



RESEARCH ARTICLE

Synergistic impact of NPK and nano-fertilisers on growth, productivity and soil microbial dynamics of wheat

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Abstract

This study looked at how nano-nutrients affected the growth, grain quality and soil health of wheat (*Triticum aestivum* L.) in the crop research centre of Sardar Vallabhbhai Patel University of Agriculture and Technology (SVPUAT), Meerut, throughout the 2018-20 rabi seasons. The wheat cultivar DBW-17 was used in 42 plots (3 × 3 m) using a randomised block design comprising 14 treatments, which were replicated thrice. Throughout the crop cycle, the arrangement permitted sequential damaging sampling and enabled the use of common field equipment. Foliar application of nano nitrogen (N) + phosphorous (P) + potassium (K) + zinc (Zn) at 100 % of the recommended NPK dose significantly enhanced growth indices, yield attributes and final grain yield. The protein content of the grain went up to 10.9 % and the protein yield went up to 584.2 kg ha⁻¹, which is a 10 % increase in protein content and a 40.6 % increase in protein yield compared to regular NPK fertilisation. Tests conducted after harvest revealed that the soil contained higher levels of microorganisms and nutrients, indicating that the soil's health had increased. Furthermore, root biomass and nutrient uptake were improved by nano-nutrient treatments. Overall, the findings demonstrate that adding nano-nutrients to conventional NPK fertilisation can significantly increase soil fertility, wheat productivity and the long-term viability of agriculture.

Keywords: rain quality; grain yield; harvest index; microbial population; nano-fertilisers; soil biological characteristics

Introduction

The King of Cereals, wheat (*Triticum aestivum* L.), is a versatile crop and a staple food that is essential to food security. About 37 % of the nation's total food grain production comes from it. Over 113.29 million metric tons of wheat were produced on 31.83 million hectares during the 2024 rabi cycle (1). By 2050, the world's population is predicted to reach 9.7 billion people, which could necessitate a 60 % increase in wheat output to fulfil the growing demand for food (2). Achieving this demand while projecting environmental sustainability is a big challenge, requiring innovative approaches to sustainable yield production, reducing environmental impact and ensuring food security for the growing population. Nanotechnology can help grow better wheat by improving crop grain quality and productivity, nutrient use efficiency, while reducing environmental harm (3–5). The increasing food demand must be balanced against sustainable resource management, as indiscriminate agricultural practices have contributed to pressing issues such as climate change, soil degradation, water quality and even health problems (6).

The Green Revolution (1970) substantially increased crop production through intensive chemical fertilisers, but it also disrupted nutrient cycling, causing depletion of soil nutrients (phosphorus (P), potassium (K), zinc (Zn)), soil degradation, water depletion, biodiversity loss and environmental pollution (7–11). Therefore, maintaining productivity while safeguarding soil health and environmental quality requires creative and environmentally beneficial methods (12). Approximately 40–70 % of N, 80–90 % of P and 50–70 % of K from conventional fertilisers are lost to the environment through leaching or volatilisation (13–15). Sustainable farming methods are increasingly concentrating on lowering chemical fertiliser inputs and employing nano-nutrients to enhance soil health, plant development and environmental sustainability in order to address these issues (16, 17).

Crop yield, soil fertility and nutrient-use efficiency can all be significantly increased by using nanotechnology in agriculture (18, 19). Nanoparticles, which range in size from 1 to 100 nm, improve the transport of nutrients to plants, encourage greater nutrient absorption and boost plant metabolism (20). Additionally, by providing a controlled supply of nutrients, their sustained and

controlled release mechanisms enhance growth, yield and resource-use efficiency over time (21). Nanosized particles are critical to soil health because they enhance nutrient preservation, increase microbial activity and encourage organic carbon recycling in the soil (22). The use of nanofertilisers increases nutrient absorption efficiency due to their huge surface area, which speeds up growth and metabolic responses and ultimately encourages photosynthesis and crop development (23). Research indicates that nano-nutrients can simultaneously minimise environmental contamination and reduce nutrient losses, while concurrently increasing crop yields by 17–54 % (24, 25).

Furthermore, nanofertilisers improve soil quality and facilitate nutrient absorption by increasing the activity of advantageous soil enzymes (26). It is hypothesised that the integrated application of nanofertilisers with conventional NPK fertilisers will significantly enhance soil fertility, nutrient use efficiency, yield, grain protein content and decrease environmental degradation. This new strategy is an example of a sustainable farming technique that can feed the world's growing population without harming the environment. Therefore, combining nanofertilisers with conventional farming techniques offers a practical and sustainable path for crop production in the future.

Materials and Methods

Experimental site

The study was conducted in the Indo-Gangetic plains of Northern India, at the Crop Research Centre (CRC), Sardar Vallabhbhai Patel University of Agriculture and Technology (SVPUA&T), Modipuram, Meerut, Uttar Pradesh. With coordinates of 29°05'–29°34' N latitude and 77°41'–77°58' E longitude, the position is 230 m above mean sea level. Temperature, relative humidity, sunlight hours, pan evaporation, rainfall and wind speed were recorded at the Indian

Institute of Farming Systems Research (IIFSR) observatory in Meerut. The mean weekly values of these meteorological parameters, which were computed from daily data recorded for the cropping seasons of 2018–19 to 2019–20, are shown in Fig. 1.

Experimental design and treatments

The randomised block design (RBD) field experiment employed 14 treatments. To enable damaging sampling of the crop using common field equipment, a total of 42 plots were created, with each treatment replicated three times. The purpose of the study was to assess how various fertiliser management techniques affected wheat (*T. aestivum* L.) growth and production.

A total of three main fertiliser management levels were used in the RBD field experiment. The treatment details are given below: (i) 100 % recommended NPK dose; (ii) 75 % of the recommended NPK dose and (iii) foliar sprays of nano- and bio-nano fertilisers containing N, P, K and Zn. The two crucial growth stages of tillering (28 DAS) and jointing (45 DAS) were when nano- and bio-nano fertilisers were applied. In order to assess the effects of conventional and nano-/bio-nano fertilisers on wheat, the experiment included 14 treatments. The subsequent treatments included different combinations of NPK fertilisers (100 % or 75 % of the recommended dose) together with nano or bio-nano fertilisers; Treatment T₁ served as the absolute control, getting no NPK fertilisers; T₂ received 100 % recommended NPK (150:60:40 kg ha⁻¹); T₃ involved 100 % NPK with water spray at tillering and jointing stages (28 and 45 DAS). Treatments T₄ to T₇ combined 100 % NPK with individual nano- or bio-nano fertilisers: Nano-N (T₄); Bio nano-P (T₅); Bio nano-K (T₆); Bio nano-Zn (T₇) applied as foliar sprays at 28 and 45 DAS; T₈ consisted of 100 % NPK combined with a foliar spray of Nano-N + Bio nano (P + K + Zn) at the same stages; similarly, the 75 % NPK treatments included T₉ (75 % NPK + water spray), T₁₀ (75 % NPK + Nano-N), T₁₁ (75 % NPK + Bio nano-P), T₁₂ (75 % NPK + Bio nano-K), T₁₃ (75 % NPK + Bio nano-Zn); and T₁₄ (75 % NPK +

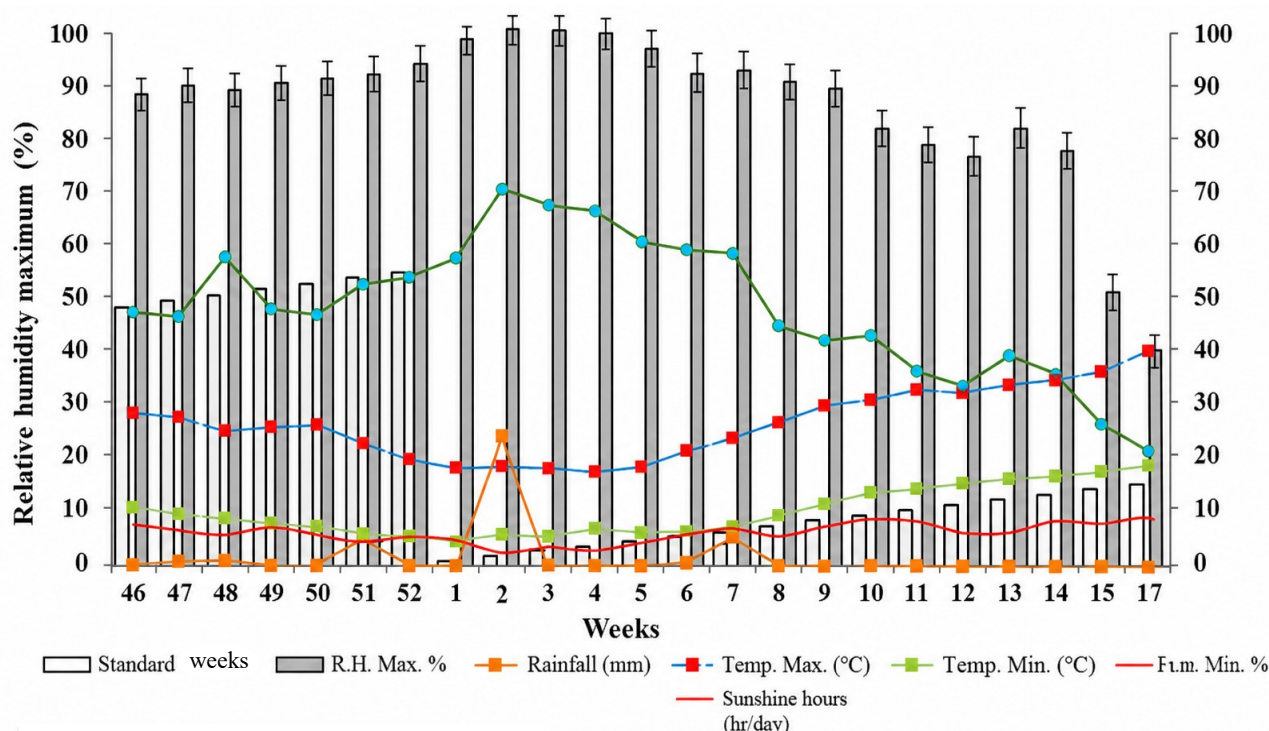


Fig. 1. Mean weekly weather parameters recorded during the rabi season 2018–19 to 2019–20. RH: relative humidity.

Nano-N + Bio nano (P + K + Zn), all applied as foliar sprays at tillering and jointing stages (28 and 45 DAS) (Note: Foliar applications were carried out at the tillering (28 DAS) and jointing (45 DAS) stages).

Nano fertiliser application

In accordance with the assigned treatments, foliar sprays of nano-fertilisers were applied. 4 mL of N, 40 mL of P, 40 mL of potash and 10 mL of Zn were administered. The sprays required 500 L of water per acre. Applications were carried out at the jointing (45 DAS) and tillering (28 DAS) stages.

Estimation of growth indices

Leaf area index (LAI): Leaf area was measured periodically at 30-day intervals throughout the crop growth period until maturity and senescence using the following formula:

$$LAI = \frac{\text{Leaf area}}{\text{Ground area}} \quad (\text{Eq. 1})$$

Leaf area duration (LAD, days): Leaf area duration, representing the persistence of leaf area over time, was calculated following Equation 2 (27):

$$LAD = \frac{(LAI_1 + LAI_2)}{2} \times (T_2 - T_1) \quad (\text{Eq. 2})$$

Where LAI_1 are the LAI at time t_1 , LAI_2 are the LAI at time t_2 and $(t_2 - t_1)$ are the time interval days.

Crop growth rate (CGR, $\text{g m}^{-2} \text{ day}^{-1}$): CGR was estimated using periodic measurements of dry matter accumulation (28)

$$CGR = \frac{(W_2 - W_1)}{A \times (t_2 - t_1)} \quad (\text{Eq. 3})$$

Where W_1 and W_2 are plant dry weights (g) at times t_1 and t_2 , A is the plot area (m^2) and $(t_2 - t_1)$ is the time interval in days.

Relative growth rate (RGR, $\text{gg}^{-1} \text{ day}^{-1}$): RGR was determined as described in the standard method (28).

$$RGR = \frac{(\log_e W_2 - \log_e W_1)}{(t_2 - t_1)} \quad (\text{Eq. 4})$$

Where W_1 and W_2 are plant dry weights at t_1 and t_2 and $(t_2 - t_1)$ is the time interval in days.

Net assimilation rate (NAR, $\text{g m}^{-2} \text{ day}^{-1}$): NAR, representing the rate of biomass accumulation per unit leaf area (28).

$$NAR = \frac{(W_2 - W_1)(\log_e L_2 - \log_e L_1)}{(L_2 - L_1)(t_2 - t_1)} \quad (\text{Eq. 5})$$

Harvest index (HI percentage): It is a measure of the efficiency with which a plant converts total biomass into economic yield (grain yield) and is calculated as:

$$HI(\%) = \frac{(\text{Grain yield})}{(\text{Total biological yield})} \times 100 \quad (\text{Eq. 6})$$

Statistical analysis

Data were analysed using SPSS version 10.0. Analysis of variance (ANOVA) was performed to evaluate significant differences among treatments at $p \leq 0.05$. The critical difference (CD) test was used as a post hoc comparison to assess differences between treatment means (29).

Results

Leaf area index (LAI)

The experiment evaluated the effects of different nutrient inputs on wheat growth at various stages of development. Table 1 and Fig. 2 reveal that the treatments with the highest LAI of 4.3 were those that combined 100 % and 75 % of the recommended NPK fertilisers with nano- and bio-nano fertilisers (Nano-N, Bio nano-P, Bio nano-K and Bio nano-Zn). The administration of individual or combined nano-nutrients in addition to 75 % NPK resulted in significant increases in LAI of 23.4 %, 20.3 %, 18.8 %, 21.9 % and 28.1 % respectively, as compared to 100 % NPK alone.

Table 1. Effect of nano-nutrients on leaf area index (LAI) and leaf area duration (LAD) at different growth stages of wheat (*Triticum aestivum* L.) (pooled data)

Treatments	Growth indices			
	LAI		Leaf area duration	
	60 DAS	90 DAS	60-90 DAS	90-harvest
T ₁	2.1	3.0	76.5	115.2
T ₂	2.4	3.4	99.0	135.3
T ₃	2.5	3.4	99.0	135.8
T ₄	2.9	4.2	106.5	167.8
T ₅	2.8	4.0	100.5	160.1
T ₆	2.7	3.9	99.0	156.4
T ₇	2.8	4.1	103.5	164.2
T ₈	3.2	4.3	112.5	171.9
T ₉	2.3	3.4	89.4	132.0
T ₁₀	2.8	4.1	103.5	163.8
T ₁₁	2.7	3.9	99.0	156.4
T ₁₂	2.7	3.9	97.9	156.1
T ₁₃	2.7	4.0	99.0	160.1
T ₁₄	3.1	4.3	111.0	171.5
S Em±	0.1	0.1	3.5	8.1
CD ($p = 0.05$)	0.3	0.4	10.2	16.8

The differences reported are based on three repetitions of each treatment and the values represent the mean of the replicates. T₁ = the absolute control, getting no NPK fertilisers; T₂: 100 % recommended NPK (150 : 60 : 40 kg ha⁻¹); T₃: 100 % NPK with water spray at tillering and jointing stages (28 and 45 DAS); T₄: combined 100 % NPK with individual nano- or bio-nano fertilisers: Nano-N; T₅: Bio nano-P; T₆: Bio nano-K; T₇: Bio nano-Zn applied as foliar sprays at 28 and 45 DAS; T₈: 100 % NPK combined with a foliar spray of Nano-N + Bio nano (P + K + Zn) at the same stages; T₉: the 75 % NPK treatments included T₉ (75 % NPK + water spray); T₁₀: 75 % NPK + Nano-N; T₁₁: 75 % NPK + Bio nano-P; T₁₂: 75 % NPK + Bio nano-K; T₁₃: 75 % NPK + Bio nano-Zn; T₁₄: 75 % NPK + nano-N + Bio nano (P + K + Zn).

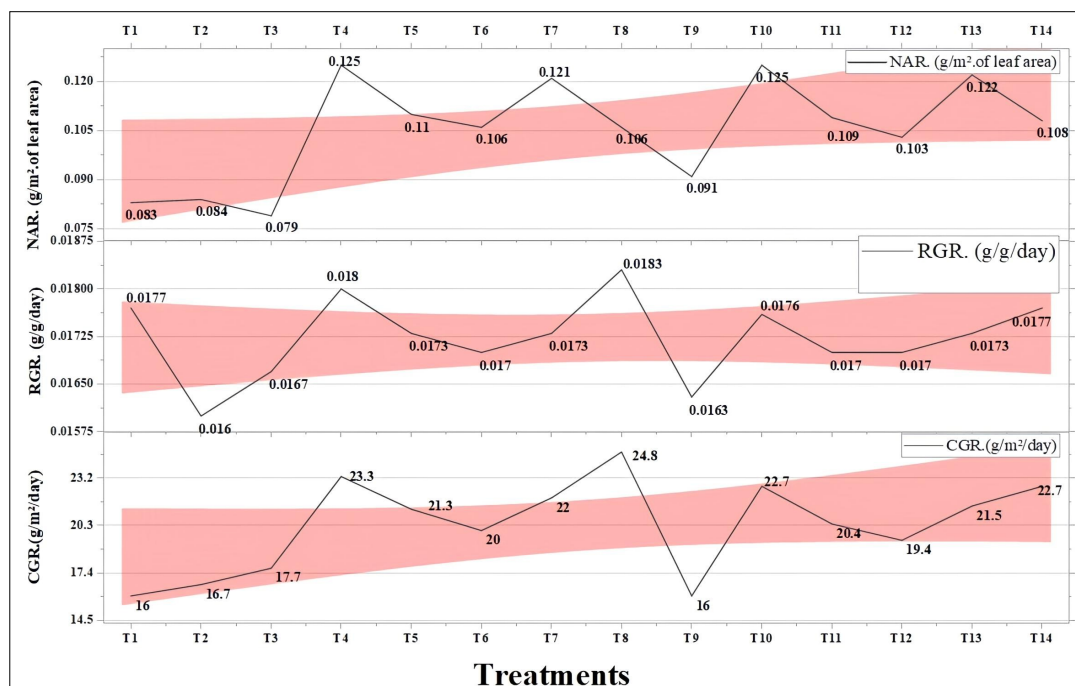


Fig. 2. Effect of nano-nutrients on wheat growth indices (pooled data). CGR: Crop growth rate; RGR: Relative growth rate; NAR: Net assimilation rate.

Leaf area duration (LAD)

Throughout the crop growth cycle, the persistence of leaf area was prolonged by fertiliser inputs. At every stage of crop growth, nitrogen-based foliar treatments greatly extended the length of leaf area. The leaf area duration peaked when 100 % NPK was mixed with nano-nutrients (nano-N, nano-P, nano-K and nano-Zn). Conversely, because the control plots were not fertilised, they displayed the shortest leaf area duration of 115 days.

Growth indices

Growth indices, including CGR, RGR and NAR, are shown in Table 2 and Fig. 3. All growth measures exhibited maximal values between 60 and 90 DAS in treatments that received 100 % NPK and all nano-nutrients. The combined nutrient management resulted in improved growth and assimilatory efficiency, as evidenced by the

CGR of 24.8 g m⁻² day⁻¹, RGR of 0.0183 g g⁻¹ day⁻¹ and NAR of 0.106 g m⁻² day⁻¹.

Yield-contributing characteristics and grain yield

In comparison to the control, fertilised treatments had a significantly larger number of effective tillers (Fig. 3). The increases of 12.7 %, 8.6 %, 7.5 % and 10.1 % were obtained with nano-N, Bio nano-P, Bio nano-K and Bio nano-Zn respectively, when 100 % NPK was applied in conjunction with nano- and bio-nano fertilisers; a 14.6 % increase was obtained when all nano-nutrients were mixed with 100 % NPK alone. In a similar vein, tiller numbers were increased by 75 % NPK with nano-nutrients, with percentage increases ranging from 10.8 % to 13.1 % in comparison to 100 % NPK. The greatest increases in tiller production were obtained when nano-nutrients were applied in combination with 100 % NPK (26.0 %, 15.3 %, 21.4 % and 40.5 % for

Table 2. Effect of nano-nutrients on grain yield, straw yield, harvest index (HI), grain protein content and protein yield of wheat

Treatments	Grain yield (t ha ⁻¹)	Straw yield (t ha ⁻¹)	Biological yield (t ha ⁻¹)	Harvest index (%)	Protein (%)	Protein (t ha ⁻¹)
T ₁	2.72	4.17	7.01	38.8	8.1	220.3
T ₂	4.13	6.04	10.28	39.6	8.4	346.9
T ₃	4.17	6.09	10.34	39.6	8.6	358.6
T ₄	5.02	6.57	11.64	43.1	9.7	486.9
T ₅	4.82	6.47	11.32	42.2	8.8	424.2
T ₆	4.79	6.39	11.24	42.1	8.8	421.5
T ₇	4.92	6.54	11.15	44.1	9.2	452.6
T ₈	5.36	6.87	12.24	44.4	10.9	584.2
T ₉	3.91	5.84	10.18	38.4	8.2	289.3
T ₁₀	4.97	6.46	11.38	42.8	10.3	501.6
T ₁₁	4.78	6.4	11.19	42.2	9.2	439.8
T ₁₂	4.73	6.34	11.12	41.9	8.7	411.5
T ₁₃	4.81	6.44	11.34	42.8	9.7	466.6
T ₁₄	5.24	6.63	11.91	44.0	10.3	539.7
SEm±	1.80	2.30	4.20	1.6	0.2	8.8
CD (P = 0.05)	5.20	6.60	12.30	NS	0.6	25.7

Significant differences were considered at $p < 0.05$. Values represent the mean of three replications for each treatment. The differences reported are based on three repetitions of each treatment and the values represent the mean of the replicates. T₁: the absolute control, getting no NPK fertilizers; T₂: 100 % recommended NPK (150 : 60 : 40 kg ha⁻¹); T₃: 100 % NPK with water spray at tillering and jointing stages (28 and 45 DAS); T₄: combined 100 % NPK with individual nano- or bio-nano fertilisers: Nano-N; T₅: Bio nano-P; T₆: Bio nano-K; T₇: Bio nano-Zn applied as foliar sprays at 28 and 45 DAS; T₈: 100 % NPK combined with a foliar spray of Nano-N + Bio nano (P + K + Zn) at the same stages; T₉: the 75 % NPK treatments included T₉ (75 % NPK + water spray), T₁₀: 75 % NPK + Nano-N; T₁₁: 75 % NPK + Bio nano-P, T₁₂: 75 % NPK + Bio nano-K, T₁₃: 75 % NPK + Bio nano-Zn; T₁₄: 75 % NPK + Nano-N + Bio nano (P + K + Zn).

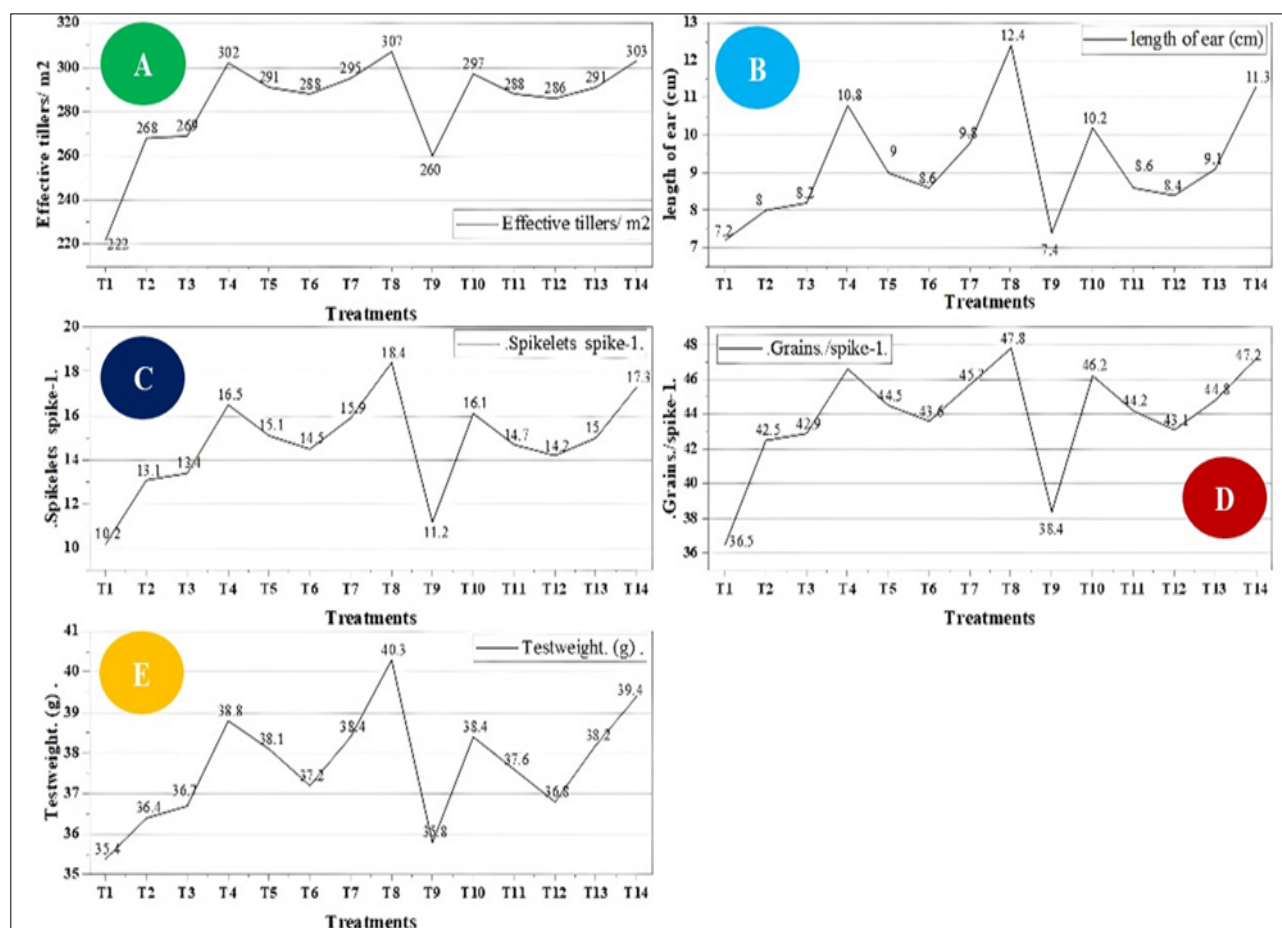


Fig. 3. Impact of nano-nutrients on yield-contributing characteristics of wheat : A. Effective tillers m⁻², B. Length of ear (cm), C. Spikelets spike⁻¹, D. Grains spike⁻¹, E. Test weight (g).

Nano-N, P, K, Zn and their combination, respectively), whereas tillers grew by 22.9%, 12.2%, 8.4%, 14.5% and 32% respectively. Nutrient treatments also increased the number of grains per spike, which ranged from 36.5 in the control to 47.8 in 100 % NPK combined with Nano-N + P + K + Zn. When compared to the control and 100 % NPK, combined nano-nutrients increased grains per spike by 29.3 % and 11.1 %, respectively. Test weight was not significantly affected by nutrient management; however, the highest values were observed under 75 % NPK + Nano-N + Bio nano P + Bio nano K + Bio nano Zn, followed by 100 % NPK with nano-nutrients (Fig. 3). Grain yield was significantly impacted by fertiliser applications (Table 2). When 100 % NPK was sprayed on nano-nutrients (T₈), grain yield increased by 0.89, 0.69, 0.66, 0.79 and 1.23 t/ha (21.5 %, 16.7 %, 16.0 %, 19.1 % and 29.8 %). The comparable gains with 75 % NPK fell between 0.74 and 1.06 t/ha. Similarly, 75 % NPK plus nano-nutrients increased straw yield by 0.36-0.59 t/ha, while 100 % NPK plus nano-nutrients increased straw yield by 0.53, 0.43, 0.35, 0.50 and 0.83 t/ha (5.8–13.7 %). The biological yield showed a similar pattern: 75 % NPK with nano-nutrients produced increases of 0.84-1.60 t/ha, whereas 100 % NPK with nano-nutrients produced increases of 0.13, 0.10, 0.96, 0.90 and 1.90 t/ha (8.5–19.1 %) over 100 % NPK. A similar pattern was seen in the biological yield: 100 % NPK combined with nano-nutrients produced increases of 0.13, 0.10, 0.96, 0.90 and 1.90 t/ha (8.5–19.1 %) over 100 % NPK, whereas 75 % NPK with nano-nutrients yielded 0.84-1.60 t/ha increases. In 100 % NPK combined with nano P + K + Zn, the harvest index (HI) was 44.4 %, compared to 38.8 % in the control. The highest HI was reported by treatments containing 100 % NPK with Nano-N + P + K + Zn, demonstrating the effectiveness of nano-nutrient integration in enhancing yield and crop partitioning.

Grain quality studies

The effect of foliar-applied nano-nutrients on wheat grain protein content and protein yield is presented in Table 2. The highest protein content (10.9 %) and protein yield (584.2 kg ha⁻¹) were recorded in T₈, which received 100 % NPK along with foliar sprays of nano N, bio-nano P, K and Zn at the tillering (28 DAS) and jointing (45 DAS) stages. Even when the NPK dose was reduced to 75 %, treatments T₁₀ and T₁₄, which included nano-nutrient sprays, achieved a protein content of 10.3 %, significantly higher than the 8.4 % observed with 100 % NPK alone (T₂). Protein yield also increased markedly with nano-nutrient treatments, ranging from 411.5 to 584.2 kg ha⁻¹, compared to only 220.3 kg ha⁻¹ in the unfertilised control, indicating the positive effect of nano-fertilisers on grain nutritional quality.

Soil studies

The treatments had a significant impact on the soil's physico-chemical and biological properties, such as microbial populations and nutrient availability (Table 3). When compared to the control, the application of nano-nutrients (N, P, K and Zn) increased soil fertility and microbial activity. There was an improvement over the control in key parameters like available organic carbon (209.5 mg kg⁻¹), available N (0.42 %), available P₂O₅ (194.4 mg kg⁻¹), available K (12.4 mg kg⁻¹), available Zn (145.6 mg kg⁻¹) and microbial populations like bacteria (0.80×10^2 cfu g⁻¹), actinomycetes (0.66×10^2 cfu g⁻¹) and fungi (0.47 - 0.68×10^1 cfu g⁻¹). The trend suggests that applying nano-nutrients can improve soil nutrient status and biological activity, enabling sustainable crop production, even though these improvements were not statistically significant.

Table 3. Effect of nano-nutrients on the chemical and biological properties of soil (pooled data)

Treatments	Organic carbon (%)	Available nutrients (kg ha ⁻¹)			Available zinc (mg kg ⁻¹)	Microbial population		
		Nitrogen	Phosphorus	Potassium		Bacteria (No × 10 ⁶ cfu g ⁻¹)	Fungi (No × 10 ⁴ cfu g ⁻¹)	Actinomycetes (No × 10 ³ cfu g ⁻¹)
T ₁	0.42	194.4	12.4	145.3	0.80	0.66	0.47	0.68
T ₂	0.43	206.5	14.6	156.2	0.81	0.69	0.48	0.78
T ₃	0.45	206.4	14.8	156.3	0.82	0.70	0.48	0.80
T ₄	0.47	211.9	15.9	157.4	0.84	0.71	0.52	0.74
T ₅	0.45	210.2	16.2	157.8	0.83	0.69	0.51	0.72
T ₆	0.45	209.8	15.4	158.2	0.84	0.68	0.50	0.71
T ₇	0.46	210.6	15.1	157.2	0.88	0.70	0.52	0.73
T ₈	0.49	212.4	16.7	158.4	0.89	0.72	0.55	0.75
T ₉	0.43	206.1	13.1	152.6	0.81	0.66	0.46	0.69
T ₁₀	0.45	208.2	13.4	153.4	0.83	0.69	0.52	0.74
T ₁₁	0.46	207.8	13.8	153.7	0.82	0.68	0.51	0.71
T ₁₂	0.44	206.9	12.4	154.4	0.83	0.67	0.49	0.69
T ₁₃	0.45	207.4	12.1	153.7	0.85	0.70	0.50	0.70
T ₁₄	0.48	209.5	13.6	154.6	0.88	0.71	0.53	0.73
SEm±	0.02	7.61	0.52	5.62	0.03	0.03	0.02	0.03
CD (p ≤ 0.05)	NS	NS	NS	NS	NS	NS	NS	NS

Bacteria (No × 10⁶ cfu g⁻¹) refers to the number of bacterial colonies present in one gram of soil, expressed in colony-forming units (cfu) per gram of soil multiplied by 10⁶. This parameter is commonly used to assess the microbial population and soil biological activity, which are important indicators of soil health and fertility. NS: not significant.

Discussion

The effectiveness of nano-fertilisers in conjunction with traditional NPK fertilisers on wheat growth, productivity and quality was assessed in this study. The results unequivocally show that important quantitative characteristics, including LAI, CGR, RGR and net NAR, were greatly improved by the combined application of nano-nutrients. In the end, these enhancements led to higher straw and grain yields as well as better protein content. These results corroborate the idea that nano-fertilisers can boost wheat yield while encouraging sustainable farming methods.

The observed rise in LAI in plants treated with nanofertiliser is consistent with earlier studies showing improved leaf area development as a result of nanoparticles' greater nutrient absorption ability (30, 31). These fertilisers' high surface area-to-volume ratio and regulated nutrient release are made possible by their nanoscale dimensions, which enable effective absorption of vital elements like N, P, K and Zn. Increased nutrient uptake contributes to overall plant growth and development by promoting strong leaf expansion, extending the duration of leaf area and optimising photosynthetic capacity (32, 33).

Improvements in CGR, RGR and NAR unequivocally show how well nano-fertilisers work to speed up biomass accumulation. In line with previous research findings, the treatment that combined 100 % NPK with nano-nutrients (T₈) showed the strongest growth indices. Improved absorption, biomass production and growth efficiency were probably encouraged by the improved nutrient availability brought about by the use of nanofertiliser, especially between 60 and 90 days after planting, which is a crucial time for wheat nutrient requirements (34–37).

Grain and straw yields significantly increased with nano-fertiliser treatments, particularly when combined with the 100 % prescribed NPK. These results corroborate earlier research showing that nano-fertilisers increase output by improving nutrient availability, absorption efficiency and assimilation (38, 39). Furthermore, the gains in protein yield (584.2 kg ha⁻¹) and grain protein content (10.9 %) under T₈ demonstrate the dual effect of nano-fertilisers in improving both yield quantity and nutritional quality, which is crucial for food security (40, 41).

The soil study revealed that the application of nano-fertilisers significantly affected microbial populations and nutrient availability, corroborating previous studies that reported enhanced soil health, nitrogen cycling and microbial activity (42). The application of nano-fertilisers, either alone or in conjunction with NPK, increased microbial diversity and biological activity in the soil, even though increases in organic carbon content and microbial abundance were not statistically significant in all treatments. Long-term agricultural productivity and soil fertility depends on the maintenance of a robust microbial ecosystem (34). In addition to enhancing soil biology, nano-fertilisers lessen pollution and nutrient leaching, two issues that are frequently associated with conventional fertilisers (43). Their improved nutrient-use efficiency, lower off-field losses and lower fertiliser requirements not only cut input costs but also support eco-friendly, sustainable agricultural practices (44–46). Overall, these findings underscore that nano-fertilisers, when applied alone or alongside conventional NPK, represent a promising strategy to enhance wheat productivity, grain quality and soil health while simultaneously supporting environmental sustainability.

Conclusion

It has been demonstrated that combining nano-fertilisers with conventional nitrogen, phosphorous and potassium (NPK) fertilisers improves wheat growth, yield, grain quality and general soil health. Crop performance and nutrient-use efficiency were most improved by foliar application of 100 % NPK in combination with nano N and Bio-nano P, K and Zn during the tillering and jointing stages. In addition to lessening the negative consequences of overusing chemical fertilisers, this integrated strategy promotes sustainable nutrient management. Future studies should examine the long-term effects of applying nano-fertiliser in a variety of climates, with an emphasis on crop productivity, soil health and environmental sustainability.

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Authors' contributions

BS was primarily responsible for conducting the experiments and meticulously recording the data. NSR provided overall supervision of the experimental plots and performed critical analysis of the experimental outcomes. RK assisted in recording the experimental data and contributed to the design of the experiments, ensuring methodological rigour. NK and MZS played a key role in conceptualising the study and conducting comprehensive data analysis, offering valuable insights into the interpretation of the results. AT and VK were responsible for preparing the initial manuscript draft and refining it according to the journal's formatting and publication standards, ensuring clarity, coherence and adherence to scientific reporting guidelines. All authors have 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

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