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RESEARCH ARTICLE

Evaluating the impact of nano-zinc and nitrogen fertilizers on growth, yield, nutritional quality and economics of wheat (*Triticum aestivum* L.) cultivation in Western Uttar Pradesh

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Abstract

Wheat (*Triticum aestivum L.*) is one of the world's most staple crops, but its productivity is increasingly constrained by widespread deficiencies in soil nutrients, particularly zinc (Zn) and nitrogen (N). This study evaluates the effectiveness of nano-fertilizers (NFs) in addressing these deficiencies under field conditions in Western Uttar Pradesh (WUP), India. Approximately, 50 % of cultivatedsoil in India, particularly in the Indo-Gangetic Plain, including WUP, suffers from Zn and N deficiencies. The experiment tested the foliar application of Nano-Urea (N-U) and Nano-zinc (N-Zn) and their interactions with various recommended doses of fertilizers (RDF) combinations. The combination of two sprays of N-U and N-Zn with 100 % RDF (T12) resulted in the highest plant height (105.93 cm), number of tillers (317.8 m^{-2}), CGR (22.315 g m^{-2} day^{-1}) and grain yield (5.59 t ha^{-1}) among all treatments. Moreover, this treatment increased Zn concentrations in grains (34.89 mg kg^{-1}) and straw (9.17 mg kg^{-1}), ensuring higher nutritional quality compared other treatments. Economic analysis showed that T12 provided the highest net returns of ₹104579 ha^{-1} and B:C ratio 3.29, making it the most economically viable option. However, the 100 % RDF (T2) treatment also showed promise as a sustainable alternative, requiring less N input while maintaining productive yields and economic viability. Adopting the superior treatment in Zn- and N-deficient zones could increase yields up to 15 %. The finding demonstrates the synergy between N-U and N-Zn in enhancing nutrient use efficiency, crop productivity and profitability, promoting a sustainable approach for wheat cultivation for nutrient-deficient soils of the Indo-Gangetic Plain.

Keywords: crop productivity; Indo-gangetic plain; nano-fertilizers; nitrogen (N) deficiencies; sustainable agriculture; zinc (Zn)

Introduction

Wheat (*Triticum aestivum* L.) is one of the important cereals in the world and a staple crop for billions of people, especially in developing countries like India (1). Wheat is cultivated on 217 million hectares across 122 countries, with a global production of 781.7 million tons in 2021-22. Global wheat consumption is approximately 777 million tonnes annually and this demand is expected to increase in the coming years (2). India ranks as the world's second-largest wheat producer after China, surpassing the USA in production and is recognized as a major wheat-producing country (3). Approximately 31.8 (m ha) of land in India come under wheat cultivation, with the production and productivity of 113.3 million tonnes and 3562 kg ha^{-1} grains, respectively, during 2024 (4). In India wheat production is concentrated in six states-Uttar Pradesh, Punjab, Haryana, Madhya Pradesh, Rajasthan and Bihar-where 91 % of the total wheat production of 31.28 million tonnes. Uttar Pradesh holds first place among all states in wheat production with an estimated 28.54 % of the total wheat production in India (5). Nutrient status-wise, as per the level of the deficit, still retaining the aforementioned national average N:P:K ratio of 4:2:1 for nutrient consumption, the whole scenario remains unearthed in the first half of the 20th century (6). The Indian soils are deficient in available S, available Zn and available B-101, 131 and 86 in districts, respectively (Fig. 1 and 2). In Fig. 2 all 6 types of Zn deficiencies denoted in all the states of India. Soil deficiency data indicate that the percentage of deficient areas is highest for sulfur (58.6 %), zinc (51.2 %) and boron (44.7 %), compared to iron (19.2 %), copper (11.4 %) and manganese (17.4 %) (7).

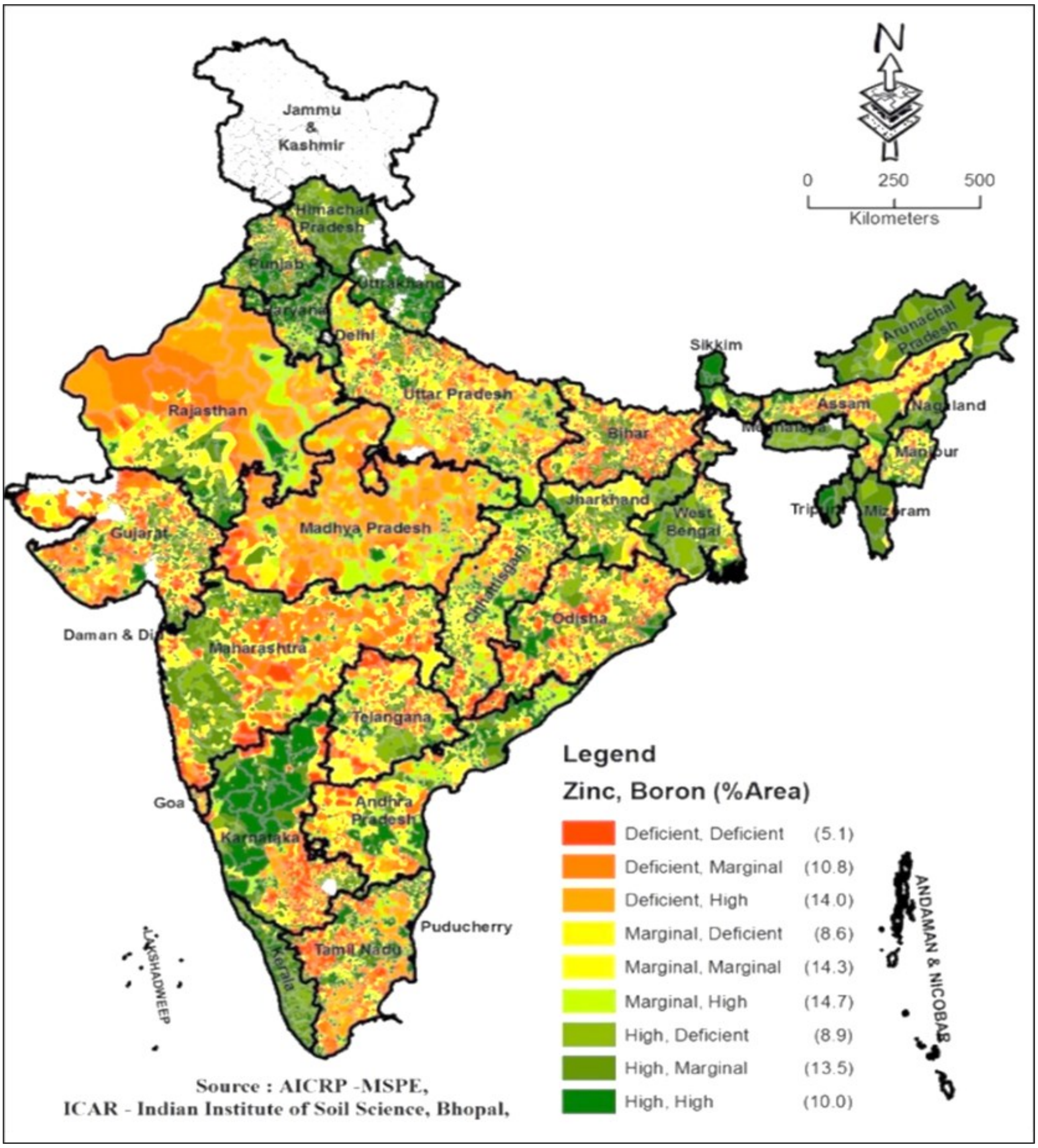


Fig. 1. Deficiency of Zn and B in the various states of the India: Source: AICRP-MSPE, ICAR - Indian Institute of Soil Science, Bhopal - 2021.

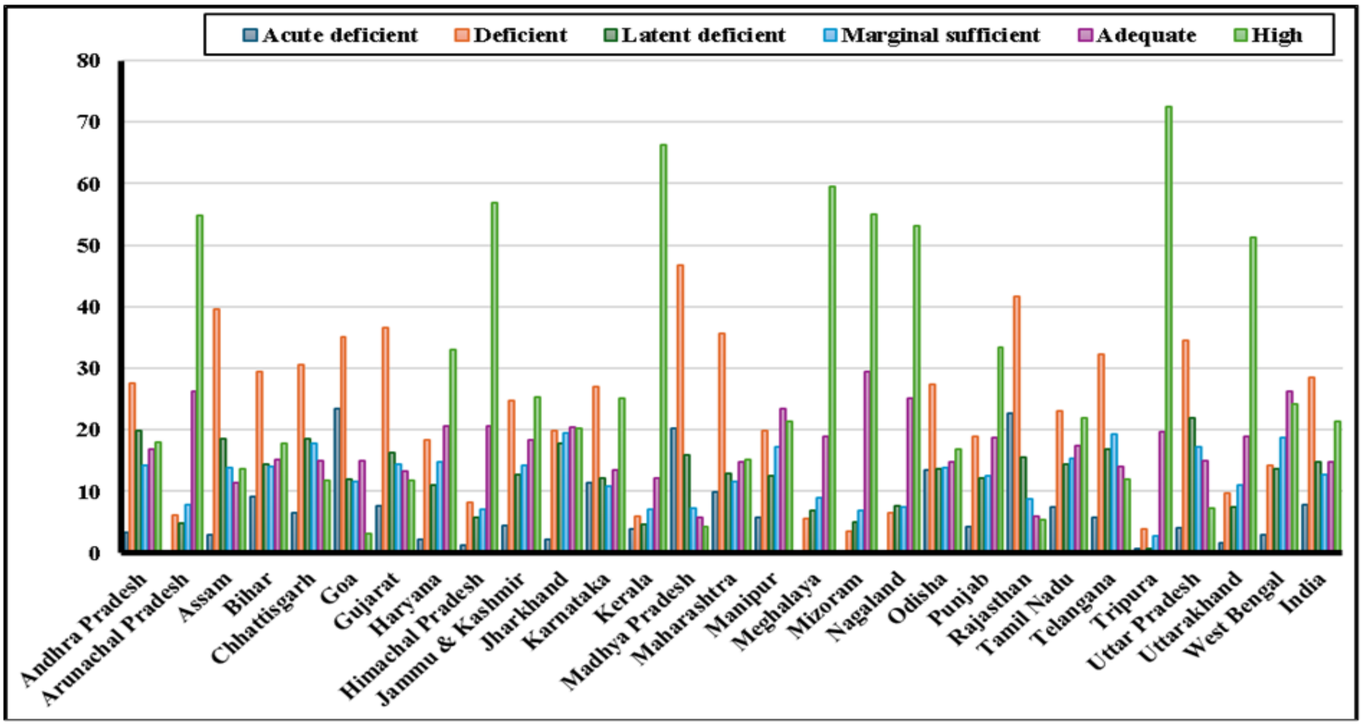


Fig. 2. India state-wise deficiency status of available Zn (% of soil samples).

The wheat crop is facing severe reduction due to soil nutrient deficiencies, particularly Zn and N, which are crucial for optimal growth, high yield and good grain quality (8). From the 50 % of cultivated area in India, the Zn deficiency in soil is a pervasive problem, especially in the Indo-Gangetic plains of Uttar Pradesh (IGPsUP) (9). The micronutrient Zn fulfils multiple physiological and biochemical roles in plant metabolic processes, including enzyme activation, protein synthesis and auxin metabolism (10). Zn deficiency reduces grain nutritional quality, contributing to malnutrition and "hidden hunger" among populations dependent on wheat as a staple food (11). Moreover, soil health deterioration due to continuous cultivation, poor cultivation practices and the imbalance of fertilizers often coexists with Zn deficiency in soils (12). N is the other nutrient constraint limiting wheat production in resource-poor agricultural systems (13). N deficiency severely reduces photosynthetic efficiency, biomass accumulation and ultimately grain yield, as N is one of the most important components of amino acids, proteins and chlorophyll (14).

In India, the overuse of conventional N fertilizers and low N use efficiency (NUE) have raised environmental concerns, including groundwater contamination and greenhouse gas emissions (15). Above all, the unbalanced use of N in farming creates low productivity of crops, making it very pertinent to design innovative fertilizers that improve NUE while ensuring sustainable agriculture (16). Nanotechnology in agriculture offers potential solutions to address these nutrient deficiencies and environmental challenges (17). NFs are fertilizers that are nano-meters in size (1 to 100 nm) and have a greater ratio of surface area-to-volume than traditionally used fertilizers (18). Nano N and Zn fertilizers have higher bioavailability and uptake efficiency in crops, combating Zn deficiency, while lowering the environmental impacts of fertilization (19).

NFs, such as **N-U**, were reported to enhance NUE by allowing controlled and targeted release of nutrients and lowering losses from leaching and volatilization (20). These technologies align with the principles of precision agriculture, which aim to optimize resource use while ensuring sustainable benefits to crops (21). In this context, wheat growing has served as part of the backbone of a whole agricultural economy in WUP. NFs combinations may set a path for the revolution in nutrient management practices for agriculture in the region (22). Applying **N-Zn** and N-based NFs could improve nutrient availability, enhance crop growth and increase yield and nutritional quality (23). The introduction of **N-Zn** and **N**-based NFs presents a novel approach to improving nutrient availability, enhancing crop growth conditions and ultimately increasing yield and nutritional value (24). The sustainability of these interventions is crucial for their adoption by smallholder farmers, who constitute the largest segment of India's agricultural workforce (25). Despite growing interest in NFs, comprehensive studies on their interactions with wheat growth, yield, nutritional quality and economic viability-both globally and in WUP-are lacking (26). NFs have gained significant adoption in modern agriculture due to its potential to enhance nutrient use efficiency, minimize losses and improve crop productivity (27). Their precise delivery mechanisms allow for better absorption by plants, reducing excessive nutrient application and associated environmental pollution (28). However, despite these advantages, concerns regarding their long-term implications remain underexplored. Studies indicate that NFs may alter soil microbial communities, potentially disrupting natural biogeochemical cycles (29). Additionally, the accumulation of nanoparticles in soil ecosystems could affect soil physicochemical properties, influencing overall fertility and sustainability (30).

Comparative research from various agroecological regions has shown mixed results regarding the efficiency and risks of NFs. World wise studies have raised concerns about their long-term bioaccumulation and potential toxicity in agricultural soils (31, 32). Cost and availability also pose significant challenges, as NFs production remains expensive, limiting accessibility for small-scale farmers in developing nations (33). Addressing these gaps is crucial to ensuring that NFs adoption is sustainable and globally applicable.

This research gap underscores the need for systematic investigations to assess the potential and limitations of NFs in real-world agricultural settings. By integrating global perspectives and experimental data, this research aims to provide a comprehensive understanding of the agronomic, environmental and economic dimensions of NFs application in the Upper Gangetic Plains of Western U.P. The present study, in this aspect, investigates the effect of **N-Zn** and **N-U** on growth, yield, nutritional quality and economics of wheat cultivation in Western U.P.

Material and Methods

Experimental site

The field experiment was conducted during the *Rabi* season (November to April) of 2021-22 at Amar Singh College Lakhaoti, Bulandshahar, U.P. site located at 28°31'39.7"N latitude and 77°58'37.3"E longitude, with an altitude of 206.2 meters above mean sea level, in the Upper Gangetic Plains of WUP, India. The region has a semi-arid climate best characterized by an average annual rainfall of 750-850 mm that is mainly conferred by the monsoon season. The experimental site comprised alluvial soil that is commonly found in IGPsUP; texture from coarse-to-fine sandy loam, with average pH 7.4 and organic carbon content of 0.48 %. The available nitrogen (N), phosphorus (P) and potassium (K) values of the soil were 220, 18 and 160 kg ha^{-1}, respectively. Other nutrients in the soil, such as Zn assessment, concluded with a deficiency diagnosis which showed the soil contained 0.60 mg kg^{-1} Zn, using the diethylenetriaminepentaacetic acid (DTPA) extraction method (34).

Treatment details and data collection

Experiment is laid out in Randomised Complete Block Design (RCBD) with three replication and twelve treatments were evaluated, combining varying levels of recommended doses of fertilizers (RDF) (120:60:40, NPK kg^{-1}) with foliar applications of nano urea and nano zinc such as T_1: Control, T_2: 100 % RDF, T_3: 50 % RDN, T_4: Control + 2 Spray of **N-U**, T_5: Control + 2 Spray of **N-Zn**, T_6: Control + 2 Spray of **N-U** + **N-Zn**,

T_7: 50 % RDN + 2 Spray of **N-U**, T_8: 50 % RDN + 2 Spray of **N-Zn**, T_9: 50 % RDN + 2 Spray of **N-U** + **N-Zn**, T_{10}: 100 % RDF + 2 Spray of **N-U**, T_{11}: 100 % RDF + 2 Spray of **N-Zn** and T_{12}: 100 % RDF + 2 Spray of **N-U** + **N-Zn**.

The wheat variety HD-2967 was developed from ICAR (New Delhi) it was double gene dwarf mega variety that was released in 2011 for general cultivation in the North Western Plain Zone under timely sown irrigated conditions (35). The variety HD-2967 became popular, also occupied over 10 million hectares because of its broad adaptability and high yielding ability, it was also recommended for cultivation in the North Eastern Plain Zone (36). There for wheat variety HD-2967 was sown at a seed rate of 100 kg ha^{-1} and a row spacing of 20 cm. The recommended dose of fertilizers (RDF) composed of N, phosphorus and potassium for wheat included 120:60:40 kg ha^{-1}; supplied by using diammonium phosphate (DAP), muriate of potash (MOP) and urea were treated. **N-U** was commercially available as IFFCO **N-U** and contained 4 % N. A solution of 0.4 % **N-U** was made by the dissolve with water and applied in a foliar way at 20 and 40 days after sowing (DAS). But the ZnO NPs prepared by sol-gel method using "$Zn(CH_3COO)_2.2H_2O$" (Zinc acetate dehydrate) as a precursor and "CH_2COOH" ethanol was used as solvent and "NaOH" (Sodium hydroxide) to manipulate *p*H of solution then distilled water were used as hydrolytic medium (37). size range of ZnO was confirmed to be 20-40 nm using Transmission Electron Microscopy (TEM) (38). Which was the synthesize by the sol-gel method from the ZnO (Fig. 3a, b). **N-Zn** was diluted to 0.4 % using distilled water and 0.2 % (v/v) Tween-20 was used as surfactant and foliar sprayed at 20 and 40 DAS. Various types of data were collected from the experimental field, including plant height and number of tillers m^{-2}, measured at CRI, booting and maturity. CGR and RGR are determined at 30-60 DAS, 60-90 DAS, 90 to just before harvest. While N and Zn content were observed at CRI, booting and harvest stages in grains and straw, respectively. Grain and straw yield were recorded along with the Grain and Straw Ratio (G:S), based on which net profit, gross return, net return and B:C ratio was calculated for our experiment.

Crop management

The crop was irrigated using the check basin method, with a total of five irrigations applied at critical growth stages: crown root initiation (CRI), tillering, flowering, grain filling and drought stages. Weed control was done through the application of a post-emergence broad-spectrum herbicide mixture of 2,4-D + Clodinafop at 700 + 60 gm active ingredient (ai) ha^{-1} respectively, at 30 DAS (39). Pest and disease management were carried out following integrated pest management (IPM) practices recommended for wheat cultivation in the region.

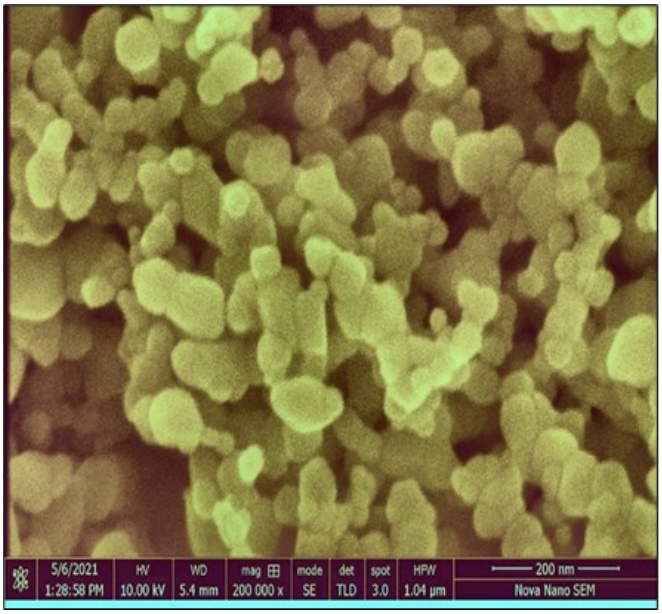
Statistical analysis

The data were subjected to prepared by variance (ANOVA) (40). The significance of comparison was tested, the standard error of mean will be calculated and critical difference (C.D. at 5 %) will be worked out in comparing the treatment means, wherever "f" test will be found. But the Proper analysing through Python panda's library in the Jupiter notebook environment using Visual Studio Software developed by Microsoft Version 1.86 (2024).

Results

Growth and development studies (plant height)

Plant height of wheat varied with a significance of ($p \leq 0.05$) across treatments at all stages of growth, namely, CRI, booting and maturity, also the simple correlation of treatments to the plant height in various stages is shown in (Table 1). Results indicate that the application of NFs either separately or in combination with RDF showed a significant (at $p \leq 0.05$) effect on wheat plant growth and development. Application of 100 % RDF + 2 Spray of **N-U** and **N-Zn**. exhibited the tallest plants, at all the stages of crop growth which were significantly better (at $p \leq 0.05$) than the control and 50 % RDN. It could be seen that the combination of **N-U** and **N-Zn** resulted in tall plants compared to their single applications which suggest the utility of these NFs interacting synergistically. The plant height at various stage



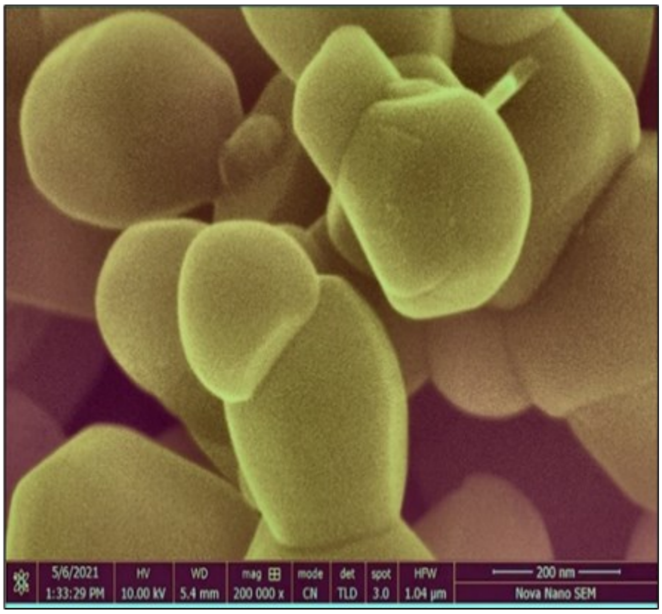


Fig. 3. (a) and (b) Picture of prepare **N-Zn** particles visualized by the TMS after synthesis of **N-Zn**.

Table 1. Effect of **N-Zn** and **N-U** treatments on plant growth parameters (plant height (cm) and no. of tillers m^{-2}).

	Height (cm) at			No. of tillers m^{-2} at		
	CRI	Booting	Maturity	CRI	Booting	Maturity
Treatments	Plant growth parameters					
T_1-Control	11.3	55.2	74.8	93.2	232.2	228.1
T_2-100 RDF	14.7	71.8	91.06	104	288.8	273.2
T_3-50 % RDN	11.9	58.1	73.72	98.3	233.8	221.2
T_4-Control + 2 Spray of **N-U**	12.8	62.5	79.29	97.8	251.5	237.9
T_5-Control + 2 Spray of **N-Zn**	12.7	62.0	78.67	95.7	249.5	236.0
T_6-Control + 2 Spray of **N-U** + **N-Zn**	13.1	64.0	81.15	99.41	257.4	243.5
T_7-50 % RDN + 2 Spray of **N-U**	12.9	63.0	79.91	100.2	253.4	239.7
T_8-50 % RDN + 2 Spray of **N-Zn**	12.1	59.1	74.96	102.5	237.7	224.9
T_9-50 % RDN + 2 Spray of **N-U** + **N-Zn**	13.4	65.5	83.01	105.7	263.3	249.0
T_{10}-100 % RDF + 2 Spray of **N-U**	16.2	79.1	100.35	109.9	318.3	301.1
T_{11}-100 % RDF + 2 Spray of **N-Zn**	16.0	78.2	99.12	110.7	314.3	297.3
T_{12}-100 % RDF + 2 Spray of **N-U** and **N-Zn**	17.1	83.5	105.93	112.1	335.9	317.8
SE m ±	2.51	2.5	3.12	3.69	9.9	9.37
CD ($p \leq 0.05$)	**NS**	7.2	9.16	10.81	29.0	27.49

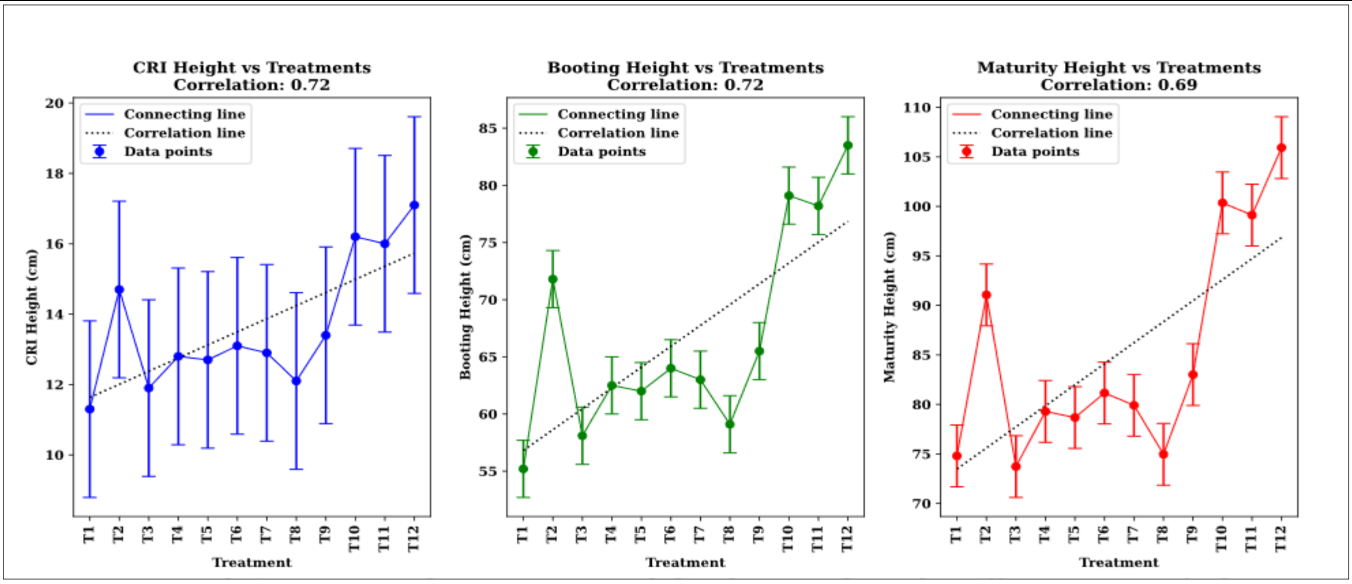


Fig. 4. Correlation between the treatments and the plant height at the different stages of wheat. It denotes the treatments on an average moderate to higher correlated from their corresponding plant height.

shows the moderate to strong correlation between the treatments and plant heights (Fig. 4).

Number of tillers m^{-2}

The number of tillers at CRI ranged from 93.2 to 112.1 m^{-2}. (T_{12}: 100 % RDF + 2 Spray of **N-U** and **N-Zn**) produced the highest number of tillers and it was statistically superior to all other treatments (Table 1, Fig. 5). It was followed by T_{11} (110.7) and T_{10} (109.9 m^{-2}), showing the positive influence of the combination of RDF with NFs. The least number of tillers were recorded with the T_1 control treatment and T_3 (50 % RDN), confirming that nutrient addition is critical for the development of tillers at an early stage. At booting, the tiller number ranged from 232.2 m^{-2} (T_1: Control) to 335.9 m^{-2} (T_{12}: 100 % RDF + 2 Spray of **N-U** and **N-Zn**). Again, T_{12} gave the highest tillers, followed by T_{10} (318.3 m^{-2}) and T_{11} (314.3 m^{-2}),

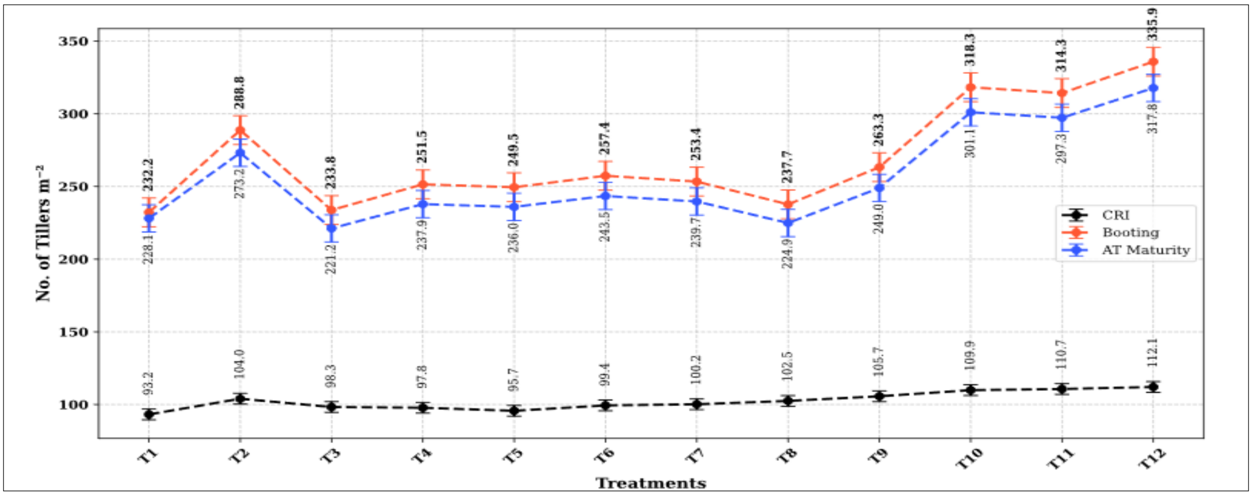


Fig. 5. Number of tillers (m^{-2}) at different growth stages and treatments. It denotes the effect of treatments on the number of tillers m^{-2} at the various stages.

while these treatments were significantly superior (at $p \leq 0.05$) to control and treatments 50 % RDN. Combined application of **N-U** and **N-Zn** consistently produced a higher number of tillers than applied individually. Therefore, a synergistic effect between these NFs improves tillering. At maturity, tiller numbers varied from 221.2 m^{-2} (T_3: 50 % RDN) to 317.8 m^{-2} (T_{12}: 100 % RDF + 2 Spray of **N-U** and **N-Zn**). T_{12} had the maximum number of tillers which was significantly higher (at $p \leq 0.05$) than that of all other treatments. This was followed by T_{10} (301.1 m^{-2}) and T_{11} (297.3 m^{-2}). control (T_1) and treatments with ammonium nitrate (T_3, T_8) showed the least number of tillers, indicating that N and Zn play important roles in tillering initiation and maintenance.

Crop growth rates (CGRs) during different growth stages

The variability of Statistically significant are tasted at ($p \leq 0.05$) were observed among the treatments tested on CGR during all growth stages of wheat: 30-60 Days After Sowing (DAS), 60-90 DAS and 90 DAS to harvest (Table 2, Fig. 6). The CGR at 30-60 DAS varied from 5.22 g m^{-2} day^{-1}(T_1: Control) to 9.67 g m^{-2} day^{-1} (T_{12}: 100 % RDF + 2 sprays of **N-U** and **N-Zn**). The treatment T_{12} produced the highest CGR, significantly superior (at $p \leq 0.05$) to all remaining treatments; it was followed by T_{11} (9.45 g m^{-2} day^{-1}) and T_{10} (8.72 g m^{-2} day^{-1}), suggesting the positive correlation of RDF + NFs pairs. T_{12} showed the greatest CGR, which was followed by T_6 (21.845 g m^{-2} day^{-1}) and T_9 (21.72 g m^{-2} day^{-1}). Comparison of control and 50 % RDN treatments showed a significant (at $p \leq 0.05$) difference with these treatments. During the period from 90 DAS to harvest, the CGR ranges from 2.75 g m^{-2} day^{-1} (T_1: Control) to 5.755 g m^{-2} day^{-1} (T_{12}: 100 % RDF + 2 Spray of **N-U** and **N-Zn**), with T_{12} recording the maximum CGR that was significantly higher (at $p \leq 0.05$) among all other treatments. It was, however, followed by T_{11} (5.7 g m^{-2} day^{-1}) and T_{10} (5.6 g m^{-2} day^{-1}). The control and treatments with low N application produced low CGR and this indicates the importance of N and Zn in maintaining growth in later stages.

Relative growth rate (RGR) at different growth stages

Relative growth rate of wheat expressed in grams per gram per day (mg g^{-1} day^{-1}) showed marked variation through the treatments and growth stages. Further data in (Table 2, Fig. 7) show that values were significantly higher (at $p \leq 0.05$) during the period of active growth (60-90 DAS) as compared to the early vegetative state (30-60 DAS) and maturity state (90 DAS to harvest). It ranged from 52.0 mg g^{-1} day^{-1} (T_1: Control) during early vegetative to 70.0 mg g^{-1} day^{-1} at T_{12}: 100 % RDF + 2 Spray of **N-U** and **N-Zn**, where T_{12} consistently outperformed then other treatments because of the combined application of **N-U** and **N-Zn**. The application of **N-U** and **N-Zn** combined (T_6, T_9 and T_{12}) generally recorded the highest RGR in all stages, that is confirming their synergistic action in better nutrient uptake and utilization efficiency. In contrast, control (T_1) and treatments with low N (T_3, T_8) recorded the lowest RGR, which highlighted the roles of N and Zn which promote growth efficiency. The results of study show that application of NFs with RDF significantly improves (at $p \leq 0.05$) the growth dynamics,

Table 2. Effect of treatments on plant growth parameters - [CGR (g $m^{-2}day^{-2}$) and RGR (mg $g^{-1}day^{-1}$)]

	CGR (g m^{-2} day^{-1})			RGR (mg $g^{-1}day^{-1}$)		
	30-60 DAS	60-90 DAS	90 to Harvest	30-60 DAS	60-90 DAS	90 to Harvest
Treatments	Plant Growth Parameters					
T_1-Control	5.22	11.07	2.75	52.0	31.0	4.0
T_2-100 RDF	5.5	12.445	3.455	56.0	35.0	5.0
T_3-50 % RDN	5.4	11.985	3.375	54.0	33.0	4.0
T_4-Control + 2 Spray of **N-U**	6.15	13.17	3.495	58.0	35.0	5.0
T_5-Control + 2 Spray of **N-Zn**	5.7	13.81	3.55	57.0	33.0	5.0
T_6-Control + 2 Spray of **N-U** + **N-Zn**	7.26	21.845	4.95	59.0	39.0	6.0
T_7-50 % RDN + 2 Spray of **N-U**	7.575	21.15	5.23	62.0	34.0	5.0
T_8-50 % RDN + 2 Spray of **N-Zn**	7.86	20.53	5.36	60.0	32.0	4.0
T_9-50 % RDN + 2 Spray of **N-U** + **N-Zn**	8.10	21.72	5.485	64.0	38.0	5.0
T_{10}-100 % RDF + 2 Spray of **N-U**	8.72	20.54	5.6	65.0	37.0	4.0
T_{11}-100 % RDF + 2 Spray of **N-Zn**	9.45	21.15	5.7	67.0	40.0	5.0
T_{12}-100 % RDF + 2 Spray of **N-U** and **N-Zn**	9.67	22.315	5.755	70.0	42.0	6.0
SE m ±	0.27	.51	0.16	1.49	8.19	2.17
CD ($p \leq 0.05$)	0.80	1.41	0.31	4.43	25.02	**NS**

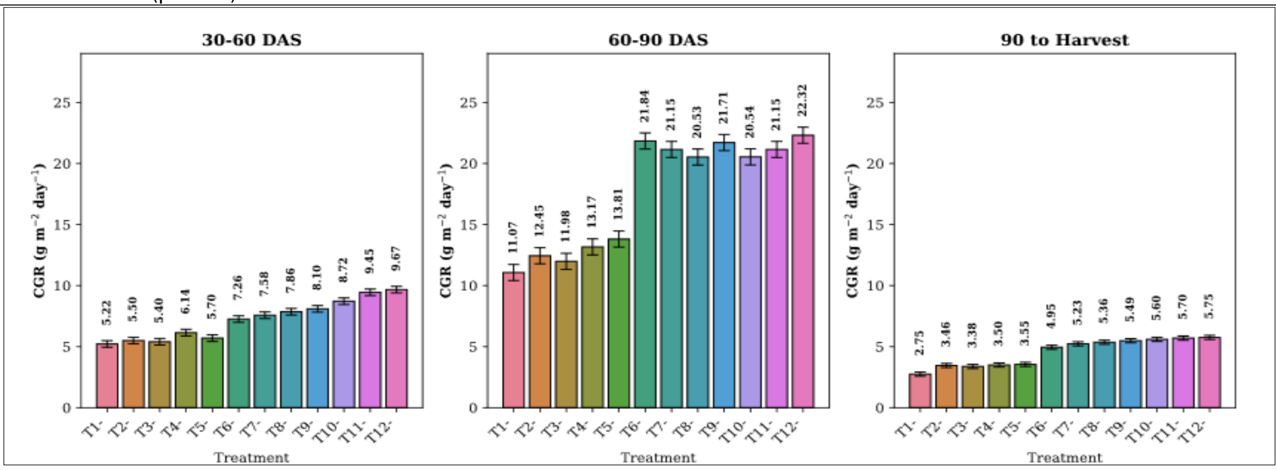


Fig. 6. CGR (g m^{-2} day^{-1}) of wheat under various treatments and growth stages. It shows the CGR is exponentially increased in the moderate (60 -90 days) stage.

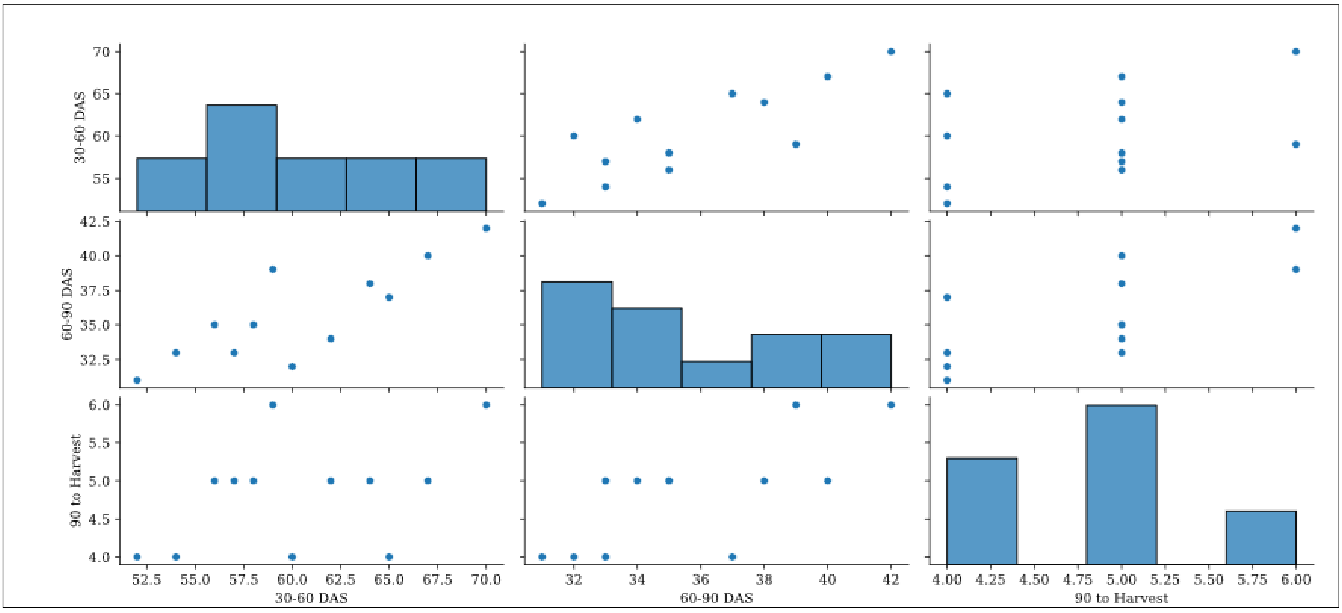


Fig. 7. Scattering of treatments in RGR (mg g^{-2} day^{-1}) at different growth stages. It shows the greater number of the treatment groups lies in which of the RGR category range (between the lower to higher) for a particular growth stage.

especially during the active growth stage, which is important for optimizing wheat productivity.

Zn content

The varying Zn levels in the wheat (in mg kg^{-1}) was significant ($p \leq 0.05$) across treatments and plant growth stages, peaking during harvest as compared to CRI and booting stages (Table 3, Fig. 8). Zn content during CRI ranged from 33.21 mg kg^{-1} (T_4: Control + 2 Spray of **N-U**) into 39.87 mg kg^{-1} (T_{12}: 100 % RDF + 2 Spray of **N-U** and **N-Zn**), where T_{12} surpassed all others through combined application of **N-U** and **N-Zn**. This trend continued into booting, both of which fell in a range from 27.89 mg kg^{-1} (T_4) to 35.46 mg kg^{-1} (T_{12}), showing that Zn availability is critical during this active stage of growth. At harvest, Zn levels in grains ranged from 29.27 mg kg^{-1} (T_4) to 34.89 mg kg^{-1} (T_{12}: 50 % RDN + 2 Spray of **N-U** + **N-Zn**) while straw had Zn content between 6.43 mg kg^{-1} (T_1: Control) and 9.17 mg kg^{-1} (T_{12}). Using NFs, especially T_{12}, T_9 and T_8, resulted in significantly enhanced performance (at $p \leq 0.05$) for Zn content over control and treatments with decreased N (T_3, T_4). During all growth stages, Zn content was maximum when **N-U** and **N-Zn** were combined (T_6, T_9 and T_{12}), thus revealing a cooperative interaction between these bio-stimulants in enhancing Zn uptake and translocation. In contrast, control (T_1) and treatments without **N-Zn** (T_4, T_{10}) recorded the lowest Zn content, illustrating Zn 's necessity in achieving growth and nutritional quality. These results clearly imply that there is potential for effective elevation of wheat Zn by inducing NFs together with an RDF which considerably enhances the nutritional value of the crop.

The grain yields, straw yields and grain-straw ratios (G:S)

Indicated significant differences ($p \leq 0.05$) for the different treatments concerning wheat (Table 4, Fig. 9). The highest grain yield (5.59 t ha^{-1}) obtained under T_{12} (100 % RDF + 2

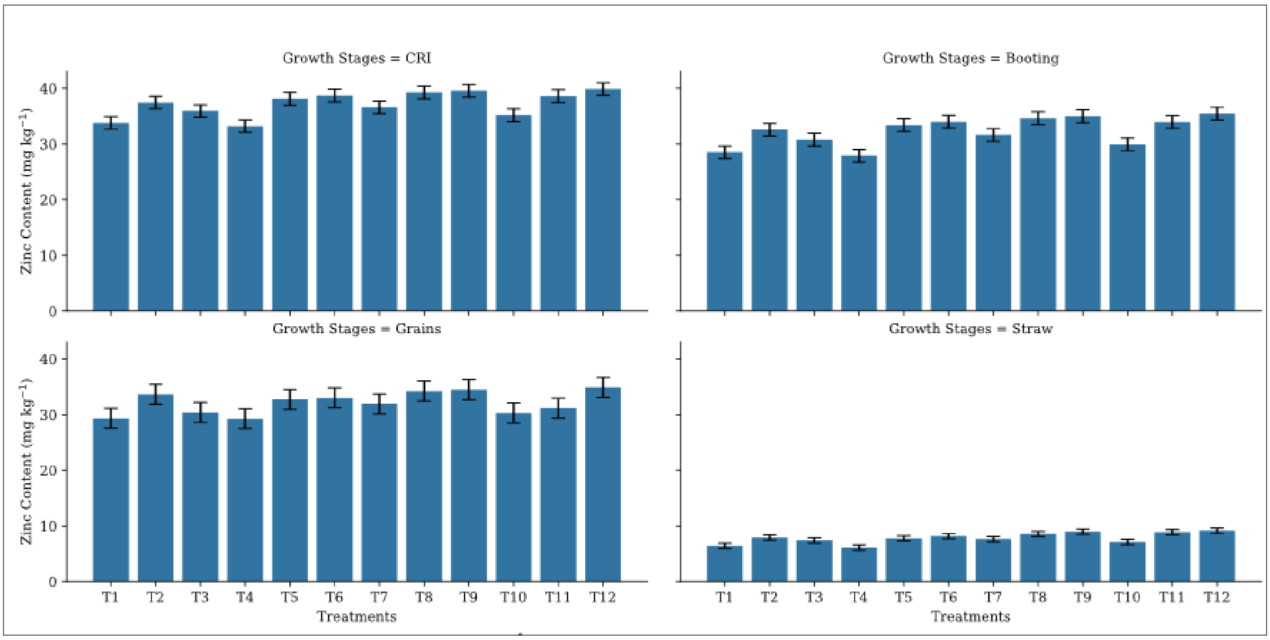


Fig. 8. Zinc content (mg kg^{-1}) influenced growth stages and by treatments. Effect of the treatments on the Zn contains in the wheat at the various crop growth stages. At the initial stage the Zn contain is become high due to low vegetative mass.

Table 3. Effect of treatments on zinc contains in wheat under various treatments mg kg^{-1}

Treatments			At harvest	
	CRI	Booting	Grains	Straw
T1-Control	33.79	28.51	29.33	6.43
T2-100 RDF	37.45	32.57	31.63	7.51
T3-50 % RDN	35.93	30.78	30.38	7.39
T4-Control + 2 Spray of **N-U**	33.21	27.89	29.27	6.11
T5-Control + 2 Spray of **N-Zn**	38.13	33.41	32.71	7.75
T6-Control + 2 Spray of **N-U** + **N-Zn**	38.71	34.0	33.01	8.16
T7-50 % RDN + 2 Spray of **N-U**	36.58	31.63	31.93	7.63
T8-50 % RDN + 2 Spray of **N-Zn**	38.75	34.63	34.21	8.55
T9-50 % RDN + 2 Spray of **N-U** + **N-Zn**	39.55	34.99	34.47	8.98
T10-100 % RDF + 2 Spray of **N-U**	35.17	29.93	30.29	7.11
T11-100 % RDF + 2 Spray of **N-Zn**	38.91	33.97	32.17	8.89
T12-100 % RDF + 2 Spray of **N-U** and **N-Zn**	39.87	35.46	34.89	9.17
SE m ±	0.97	0.88	1.11	0.48
CD (p ≤ 0.05)	2.95	2.67	3.42	1.41

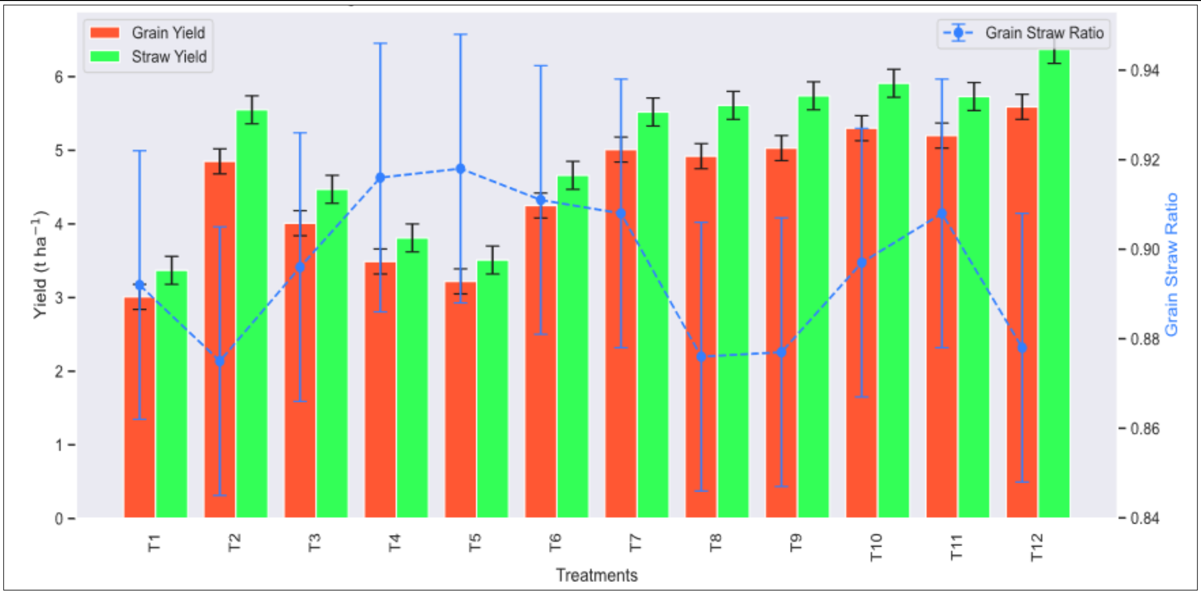


Fig. 9. Grain yield, straw yield and grain straw ratio across treatments. Yield in t ha^{-1} in the left Y axis and the grain straw ration on the right secondary axis.

spray of **N-U** and **N-Zn**), with T_{10} yielding 5.3 t ha^{-1} and T_9 at 5.03 t ha^{-1}. in the same way highest straw yield (5.73 t ha^{-1}) was also recorded in T_{12}, while T_{10} and T_9 had 5.91 and 5.74 t ha^{-1} straw yields, respectively. The ratio of grain to straw remained generally Constant meaning minute change or unchanged for all treatments, staying between 0.875 (T_2: 100 RDF) and 0.918 (T_5: control + 2 sprays of **N-Zn**). Despite considerable variation in grain and straw yields, there was no marked variation in the grains-to-straw ratio across treatments. Combined applications of **N-U** and **N-Zn** (T_6, T_9 and T_{12}) yielded better grain and straw yields than treatments of the single application of nutrient. Such a response indicates that these nutrients could work synergistically to boost productivity. Hence, the control (T_1) yielded the least, with 3.01 t ha^{-1} grain and 3.37 t ha^{-1} straw, pointing to the necessity for adequate nutrient supply to obtain optimum yield. Treatments of low N also showed lower yields than those containing complete N supplementation, drawing attention to the need for N in wheat productivity. The findings here warrant the use of NFs, together with RDF to result in the elevation of grain and straw yields, providing an inspirational framework for enhancing wheat productivity under the Agro-climatic conditions of WUP.

Economic returns and profitability

The highest gross returns (₹150871 ha^{-1}) and net returns (₹104579 ha^{-1}) were obtained under T_{12} (100 % RDF + 2 Spray of **N-U** and **N-Zn**), which was significantly superior (at $p \leq 0.05$) to all other treatments (Table 4, Fig. 10). However, T_{10} (100 % RDF + 2 Spray of **N-U**) and T_{11} (100 % RDF + 2 Spray of **N-Zn**) recorded comparable gross and net returns, suggesting that additional foliar application of NFs further enhanced yield and profitability. Among the treatments receiving 50 % RDN, the highest gross returns (₹143212 ha^{-1}) and net returns (₹98139 ha^{-1}) were observed in T_9 (50 % RDN + 2 Spray of **N-U** + **N-Zn**), which were statistically *at par* with T_7 (50 % RDN + 2 Spray of **N-U**) and T_8 (50 % RDN + 2 Spray of **N-Zn**). This suggests that a foliar application of NFs can compensate somewhat for the reduced application of N and keep it economically sound. In contrast, gross returns (₹81776 ha^{-1}) and net returns (₹40567 ha^{-1}) were recorded lowest under T_1 (Control) due to the lesser nutrient availability, which would limit wheat productivity.

Benefit-cost ratio

T_2 (100 % RDF) gave the best value for B:C ratio (3.29), which meant that fertilizer application alone gave decent profitability (Table 4, Fig. 10). T_{10} (3.25), T_{11} (3.23) and T_{12} (3.26) remained statistically comparable to T_2; hence the

Table 4. Effect of various treatments on the Grain yield, Straw yield and the economics of the wheat

TREATMENTS	Grain Yield (t ha^{-1})	Straw Yield (t ha^{-1})	Gran Straw Ratio	Cost of cultivation	Gross returns	Net returns	B:C ratio
	Yield Parameters			Economic Parameters			
T1-Control	3.01	3.37	0.892	41209	81776	40567	1.98
T2-100 RDF	4.95	5.55	0.875	43649	143525	99876	3.26
T3-50 % RDN	4.01	4.47	0.896	42429	108214	65785	2.55
T4-Control + 2 Spray of **N-U**	3.49	3.81	0.916	42817	110804	67987	2.59
T5-Control + 2 Spray of **N-Zn**	3.22	3.51	0.918	43257	109669	66412	2.54
T6-Control + 2 Spray of **N-U** + **N-Zn**	4.25	4.66	0.911	43853	117420	73567	2.68
T7-50 % RDN + 2 Spray of **N-U**	5.01	5.52	0.908	44037	141469	97432	3.21
T8-50 % RDN + 2 Spray of **N-Zn**	4.82	5.61	0.876	44477	141514	97037	3.18
T9-50 % RDN + 2 Spray of **N-U** + **N-Zn**	5.03	5.74	0.877	45073	143212	98139	3.20
T10-100 % RDF + 2 Spray of **N-U**	5.3	5.91	0.897	45253	146957	101704	3.25
T11-100% RDF + 2 Spray of **N-Zn**	5.2	5.73	0.908	45693	147671	101978	3.23
T12-100% RDF + 2 Spray of **N-U** and **N-Zn**	5.59	6.37	0.878	46292	150871	104579	3.29
SE m ±	0.17	0.19	0.03	-	-	-	-
CD ($p \leq 0.05$)	0.39	0.55	**NS**	-	-	-	-

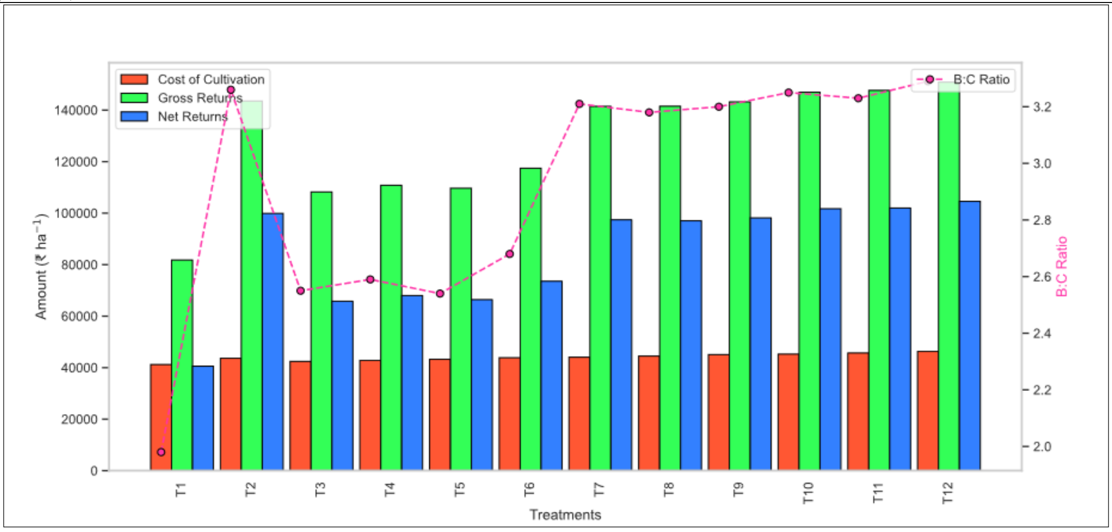


Fig. 10. Economic analysis of wheat across all treatments. Interactions of treatments to the economics of wheat (amount ₹ ha^{-1} in the Y primary axis) and (benefit cost ratio B:C on the secondary axis).

integration of NFs did not produce a significant difference (at $p \leq 0.05$) with regard to cost-effectiveness. Those included yield improvement. T_7 (3.21), T_8 (3.18) and T_9 (3.20) had moderately high B:C ratios among the reduced N treatments that are comparable to the combination of full RDF treatments; this solidifies the case that the supplementing of the foliar NFs maintains economic efficiency with reduced N applications. In contrast, treatments based solely on foliar application of NFs to pure control (T_4, T_5 and T_6) exhibited moderate B:C ratios (2.54-2.68), depicted better performance than the control but less than 50 % RDN and 100 % RDF value-based treatments.

Comparative result of analysis and implications

The findings reveal that the inclusion of **N-U** and **N-Zn** sprays could be valuable to economic returns when applied with 50 % RDN or 100 % RDF, thereby ensuring sustainable, cost-effective production of wheat. Hence, T_{12} (100 % RDF + **N-U** + **N-Zn** Spray) is recommended to maximize profitability, while T_9 (50 % RDN + **N-U** + **N-Zn** Spray) offers an alternative for reducing N application without incurring significant (at $p \leq 0.05$) economic losses. Together, the data confirm that the application of NFs not only increases production but also aids economic returns by improving the efficiency of elemental use.

Discussion

The application of **N-Zn** and **N-U** fertilizers demonstrated a significant (at $p \leq 0.05$) improvement in the growth and yield parameters of wheat (*Triticum aestivum* L.) in WUP that can be describe as follows

Growth and yield response to NFs

The application of **N-Zn** and **N-U** fertilizers shows ~15-18% increase in plant height, dry matter accumulation and leaf area index (LAI) compared to control treatments (Table 1) similar results are found by (41-43). The combined application of **N-U** and **N-Zn** synergistically enhanced NUE and Zn bioavailability, both vital for enzymatic catalysis, chlorophyll synthesis and metabolic processes in wheat (44).

Nutrient uptake and use efficiency

The synergy between **N-U** and **N-Zn** significantly improved (at $p \leq 0.05$) nutrient uptake and use efficiency in wheat cultivation. NFs (NFs) facilitate slow and targeted nutrient release, ensuring a steady supply of N and Zn during critical growth stages such as tillering, flowering and grain filling (45). This controlled release mechanism enhances NUE by reducing losses due to volatilization, leaching and denitrification (46). Application of **N-Zn** increased Zn uptake by 35-40% from 4% of traditional fertilizers, which addresses Zn deficiency in soils and improves the nutritional quality of wheat grains.

Economic and sustainability aspects

The economic analysis showed that the use of NFs is highly profitable for wheat cultivation (47). Although the initial cost of NFs is higher than that of conventional fertilizers, the significant (at $p \leq 0.05$) increase in grain yield and nutritional quality offsets this cost, resulting in higher net returns (48). In addition to economic benefits, NFs contribute to the sustainability of wheat production systems by improving nutrient use efficiency and reducing fertilizer application rates, NFs minimize nutrient losses and environmental pollution (49).

Comparison with previous studies

The findings compared with prior research on NF benefits in farming. Many studies reported a 15-20% increase in wheat yield with nano-N (47, 50), while another observed a 30-35% rise in Zn uptake with **N-Zn** (42). Research highlighted the combined application of **N-Zn** and nano-N, demonstrating their synergistic effects on growth, yield and nutrient uptake. These findings of previous research provide comprehensive understanding, not only economic benefits, but also NF enhance wheat sustainability by improving nutrient use efficiency, reducing application rates and minimizing nutrient losses and environmental pollution (51). Whereas, the potential risks associated with prolonged NFs use, such as soil microbial diversity loss, uncontrolled release create toxicity in plant parts and Zn toxicity, warrant further investigation (52).

Potential limitations and future perspectives

NF offer enhanced nutrient efficiency but face challenges like high costs, environmental risks and regulatory gaps (53). Due to high surface area and penetration can cause unintended bioaccumulation, leading to toxicity in crops and soil microorganisms (54). while Zn oxide nanoparticles reduce soil microbial diversity by 15-20% (55). Only the EU and US have nano-specific regulations, slowing global adoption (56, 57). Future view NF with controlled nutrient release to mitigate ecotoxicity risks, enhance microbiome synergy and boost climate resilience, while integrating eco-design and robust safety protocols for sustainable agroecosystems (58). Prioritize macronutrient innovation, microbial compatibility and stress-tolerant formulations to reduce conventional fertilizer dependency, ensuring ecological safety through multi-omics assessments and biodegradable solutions (59).

Conclusion

The study represents a comprehensive framework of **N-U** and **N-Zn** nutrient integration, that optimizes wheat productivity, profitability and nutrient economics in WUP. This study shows how the combined use of **N-U** + **N-Zn** nutrient management affects the region's wheat dynamics, concluding that:

i) **Nitrogen management and yield maximization:** Incremental N dosing is an economically viable option at a level but requires a calibrated application that can achieve agro-productivity and environmental risk balancing. Farmers can improve wheat yield up to 15% by the adopting of **N-Zn** and **N-U** foliar applications at key growth stages (CRI and pre-booting) and improve Zn biofortification, with **N-Zn** demonstrating superior phytohormonal modulation and growth stimulation compared to **N-U**.

ii) **Soil, ecosystem health and agronomic protocol development:** Long-term assessments of NFs impact soil microbiota, enzymatic activity and nutrient cycling, that is crucial to agroecological sustainability. Research at the region-specific scale is essential to enhance the timing, dosage and rate of NFs applications and to maximize NUE across soils and climatic zones.

iii) **Farmer adoption and environmental policy support:** Highlight field trials in helping farmers to use NFs more efficiently, along with framing useful policies for small farmers and regulations for the use of foliar application. Create monitoring structures to reduce the risks of N leaching and Zn bioaccumulation, without compromising environmental safety.

iv) **Sustainable innovations for the future:** This study highlights the practical application of NFs in Zn/N-deficient soils, demonstrating their potential to enhance crop productivity and farmer profitability. Although to ensure the sustainable integration of NFs into global agriculture, optimization of NFs must address and remove any ecotoxicological and negative environmental effects.

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Authors' contributions

KKS carried out the experiment, data collection, analyses and manuscript writing. VP, D, SP and SS, providing valuable help to input in the experimental design, data analysis and interpretation of results. MK, RS and NM design of the study, supervised the whole research, guidance identifies the research problem. SC, SS, KMR and SKD support in the data analysis in lab, operating instruments and assisted in refining the overall data interpretation. All authors reviewed 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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