K (T_{12}) with 6151 kg/ha. Among the nano fertilizer treatments, lower grain yields were observed in treatments such as foliar application of nano N, P and K at two stages (T_{10}), nano N and K at two stages (T_4), nano P and K at two stages (T_7) and nano N and P at two stages (T_1), ranging from 3080 to 3284 kg/ha. The minimum grain yield of 2330 kg/ha was recorded in the absolute control (T_{14}). The improved yields observed with nanofertilizer applications can be largely attributed to their superior absorption efficiency and enhanced solubility in water when compared to conventional bulk fertilizers. Due to their ultra-small particle size and high surface-area-to-volume ratio, nanofertilizers dissolve more readily in water, ensuring better

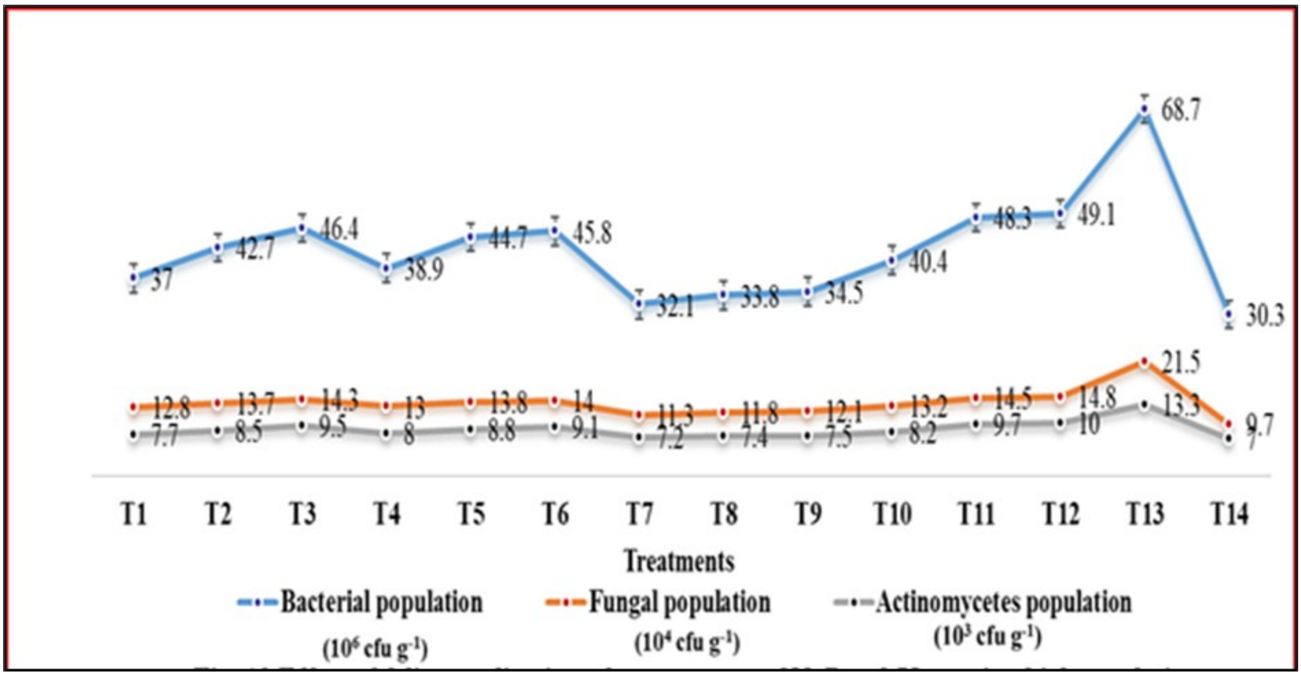

Fig. 3. Influence of foliar application of nanofertilizers on microbial population of puddled transplanted rice. T_1- foliar application of nano N & P at two times, T_2- foliar application of Nano N & P at three times, T_3- foliar application of nano N & P at four times, T_4- foliar application of nano N & K at two times, T_5- foliar application of nano N & K at three times, T_6- foliar application of nano N & K at four times, T_7- foliar application of nano P & K at two times, T_8- foliar application of nano P & K at three times, T_9- foliar application of nano P & K at four times, T_{10}- foliar application of nano N, P & K at two times, T_{11}- foliar application of nano N, P & K at three times, T_{12}- foliar application of nano N, P & K at four times and these treatments were compared with T_{13}- 100 % RDF as soil application and T_{14}- absolute control.

dispersion and availability of nutrients. This leads to more efficient uptake by plant tissues, particularly when applied foliar. As a result, plants receive a timely and sufficient supply of essential nutrients, which supports better physiological processes, promotes vigorous growth and ultimately contributes to higher crop yields. Additionally, the application of 100 % RDF as soil application in three splits likely improved nutrient uptake and use efficiency, thereby boosting grain yield. Fig. 4 highlights the influence of nanofertilizer foliar application on the grain yield of puddled transplanted rice.

Effect of foliar nanofertilizers application on the economics of puddled transplanted rice

Foliar application of nano N, P & K at four different stages of rice resulted in a higher cultivation cost of ₹62261 ha^{-1}. Following foliar application of nano P & K at four times with a cost of ₹58261 ha^{-1} and foliar application of nano N, P & K at three times with a cost of ₹53876 ha^{-1}. Conversely, the absolute control showed the lower cultivation cost at ₹33890 ha^{-1}. However, the cost of cultivation for the recommended dose of NPK recorded only ₹40487 ha^{-1}which was a difference of ₹21774 ha^{-1} (34 %) less than the treatment involving foliar application of nano N, P & K at four different stages of rice. The higher gross income of ₹133709 ha^{-1} was recorded in the treatment of 100 % RDF as soil application, followed by foliar application of nano N, P & K at four times with a gross income of ₹122021 ha^{-1} and foliar application of nano N, P & K at three times with a gross income of ₹119503 ha^{-1}. Conversely, the lower gross income of ₹46433 ha^{-1}was fetched with the absolute control.

The 100 % RDF as soil application accounted higher net return of ₹93222 ha^{-1} and it was followed by foliar application of nano N, P & K at three times, with a net return of ₹65627 ha^{-1} and foliar application of nano N, P & K at four times recorded the net return of ₹59760 ha^{-1}. Conversely, the absolute control showed the lower net return of ₹12543 ha^{-1} compared to other treatments. The higher B:C ratio of 3.30 was observed in 100 % RDF given as soil application. Following the foliar application of nano N, P & K at three times resulted in next best B:C ratio of 2.22 and foliar application of nano N, P & K at four times recorded the B:C ratio of 1.96. The lower B:C ratio was recorded in the absolute control, foliar application of nano N, P & K at two times and nano P & K at two times, with 1.37. Treatment 100 % RDF as soil application showed the highest net income among all treatments and it might be due to higher grain and straw yields, coupled with lower costs for conventional fertilizers and application charges as compared to the cost and application expenses of nanofertilizers. Foliar application of nano N, P & K at three times recorded a higher net income than foliar application of nano N, P & K at four times. A lower net income in foliar nano N, P & K at four times compared to three times applications was due to the higher fertilizer requirement and increased application costs associated with the four-time schedule, which were minimal in the three-time nanofertilizer application. Application of the recommended dose of fertilizers reduced cost of cultivation and increased the gross income. Research indicates similar findings in previous studies (23). The four-times foliar application of nanofertilizers resulted in a lower B:C ratio due to higher material and application costs compared to the three-time application. In the four-time schedule, the final spray did not significantly enhance yield, which consequently lowered the B:C ratio. Table 2 showed the effect of applying nano sources of N, P and K through foliar spray on the economic returns of transplanted rice.

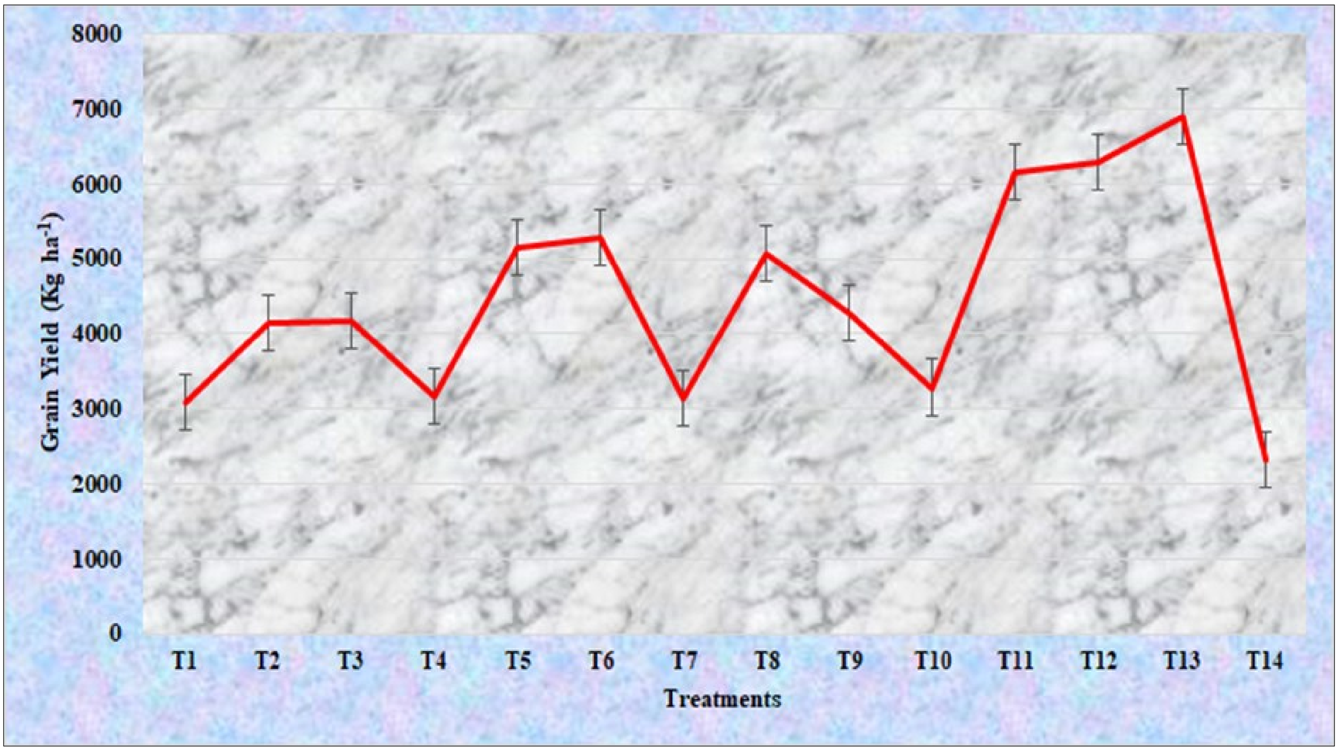

Fig. 4. Influence of foliar application of nanofertilizers on grain yield of puddled transplanted rice. T_1- foliar application of nano N & P at two times, T_2- foliar application of Nano N & P at three times, T_3- foliar application of nano N & P at four times, T_4- foliar application of nano N & K at two times, T_5- foliar application of nano N & K at three times, T_6- foliar application of nano N & K at four times, T_7- foliar application of nano P & K at two times, T_8- foliar application of nano P & K at three times, T_9- foliar application of nano P & K at four times, T_{10}- foliar application of nano N, P & K at two times, T_{11}- foliar application of nano N, P & K at three times, T_{12}- foliar application of nano N, P & K at four times and these treatments were compared with T_{13}- 100 % RDF as soil application and T_{14}- absolute control.

Table 2. Effect of foliar application of nano source of N, P and K on the economics of transplanted rice

	Treatments	Cost of cultivation (₹/ha)	Gross return (₹/ha)	Net return (₹/ha)	B: C Ratio
T_1	Foliar application of Nano N & P at two times*	42298	60353	18055	1.43
T_2	Foliar application of Nano N & P at three times **	46676	81006	34330	1.74
T_3	Foliar application of Nano N & P at four times ***	52661	81727	29066	1.55
T_4	Foliar application of Nano N & K at two times*	42298	62069	19771	1.47
T_5	Foliar application of Nano N & K at three times **	46676	100119	53443	2.14
T_6	Foliar application of Nano N & K at four times ***	52661	102485	49824	1.95
T_7	Foliar application of Nano P & K at two times *	45098	61718	16620	1.37
T_8	Foliar application of Nano P & K at three times **	50876	98708	47832	1.94
T_9	Foliar application of Nano P & K at four times ***	58261	83621	25360	1.44
T_{10}	Foliar application of Nano N, P & K at two times *	47098	64352	17254	1.37
T_{11}	Foliar application of Nano N, P & K at three times **	53876	119503	65627	2.22
T_{12}	Foliar application of Nano N, P & K at Four times ***	62261	122021	59760	1.96
T_{13}	100 % RDF as Soil Application	40487	133709	93222	3.30
T_{14}	Absolute Control	33890	46433	12543	1.37

Conclusion

The study demonstrated the potential benefits of using nanofertilizers as a foliar spray in transplanted puddled rice, comparing their effectiveness to traditional soil applications of recommended doses of fertilizers (RDF). The results showed that while RDF treatments achieved the highest nutrient uptake (N, P, K) and grain yield, foliar application of nano N, P and K fertilizers, particularly when applied four times, closely matched with the performance of 100 % RDF. Nanofertilizers enhanced nutrient absorption due to their smaller particle size and better leaf penetration. However, both RDF and nanofertilizers had minimal impact on soil chemical properties (pH, EC and organic carbon) and microbial activity, indicating that nutrient delivery primarily occurred through the foliage rather than altering the soil environment. Foliar application of nanofertilizers does not directly add nutrients to the soil but can indirectly influence soil-available N, P and K. By supplying nutrients through leaves, it reduces the plant's dependence on soil reserves, thereby minimizing nutrient depletion. Enhanced nutrient use efficiency leads to less fertilizer loss and better nutrient conservation in the soil. Additionally, improved plant health may alter root exudation and stimulate beneficial microbial activity, promoting nutrient solubilization. Over time, this can help maintain or even improve soil fertility. In terms of economics, foliar application of nano N, P and K at three times was more cost-effective and profitable than four times. Overall, nanofertilizers present a promising alternative to conventional methods, potentially reducing nutrient losses and improving nutrient use efficiency in rice cultivation.

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Authors' contributions

MJ and RSB contributed to the research activities, field establishment and drafting of the research article. MH and NV reviewed and proofread the manuscript, performed statistical analysis on the data collected during the research, assisted with the analysis process and participated in sequence alignment. All authors reviewed and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare no conflicts of interest.

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