



RESEARCH ARTICLE

Comparative performance of biostimulants, nano urea on nutrient uptake efficiency and productivity of transplanted rice

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Abstract

The experiment was conducted at the Wetland Farm of SRM College of Agricultural Sciences, Chengalpattu, during the navarai season of 2025 to evaluate the effects of biostimulants and nano urea on nutrient uptake efficiency and yield productivity in transplanted rice. The study was laid out in a randomised block design (RBD) comprising 8 treatments. Conventional fertiliser application was combined with foliar sprays of nano urea, potassium humate, humic acid and iron chelate. The treatments significantly influenced growth parameters such as plant height, tiller number, dry matter accumulation, leaf area index (LAI) and chlorophyll index. Among the treatments, T₇ (N₇₅P₁₀₀K₁₀₀ + 1.5 % nano urea + 3 % potassium humate) consistently recorded superior vegetative growth, exhibiting the highest plant height, LAI, chlorophyll index and dry matter production. Yield attributes, including productive tillers per hill, panicle length, panicle weight, test weight and number of filled grains per panicle, were also highest under T₇, followed by the humic acid treatment. Treatment T₇ produced the highest grain and straw yields as well as the greatest harvest index, indicating efficient assimilate partitioning and enhanced nitrogen use efficiency. In contrast, iron chelate treatments, although they increased the total number of tillers, frequently resulted in fewer productive tillers and reduced reproductive efficiency. Overall, the findings demonstrate that the combined application of nano urea and biostimulants, particularly potassium humate, is an effective and sustainable strategy for improving nutrient uptake, physiological performance and productivity in transplanted rice. However, the results also highlight the importance of balanced nutrient management and caution against excessive reliance on iron chelate applications.

Keywords: growth and yield; humic acid; iron chelate; nano urea; nutrient uptake; potassium humate

Introduction

Most of the world's population relies on rice (*Oryza sativa* L.) as a staple food, most people on the planet and its cultivation supports over two billion people. Rice is said to be at the vanguard of the fight against poverty and world hunger. India is the world's largest producer of rice among all food crops. It is the primary staple food crop in India, with a productivity of 2798 kg ha⁻¹ and the largest cultivated area of 46.27 Mha. Every year, it produces 129.47 million tonnes (1). Rice (*O. sativa*) is the primary food source for a large proportion of the world's population and plays a crucial role in global food security (2). More than 90 % of the world's rice is produced and consumed in Asia, where it is cultivated in over 100 countries, making it one of the oldest and most widely grown cereal crops. Global rice production is estimated at approximately 505.4 million tonnes. In India, the major rice-producing states include West Bengal, Andhra Pradesh, Chhattisgarh, Tamil Nadu, Karnataka, Assam, Maharashtra, Odisha, Punjab and Gujarat. In Karnataka, rice is cultivated on approximately 14 lakh hectares, with a productivity of 3089 kg ha⁻¹ and an annual production of 43.18 lakh tonnes (1).

Biostimulants are naturally occurring organic compounds or substances that have considerable potential to enhance crop productivity in modern agricultural systems. Applied in small quantities, biostimulants stimulate physiological processes in plants, resulting in improved growth, yield and product quality (3, 4). They enhance enzymatic and metabolic activities, particularly during the early stages of crop development and improve nutrient uptake efficiency, stress tolerance and overall plant performance. Biostimulants encompass a wide range of materials, including botanical extracts, protein hydrolysates, amino acids, vitamins, microbial products, antioxidants, anti-transpirants and derivatives of humic and fulvic acids. By improving nutrient absorption and utilisation, they contribute to increased productivity and strengthen plant resilience under adverse environmental conditions. Consequently, the use of biostimulants represents a sustainable agricultural approach that enhances crop performance while reducing environmental impacts (5). Potassium humate is the potassium salt of humic acid and represents a highly concentrated form of humus. Humic acid is a dark-coloured, stable organic

substance formed through the microbial decomposition of plant and animal residues. It is commonly derived from lignite (brown coal), a partially coalified peat material and functions as an effective biostimulant by enhancing nutrient availability, root growth and plant development (6).

This complex organic molecule occurs naturally in soils, peat, freshwater and marine environments. Leonardite is considered one of the richest natural sources of humic acid (7). Humic acid typically contains 51–57 % carbon, 4–6 % nitrogen, 0.2–1 % phosphorus and trace amounts of several micronutrients. In addition to improving soil fertility and nutrient availability, humic substances play an important role in enhancing plant growth and development.

Iron (Fe) is one of the most essential micronutrients for plant growth and metabolism (7). It is involved in numerous physiological processes, including respiration, redox reactions, RNA synthesis, chlorophyll biosynthesis and the activation of various enzymes (8, 9). Iron deficiency can adversely affect photosynthesis, nutrient utilisation and overall plant productivity. Iron chelates are commonly used as foliar nutrient sources because they provide readily available iron that can rapidly improve the nutritional status of plants and correct iron deficiency symptoms.

Iron plays a vital role in nitrogen metabolism, protein synthesis, chlorophyll formation, photosynthesis, carbonic anhydrase activity and protection against oxidative damage. It also enhances plant tolerance to biotic and abiotic stresses, thereby contributing to improved crop growth and productivity (10). Iron deficiency is a common nutritional disorder in agriculture, particularly in crops grown on calcareous soils and under semi-arid conditions, where iron availability is often limited. Nano urea has emerged as an innovative nitrogen source capable of improving nitrogen use efficiency in rice cultivation. Owing to its nano-sized particles, nano urea facilitates efficient absorption and utilisation of nitrogen by plants, resulting in enhanced nutrient uptake (10). Improved nitrogen availability promotes vegetative growth, chlorophyll synthesis, photosynthetic efficiency and grain development, ultimately leading to higher yields and better nitrogen use efficiency. Foliar application of nano urea during critical growth stages effectively meets the crop's nitrogen requirements and has been reported to improve crop productivity and quality compared with conventional urea fertilisation.

Materials and Methods

A field experiment was conducted in wetland farm of SRM College of Agricultural Sciences, Baburayanpettai, Chengalpattu during navarai season (December 2025–January 2026). The experimental site is located at 12°25'4" N latitude, 77°42'10" E longitude; 50 m above mean sea level. During the crop season the prevailed weather data where the experiment was conducted under a warm and humid climatic regime. The mean maximum temperature recorded during the crop growth period was 30.50°C, while the mean minimum temperature was 19.28°C, indicating moderate diurnal variation favourable for rice cultivation. With values ranging from a minimum of 55.82 % to a maximum of 92.13 %, relative humidity varied significantly, indicating extremely humid weather in the mornings and nights. With an average of 6.18 hr of sunshine each day, there was sufficient light interception for photosynthetic activity. Due to the 14.13 mm of rainfall, additional irrigation was

required to maintain the ideal level of soil hydration. In addition to fostering vegetative development, leaf area expansion and tiller initiation, the combination of warm temperature, high humidity, moderate sunshine and minimal rainfall needed careful water management to maintain crop performance. This weather profile supplied the background circumstances under which the current investigation was conducted and exemplifies the transplanted rice environment. The weather parameters are shown in the fig:1 With a mechanical composition of 36.7 % clay, 20.4 % silt and 41.7 % sand, the experimental soil was categorised as clay loam. A neutral reaction and non-saline circumstances were indicated by the soils pH of 0.46 dS/m, according to chemical analysis. The low organic matter state was indicated by the organic carbon concentration of 0.26 %, The available nutrient levels were 207.3 kg/ha nitrogen, 7 kg/ha phosphorus and 13.8 kg/ha potassium, indicating a fertility state of medium nitrogen, low phosphorus and medium potassium. The baseline soil conditions under which the treatment were applied and crop response was assessed were provided by these Physicochemical characteristics.

Experimental treatment details

The experiment was laid out in a randomised block design (RBD) with three replications to account for field variability. Eight treatment combinations involving conventional fertilisers, nano urea and biostimulants were evaluated as follows:

T₁: N₁₀₀P₁₀₀K₁₀₀

T₂: N₁₀₀P₁₀₀K₁₀₀ + iron chelate at 3 %

T₃: N₁₀₀P₁₀₀K₁₀₀ + potassium humate at 3 %

T₄: N₁₀₀P₁₀₀K₁₀₀ + humic acid at 3 %

T₅: N₇₅P₁₀₀K₁₀₀ + 1.5 % nano urea + iron chelate at 3 %

T₆: N₇₅P₁₀₀K₁₀₀ + 1.5 % nano urea + potassium humate at 3 %

T₇: N₇₅P₁₀₀K₁₀₀ + 1.5 % nano urea

T₈: N₇₅P₁₀₀K₁₀₀ + 1.5 % nano urea + humic acid at 3 %

Rice variety CO 55 was transplanted at a spacing of 20 × 15 cm. The crop duration was approximately 110–115 days and harvesting was completed on 13 March 2025. Biometric observations, including plant height, number of tillers m², LAI and dry matter accumulation, were recorded at 30 DAT, 60 DAT and at harvest. Yield attributes and grain yield were assessed at harvest.

The Dimethyl Sulfoxide (DMSO) extraction method was used to determine the amount of chlorophyll in rice leaves. After cutting fresh leaf samples (about 50 mg) into small pieces, they were incubated in 5 mL of DMSO at 65 °C for about 3 hr to achieve full pigment extraction. Spectrophotometric analysis of the clear extract yielded absorbance values at 645 and 663 nm. The concentrations of chlorophyll a, chlorophyll b and total chlorophyll were determined using the Arnon formulae modified for the DMSO solvent (11). This method is advantageous as it avoids grinding, minimizes pigment degradation and ensures efficient extraction of chlorophyll from intact leaf tissues, thereby providing reliable estimates of photosynthetic pigment status under different treatment conditions.

Plant N uptake (kg ha⁻¹) =

Nitrogen content (%) × Yield (kg ha⁻¹)

100

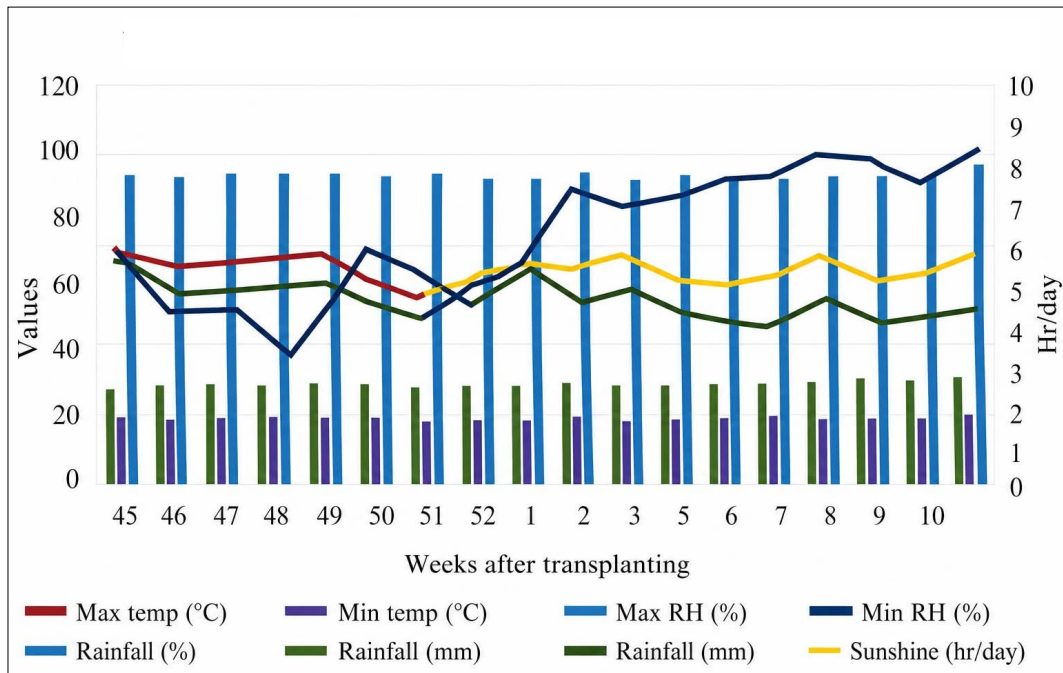


Fig. 1. Weather parameters prevailed during the cropping period (Navarai 2025).

Leaf area index

LAI=

$$\frac{L \times W \times K \times \text{Number of leaves plant}^{-1}}{\text{Leaf area occupied by the plant}}$$

Leaf area occupied by the plant

Results and Discussion

Growth attributes

Application of nano urea and biostimulants significantly influenced the growth attributes of transplanted rice, including plant height, tiller number, dry matter production, leaf area index (LAI) and chlorophyll index. The Growth parameters datas are given in Table 1. Among the treatments, $T_7(N_{75}P_{100}K_{100} + 1.5\% \text{ Nano Urea} + \text{Potassium Humate at } 3\%)$, consistently recorded the tallest plants with values of 94.04 cm at harvest, this could be because the nano encapsulated nitrogen efficiently releases nutrients, controlling plant growth and boosting target activity (11).

Nano fertiliser, a colloidal farming fertiliser additive, makes it easier for nutrients to be absorbed, transfer and absorbed. Potassium humate foliar application at different dosages and stages clearly affected the growth characteristics of rice cultivar hasanta. As the growth phases advanced, plant height was followed by T_4 plant height at harvest, which was 96.85 was followed by T_4 plant height at harvest, which was 96.85 $T_4 (T_4-N_{100}P_{100}K_{100} + \text{Humic acid at } 3\%)$ (12). Foliar application of humic acid improves soil and plant parameters such as plant height and yield T_8 plant height at harvest 94.16 ($N_{75}P_{100}K_{100} + 1.5\% \text{ Nano Urea} + \text{Humic acid at } 3\%$) as compared to traditional application (13).

Foliar application of nano urea has been reported to enhance basic growth parameters of rice, including plant height and the number of tillers per plant (14). Humic acid increases the permeability of the plasma membrane, thereby facilitating nutrient absorption. It also stimulates root and shoot growth by enhancing the synthesis of metabolic enzymes and plant growth-promoting hormones such as auxins and cytokinins (15). The T_1 had the shortest plant height (82.64cm at harvest). Additionally, tillering was

Table 1. Effect of nano urea and biostimulants on growth attributes of rice

Treatment	Plant height (cm)	No of tillers (m^{-2})	Dry matter production ($kg\ ha^{-1}$)	Leaf area index		Chlorophyll index ($mg\ g^{-1}$)			
	At harvest	At harvest	At harvest	30 DAT	60 DAT	At harvest	30DAT	60DAT	At harvest
$T_1 - N_{100}P_{100}K_{100}$	82.64	420	8349	2.8	3.2	4.5	33.1	38.4	33.67
$T_2 - N_{100}P_{100}K_{100} + \text{iron chelate at } 3\%$	86.01	460	9780	3.05	3.74	4.9	34.95	41.9	37.2
$T_3 - N_{100}P_{100}K_{100} + \text{potassium humate at } 3\%$	84.4	440	9025	2.9	3.4	4.7	34.2	40.5	35.23
$T_4 - N_{100}P_{100}K_{100} + \text{humic acid at } 3\%$	94.85	550	13100	3.27	4.75	5.85	38.31	45.13	41.54
$T_5 - N_{75}P_{100}K_{100} + 1.5\% \text{ nano urea}$	90.02	530	11285	3.2	4.25	5.6	36.95	43.6	39.6
$T_6 - N_{75}P_{100}K_{100} + 1.5\% \text{ nano urea} + \text{iron chelate at } 3\%$	85.5	525	10540	3.15	4.2	5.55	35.8	42.75	38.45
$T_7 - N_{75}P_{100}K_{100} + 1.5\% \text{ nano urea} + \text{potassium humate at } 3\%$	96.04	590	14250	3.3	4.88	6.23	38.18	46.1	42
$T_8 - N_{75}P_{100}K_{100} + 1.5\% \text{ nano urea} + \text{humic acid at } 3\%$	94.16	545	12030	3.25	4.45	5.8	37.4	44.76	40.46
SE (d)	4.08	14.31	646.8	0.21	0.29	0.36	3.10	1.96	1.78
CD (5 %)	8.54	29.9	1351.2	NS	0.61	0.76	NS	4.11	3.72

optimised in T_7 , which is 590 at harvest ($N_{75}P_{100}K_{100} + 1.5\%$ nano urea + Potassium Humate at 3 %). Rice yield will rise and input efficiency will be enhanced by using nano urea during the active tillering stage (16). Tiller numbers were maintained constant due to the extremely small size of nano urea particles.

Because of the surface area, there are more locations for contact with plant tissues. The probability of absorption is increased since there are more particles per unit area (17). At harvest, the highest number of tillers (550) was recorded in the treatment. The number of tillers in T_4 ($N_{100}P_{100}K_{100} + 3\%$ humic acid) was statistically on par with the highest treatment. Because humic acid improves nitrogen availability, which is essential for vegetative development, there are more tillers per hill (18) and T_8 ($N_{75}P_{100}K_{100} + 1.5\%$ nano urea + humic acid at 3 %) tillers at harvest 545. Rice yield will rise and input efficiency will be enhanced by using nano urea during the active tillering stage. T_1 ($N_{100}P_{100}K_{100} + \text{Iron Chelate at } 3\%$) recorded the lowest productivity because iron chelates increase the number of tillers, but nutritional imbalance may cause many of them to remain unproductive, resulting in low reproductive efficiency (20).

In contrast, increased growth of plant parts and metabolic processes, such as photosynthesis due to increased enzymatic activity, ultimately resulted in higher photosynthate accumulation and their translocation to economically significant parts of the plant (19). Dry matter production was highest in T_7 ($N_{75}P_{100}K_{100} + 1.5\%$ nano urea + potassium humate at 3 %) with 14250 kg ha⁻¹ at harvest. Because nano urea produced most dry matter. This impact was brought about by the plants larger surface area, which increases the synthesis of dry matter by facilitating the entry of particles smaller than leaves and improving nutrient use efficiency (21). Due to increased cell division and root and shoot proliferation, the foliar spray of potassium humate has improves rice growth characteristics and dry matter (22), followed by T_4 ($N_{100}P_{100}K_{100} + \text{humic acid at } 3\%$). Humic acid is one of the most powerful biostimulants among the humic chemicals that have several positive impacts on rice growth and development. Humic acid effectively enhances photosynthesis, promotes plant growth and increases the accumulation of dry matter and organic matter (23). The highest dry matter production (13100 kg ha⁻¹) was recorded in this treatment, whereas T_6 ($N_{100}P_{100}K_{100} + 3\%$ iron chelate) produced the lowest amount of dry matter.

The foliar iron chelate treatment causes overstimulation of vegetative tissues, which raises the respiration requirement and reduces the efficiency of nutrient partitioning to seeds of 8349 kg ha⁻¹ (24). In a similar the LAI was better in T_7 (6.23 at harvest). Nano urea

helps plants better absorb nutrients and enhance their metabolic processes because of its unique form, size and increased surface area.

Nano urea promotes meristematic activity, enhances leaf expansion and terminal growth, activates key plant enzymes and physiological processes and helps maintain optimal nitrogen levels in plants (25). The LAI recorded under this treatment was statistically comparable to that of T_4 ($N_{100}P_{100}K_{100} + 3\%$ humic acid) and T_8 ($N_{75}P_{100}K_{100} + 1.5\%$ nano urea + 3 % humic acid). Application of nano urea significantly influenced LAI, likely due to improved nutrient absorption and utilisation, which promoted greater leaf development and canopy expansion. The nanoscale formulation ensures better nutrient absorption and penetration through leaves, thereby promoting leaf growth and overall canopy development (26). This was considerably higher than the lowest value recorded in T_1 . Iron chelate may reduce net photosynthetic efficiency by increasing respiratory demand and susceptibility to leaf burn or stress (27). Chlorophyll index values further confirmed the superiority of T_7 ($N_{75}P_{100}K_{100} + 1.5\%$ nano urea + 3 % potassium humate), which recorded the highest value (42.00) at harvest, followed by T_4 (41.54). Application of humic acid increased leaf chlorophyll concentration through enhanced uptake of macro and micronutrients, which positively influenced shoot growth and indicated improved photosynthetic efficiency (28). These results clearly demonstrate that the combination of nano urea and potassium humate (T_7) markedly improved vegetative growth, in agreement with earlier findings that biostimulants enhance enzymatic activity, nutrient uptake efficiency and overall crop vigour.

Yield

Grain and straw yields of transplanted rice were significantly enhanced by the application of nano urea and biostimulants. The yield parameters data are given in the Table 2. The treatment T_7 ($N_{75}P_{100}K_{100} + 1.5\%$ Nano Urea + Potassium Humate at 3 %) produced the highest grain yield of 5650 kg ha⁻¹ (%). The nanoparticles effectively enter plant cells, improving photosynthetic efficiency, meristematic activity and metabolic processes. Consequently, nano-urea enhances rice's ability to absorb nitrogen, increasing grain production (34). The highest grain yield recorded in the present study under potassium humate application indicates that humic acid enhanced nutrient availability, yield attributes and overall rice productivity (35). T_7 ($N_{75}P_{100}K_{100} + 1.5\%$ nano urea + 3 % potassium humate) produced the highest grain yield, followed by T_4 (5221 kg ha⁻¹). Humic acid has been reported to increase grain yield by 21–25% through enhanced nutrient accumulation, which

Table 2. Effect of nano urea and biostimulants on yield of rice

Treatment details	No of filled grains	Grain yield (kg ha ⁻¹)	Straw yield (kg ha ⁻¹)	Harvest index	Grain uptake (kg ha ⁻¹)	Straw yield (kg ha ⁻¹)
$T_1 - N_{100}P_{100}K_{100}$	101	3902	5600	0.41	21.50	16.00
$T_2 - N_{100}P_{100}K_{100} + \text{iron chelate at } 3\%$	108	4362	6002	0.42	38.00	24.50
$T_3 - N_{100}P_{100}K_{100} + \text{potassium humate at } 3\%$	105	4116	5880	0.41	36.00	23.50
$T_4 - N_{100}P_{100}K_{100} + \text{humic acid at } 3\%$	124	5221	6928	0.42	52.00	31.50
$T_5 - N_{75}P_{100}K_{100} + 1.5\%$ nano urea	115	4813	6513	0.42	46.00	28.50
$T_6 - N_{75}P_{100}K_{100} + 1.5\%$ nano urea + iron chelate at 3 %	114	4736	6405	0.42	44.00	27.50
$T_7 - N_{75}P_{100}K_{100} + 1.5\%$ nano urea + potassium humate at 3 %	138	5650	7350	0.46	56.50	34.00
$T_8 - N_{75}P_{100}K_{100} + 1.5\%$ nano urea + humic acid at 3 %	119	5114	6809	0.42	50.50	30.50
SE(d)	6.77	304.5	399.5	0.013	1.70	1.43
CD (5 %)	14.14	636.2	834.7	NS	3.56	2.99

may be attributed to its ability to facilitate the gradual release of nutrients through residue decomposition over an extended period (36). T_8 also recorded a high grain yield (5114 kg ha^{-1}). Increased foliar application of nano-nutrients significantly improved grain yield by enhancing yield attributes, promoting the accumulation of photosynthates and facilitating their translocation to economically important plant parts (37). Humic acid also improves nitrogen uptake by the sink, thereby increasing grain protein content (38). In contrast, the lowest grain yield was recorded in the control treatment, T_1 (3902 kg ha^{-1}). Although foliar iron application may promote vegetative growth, excessive dosage or inappropriate timing can reduce reproductive efficiency and ultimately lower grain yield (39).

Straw yield also followed a similar trend, with T_7 recording the highest value of 7350 kg ha^{-1} . The rapid uptake of nano urea by plants and its efficient translocation may have enhanced photosynthetic activity and dry matter accumulation, thereby increasing straw production under foliar application of higher doses (40). In contrast, the lowest straw yield (5600 kg ha^{-1}) was recorded in T_1 . Increased straw production under iron chelate treatments often reflects enhanced vegetative growth at the expense of reproductive allocation, resulting in reduced overall productivity and harvest index (39). The harvest index was highest in T_7 (0.45), indicating efficient conversion of biomass into grain. These results clearly demonstrate that the integration of nano urea with potassium humate (T_7) was the most effective treatment for enhancing both grain and straw productivity, corroborating earlier findings that the combined use of nitrogen and biostimulants improves rice yield through enhanced nutrient assimilation and assimilate partitioning.

Yield attributes

Yield components of transplanted rice were significantly improved by the application of nano urea and biostimulants. The yield attribute parameters are presented in Table 3. Treatment T_7 ($N_{75}P_{100}K_{100} + 1.5\% \text{ nano urea} + 3\% \text{ potassium humate}$) recorded the highest number of productive tillers per hill (395). Foliar application of nano urea enhances nutrient uptake and translocation through stomatal pore openings, thereby promoting tiller production and improving crop growth.

Plants produced more productive tillers because of enhanced cell division, meristematic activity and cell elongation stimulated by increased nutrient uptake (29). Panicle length is an important yield attribute because of its positive association with other yield components, such as grain number and 1000-grain weight. Foliar application of potassium humate significantly

influenced panicle length in rice, resulting in increased panicle development (30).

Treatment T_4 ($N_{100}P_{100}K_{100} + 3\% \text{ humic acid}$) recorded 388 productive tillers per hill and closely followed T_7 . The application of humic acid markedly enhanced tiller production, with higher levels promoting the development of more productive tillers. These findings highlight the importance of balanced nutrient management in increasing tiller production and sustaining crop growth (31).

In contrast, T_1 recorded the lowest number of productive tillers per hill (280). Iron deficiency can lead to spikelet sterility, reducing the conversion of tillers into productive panicles (32). Panicle development was also superior in T_7 , which produced the longest panicles (25.2 cm) and the heaviest panicles (2.46 g).

Grain filling was markedly enhanced under T_7 ($N_{75}P_{100}K_{100} + 1.5\% \text{ nano urea} + 3\% \text{ potassium humate}$), which recorded the maximum number of filled grains per panicle (138), followed by T_4 . The improved grain filling may be attributed to foliar application of nano urea, which ensured an adequate supply of nitrogen during the later stages of grain development. Foliar nutrient application can promote assimilate accumulation in grains and increase grain weight (33). In contrast, the control treatment (T_1) recorded the lowest number of filled grains per panicle (108).

The highest test weight was also observed in T_7 (17.72 g), whereas T_1 registered the lowest value (16.8 g). The superior performance of T_7 indicates that the combined application of nano urea and potassium humate enhanced assimilate translocation, nutrient utilisation and grain filling. Conversely, excess iron may increase the proportion of unfilled grains and restrict carbohydrate translocation to developing grains, resulting in lower grain weight despite apparent improvements in panicle development.

These findings clearly demonstrate the synergistic effect of nano urea and potassium humate on reproductive growth, grain filling and yield formation. The results are consistent with earlier reports indicating that biostimulants improve nutrient assimilation, assimilate partitioning and yield attributes in rice, thereby enhancing both grain and straw productivity.

Nitrogen content and uptake (kg ha^{-1})

The application of nano urea and biostimulants significantly influenced nitrogen content and uptake in transplanted rice. The nitrogen uptake data are presented in Table 3. Treatment T_7 ($N_{75}P_{100}K_{100} + 1.5\% \text{ nano urea} + 3\% \text{ potassium humate}$) recorded the highest nitrogen uptake, with 56.5 kg ha^{-1} in grain and 34.0 kg ha^{-1}

Table 3. Effect of nano urea and biostimulants on yield attributes of rice

Treatment details	Productive tillers per hill (m^{-2})	Panicle length (cm)	Panicle weight (g)	Test weight (g)	Total grains
$T_1 - N_{100}P_{100}K_{100}$	280	18.5	1.58	16.81	108
$T_2 - N_{100}P_{100}K_{100} + \text{iron chelate at } 3\%$	310	20.5	1.74	17.05	115
$T_3 - N_{100}P_{100}K_{100} + \text{potassium humate at } 3\%$	295	19.8	1.62	16.92	112
$T_4 - N_{100}P_{100}K_{100} + \text{humic acid at } 3\%$	388	24	2.28	17.58	128
$T_5 - N_{75}P_{100}K_{100} + 1.5\% \text{ nano urea}$	350	22.5	1.98	17.32	122
$T_6 - N_{75}P_{100}K_{100} + 1.5\% \text{ nano urea} + \text{iron chelate at } 3\%$	345	22.2	1.86	17.18	121
$T_7 - N_{75}P_{100}K_{100} + 1.5\% \text{ nano urea} + \text{potassium humate at } 3\%$	395	25.2	2.46	17.72	136
$T_8 - N_{75}P_{100}K_{100} + 1.5\% \text{ nano urea} + \text{humic acid at } 3\%$	376	23.8	2.19	17.45	126
SE(d)	23.86	1.09	0.14	0.903	6.21
CD (5 %)	49.85	2.28	0.30	NS	12.99

¹ in straw. In contrast, the control treatment (T₁) exhibited the lowest nitrogen uptake, recording 21.5 kg ha⁻¹ in grain and 16.0 kg ha⁻¹ in straw.

The enhanced nitrogen uptake observed in T₇ may be attributed to the rapid absorption of nano urea through foliar application and the nutrient-mobilising effect of potassium humate, which together improved nitrogen use efficiency. The combined application of nano urea and potassium humate likely facilitated greater nutrient availability, uptake and translocation within the plant, resulting in higher nitrogen accumulation in both grain and straw. These findings are consistent with earlier studies in kharif rice, which reported synergistic effects of biostimulants and nitrogen fertilisation on nutrient uptake, utilisation efficiency and crop productivity.

Conclusion

The combined application of nano urea with biostimulants, particularly potassium humate and humic acid, proved highly effective in enhancing growth attributes such as plant height, tiller number, dry matter accumulation, leaf area index and chlorophyll index in transplanted rice cv. CO 55. These treatments also improved yield attributes, including the number of productive tillers, panicle length, panicle weight, test weight and the number of filled grains per panicle. Consequently, they produced higher grain and straw yields along with an increased harvest index, indicating efficient nutrient uptake, utilisation and partitioning.

In contrast, treatments involving iron chelates, although they promoted the production of more tillers, often resulted in a greater proportion of unproductive tillers and reduced reproductive efficiency. This highlights the importance of balanced nutrient management for achieving optimum crop performance and yield stability.

Overall, the findings demonstrate that the integration of nano urea with biostimulants is a sustainable approach for improving rice productivity, physiological performance and nitrogen use efficiency. However, the results also emphasise the need to avoid nutrient imbalances, as excessive or inappropriate nutrient application may adversely affect reproductive development and lead to yield instability.

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Authors' contributions

HT, JR, BP and C developed the methodology, performed validation, conducted formal analysis, undertook data curation and prepared the original draft. HT, JR and BP conceptualised the study. HT, JR, BS and CS carried out the writing, review and editing. HT, JR,

BS and C provided supervision. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT (OpenAI) to assist with language refinement, grammar correction, and improving sentence clarity. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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