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ARTICLE

Ecological Assessment of Nano Micronutrient Composites on Growth Dynamics and Yield Performance of Late-Sown Wheat (Triticum aestivum L.)

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ABSTRACT

Background: The study examines the ecological impact of nano-micronutrient composites on the growth and maturation of late-planted wheat within an agroecological framework. **Methods:** Experiments conducted using a

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Randomized Block Design (RBD) with three replications and eight treatment combinations, ensured uniform plant populations prior to treatment applications. Significant variations were observed across multiple growth parameters, including tiller density per square meter and dry matter accumulation at 30, 60, 90, and 120 days after sowing (DAS). **Results:** Notably, the treatment involving RDF + 20 ppm rGO-Fe + rGO-Zn with two foliar sprays at 45 and 60 DAS (T6) exhibited markedly superior growth performance compared to the control and conventional zinc and iron applications. Maximum grain yield (29.2 q/ha) was achieved in T8 (RDF + 20ppm rGO-Fe + rGO-Zn with two sprays at 45 and 60 DAS) whereas straw yield (50.5 q/ha), biological yield (77.1 q/ha), Harvest Index (38.7 %) and Grain Straw ratio (0.6) were found maximum in RDF + 20ppm rGO-Fe + rGO (Reduced Graphene oxide) − Zn with two sprays at 45 and 60 DAS (T6). **Conclusion:** The application of reduced graphene oxide (rGO)-based iron and zinc nanoparticles significantly improved nutrient uptake and utilization efficiency, leading to enhanced crop vigor and yield. The study underscores the ecological importance of integrating nanotechnology with nutrient management to sustain a healthy and balanced agroecosystem. This research focuses on **sustainable agriculture, nanofertilizers, nutrient use efficiency, and ecological impact,** which follows the Q16, Q57, and O13 JEL (Journal of Economic Literature) classification.

Keywords: Ecology; Sustainability; Nano fertiliser; rGO-Zn; rGO-Fe; Micronutrients; Wheat

1. Introduction

Wheat (*Triticum aestivum* L.) holds a significant position in India's agricultural landscape, playing a crucial role in the nation's economy and food security [1]. Wheat is extensively cultivated across various agro-climatic zones, and wheat stands as the second most important cereal crop after rice in India [2]. Its cultivation spans diverse regions, from the fertile plains of Northern India to the peninsular areas, owing to its adaptability to different soil types and climates [3]. The success and prominence of wheat cultivation in India can be attributed to various factors, including technological advancements, improved seed varieties, efficient irrigation practices, and government support through agricultural policies and initiatives [4]. Furthermore, the Green Revolution in the 1960s brought about a transformation in wheat farming techniques, introducing high-yielding varieties and modern agricultural practices that substantially boosted wheat production in the country [5].

However, despite India's remarkable progress in wheat production, challenges such as maintaining sustainable yields amidst varying climatic conditions, pest and disease management, soil health preservation, and ensuring equitable distribution of improved technologies and practices to smallholder farmers persist [6,7]. In India, wheat is grown on 23.61 million hectares, producing 44.25 million tonnes of grain annually [8]. Wheat is the country's main cereal crop, and production has increased significantly in recent years. Uttarakhand has 0.4 million hectares of land under wheat cultivation. In 2021, the state produced 955,000 metric tons of wheat, which was an increase from 2015.

In recent years, agriculture has seen a notable surge in the adoption of nanotechnology. This method holds promise in revolutionizing current agricultural practices by enhancing the management, upkeep, and sustainability of inputs crucial for agricultural production [9]. Numerous studies have focused on exploring the potential of metal nanoparticles (NPs), such as zinc oxide, copper oxide, and metal micronutrient chelates [10]**.** Joshi and their colleague [11] conducted research indicating that the application of nano chelated iron to wheat crops resulted in a substantial effect on both grain yield and yield components, showcasing an increase in grain yield ranging from 5.19% to 9.17%. Additionally, the application of nano-fertilizers in small quantities, whether applied to the soil or as foliar sprays, exhibited superior effectiveness in promoting crop growth and yield in comparison to conventional bulky fertilizers containing similar elements. This enhanced efficiency in fertilizer utilization was attributed to their improved ability to penetrate and translocate within different plant parts [12]. Nano-fertilizers enhance nutrient use efficiency by releasing nutrients in a controlled manner, reducing excess application and minimizing chemical runoff. This mitigates soil degradation by preserving microbial diversity and maintaining soil structure and fertility. By curbing anthropogenic impacts, they support sustainable soil ecology and reduce environmental contamination [10].

Integrating nanotechnology in wheat farming has great ecological potential, as it promotes sustainable agriculture by optimizing resource utilization and reducing environmental impact. Using nano-sized micronutrient composites such as rGO-based iron and zinc nanoparticles improves nutrient absorption efficiency, thereby lowering excessive fertiliser use and minimising soil and water contamination [10–12]. This method ensures better crop yields as well as helps to preserve soil health, thereby safeguarding biodiversity, and lowers agricultural runoff, a key cause of eutrophication in water bodies. Furthermore, by increasing crop tolerance to abiotic stresses, such as drought and temperature changes, the exact and regulated release of nutrients made by nanotechnology assists in adjusting to climate unpredictability [5–8]. Reduced chemical inputs, enhanced nutrient efficiency, and long-term soil preservation can be achieved by incorporating nanotechnology into wheat farming, thereby helping to attain ecological sustainability and paving the way for a more ecologically friendly method of agricultural output [9,12].

Consequently, this study aimed to assess the impact of foliar feeding using nano-micronutrient composites on wheat growth and yield. This study aimed to clarify how these nanocomposites might help to raise wheat farming agricultural output.

2. Materials and Methods

2.1. Research Subjects and Areas

The research titled "Impact of Nano Micronutrient Composites on the Growth and Yield of Late-Sown Wheat (*Triticum aestivum L.*)" was conducted at the Agricultural Research Farm of Graphic Era Hill University in Dehradun during the Rabi season of 2021-2022. The experimental site is situated in the foothills of the Shivalik range of the Himalayas (Dehradun), geographically positioned at 30.34º N latitude, 78.02º E longitude, and an altitude of 640 meters above mean sea level. This region experiences an average annual rainfall of 2025 mm, with 70% of the rainfall occurring during the rainy season (July–September). The soil in this area ranges from clay loam to silt loam and possesses good water retention capabilities. Soil pH levels vary from slightly acidic to neutral.

2.2. Research Design

The experiment was laid out in randomized block design comprising eight distinct treatments with three replications each. The treatments detail is presented in **Table 1**. The wheat variety used for the experiment was 'PBW-292', sown on December 27, 2021, with a row spacing of 22.5 cm and a recommended seed rate of 125 kg/ha. Urea, DAP, and MOP were used to supply the crop with 120 kg N, 60 kg P_2O_5/ha, and 40 kg K_2O/ha. Half of the nitrogen, the full dose of phosphorus, and the full dose of potassium were applied during sowing, while the remaining nitrogen was split equally and top-dressed during the first and second irrigations. Before sowing, the crop received a light irrigation for uniform germination, followed by the application of pre-emergence herbicides.

Table 1. Treatments Detail.

Treatment Number	Treatments Description
T1	Control (Recommended Dose of Fertilizer) (120:60:40),
T2	RDF + $ZnSO_4$ @45kg/ha + $FeSO_4$ @5kg/ha
T3	RDF + 20ppm NS-Fe + NS-Zn (NS -Nano silica) One Spray@ 45 DAS
T4	RDF + 20ppm NS-Fe+NS-Zn Two Spray@ 45 and 60 DAS
T5	RDF + 20ppm rGO-Fe + rGO-Zn (rGO -Reduced Graphene oxide) One Spray@ 45 DAS
T6	RDF + 20ppm rGO-Fe + rGO-Zn Two Spray@ 45and 60 DAS
T7	RDF + 0.5% Fe and Zn One Spray @ 45 DAS
T8	RDF + 0.5% Fe and Zn Two Spray @ 45 and 60 DAS.

2.3. Data Analysis

The Statistical analysis of the experimental data was done using the analysis of variance technique. A critical difference at a 5% significance level was calculated to determine the significance of differences between any two means when the F-test showed significance [13]. The data obtained during the investigation underwent statistical analysis through OP STAT to ascertain the statistical differences between treatments and draw appropriate conclusions.

3. Results

3.1. Effect of Nano-micronutrient and Tillers on Wheat Crop

The data pertaining to plant population, presented in **Table 2,** revealing the effect of different treatment combinations on the plant population of late-sown wheat at 20 DAS. The mean value of plant population (m^2) varied from 203 to 241 plants/m^2 with the maximum plant population (241 plants /m^2) observed under treatment T6 which was significantly superior over T1 (203 plants/m^2), T2 (214 plants/m^2) and T5 (221 plants/m^2) and T8 (218 plants/m^2) and stands at par with T3 (225 plants/m^2), T4 (231 plants/m^2) and T7 (225 plants/m^2). The enhanced seed emergence with application of nanoparticles may be accorded with the fact that nanoparticles containing essential nutrients ensure efficient nutrient delivery. They may facilitate better nutrient uptake by seeds during germination, ensuring improved initial growth stages. The results were in close proximity to those of Zain et al. [14], who demonstrated that the foliar application of a combined $FeSO_4$ + $ZnSO_4$ + $MnSO_4$ enhanced growth parameters and yield attributes. Extensive research has been conducted on foliar application of micronutrients, including ferrous sulphate ($FeSO_4$), zinc sulphate ($ZnSO_4$), and manganese sulphate ($MnSO_4$), in order to improve plant growth metrics and yield qualities over several crops. Many physiological and biochemical activities in plants depend on these micronutrients; their direct application to leaves can efficiently solve deficits, improving plant health and production **(Figure 1)**.

Table 2. Effect of nano-micronutrient composites on the plant population, plant height, and number of tillers of late sown variety of wheat crop.

Treatment		Plant Population (m^2)	Plant Height (cm) Days after Sowing		Plant Tillers (m^{-2}) Days after Sowing	
			90 DAS	120 DAS	60	90
T1	Control (RDF) (120:60:40)	203.0	70.5	85.4	324	239
T2	RDF + ZnSo4 @45kg/ha + FeSo4 @5kg/ha	214.0	77.5	91.2	334	245
T3	RDF + 20ppm NS-Fe+ NS-Zn One Spray@ 45 DAS.	225.0	73.6	90.8	339	248
T4	RDF + 20ppm NS-Fe + NS-Zn Two Spray@ 45 and 60 DAS	231.0	83.0	95.4	343	254
T5	RDF + 20ppm rGO-Fe + rGO-Zn One Spray@ 45 DAS.	221.0	74.6	90.6	346	244
T6	RDF + 20ppm rGO-Fe + rGO-Zn Two Spray@ 45and 60 DAS.	241.0	84.6	98.4	350	262
T7	RDF + 0.5% Fe and Zn One Spray @ 45 DAS.	225.0	71.6	90.7	340	249

Table 2. *Cont.*

Treatment		Plant Population (m^2)	Plant Height (cm) Days after Sowing		Plant Tillers (m^{-2}) Days after Sowing	
			90 DAS	120 DAS	60	90
T8	RDF + 0.5% Fe and Zn Two Spray @ 45 and 60 DAS	218.0	79.1	94.2	348	255
C.D. ($p = 0.05$)		**19.1**	**9.2**	**7.1**	**15.1**	**12.4**
SE(m)		**6.2**	**3.0**	**2.3**	**5.0**	**4.03**

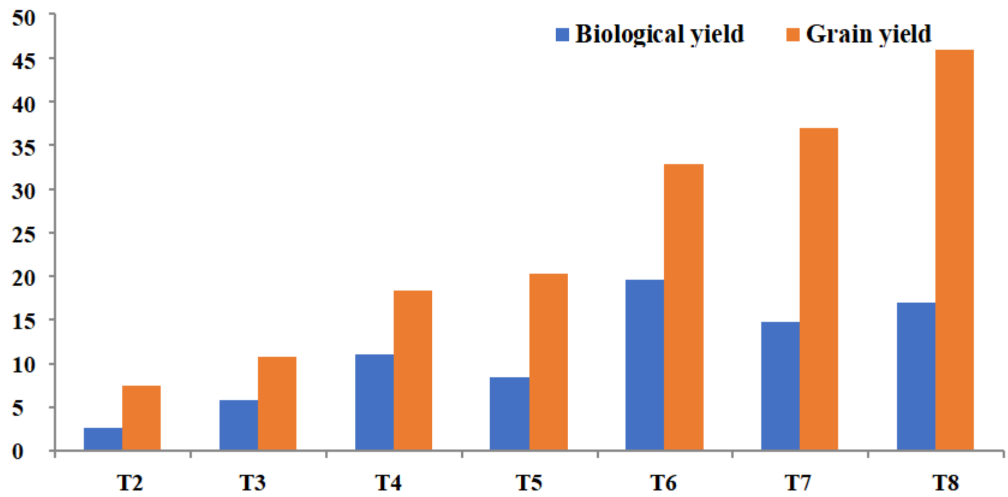

Figure 1. Effect of Nano Micronutrient Composites on the Biological and Grain Yield of the Late Sown Variety of Wheat Crop.

The number of tillers for 60 DAS was found to be significant and is clear from the data that the readings for 60 DAS the highest data was recorded in T6 (350 till/m2) which was at par with T3, T4, T5, T7, and T8 and was significantly higher than T1 and T2 and for 90 DAS the highest reading was recorded for treatment T4 (263 till/m2) which was at par with T6 and was significantly higher than all the other treatments. The readings for 60 DAS were also found to be significant, and the highest readings were recorded for T_4 (172.29), which was at par with T_5 (168.94) and T_7 (169.55), while it was significantly higher than all the other treatments. The readings for the dry matter at 90 DAS, the highest data was recorded for treatment T_8 (319.59), which was at par with T_5 (317.01), but was significantly higher than all the other remaining treatments. The data at the time of harvesting were recorded, and the highest data was recorded for treatment T_8 (500.18), which was significantly higher than all the other treatments.

The number of tillers is presented in **Table 2**. The reading for 60 DAS was found significant and is clear from the data that the readings for 60 DAS the highest data were recorded in T6 (350 till/m2) which was at par with T3, T4, T5, T7, and T8 and was significantly higher than T1 and T2 and for 90 DAS the highest reading was recorded for treatment T4 (263 till/m2), which was at par with T6 and was significantly higher than all the other treatments.

3.2. Effect of Foliar Application of Nano-micronutrient on Dry Matter Content, No. of Spikes and Number of Grains per Spike

The data for Dry matter content, number of spikes and number of grains per spike are presented in **Table 3** revealed the dry matter content for 60 DAS was found significant. the highest readings were recorded for T4 (172.29), which was at par with T5 (168.94) and T7 (169.55), while it was significantly higher than with all the other treatments. The readings for the dry matter at 90 DAS, the highest data was recorded for treatment T8 (319.59), which was at par with T5 (317.01), but was significantly higher than all the other remaining treatments. The data at the time of harvesting was recorded, and the highest data was recorded for treatment T8 (500.18), which was significantly higher than all the other treatments.

Table 3. Effect of Nano Micronutrient Composites on the Dry Matter Accumulation, No. of Spikes (m−2) and No. of Grains / Spike of Late Sown Variety of Wheat Crop.

Treatment		Dry Matter Accumulation (g/m^2)			No. of Spikes(m^{-2})	No. of Grain/Spike
		60 DAS	90 DAS	120 DAS		
T1	Control (RDF) (120:60:40)	153.0	303.9	472.9	203.3	35.2
T2	RDF + ZnSo4 @45kg/ha + Fe So4 @5kg/ha	156.3	310.0	475.9	216.6	37.6
T3	RDF + 20ppm NS-Fe + NS-Zn One Spray@ 45 DAS.	158.9	313.1	478.6	220.0	37.0
T4	RDF + 20ppm NS-Fe + NS-Zn Two Spray@ 45 and 60 DAS	165.9	315.3	482.1	236.6	36.6
T5	RDF + 20ppm rGO-Fe + rGO-Zn One Spray@ 45 DAS.	163.6	314.7	489.6	210.0	37.8
T6	RDF + 20ppm rGO-Fe + rGO-Zn Two Spray@ 45and 60 DAS.	172.7	317.0	500.1	240.0	38.2
T7	RDF + 0.5% Fe and Zn One Spray @ 45 DAS.	160.5	315.2	492.1	213.3	37.4
T8	RDF + 0.5% Fe and Zn Two Spray @ 45 and 60 DAS	168.3	319.6	496.8	223.3	38.9
	C.D. (p = 0.05)	**11.7**	**8.5**	**15.9**	**22.0**	**1.7**
	SE(m)	**3.8**	**2.8**	**5.2**	**7.1**	**0.5**

The highest number of spikes was recorded in treatment T_6 (240.0), which is at par with T_4 (236.7), but is significantly higher than all the other treatments. Number of grains per spike data was found to be maximum in T_8, which is at par with T_2, T_5, T_6 and was significant over all the other treatments.

3.3. Grain, Straw and Biological Yield, Harvest Index and Grain Straw Ratio of the Late Sown Variety of Wheat Crop

The biological yield for the late sown variety of wheat was found to be highest (77.11 q/ha) in T6 (Foliar application of NPK +20ppm RGO-Fe+RGO-Zn two spray@ 60 and 80 DAS), which is at par with T4, T5, T7, and T8 but is significantly higher than all the other treatments. The data for grain yield was also recorded as the highest (29.17 q/ha) for treatment T8, which was at par with T4, T5, T6, and T7, but was significantly higher than all the other treatments. The data clearly shows that the readings for the straw yield were found to be non-significant, and the highest reading was recorded in treatment T6 (Foliar application of NPK +20ppm RGO-Fe+RGO-Zn Two Spray@ 60 and 80 DAS). The findings were in line with the results of Verma et al. [15], who found that application of foliar spray of zinc sulphate @ 0.5% doses was significantly higher with grain yield and protein content. Harvest index and grain straw both have significant relations with control. Maximum harvest index was recorded in T6 (38.71), which is significantly superior over all other treatments except T7 (37.04). Grain straw ratio was recorded as highest in treatment T6 (0.65), which is significantly superior to all other treatments (**Table 4**).

Table 4. Effect of Nano Micronutrient Composites on the Grain, Straw and Biological Yield, Grain Straw Ratio and Harvest Index of the Late Sown Variety of Wheat Crop.

	Treatment	GrainYield (q/ha)	Straw Yield (q/ha)	Biological Yield (q/ha)	Harvest Index (%)	Grain: Straw Ratio
T1	Control (RDF) (120:60:40)	20.0	44.4	64.5	31.1	0.4
T2	RDF + ZnSo4 @45kg/ha +Fe So4 @5kg/ha	21.5	44.6	66.1	32.4	0.5
T3	RDF + 20ppm NS-Fe+NS-Zn One Spray@ 45 DAS.	22.1	46.7	68.2	32.4	0.5
T4	RDF + 20ppm NS-Fe+NS-Zn Two Spray@ 45 and 60 DAS	23.7	47.9	71.6	33.1	0.5
T5	RDF + 20ppm rGO-Fe + rGO-Zn One Spray@ 45 DAS.	24.0	45.8	69.9	34.5	0.5
T6	RDF + 20ppm rGO-Fe + rGO-Zn Two Spray@ 45and 60 DAS.	26.5	50.5	77.1	38.7	0.6
T7	RDF + 0.5% Fe and Zn One Spray @ 45 DAS.	27.4	46.5	73.9	37.0	0.5
T8	RDF + 0.5% Fe and Zn Two Spray @ 45 and 60 DAS	29.2	46.3	75.4	34.4	0.5
	C.D. (*p = 0.05*)	**5.6**	**NS**	**7.6**	**2.4**	**0.05**
	SE(m)	**1.8**	**2.5**	**2.5**	**0.8**	**0.01**

4. Discussion

The improved yield characteriztics observed from applying macro and micronutrients through foliar application draw out the fact that better nutrient availability led to increased uptake, consequently boosting wheat yield attributes. The foliar spray enhanced nutrient efficiency, contributing to the overall improvement in yield-related traits, and ultimately resulting in increased yield. Anjum et al. [16–22] applied Zn and B through foliar application to the maize crop and found significant enhancement of plant growth and yield, and suggested that combined foliar application of these nutrients is more impactful than applying them alone. Wheat crop in calcareous soil treated with foliar application of different micronutrients (Zn, Cu, Mo, and Fe) and found the combined application of the Fe + Mo (3480 kg/ha) gives highest yield, the heaviest seed weight was observed under the treatment of Cu + Mo (44.62g) [17]. Similarly, several studies have supported the application of zinc in significantly enhancing plant health, physiology, growth attributes, yield parameters, quality, and overall plant performance [23–32].

Over three successive kharif seasons (2014–2016), a field experiment was carried out in the acid soils of the eastern Himalayan region to assess the effects of folious-applied Zn and Fe on rice. Grain yield increased 36.34% by foliar spray of 2% $ZnSO_4$ given in four split doses of 0.5% each at tillering, stem elongation, booting, and grain filling stages. With a return per rupee invested of 2.3 ppm, this treatment also improved the economics of rice production and raised grain Zn content to 48.17 ppm. With a return per rupee spent of 2.24, foliar spraying of 1.5% $FeSO_4$ (0.5% during tillering, booting, and grain filling phases) likewise produced a 26.56% increase in grain production and boosted grain Fe content to 40.0 ppm. These results highlight how well folious Zn and Fe increase rice productivity and nutritional quality in acidic soils [12–14].

The effects of foliar treatments of $MnSO_4$ and $FeSO_4$ on vegetative development, fruit output, and quality of

Kinnow mandarin were evaluated in a field experiment carried out in 2016–2017. Applied during fruit set and pea-size stages, the treatments consisted of different concentrations and combinations of $MnSO_4$ and $FeSO_4$. The results showed that all treatments, except for the control, much improved vegetative growth parameters, including shoot length, canopy area, and tree height. With 1.0% $MnSO_4$ and 0.5% $FeSO_4$ (T8) applied together, the fruit weight (170.13%), fruit retention (69.74%), and yield per plant (78.23 kg) were especially high. With this treatment, quality factors, including total soluble solids (TSS), ascorbic acid content, and juice content, were also improved. The study found that foliar application of Mn and Fe improves the quality of Kinnow mandarin fruit, as well as yield [33,34].

Chilli plants were subjected to foliar spray of $ZnSO_4$, $MnSO_4$, $FeSO_4$, and $CuSO_4$ in a winter experiment spanning 2020–2021. Applied at 30 and 60 days following transplanting, the study consisted of thirteen treatments with different dosages of these micronutrients. $ZnSO_4$ applied at 0.2% (T4) significantly improved growth parameters, including the number of leaves per plant (207.33) and plant spread (67.33 cm North-West and 60 cm East-West). With this treatment, yields for fruit length (11.43 cm), fruit width (1.04 cm), fresh weight of fruit (4.53 g), and overall fruit yield (168.96 q/ha) were also maximized. These results imply that the development and productivity of chilli plants can be much improved by foliar treatment with $ZnSO_4$ [35].

A thorough analysis of the effects of micronutrients on the development, yield, and quality of citrus fruits underlined various studies proving the advantages of folious treatments. For Feutrell's Early (Citrus reticulata Blanco), for example, folious treatment of 0.5% $ZnSO_4$ and 0.3% boric acid during the fruit set stage greatly raised plant height, tree spread, and stem girth. Combining folious sprays of 0.2% boric acid and 0.5% $ZnSO_4$ during fruit set and pea-size stages favourably affected plant height, tree spread, and branch length in Kinnow mandarin. Furthermore, with sweet orange foliar spray of 0.75% $ZnSO_4$, improved plant height and spread were observed. These studies, taken together, show that in many citrus species, foliar treatment with micronutrients such as Zn and B can significantly enhance vegetative growth indices [33]. Factors that affect the effectiveness of foliar application of micronutrients include the concentration of the nutrient solution, the timing and frequency of administration, and the particular growth stage of the plant. For rice, for example, it was shown that spreading the application of $ZnSO_4$ and $FeSO_4$ over important growth stages (tillering, stem elongation, booting, and grain filling) was more beneficial than a single application. In citrus fruits, too, adding micronutrients during the fruit set and pea-sized phases produced improved growth and production [33,36].

Moreover, the combined use of several micronutrients usually has synergistic effects, resulting in higher gains in plant growth and yield than the administration of single nutrients. For Kinnow mandarins, for instance, the combined foliar treatment of $MnSO_4$ and $FeSO_4$ enhanced both vegetative growth and fruit quality parameters, including TSS, ascorbic acid content, and juice content. This implies that a balanced supply of several micronutrients would help plants, as they support different physiological and metabolic activities simultaneously [33]. Furthermore, it is remarkablethat the effectiveness of micronutrient supplementation depends significantly on the application technique. Foliar application lets nutrients be directly absorbed by the leaves, bypassing any soil-related problems, including nutrient fixation or leaching. This approach is especially helpful in high-pH or calcareous soils, where the availability of micronutrients is limited.

The ecological rationale behind these benefits can be understood through the lens of Nutrient Use Efficiency (NUE) theory and Ecological Stoichiometry Theory (EST). NUE emphasizes the importance of synchronizing nutrient supply with plant demand to minimize losses and maximize productivity, a principle inherently supported by the targeted and controlled-release nature of nanofertilizers. EST, on the other hand, explains how balanced elemental ratios influence ecological interactions and nutrient cycling. The use of rGO-based iron and zinc nanocomposites ensures more balanced nutrient availability in the soil-plant-microbe continuum, reducing the risks of elemental imbalances that can disrupt microbial communities and nutrient flow. By aligning with these theories, the nano-enabled fertilization strategy promotes sustainable intensification, enhancing crop performance while safeguarding ecological health. By reducing dependency on excessive chemical fertilizers and promoting nutrient use efficiency, this nano-enabled strategy contributes to the ecological sustainability of crop production systems. It fosters a resilient, low-impact agricultural model that aligns with the principles of agroecology, ensuring both environmental stewardship and sustainable productivity. Overall, the study underscores the ecological importance of integrating nanotechnology with nutrient management to sustain a healthy and balanced agroecosystem.

5. Conclusion

From the above investigation, it is evident that the application of 20 ppm of rGO-based iron and zinc nanoparticles through foliar spray substantially enhanced the growth and yield parameters of wheat crops. The utilization of nanoparticle micronutrient composites enabled a controlled and sustained nutrient release, ensuring their sufficient presence in the soil, thus leading to enhanced nutrient absorption. The use of nanoparticles can be adopted as one of the practices to increase crop nutrient use efficiency and ensure better crop yields. This study strongly advocates for the utilization of nanoparticle micronutrient composites as a viable strategy to augment wheat production.

From an ecological perspective, the use of rGO-based iron and zinc nanoparticles offers a sustainable method to maximize wheat output while reducing environmental effects. These nanoparticles lower the excessive use of conventional fertilizers by guaranteeing controlled and effective nitrogen release, therefore reducing soil and water contamination. Moreover, better nitrogen absorption by plants helps to reduce the risk of nutrient leaching and runoff, thereby protecting soil conditions and ecological balance. Thus, by lowering chemical inputs and improving resource economy, the integration of nanoparticle-based nutrient management techniques not only helps agricultural sustainability but also promotes environmental preservation.

Author Contributions

S.J. (Samyak Jain) and V.K.P.: Writing – review & editing, Writing – original draft: Methodology, Investigation, Formal analysis, Data curation, Conceptualization; A.D., D.K., and G.K.: Visualization, Validation, Supervision, and Project administration; K.G., S.G. (Saurabh Gangola), D., P.S., S.K., A.R., and P.B.: Writing – review & editing, Visualization, Validation, Supervision, Project administration; R.K., S.G. (Supriya Gupta), S.M. and A.G.: Visualization, Validation, Supervision, Project administration; P.V.: Visualization, Validation, Supervision, Project administration; S.J. (Samiksha Joshi) and R.B.: Software, Formal analysis. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement

Informed consent was obtained from all participants involved in the study.

Data Availability Statement

The data will be available on request to the corresponding author.

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Conflicts of Interest

The authors have no relevant financial or non-financial interests to disclose.

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