EFFECT OF FOLIAR APPLICATION OF NANO ZINC ON NUTRIENT UPTAKE, YIELD AND QUALITY OF WHEAT ON ZINC DEFICIENT AND SUFFICIENT SOILS OF INCEPTISOL

by

Mr. Nakhate Pavan Ramesh
(Reg. No. 020/23)

A Thesis submitted to the
MAHATMA PHULE KRISHI VIDYAPEETH,
RAHURI - 413 722, DIST- AHMEDNAGAR,
MAHARASHTRA, INDIA.

In partial fulfilment of the requirements for the degree

of

DOCTOR OF PHILOSOPHY (AGRICULTURE)

in

SOIL SCIENCE AND AGRICULTURAL CHEMISTRY

DEPARTMENT OF SOIL SCIENCE AND AGRICULTURAL CHEMISTRY
POST GRADUATE INSTITUTE
MAHATMA PHULE KRISHI VIDYAPEETH
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CANDIDATE’S DECLARATION

I hereby declare that this thesis or part
thereof has not been submitted
by me or other person to any
other University or Institute
for a Degree or
Diploma

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Date : / /2024

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CERTIFICATE

This is to certify that the thesis entitled, "**EFFECT OF FOLIAR APPLICATION OF NANO ZINC ON NUTRIENT UPTAKE, YIELD AND QUALITY OF WHEAT ON ZINC DEFICIENT AND SUFFICIENT SOILS OF INCEPTISOL**", submitted to the Faculty of Agriculture, Mahatma Phule Krishi Vidyapeeth, Rahuri, Dist. Ahmednagar (Maharashtra) in partial fulfilment of the requirement for the award of the degree of **DOCTOR OF PHILOSOPHY (AGRICULTURE)** in **SOIL SCIENCE AND AGRICULTURAL CHEMISTRY**, embodies the results of a piece of bonafide research work carried out by **MR. NAKHATE PAVAN RAMESH** under my guidance and supervision and that no part of the thesis has been submitted for any other degree or diploma.

The assistance and help received during the course of this investigation have been duly acknowledged.

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CERTIFICATE

This is to certify that the thesis entitled, "**EFFECT OF FOLIAR APPLICATION OF NANO ZINC ON NUTRIENT UPTAKE, YIELD AND QUALITY OF WHEAT ON ZINC DEFICIENT AND SUFFICIENT SOILS OF INCEPTISOL**", submitted to the Faculty of Agriculture, Mahatma Phule Krishi Vidyapeeth, Rahuri, Dist. Ahmednagar (Maharashtra) in partial fulfilment of the requirements for the award of the degree of **DOCTOR OF PHILOSOPHY (AGRICULTURE)** in **SOIL SCIENCE AND AGRICULTURAL CHEMISTRY**, embodies the results of a piece of bonafide research work carried out by **MR. NAKHATE PAVAN RAMESH** under the guidance and supervision of **DR. A.G. DURGUDE,** Sr. Scientist (Soil), AICRP on Irrigation Water Management, Department of Agronomy, M.P.K.V., Rahuri and that no part of the thesis has been submitted for any other degree or diploma.

Place : M.P.K.V., Rahuri **(V.S. Shirke)**
Date : / /2024

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Moreover, Sarthi Institute's fellowship program fosters a sense of community and belonging among scholars. Through various networking opportunities, workshops, and seminars, we have had the privilege of engaging with fellow recipients of the fellowship, forging meaningful connections, and exchanging ideas. This sense of camaraderie not only enriches our academic experience but also reinforces our commitment to collaborative scholarship and knowledge sharing. Importantly, Sarthi Institute's support extends beyond the realm of financial aid. Their holistic approach to fellowship encompasses mentorship, professional development, and access to resources essential for academic success. Whether through guidance from experienced mentors, workshops on research methodologies, or access to state-of-the-art facilities, Sarthi Institute equips us with the tools and knowledge necessary to excel in our scholarly endeavors.

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Place : M.P.K.V., Rahuri
Date : / /2024 (Pavan R. Nakhate)

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LIST OF ABBREVIATIONS

@	:	At the rate of
/		Per
%	:	Per cent
^{o}C	:	Degree Celsius
Ca	:	Calcium
$CaCO_3$	:	Calcium Carbonate
CD	:	Critical Difference
cm	:	Centimeters
CO_2	:	Carbon dioxide
Cu	:	Copper
EC	:	Electrical Conductivity
ed^{n}.	:	Edition
DAS	:	Days After Sowing
ds m^{-1}	:	Deci Siemen per meter
et al.	:	Et alli.(any other)
etc.	:	Excetera (and so on)
Fe	:	Iron
fig.	:	Figure
FYM	:	Farm yard manure
g	:	Gram (s)
g kg^{-1}	:	Gram per kilogram
GRDF	:	General recommended dose of fertilizer
ha	:	Hectare
i.e.	:	Id est (That is)
J.	:	Journal
K	:	Potassium
K_2O	:	Potassium oxide
kg	:	Kilogram (s)
kg ha^{-1}	:	Kilogram (s) per hectare
L ha^{-1}	:	Liter per hectare
m	:	Meter
mg	:	Milligram (s)
mg kg^{-1}	:	Milligram per kilogram
mL	:	Milliliter (s)
MT	:	Metric tons
Mn	:	Manganese
N	:	Nitrogen
Na	:	Sodium
no.	:	Number
NS	:	Non-significant
No.	:	Number

P_2O_5	:	Phosphorus pentoxide
pH	:	Negative logarithm of hydrogen ion activity
PNP	:	P-nitrophenol
ppm	:	Parts per million
q	:	Quintal (s)
q ha^{-1}	:	Quintal per hectare
Res.	:	Research
RBD	:	Randomized block design
SPAD		Soil Plant Analysis Development
μ moles m^{-2} s^{-1}		micro moles meter square per second
m moles m^{-2} s^{-1}		milli moles meter square per second
μ moles CO_2 m^{-2} s^{-1}		micro moles carbon dioxide meter square per second
μ moles H_2O m^{-2} s^{-1}		micro moles dihydrogen oxide meter square per second
SE(m$\underline{+}$)	:	Standard Error of mean
S	:	Sulphur
SE	:	Standard error
t ha^{-1}	:	Tons per hectare
viz.	:	Videlicent (namely)
wt	:	Weight
Zn	:	Zinc

ABSTRACT

EFFECT OF FOLIAR APPLICATION OF NANO ZINC ON NUTRIENT UPTAKE, YIELD AND QUALITY OF WHEAT ON ZINC DEFICIENT AND SUFFICIENT SOILS OF INCEPTISOL

by

Mr. Nakhate Pavan Ramesh

A candidate for the degree of
DOCTOR OF PHILOSOPHY (AGRICULTURE)
in
SOIL SCIENCE AND AGRICULTURAL CHEMISTRY
2024

Research Guide	**:**	**Dr. A.G. Durgude**
Department	**:**	**Soil Science and Agricultural Chemistry**

The field experiment entitled “Effect of foliar application of Nano zinc on nutrient uptake, yield and quality of wheat on zinc deficient and sufficient soils of Inceptisols” was conducted during 2022-23 *rabi* season at Post Graduate Institute Research Farm Department of Soil Science and Agricultural Chemistry, Mahatma Phule Krishi Vidyapeeth, Rahuri. The experiment was laid out in randomized block design with eight treatments and three replications for wheat crop. The treatments comprised of T_1: Absolute control, T_2: GRDF (120:60:40 N:P_2O_5:K_2O kg ha^{-1} + FYM 10 t ha^{-1}), T_3: GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}, T_4: GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS, T_5: GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS, T_6: GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS, T_7: GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS, T_8: GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS..

Under zinc deficient soil number of tillers per plant, length of spikelet and number of grains per spikelet recorded significantly higher (8.66, 8.76 and 44.59, respectively) in treatment GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}. However, under zinc sufficient soil, it was found highest (8.94, 8.86 and 54.69, respectively) in treatment GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.

Total chlorophyll content in fresh tissue (SPAD Values) under zinc deficient soil was found significantly higher (40.47) in treatment GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1} at 40 DAS however, it was significantly higher (42.40) at 55 DAS in treatment GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS. However, under zinc sufficient soil it was found significantly higher (42.27) in treatment T_3 at 40 DAS however at 55 DAS, it was found higher in treatment T_6 (45.10).

The physiological traits like photosynthetic rate, stomatal conductance, stomatal resistance, intercellular CO_2 concentration and transpiration rate under zinc deficient soil recorded highest in treatment T_3 at 40 DAS and 55 DAS in treatment T_6. Under zinc sufficient soil, it was found highest in treatment T_6 at 40 DAS and 55 DAS.

The grain and straw yield under zinc deficient soil recorded higher in treatment T_3 (42.61 and 60.14 q ha^{-1}, respectively) and under zinc sufficient soil it was found higher in treatment T_6 (44.15 and 63.50 q ha^{-1}, respectively). Which was 9.0 and 8.61 per cent, respectively higher over GRDF treatment.

Total uptake of N, P and K (141.09, 23.67 and 93.87 kg ha^{-1}, respectively) and Fe, Mn and Zn (1498, 901 and 419 g ha^{-1}, respectively) by wheat under zinc deficient soil recorded highest in treatment T_3. However, under zinc sufficient soil it was recorded significantly higher (147.22, 24.80 and 97.34 kg ha^{-1}) in treatment T_6 and copper recorded higher in treatment T_8. (1665, 923 and 455 g ha^{-1}, respectively)

Crude protein and test weight in grain under zinc deficient soil was found significantly higher in treatment T_3 and gluten was found higher in treatment T_5. However, under zinc sufficient soil it recorded higher in treatment T_5.

The study probed soil chemical properties including pH, electrical conductivity, calcium carbonate and organic carbon content in soil, revealed minimal variations induced by the various treatments across both the soil types.

The available nitrogen, phosphorus and potassium were significantly highest (170, 13.24 and 497 kg ha^{-1}, respectively) in treatment T_2 - GRDF @ 120:60:40 N, P_2O_5, K_2O kg ha^{-1} + FYM 10 t ha^{-1}. However, under zinc sufficient soil it recorded highest (191, 12.90 and 538 kg ha^{-1}, respectively) for available nitrogen in treatment T_4, available phosphorus in treatment T_2 and available potassium was found highest in treatment T_5.

In micronutrients, available iron (Fe) content under zinc deficient soil was found significant in treatment T_2, available zinc was found significantly highest in treatment T_3 and available manganese was found maximum in treatment T_4. However, under zinc sufficient soil, available iron (Fe) was found significantly higher in treatment T_5, available zinc was found highest in treatment T_3 and available manganese and copper were found significantly higher in treatment T_4.

The nutrient use efficiency i.e apparent nutrient recovery efficiency of N, P and K were found higher (97, 13 and 148 %, respectively) in treatment T_3 (GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}) under zinc deficient soil i.e wheat crop responded for soil application of Zn through $ZnSO_4$. However, under zinc sufficient soil, the apparent nutrient recovery efficiency of N, P and K were found higher (98, 14 and 152 %, respectively) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) which indicate that under zinc sufficient, soil wheat crop responded to two foliar application of Nano zinc @ 0.15%.

It can be concluded that, the application of General Recommended Dose of Fertilizers (120:60:40 kg ha^{-1} $N:P_2O_5:K_2O$ + 10 t ha^{-1} FYM) along with soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1} found beneficial under Zn deficient soil for increase in yield contributing characteristics, total chlorophyll, photosynthetic rate, stomatal conductance, stomatal resistance, intercellular CO_2 concentration, transpiration rate, total uptake of macro as well as micronutrients, grain and straw yield, crude protein, test weight, B:C ratio of wheat as well as maintaining the Zn status in **zinc deficient** soil of Inceptisol. However, the treatment of GRDF + Two foliar sprays of Nano zinc (0.15%) at 20 and 40 DAS found at par.

Application of General Recommended Dose of Fertilizers (120:60:40 kg ha^{-1} N:P_2O_5:K_2O + 10 t ha^{-1} FYM) along with Two foliar sprays of nano zinc @ 0.15% at 20 and 40 DAS found beneficial under **zinc sufficient** soil for increase in yield contributing characteristics, total chlorophyll, photosynthetic rate, stomatal conductance, stomatal resistance, intercellular CO_2 concentration, transpiration rate, total uptake of macro as well as micronutrients, grain and straw yield, test weight, gluten of wheat. However, the treatment of GRDF + Two foliar sprays of Nano zinc (0.10%) at 20 and 40 DAS found at par.

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1. INTRODUCTION

Wheat, a cereal grain originating from the Levant region (Feldman *et al*. 2007), is now cultivated globally. It serves as a significant source of carbohydrates (Shewry and Hey, 2015). Internationally, it stands as the primary supplier of plant-based protein in human diets, containing around 13 percent protein content. This content is comparatively high among major cereals, yet relatively subpar in supplying essential amino acids for optimal protein quality. When consumed as whole grains, wheat offers diverse nutrients and dietary fiber. However, a subset of the population faces issues due to gluten, the major component of wheat protein. This fraction can trigger ailments such as coeliac disease, non-coeliac gluten sensitivity, gluten ataxia, and dermatitis herpetiformis (Ludvigsson *et al*. 2013). The cultivation of wheat in India spans approximately 30.5 million hectares, yielding 112.74 million tons with a productivity of 3.5 tons per hectare (Anonymous, 2022).

Wheat holds a crucial role as a staple food crop in temperate zones and is increasingly sought after in urbanizing and industrializing nations. Besides being a key source of starch and energy, wheat offers substantial quantities of essential or beneficial components for health, including protein, vitamins (notably B vitamins), dietary fiber, and phytochemicals. Among these, wheat is particularly noteworthy for its dietary fiber content, with bread alone accounting for 20 percent of the UK’s daily intake. This dietary fiber intake has established connections with lowered risks of cardiovascular disease, type 2 diabetes, and certain cancers (notably colorectal cancer). The surging global demand for wheat is driven by its versatility in producing unique food items, aligning with industrialization and westernization trends. The distinct attributes of the gluten protein fraction enable wheat processing for bread, baked goods, noodles, pasta, and functional ingredients, catering to modern lifestyles.

India, occupying 329 million hectares of land, ranks seventh globally in terms of area, representing 17 percent of the world's population and 2.5 percent of its total land area. Signs indicate that by 2050, India could become the world's most populous nation, presenting substantial challenges in fulfilling food grain demands while maintaining quality and quantity. Effective fertilizer management emerges as a pivotal factor in maximizing yield potential.

Indian soils have been experiencing significant depletion, with crops removing 30 million tons of nutrients annually, while only 20 million tons are replenished. This deficit of 10 million tons has led to a sharp decline in the fertilizer response ratio of crops. Socioeconomic concerns, including migration from farming, labor shortages, and escalating cultivation costs, compound the pressure on agricultural scientists to devise technologies that address multifaceted challenges in Indian agriculture. Soil fertility, a determining factor for plant growth, hinges on the presence of macro and micronutrients. The availability of micronutrients is profoundly influenced by soil conditions such as organic matter, pH, and soil texture. Intensive cropping, imbalanced fertilizer usage, reliance on macronutrients, and disregard for micronutrients and organic manures have led to soil fertility decline in India.

Zinc a crucial element for plant nourishments, plays crucial roles in enzyme activation, enzyme and hormone biosynthesis, and oxidative stress mitigation. Zinc deficiency is prevalent in Indian soils, primarily due to varying soil and climatic conditions affecting its availability. Cereal-based cropping systems frequently experience zinc deficiency (Cakmak, 2002), significantly impacting wheat production and grain quality (Cakmak *et al*. 1996). Amidst these challenges, nanotechnology emerges as a potential solution, allowing precise nutrient delivery and addressing crop needs while ensuring environmental safety. Fertilizers, contributing 35-40% to crop productivity, hold a pivotal role. Zeolite-based nano fertilizers exhibit prolonged nutrient release, surpassing traditional fertilizers' capabilities. Research endeavors focus on developing nano composites to deliver essential nutrients in optimal proportions, ensuring nutritional security.

An emerging technological breakthrough exhibiting targeted enhancements in strength is nanoparticle engineering. Originating with Norio Taniguichi, a professor at Tokyo University of Science, who introduced the term "nanotechnology" in 1974 (Khan and Rizvi, 2014), this concept has grown across various fields. The application of nanoparticles (NPs) for agricultural advancement, a more recent innovation, is currently in development (Gogos *et al*. 2012). Nanomaterials have found applications in medical, environmental, agricultural, and food processing domains due to recent advances in manufacturing. This burgeoning scientific field has the potential to address challenges beyond the reach of traditional engineering and biological sciences. Nanotechnology is envisioned as a dynamic discipline capable of revolutionizing agriculture and food systems, ultimately benefiting impoverished populations.

Nanotechnology presents a contemporary avenue to enhance agricultural value and mitigate environmental concerns. Nanomaterials are poised to shape the materials landscape of the new millennium. Nano-based fertilizers enable controlled and slow nutrient release, improving absorption and yielding positive effects on seedling growth and development (Zhu *et al*. 2008). This technology is transitioning from experimental to practical stages, making a tangible impact on agriculture. Nano fertilizers hold the potential for efficient nutrient release, contributing to sustainable agriculture and a healthier environment (Cui *et al*. 2010).

Zinc, a vital micronutrient for humans, animals, and plants, serves as an indicator of soil inadequacy through wheat plants. It plays roles in metabolic processes, enzyme activity, and cellular protection against oxidative stress. Symptoms of zinc deficiency, such as poor growth and interveinal chlorosis, are common in field crops. In India, zinc ranks as the fourth most limiting nutrient for yield, following nitrogen, phosphorus, and potassium. A significant portion of wheat growing soils in India (50%) is deficient in zinc, causing substantial yield losses (Singh, 2010). Zinc deficiency impacts biomass production and exacerbates susceptibility to drought stress. Remedies include inorganic salt foliar sprays and synthetic chelates. However, challenges persist, such as limited leaf penetration and high costs. Nano fertilizers offer a promising solution, rapidly absorbed by plants to address nutrient shortages. These fertilizers, based on natural and organic materials, provide compatibility with both the environment and agricultural practices.

Utilizing nano-added foliar fertilizers enhances element efficiency, reduces soil toxicity, and mitigates negative effects associated with excessive fertilizer use. Farmers employ sulfates and chelated EDTA for soil and foliar applications. However, efficacy remains limited. The present study investigation enlightened the impact of various concentrations of ZnO nanoparticles on wheat growth, development, and yield. Nanoparticles' small size and expansive surface area offer potential as effective forms of zinc fertilizer. This study, “Effect of foliar application of Nano zinc on nutrient uptake, yield and quality of wheat on zinc deficient and sufficient soils of Inceptisol’’ was encompassed with the following planned objectives.

1. To study the growth and yield attributes of wheat as influenced by foliar application of Nano zinc.
2. To study the micronutrient uptake by wheat as influenced by foliar application of Nano zinc.
3. To assess nutrient use efficiency as influenced by Nano zinc.
4. To study the yield and economics of wheat.

2. REVIEW OF LITERATURE

Fertilizers have an important role in enhancing food production and quality especially after the introduction of high-yielding and fertilizer responsive varieties. Most of the major crops grown such as wheat require large quantities of inorganic inputs. Overuse of fertilizers and pesticides is one of the causes for the degradation of environment and soil. Nano-fertilizers are the newest and most technically advanced way of supplying mineral nutrients to crops. Compared to conventional fertilizers, their gradual pattern of nutrient release meets plant needs, minimizes leaching, and therefore improves fertilizer use efficiency. Numerous studies have been conducted to improve wheat production but only a few can be seen in the literatures involving nano-materials (NMs).

2.1 Zinc Status in Indian Soils
2.2 Role of Zinc in Plant Nutrition
2.3 Nanomaterials
2.3.1 Synthesis and Characterization of Zinc Nano Fertilizer
2.3.2 Zinc Nutrition through Nanotechnology
2.4 Effect of Nano Fertilizers on Growth and Yield Attributes
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2.6 Effect of Nano Fertilizers on Quality Parameters
2.7 Effect of Nano Fertilizers on Nutrient Use Efficiency
2.8 Effect of Nano Fertilizers on Yield and Economics

2.1 Zinc Status in Indian Soils

Analysis of more than 15,000 soil samples from different districts of Punjab have shown that available Zn, Fe and Mn content of Punjab soils ranged from 0.02 to 10.4, 0.5 to 176, and 0.8 to 120 mg kg^{-1} soil with mean values of 0.95, 10.7, and 11.3 mg kg^{-1} soil, respectively. Considering 0.6 ppm DTPA-extractable Zn as the critical limit for Zn deficiency, 22 percent of soils in the state are presently deficient, which has decreased from 43% in 1990 (Nayyar *et al.* 1990).

Jethra *et al.* (1993) reported that the available zinc in soils of semi-arid eastern plain zone of Rajasthan ranged from 0.34 to 5.76 mg kg^{-1} with a mean value of 1.17 mg kg^{-1} and per cent deficiency of 12 percent.

The DTPA extractable zinc contents of alluvial soils in submontane region of Punjab varied widely from 0.14 to 7.8 mg kg^{-1} with a mean value of 1.2 mg kg^{-1} and per cent deficiency of 10 percent (Manchanda and Chhibba, 1993).

Ramesh *et al.* (1994) assessed the available zinc content in Vertisols of Guntur district and observed that it ranged from 0.2 to 4 mg kg^{-1} with a mean value of 1.6 mg kg^{-1} and 30 percent of the soils were deficient in available zinc.

Tripathi *et al.* (1994) reported that the available Zn content of the alfisols of Himachal Pradesh varied from 0.1 to 2.8 mg kg^{-1} with a mean value of 0.5 mg kg^{-1} and per cent deficiency of 42 percent.

The soils of Northern Telangana zone of Andhra Pradesh showed zinc sufficiency over time which might be due to continuous application of $ZnSO_4$ (Vijay Kumar *et al.* 1996).

Survey carried out in All India Coordinated Research Projects on micro and secondary nutrients (Hyderabad centre) during 1990-2002 revealed that the zinc deficiency was found more than 50 percent in the districts of Karimnagar, Adilabad and Nalgonda and the content ranged from 0.29 to 1.78, 0.29 to 1.24 and 0.22 to 4.10 mg kg^{-1} with mean values of 0.59, 0.55 and 0.74 mg kg^{-1}, respectively. While it was less than 50 percent in Mahaboobnagar and Nizamabad district; where the content ranged from 0.31 to 1.4 and 0.35 to 4.28 mg kg^{-1} with mean values of 0.60 and 0.63 mg kg^{-1}, respectively and the deficiency was very low in East Godavari and Krishna districts and it ranged from 0.31 to 3.28 and 0.46 to 3.32 with mean values of 1.32 and 1.44 mg kg^{-1}, respectively (Subbaiah *et al.* 1998).

Siddhamalai *et al.* (1999) observed that the available zinc extracted by DTPA varied from 0.52 to 8.40 mg kg^{-1} with a mean of 3.8 mg kg^{-1} and 9 percent deficiency in clay loamy soils of Tamil Nadu.

Nayak *et al.* (2000) reported that the available Zn content of alluvial soils of arunachal Pradesh ranged from 0.2 to 1.12 mg kg^{-1} with a mean of 0.76 mg kg^{-1} and found 60 percent deficiency

Patiram *et al.* (2000) reported that the available zinc content in acid soils of Sikkim mandarin orchards varied from 2.9 to 11.8 mg kg^{-1} with a mean of 5.1 mg kg^{-1} and zero percent deficiency.

Vasudeva and Ananthnarayana (2001) reported that the range of available zinc extracted by DTPA was 0.73 to 2.63 mg kg^{-1} in acid soils of Karnataka and zinc was in sufficient range. Fifty four soil samples from ten pedons of Andhra Pradesh were studied for vertical distribution of DTPA extractable Zn, Cu, Fe and Mn and their relationship with some soil properties.

As per critical limit prescribed for Zn and Fe, 44 and 20 percent of the soils were rated as deficient in available zinc and iron, respectively. Copper and manganese were found adequate (Satyavathi and Reddy, 2004).

Systematic survey and analysis of 4,799 soil samples analyzed under the aegil of AICRP on Micronutrients indicated wide spread Zn deficiency in the state. On an average, 27 percent soil samples were deficient in Zn. DTPA-extractable Zn content in soils of the state ranged from 0.10-7.00 mg kg^{-1} soil and based on the critical limit (0.6 mg Zn kg^{-1}), Zn deficiency varied from 7.42 to 51.30 percent. Among the districts, the highest Zn deficiency was recorded in Adilabad (51.30 %) followed by Warangal district (48 %), while more than 20 percent Zn deficiency was reported in Mahabubnagar and Karimnagar districts (Sharma *et al.* 2004).

Raj *et al.* (2006) revealed that the mean zinc content ranged from 0.63 to1.33 with a mean of 0.87 mg kg^{-1} for Telangana region, 0.78 to 0.83 and mean of 0.82 mg kg^{-1} for Rayalaseema region and 0.71 to 2.70 with a mean of 1.11 mg kg^{-1} for Coastal region the percent deficiency of Zn abnormal in different regions of Andhra Pradesh.

Analysis of soil samples collected from various states of India has indicated that 49 percent of soils are deficient in Zn, 12 percent in Fe, 5 percent in Mn, 3 percent in Cu, 33 percent in B and 11 percent in molybdenum (Velu *et al.* 2008). Hence, application of micronutrient fertilizers is warranted to mitigate the deficiency of these nutrients and help in exploiting the potential yield of crops.

Results of 269,000 soil samples analysis revealed that mean deficiency of zinc, iron, copper, manganese, boron, molybdenum was found in 49, 12, 3, 5, 33 and 13 percent samples, respectively. Throughout the country, zinc deficiency is increasing except Punjab, Haryana and Uttar Pradesh where zinc deficiency is declining from initial 70- 90 percent in Punjab and Haryana to the level of 13-20 percent due to regular application of zinc sulphate. On the other hand, deficiency of zinc has increased in southern states due to extensive use of multi micronutrient mixtures containing less zinc. Periodic assessment of soil data also suggests that zinc deficiency in soils of India is likely to increase from 49 to 63 percent by the year 2025 (Singh *et al.* 2009).

Kumar and Naidu (2012) classified the soils of Chitoor district of Andhra Pradesh and revealed that DTPA - Zn varied from 6.28 to 26.74 mg kg^{-1}.

Chouhan *et al.* (2012) reported that DTPA-Zn varied from 0.04 to 4.9 mg kg^{-1} with a mean of 0.49 mg kg^{-1} and about 72.7 per cent soil samples were deficient in medium black soils of Dewas district of Madhya Pradesh.

High productive soil of Krishna district recorded deficiencies of Zn to an extent of

2.5 percent more than one micronutrient deficiency was recorded to negligible extent of 1.25 percent. Anonymous (2014).

Shukla *et al*. (2015) reported that out of 4,799 geo-referenced surface soil samples, collected using stratified random sampling techniques, 27 percent soils of Telangana state were deficient in Zn, 17 percent in Fe, 12 percent in B, less than 5 percent in Mn and 2 percent in Cu. Frequency distribution analysis showed that 34, 11.4, 9.8, 6.3 and 22 percent soil samples fall under grey area of Zn, Fe, Mn, Cu, and B availability status, respectively.

2.2 Role of Zinc in Plant Nutrition

Verma (1983) found the response of $ZnSO_4$ @ 25 kg ha^{-1} to wheat grown on newly reclaimed sodic soils.

Gupta and Raj (1984) reported that, application of 5 ppm and 10 ppm zinc gave average increase in grain yield ranging from 1.2 to 46.3 percent.

Shankar and Mahrotra (1987) conducted a field experiment on response of wheat varieties to zinc application under varying levels of fertility, they observed that, application of 20 kg $ZnSO_4$ ha^{-1} significantly increased grain yield of wheat as compared to the control.

Venkateswarlu and Misra (1987) observed that application of 12 kg $ZnSO_4$ ha^{-1} to wheat gave maximum yield i.e. 2.35 t ha^{-1}.

Verma and Yadav (1992) observed that, application of 25 kg $ZnSO_4$ ha^{-1} along with recommended dose of NPK increased grain yield of wheat (3.21 t ha^{-1}).

Khamparia *et al*. (1994) observed that, yield of wheat grain was increased significantly with 10 ppm of Zn/plot.

Patel *et al*. (1995) observed that, application of 25 kg $ZnSO_4$ ha^{-1} significantly increased yield of wheat (43.88 q ha^{-1}) over control.

Sharma and Bhardwaj (1998) observed that, application of 90 kg P_2O_5 ha^{-1} along with 2.3 kg Zn ha^{-1} increased wheat grain yield by 12 per cent compared with the control.

Zinc is essential in protein synthesis and gene expression in plants (Cakmak, 2000) (Broadley *et al*. 2007). It has been estimated that about 10 percent of the proteins in biological systems need Zn for their structural and functional integrity. This element has also been indicated to be required as a cofactor in over 300 enzymes. During germination, production of reactive oxygen species (ROS) is well known and Zn plays a central role in detoxification of ROS in plant cells.

Zinc is one of the important micronutrient which is essential for plant growth. Plant roots absorb zinc as ion (Zn^{2+}). Zinc is closely involved in the diversity of enzymatic and N metabolism of plant. Zinc application to zinc deficient plant has been found to boost the growth of plants and yield of crop to a great extant. Zinc is the essential mineral element for protein synthesis (Dixit *et al*. 2012).

Zn plays very important role in plant metabolism by influencing the activities of hydrogenase and carbonic anhydrase, stabilization of ribosomal fractions and synthesis of cytochrome. Plant enzymes activated by Zn are involved in carbohydrate metabolism, maintenance of the integrity of cellular membranes, protein synthesis and regulation of auxin synthesis and pollen formation. Its deficiency results in the development of abnormalities in plants which become visible as deficiency symptoms such as stunted growth, chlorosis and smaller leaves, spikelet sterility. Micronutrient Zn deficiency can also adversely affect the quality of harvested products, plants susceptibility to injury by high light or temperature intensity and to infection by fungal diseases can also increase. (Hafeez *et al.* 2013).

Kumar *et al*. (2016) conducted an experiment on *Phaseolus vulgaris* L., a micronutrient sensitive crop, which was grown in seven combinations of macro and micronutrients. The results suggested that on acidic soils, micronutrients application is indispensable for improving growth and yield of crops, particularly pulses, which are more sensitive to micronutrients. Its supplement can also increase the plant's use efficiency of macronutrients (NPK) due to their improved recovery efficiency by plant.

2.3 Nanomaterials

2.3.1 Synthesis and Characterization of Zinc Nanofertilizer

Like most of the nano scale formulations, ZnO nanoparticles can be synthesized by two fundamental approaches,

I. Bottom up approach

II. Top down approach

I. Bottom up approach

Bottom up approach refers to the build-up of a material from the bottom: atom by atom, molecule by molecule or cluster by cluster. In other words, it represents constructing nanomaterials from basic building blocks such as atoms or molecules (Tavakoli *et al.* 2007) and usually include aggregation of atoms or molecules in solution or in the gas to form particles with distinctive size, shape and structure (Schmid, 2001). Colloidal dispersion is also a good example of bottom up approach in the synthesis of nano particles.

The bottom up approach involves two fundamental methods of synthesis, Chemical synthesis and Biological synthesis (Green synthesis). Chemical synthesis involves a direct chemical synthesis route that yields particles in the nano size range; while a biological synthesis route comprises a plant/ plant extracts or microorganism for the synthesis of nanoparticles. Biological synthesis considered as safe alternatives to chemical methods, therefore it is also known as Green synthesis methods. On the contrary, green synthesis methods involve elaborate process of maintaining cell cultures, intracellular synthesis and multiple purification steps and hence, the method is somewhat difficult as compared to chemical synthesis.

Chemical synthesis is one of the most important techniques which can be performed by using a range of precursors and different conditions like temperature, time, concentration of reactants and so forth. Chemical synthesis of nanoparticles involves variety of methods such as hydrothermal, sol-gel, thermal decomposition, spray pyrolysis, chemical vapour deposition, and laser ablation. Among these techniques available, the hydrothermal method have been considered to be the most attractive due to its robust and reliable control on the shape and size of the nanoparticles without requiring the expensive and complex equipment.

Ni *et al.* (2005) reported by ZnO nanorods with the mean size of 50 nm x 250 nm were successfully synthesized via a hydrothermal synthesis route in the presence of cetyl trimethyl ammonium bromide (CTAB) at a reaction temperature of 120°C for 5 hours in the presence of $ZnCl_2$ and KOH as precursors. The resultant ZnO NPs was characterized using X-ray Diffractometer (XRD), Transmission Electron Microscopy (TEM) and selected area electron diffraction (SAED).

Sun *et al.* (2006) reported one step rapid synthesis of ZnO NPs using zinc acetate, CTAB and NaOH at room temperature. In this typical method, zinc acetate dihydrate, CTAB and NaOH were mixed (molar ratio 1:0.4:3) and ground together in an agate mortar for 50 min. at room temperature. ZnO NPs of 10-30 nm diameters can be synthesized conveniently with this method.

Moreover, the energy required for decomposition of metal precursors can be supplied through thermal energy, electricity, photoenergy (ultraviolet and visible light) or sonochemical energy (Tavakoli *et al.* 2007). In addition, many other methods for synthesizing ZnO nanoparticles have been published, such as hydrothermal synthesis, the micro-emulsion hydrothermal process, chemical vapour deposition (CVD) and a catalyst-free CVD method (Jiang *et al.* 2005, Sun *et al.* 2003, Wu and Liu, 2002a and Wu and Liu, 2002b).

In another investigation, Aneesh *et al.* (2007) presented the synthesis of stable, OH free ZnO NPs via hydrothermal route at variable growth temperature and concentration of the precursors. The formation of ZnO nanoparticles were confirmed by XRD, TEM, and SAED studies. The average particle size was found to be about 7-24 nm. Diffuse reflectance spectroscopy (DRS) results showed that the band gap of ZnO NPs is blue shifted with decrease in particle size.

Liu *et al*. (2007) reported the synthesis of Zn nanoparticles by sol gel route using zinc acetate and sodium hydroxide. Nanoparticles with average diameter 20 nm were synthesized successfully.

Yong *et al*. (2008) reported synthesis of ZnO nanoparticles by hydrothermal method where ZnO nanoparticles with an average particle size of 20-30 nm were readily synthesized by the reaction between zinc acetate and oxalic acid under hydrothermal.

Chen *et al*. (2008) reported the ZnO nanoparticles synthesis by hydrothermal method using zinc nitrate and urea. 20-25 nm size range can be easily achieved. Similarly, Ni *et al*. (2005) also reported synthesis of ZnO NPs by hydrothermal method where ZnO NPs with an average particle size of 20-30 nm were readily synthesized through the reaction between zinc acetate and oxalic acid under hydrothermal conditions.

Zak *et al.* (2011) reported the synthesis of ZnO nanoparticles by sol-gel route; wherein the precursor molecules were Zinc acetate and Tri-ethanol amine (TEA). Here, TEA molecule was used to control the growth of ZnO. The average size obtained was in the range of 33 nm.

Askarinejad *et al*. (2011) reported synthesis of ZnO nanoparticles by using ultra sonicator instrument, avoiding high temperature calcination step using zinc acetate and NaOH as precursors. Spherical nanoparticles with diameter varying between 20 to 100 nm were synthesized effectively. The difficult component in chemical synthesis route is controlling the size and shape precisely. In chemical synthesis, the size and shape of nanoparticle is controlled and modified by capping agents like different biomolecules and surfactants such as CTAB, TEA, Chitosan, Cyclodextrin etc.

Prasad *et al*. (2012) reported synthesis of ZnO nanoparticles by oxalate decomposition method (hydrothermal method) where capping agent is oxalate molecule, while Sridevi *et al*. (2009) reported low temperature CTAB assisted hydrothermal method for the synthesis of ZnO nanoparticles where the size is less than 100 nm.

Barreto *et al.* (2013) prepared zinc oxide nanoparticle via microwave irradiation at different temperature 80, 100, 120, or 140°C using sodium di-2-ethylhexyl-sulfosuccinate aqueous solution, NaOH, KOH and NH_4OH as precursor salt.

Nafees *et al*. (2013) fabricated pure ZnO and Al-doped ZnO nanomaterial have been successfully by using zinc acetate dihydrate in a basic aqueous solution of KOH through solution precipitation method then treated at 600°C in air.

Kumar *et al.* (2013) synthesized ZnO NPs by simple precipitation method, to the aqueous solution of zinc sulfate, sodium hydroxide solution was added slowly dropwise in a molar ratio of 1:2 under vigorous stirring, and the stirring was continued for 12 hr. The precipitate obtained was filtered and washed thoroughly with deionized water. The precipitate was dried in an oven at 100°C and ground to fine powder using agate mortar. The powder obtained from the above method was calcined at different temperatures such as 300°C, 500°C, 700°C and 900°C for 2 hr.

Bagheri *et al.* (2013) synthesized zinc oxide (ZnO) nanoparticles by precipitation method by using zinc nitrate and urea in aqueous solution the obtained precipitated compound was calcined and structurally characterized by Powder X-ray diffraction (XRD), Thermogravimetric analysis (TGA), Scanning electron microscopy (SEM), Transmission electron microscopy (TEM), Fourier transform infrared spectroscopy (FTIR) and UV-Vis spectroscopic techniques. The FTIR results shows the existence of OH^-, NO^{2-}, CO, CO_2 groups in uncalcined sample. The band gap was higher for synthesized ZnO particles than their bulk counterparts. The results indicate that urea is an attractive material that can be used as precipitation agent for preparing ZnO.

Swaroop and Somashekarappa (2015) synthesized zinc oxide (ZnO) nanoparticles by co-precipitation method using zinc acetate dihydrate [$Zn(CH_3COO)_2.2H_2O$] and sodium hydroxide (NaOH) as precursor materials. They found that size varying from 16 to 31 nm.

Ghorbani *et al*. (2015) synthesized ZnO nanoparticles using zinc nitrate and KOH in aqueous solution. The precipitated compound was calcined and characterized by UV-Vis spectroscopy, transmission electron microscopy (TEM), and dynamic light scattering (DLS). The ZnO nanoparticles displayed characteristic Surface Plasmon Resonance peak at around 372 nm. Particle size distribution by dynamic light scattering technique (DLS) showed that the particles are in the range of 30±15 nm.

Hasnidawani *et al.* (2016) synthesized ZnO NPs via sol gel method using zinc acetate dehydrate [$Zn(CH_3COO)_2.2H_2O$] as a precursor and ethanol as solvent, while, NaOH and distilled water were used as medium. Result of EDX characterization showed that the ZnO NPs has good purity with (Zn: 55.38% and O_2: 44.62%). While, XRD result spectrum displayed mainly O_2 and Zn peaks, which indicate the crystallinity in nature as exhibited. The FESEM micrographs shows that synthesized ZnO have a rod-like structure. The obtained ZnO NPs are homogenous and consistent in size which corresponds to the XRD result that exhibit good crystallinity. Through this method ZnO NPs were successfully synthesized in nano- size range within 81.28 nm to 84.98 nm.

Large-scale and inexpensive synthesis of ZnO NPs can also be performed using a simple mixing technique of precipitation. As demonstrated by Sadraei (2016), $ZnSO_4$ and NH_4OH can be used as precipitating agent in aqueous solutions. Alkali solution (25% NH_4OH) was slowly dropped into the mother solution of 0.2 M $ZnSO_4$ at controlled temperature of about 50-60ºC before drying at 60ºC for 8 hours in oven. Characterization done through SEM images, EDX and XRD pattern indicated that the prepared ZnO NPs have uniform structure (average of particle size about 30 nm) and high purity.

Tiwari (2017) synthesized ZnO NPs by oxalate decomposition technique (hydrothermal method). First the zinc oxalate was prepared through mixing equimolar (0.2 M) solution of zinc acetate and oxalic acid. The resultant precipitate was collected and rinsed extensively with deionized water and dried in air to obtain zinc oxalate. Subsequently, the zinc oxalate was ground and allowed to decompose in air for 45 min inside pre-heated furnace at a temperature of 500°C. The ZnO NPs thus formed were quite uniform with size of 65 nm.

Awasthi *et al.* (2017) synthesized of Zno NPs by Zinc acetate was used as a precursor for the synthesis of ZnO nanoparticles. 3.07 g (0.2 M) of zinc acetate dihydrate was dissolved in 70 mL of distilled water and stirred for 30–40 min. Another solution of 5 g dried green tea leaf powder in 100 mL of distilled water was prepared with stirring for 2 h at 80ºC then cooled to room temperature and filtered through Whatman filter paper. 30 mL of this green tea extract was mixed homogeneously with the zinc acetate solution. The solution was filtered and dried at room temperature. The obtained powder was annealed at 300ºC for 1 h. Brown coloured ZnO nanoparticles were obtained. Obtained the particle size has been found to be 13± 2 nm.

Haripriya *et al.* (2019) synthesized ZnO-NPs by direct precipitation method using zinc sulphate and sodium hydroxide as precursors to the aqueous zinc sulphate (heptahydrate), sodium hydroxide was added drop-wise in the ratio (1:2) under vigorous stirring for 12 hrs. The white precipitate obtained was centrifuged at 5000 rpm for 20 min. and washed three times with deionized double distilled water. The synthesized ZnO NPs was monitore by UV- VIS spectrum from 200 nm to 500 nm for confirmation of nanoparticle formation.

II. Top down approach

Yang *et al.* (2004) reported synthesis of ZnO nanoparticles by thermal decomposition using zinc acetate and capping agents like β-Cyclodextrin (β-CD), amylose and poly ethylene oxide (PEO). Among the selected capping agents, β- Cyclodextrin (β-CD) was proved to be the most favourable for preparation of uniform ZnO nanoparticles with mean size of 18-20 nm range.

Top down approach involves physical methods such as mechanical attrition or milling or grinding of macro particulates into micro particles and so forth. It has been shown that there is an equilibrium limit to the size of particle that could be achieved by mechanical grinding, such as ball milling, and this could be as high as 300 nm (Yokoyama and Huang, 2005).

Shen *et al.* (2006) reported controlled mechano-chemical synthesis of ZnO NPs in presence of oxalic acid and zinc acetate. The initial reactant mixture of zinc acetate and oxalic acid was milled from 30 minutes to 4 hours and thermally treated at 450°C for 30 minutes. The ZnO NPs thus formed were quite uniform with size range of 20-40 nm.

2.3.2 Zinc Nutrition through Nanotechnology

Nano-fertilizer technology is very innovative but scantily reported in the literature. However, some of the reports and patents strongly suggest that there is a vast scope for the formulation of nano-fertilizers. Significant increase in yields have been observed due to foliar application of nano particles as fertilizer (Tarafdar *et al*. 2012b). It was shown that foliar application 40 ppm concentration of nanophophorous (640 mg ha^{-1}) gave 80 kg ha^{-1} P equivalent yield of cluster bean and pearl millet under arid environment.

Currently, research is underway to develop nano-composites to supply all the required essential nutrients in suitable proportion through smart delivery system. Preliminary results suggest that balanced fertilization may be achieved through nanotechnology (Tarafdar *et al*. 2012a). Indeed, the metabolic assimilation within the plant biomass of the metals e.g. micronutrients, applied as nano-formulations through soil-borne and foliar application or otherwise needs to be ascertained.

Further, the nano-composites being contemplated to supply all the nutrients in right proportions through the “smart” delivery systems also needs to be examined closely. Currently, the nitrogen use efficiency is low due to the loss of 50-70 percent of the nitrogen supplied in conventional fertilizers. New nutrient delivery systems that exploit the porous nano scale parts of plants could reduce nitrogen loss by increasing plant uptake. Fertilizers encapsulated in nanoparticles will increase the uptake of nutrients (Tarafdar *et al*. 2012c). In the next generation of nano fertilizers, the release of the nutrients can be triggered by an environmental condition or simply released at desired specific time.

Nano scale carriers can be utilized for the efficient delivery of fertilizers, pesticides, herbicides, plant growth regulators, etc. The mechanisms involved in the efficient delivery, better storage and controlled release include: encapsulation and entrapment, polymers and dendrimers, surface ionic and weak bond attachments among others. These help to improve stability against degradation in the environment and ultimately reduce the amount to be applied, which reduces chemical runoff and alleviates environmental problems. These carriers can be designed in such a way that they can anchor plant roots to the surrounding soil constituents and organic matter. This can only be possible if we unravel the molecular and conformational mechanisms between the nano scale delivery and targeted structures and soil fractions. Such advances as and when they happen will help in solving the uptake of active ingredients, thereby reducing the amount of inputs to be used and also the waste produced.

Nanotechnology is an interdisciplinary research field. In recent past efforts have been made to improve agricultural yield through exhaustive research in nanotechnology. The green revolution resulted in blind usage of pesticides and chemical fertilizers which caused loss of soil biodiversity and developed resistance against pathogens and pests as well. Nanoparticle-mediated material delivery to plants and advanced biosensors for precision farming are possible only by nanoparticles or nanochips. Nano encapsulated conventional fertilizers, pesticides and herbicides helps in slow and sustained release of nutrients and agrochemicals resulting in precise dosage to the plants (Duhan *et al*. 2017).

Nanoparticles have smaller particle sizes, higher specific surface area and an increased proportion of reactive surface atoms as compared to bulk particles (Wigginton *et al*. 2007). Since engineered nanoparticles do not occur naturally in the environment so, they are intentionally synthesized for specific applications. The Anonymous (2005) has grouped manufactured nanomaterials into four types: (i) carbon (C)-based nanoparticles that are composed entirely of C; (ii) metal-based materials such as nano-Zn, nano-Al, and nano-scale metal oxides like TiO_2, ZnO, Fe_2O_3, Al_2O_3; (iii) dendrimers; which are nano-sized polymers built from branched units capable of being tailored to perform specific chemical functions; and (iv) composites, which combine nanoparticles with other nanoparticles or with bulk materials.

NPs, considering the building blocks of nanotechnology (Stern and McNeil, 2007) have at least one dimension at 100 nm or less, which provides a high surface/volume ratio, leading to high reactivity (increasing the potential to cross cell membranes) (Farré *et al*. 2011). The use of nanoparticles in agriculture is a promising area which could potentially improve prevailing crop management techniques in long term prospective. One potential application of nanotechnology in soil science is to address issues related to micronutrients deficiency, which is one of the major problems in agricultural productivity.

In recent years, the application of nano scale particle of Zn is being preferred to enhance the uptake by plants. Particle size may affect agronomic effectiveness of Zn fertilizers. Decreased particle size results in increased number of particles per unit weight of applied Zn and also increases the specific surface area of a fertilizer, which will increase the dissolution rate of fertilizers with low solubility in water such as Zn oxide (ZnO) (Mortvedt, 1992). Granular Zn sulphate ($ZnSO_4$) (1.4 to 2 mm) was somewhat less effective than fine $ZnSO_4$ (0.8 to 1.2 mm) whereas, granular ZnO was completely ineffective (Allen and Terman, 1966).

Gradual increase in Zn uptake could be observed with decreasing granule size. Since granules of 1.5 mm weigh less than granules of 2.0 or 2.5 mm, smaller granules were used for the same weight, resulting in a better distribution of Zn and the higher surface area of contact of Zn fertilizer resulted in better Zn uptake (Liscano *et al*. 2000) Therefore, ample work has been done and emphasis was made on the particle size to increase the efficiency of the fertilizers for better uptake and higher yields.

Prasad *et al*. (2012) studied that effectiveness of ZnO was studied on seed germination, seedling vigour, plant growth, flowering, chlorophyll content, pod yield and root growth of peanut. Peanut seeds which are treated with different concentrations of nano ZnO along with chelated Zn Sulphate ($ZnSO_4$). Treatment of nano scale ZnO (25 nm mean particle size) at 1000 ppm concentration promoted both seed germination and seedling vigour and in turn seedlings showed early establishment in soil. Higher leaf chlorophyll content and manifested by early flowering. These particles proved effective in increasing stem and root growth. Pod yield per plant was 34 percent higher compared to chelated bulk $ZnSO_4$.

Spraying optimum concentrations of nano-ZnO, nano- FeO and nano $ZnCuFe^-$ oxide nanoparticles in suspension form on hydroponically grown test units of Mung (*Vigna radiata* L.) seedling and examining the effect on the shoot growth of seedlings (Dhoke *et al*. 2013). It was found that the seedlings displayed good growth over control, demonstrating a positive effect of the nanoparticle treatment. The best performance was observed for nano Zn/CuFe-Oxide followed by nano FeO and nano ZnO. Increased absorption of nanoparticles by plant leaves was also detected by inductive coupled plasma/atomic emission spectroscopy.

Mahajan *et al*. (2011) conducted an experiment in agar media. They studied the effect of nano ZnO particles on the growth of plant seedlings of mung (*Vigna radiate* L.) and gram (*Cicer arietinum* L.). Various concentrations of nano ZnO particles in suspension form were introduced to the agar media and their effect on the root and shoot growth of the seedlings was examined. The main experimental approach using correlative light and scanning electron microscopy provided evidence of adsorption of nanoparticles on the root surface. Absorption of nanoparticles by seedlings root was also detected by inductive coupled plasma/atomic emission spectroscopy (ICP-AES). It was found that at certain optimum concentration, the seedlings displayed good growth over control and beyond that retardation in growth was observed due to toxicity.

The solubility and particle size of Zn source in the conventional Zn fertilizers are among the main parameters that determine their effectiveness (Mortvedt, 1992).

Application of nanotechnological tools in Zn fertilizer formulations may improve their performance in enhancing crop yields. Since the dissolution kinetics of particles depends on surface area, it is expected that rate and extent of dissolution is greater for nanoparticles compared to that of micron sized particles and/or bulk materials (Borm *et al*. 2006).

The rapid development and potential release of engineered nanoparticles (ENPs) have raised considerable concerns due to the unique properties of nanomaterials. The impact of ENPs on plant varies, depending on the composition, concentration, size and other important physical chemical properties of ENPs and plant species. Both enhancive and inhibitive effects of ENPs on plant growth at different developmental stages have been documented. ENPs could be potentially taken up by plant roots and transported to shoots through vascular systems depending upon the composition, shape, size of ENPs and plant anatomy (Ma *et al*. 2010).

Mortvedt (1992) also cited that fine $ZnSO_4$ particles (1.4-2.0 mm and 0.8-1.2 mm in diameter). Additionally, when smaller Zn particles are used, then number of Zn particles per unit of applied Zn to soil would increase. Owing to all these characteristics, nano Zn formulations are expected to enhance dissolution rate of Zn sources, especially in Zn sources with lower solubility such as ZnO.

In addition, ZnO nanoparticles is the most common Zn nanomaterial which is being used as UV protector (e.g. in personal care products, coatings and paints), biosensors, electronics, and rubber manufacture (Brayner *et al*. 2010 and Kool *et al*. 2011). The wide range of industrial applications for ZnO nanoparticles can predict future increase in the production volume of these nanoparticles by developing economical synthesis methods and reducing the manufacture costs. Hence, economical application of ZnO nanoparticles as Zn fertilizers can turn out to be practical in large scale globally.

The integration of nanotechnology in fertilizer products can improve fertilizer use efficiency and significantly increase of barley yield. However, plant response to nanoparticles significantly depends on concentration and time of application as well as size, shape, and surface functionalization of the particles (Janmohammadi *et al*. 2016).

Moreover, nanotechnology may assist fertilizer industry by designing Zn fertilizers which could release Zn on demand and therefore preventing the interactions of Zn in soil with soil compartments, water and microorganisms which reduce availability of Zn for crops (DeRosa *et al*. 2010). However, it is important to consider that different properties of soils (pH, ionic strength, organic matter, solid phases etc.) may strongly affect the fate of nanoparticles in the soil. Therefore, the behaviour of nanoparticles can deviate from the ones theoretically expected.

NPs have been extensively used as antimicrobial agents against pathogenic bacteria, but this abusive use is leading to negative consequences against the populations of soil microbes that play beneficial roles in the environment, such as promoting plant growth, element cycling, and degradation of pollutants. The NPs of Ag, CuO, and ZnO showed both toxicity on pathogenic bacteria (e.g., *Escherichia coli* and *Staphylococcus aureus*) and beneficial effects on microbes, as *Pseudomonas putida*, which has bioremediation potential and is a strong root colonizer (Molina *et al*. 2006 and Ramos-González *et al*. 2005). These NPs showed higher toxicity when compared to their equivalent bulk materials (Gajjar *et al*. 2009 and Hardman, 2005).

So far, research on the transformation of ZnO nanoparticles in soil-plant system is in infancy stage. Hence, it is critical to develop understanding on the fate and behaviour of ZnO NPs in soils and their possible influence on the Zn uptake by plants in Zn deficient area. A proactive understanding of the environmental impact and fate of nanotechnology-based products is needed to ensure safe and sustainable use of nanoparticles in agriculture and better management of their associated risks (Thomas *et al*. 2011, Bernhardt *et al.* 2010, Klaine *et al*. 2008, Rickerby and Morrison, 2007 and Weisner *et al.* 2006). Thus, this study presents the use of in-house synthesized ZnO nanoparticles and its effect on the wheat yield.

2.4 Effect of Nano Fertilizers on Growth and Yield Attributes

Increased seed Zn content from 0.25 to 0.70 µg per seed significantly improves the shoot and root growth of wheat under Zn deficiency in pot culture experiments (Rengel and Graham, 1995).

Yilmaz *et al.* (2005) revealed that plants emerging from wheat seeds with low Zn content have poor field establishment and seedling vigour on Zn-deficient soils.

The effects of five types of nanoparticles (multi-walled carbon nanotube, aluminum, alumina, zinc and zinc oxide) on the germination and growth of the roots of the six species of higher plants (radish, rapeseed, ryegrass, lettuce, corn and cucumbers) has been studied by Lin and Xing (2007). The results revealed that the germination of the seeds was not affected except for the inhibition of germination on ryegrass by nanoscale zinc and nano-ZnO on maize at 2000 mg L^{-1}. Inhibition of root growth varied widely between nanoparticles and plants. Suspensions of 2000 mg L^{-1} nano-Zn or nano-ZnO practically inhibit the root elongation of the tested plant species. These results clearly show that at low concentrations either Zn or ZnO nano particles may be beneficial in enhancing crop growth and development.

Jian *et al.* (2008) conducted an experiment to explore the application effect of high amount of nano-synergism fertilizer on winter wheat and reported 12.34 percent -19.76 percent significant increase in wheat yield due to application of nano-fertilizers. The yield of wheat applied by the high amount urea fertilizer was reported to be 2.31 percent than that of wheat applied by the low amount nano-synergism fertilizer (10 kg ha^{-1}).

Habib (2009) reported that, the yield of wheat grains was increased significantly by foliar application of zinc and iron either alone or in combination and the highest seed yield was recorded in the case of combined application of zinc and iron than no application of Iron and Zinc in comparison.

Application of ZnO NPs (10-1000 mg L^{-1}) results in 100 percent germination of rice seeds because ZnO NPs did not affect the seed germination. Little increase in number of roots and root length was observed at low concentration i.e. 10 mg L^{-1}. However, a higher concentration of ZnO NPs is toxic to rice roots was evident from number of roots and root length (Boonyanitipong *et al.* 2011).

Du *et al.* (2011) reported that, the biomass of wheat was reduced when the plants were grown in the soil supplied with titanium dioxide and zinc oxide nano-particles because of over exploitation of these nano-particles by the plants.

Mustafa *et al.* (2011) observed that Zn application had significantly pronounced effect on growth and yield of rice. Maximum productive tillers m^{-2} (249.80) and maximum grain yield (5.21 t ha^{-1}) were noted with basal application at the rate 25 kg ha^{-1}, 21 percent $ZnSO_4$ and minimum productive tillers (220.28) and minimum grain yield (4.17 t ha^{-1}) was noted in foliar application at 75 DAT @ 0.5 percent Zn solution.

Fan *et al*. (2012) showed that significantly higher dry biomass of aerial part of rice A1 (N 215 kg hm^{-2} + nano-carbon 1.194 kg hm^{-2}), A2 (N 150.5 kg hm^{-2} + nano carbon 0.836 kg hm^{-2}) and A3 (N 107.5 kg hm^{-2} + nano carbon 0.597 kg hm^{-2}) treatments with 58, 15.7 and 19.3 % compared to B1 (N 215 kg hm^{-2}), B2 (N 150.5 kg hm^{-2}) and B3 (N 107.5 kg hm^{-2}) treatments, respectively. The yield obtained under combined application of N and nano-carbon were higher than those in treatments received only nitrogenous fertilizer. The yield of A1, A2 and A3 treatments were 18.36 per cent, 8.51 per cent and 10.19 per cent higher compared to B1, B2 and B3.

The average time of higher germination and lower (0.89 versus 1.35 days) was observed at 10 ppm concentration of nanosized TiO_2 and control treatments, respectively. Additionally, shoot length, the length of seedlings and root dry matter were influenced by the mass concentrations and nano sized TiO_2 concentrations significantly. At 2 and 10 ppm concentrations of nano sized TiO_2 the shoot length and length of seedlings were greater than those of the untreated control. The use of nano sized TiO_2 concentration would adequately promote the germination of wheat seeds with respect to bulk TiO_2 but in high concentrations had inhibitory effect on wheat. At 100 ppm nano sized TiO_2 and 2 ppm bulk TiO_2 treatments recorded the lowest shoot length (Hassan *et al.* 2012).

Rajendran and Kannan (2012) reported the germination percentage increased (95.5 %), dry weight (6.52 ± 0.2), the accumulation of silica (18.2%), and better nutrient alleviation in seeds exposed to nano-SiO_2 compared to those exposed to the bulk sources. Corn seeds and roots during pot experiments absorbed nano-SiO_2 better when compared with absorption of other micron sources which led to the conclusion that nano-SiO_2 can be used as an immediately usable for the plants.

Priester *et al*. (2012) reported that, the soybean plants grown on the soils mixed with ZnO and CeO_2 nano-particles showed a significant increase in their pod and seed biomass when compared to that of control, whereas, the reduced growth in case of CeO_2 nano-particles treated plants indicated the differential behavior of the soybean plants to the two types of nano-particles.

The growth characteristics were affected as the concentration of silica nanoparticles (SNPs) up to 15 kg ha^{-1} whereas, 20 kg ha^{-1} has no significant increased were observed.

Silica accumulation in leaves was higher in SNP concentrations 10:15 kg ha^{-1} (0.57 % and 0.82%) concentrations of SNPs. Physiological changes observed indicate that the expression of organic compounds such as proteins, chlorophyll and phenols favoured treated silica nano especially 15 kg ha^{-1} compared to controls and corn bulk silica. Silica nanoscale regimes 15 kg ha^{-1} have a positive mass silica response helped improve sustainable agriculture of maize crop as an alternative source of silica fertilizer (Suriyaprabha *et al.* 2012).

Afshar *et al.* (2013) evaluated the impact of nano-iron on cowpea crop under irrigation deficit and found significant increase in number of seeds per pod. It was observed that increasing nano-iron concentration increased number of seeds per pod but decreased 1000-seed weight significantly in cowpea.

Ghafari and Jamshid (2013) revealed the influence of foliar application of nano-iron oxide (2 and 4 g L^{-1}), iron chelate (4 and 8 g L^{-1}) and iron sulphate (4 and 8 g L^{-1}) on grain yield, yield components, chlorophyll content of the leaves, the content of carotenoids, peroxidase (POX), catalase (CAT) activity and wheat bread ascorbate peroxidase (APX). The results suggest that fertilization of Fe increased the antioxidant enzyme activities and chlorophyll content, yield components and the quality of the grain however, application of 2 g L^{-1} iron oxide nano was more effective than other sources.

Ghafari and Razmjoo (2015) from Iran conducted an experiment to study the effect of foliar application of nano-iron oxide (2 and 4 g L^{-1}), iron chelate (4 and 8 g L^{-1}) and iron sulphate (4 and 8 g L^{-1}) and reported that harvest index, 1000 grain weight and grain yield of wheat was significantly higher due to application of iron sulphate (8 g L^{-1}) and iron oxide (2 g L^{-1}), but these parameters decreased when higher concentration of nano-iron oxide (4 g L^{-1}) was applied to the crop.

Hadiat and Salama (2013) observed that small concentrations of silver nanoparticles have a stimulating effect on the growth of corn and *Phaseolus vulgaris* L. plants. While increased concentrations induce an inhibitory effect. However, the increase in the concentration of silver nanoparticles of 20 to 60 ppm has led to an increase in outbreaks and longitude roots, the surface of the sheet, chlorophyll, carbohydrate and protein content of the two systems tested culture. In addition, it was found that the lowest amount of these parameters with the control plants, but the level of improvement of silver nanoparticles with a consequent reduction of these compounds.

Jaberzadeh *et al.* (2013) conducted a field experiment to study the influence of bulk and nano titanium dioxide particles in wheat and reported that titanium dioxide nanoparticles under water deficit stress increased the yield and yield components such as ear number, 1000-seed weight, highest biomass and harvest index at 0.02 percent concentration and above than control and other treatments in comparison.

Morteza *et al.* (2013) conducted tests on the effect of treatments of titanium dioxide spray on corn (*Zea mays* L.) and reported that application of nano TiO_2 sprays increased crop yield significantly than control and other treatments in comparison.

Nadi *et al.* (2013) conducted a research experiment to study the effect of time and concentration of nano-Iron on yield and yield components of faba bean and the results showed that increase of nano-Iron concentration had a positive and significant effect on grain yield. Moreover, spraying at vegetation period had the lowest effect on grain yield, whereas the highest grain yield was obtained with spraying nano-Iron @ 6 g L^{-1} water during flowering period.

Application of nano-K fertilizer at the rate of 20 kg K_2O ha^{-1} showed significant increase in grain yield over 0 kg K_2O ha^{-1}. Yield difference between nano-K and MOP treated plots was significant and the yield increase by nano-fertilizer over MOP at 20 kg K_2O ha^{-1} is 8 per cent. Difference in yield between 20, 30 and 40 kg K_2O ha^{-1} was not significant when K was applied as nano-K fertilizer. Application of 20 kg K_2O ha^{-1} only at basal is enough to obtain the yield that obtained with MOP at 40 kg K_2O ha^{-1} (Sirisena *et al.* 2013).

Ghahremani *et al.* (2014) conducted a greenhouse experiment in order to investigate the effects of different levels of nano-calcium and nano-potassium chelate fertilizers on quantitative and qualitative characteristics of Basil and reported that application of nano-calcium and nano-potassium chelate fertilizers resulted in significant increase in 1000-seed weight, harvest index, grain yield and biological yield than check and other treatments in comparison.

Armin *et al.* (2014) conducted an experiment to study the effect of different concentrations and different application times of Nano-Fe fertilizer on wheat crop and observed that increasing concentration of nano-fertilizers and time of application had a significant effect on tillers number, seeds per spike, grain yield, biological yield and 1000-grain weight. He reported that foliar application of Fe at tillering + stem elongation and at tillering had 9.17 percent and 5.19 percent more grain yield, respectively as compared to foliar application of Fe at stem elongation.

Farnia and Ghorbani (2014) conducted research in order to study the effect of Nano and Bio fertilizers on yield and yield components of red bean (*Phaseolus vulgaris* L.) and reported significant increase in yield attributes and yield of red bean increased with application of N bio-fertilizer and nano-fertilizers.

Harsini *et al.* (2014) from Iran conducted research in order to study the effects of foliar application of iron nano-chelated fertilizers on yield and yield components of wheat and the results revealed that application of foliar application of nano iron -chelate on wheat cultivars resulted in significant increase in spike number, 1000-grain weight, grains number per spike, biological yield, grain yield and harvest index in wheat crop than control and other treatments in comparison. The highest grain yield, biological yield and harvest index of treatment a1b5 sprayed at tillering stages.

Kumar *et al.* (2014) based on an experiment conducted at Pant Nagar to study the effect of nano-fertilizers of gypsum and rock phosphate at the rate of 3 kg ha^{-1} on wheat crop and reported that yield parameters and yield obtained at 50 percent RDF with nano-materials was almost statistically similar with 100 % RDF without nano-materials.

Mohammad *et al.* (2014) reported that the application time had a significant effect on number of tillers, seeds per spike, grain yield, biological yield and thousand kernel weight. Foliar spray of nano Fe chelates at tillering + stem elongation and tillering had 9.17 percent and 5.19 percent more grain yield respectively, compared to the foliar application of Fe at stem elongation. Increasing Nano-Fe concentration, increased wheat yield and yield attributes. Foliar application of Fe at 2 percent, 4 percent and 6 percent produced an increase of 12 percent, 22.09 percent and 19.07 percent grain yield, respectively over the control.

Reazaei *et al.* (2014) conducted an experiment to investigate the effect of foliar application of iron nano-chelated fertilizers on three wheat cultivars and the results revealed that foliar application of iron nano-chelated fertilizers resulted in significant increase in the yield attributes *viz.* spike number, grain per spike, 1000-grain weight, biological yield and harvest index besides the grain yield of wheat than control and other treatments in comparison.

Reazaei and Abbasi (2014) conducted an experiment to compare the effects of mineral fertilizer of zinc (Mi), chelate of zinc (Ch) and nano chelate of zinc (NCh) on the growth, physiological and some biochemical process of the cotton plant and reported that application of zinc chelates and specially the nano-chelate of zinc resulted in significant increase in yield of cotton by significantly increasing the yield attributes like number of bolls per plant and mean weight of 20 bolls.

Tarafdar *et al.* (2014) conducted an experiment by using zinc nano-fertilizers to enhance crop production in pearl millet (*Pennisetum americanum* L.) cv. HHB 67 and reported a significant increase in the grain yield and chlorophyll content (24.4 %) at crop maturity to an extent of 37.7 percent owing to the use of these zinc nano-fertilizer than control and other treatments in comparison.

Asadzade *et al.* (2015) investigated the effect of foliar application of conventional and nano-fertilizers (ZnO and SiO_2) on yield and harvest index of sunflowers. Application of ZnO nano-fertilizer was found to increase head diameter, seed yield, 1000-seed weight and number of seeds per head significantly than other treatments and control plot in comparison.

Benzon *et al.* (2015) conducted an experiment to determine the effects of nano-fertilizer on the growth, development, yield and chemical properties of rice. The results revealed that the full recommended rate of conventional and nano-fertilizer enhanced the grain yield and yield attributes *viz.* chlorophyll content, number of reproductive tillers, panicles, panicle weight, total grain weight (unpolished-17.5 %, polished - 20.7 %), total shoot dry weight and harvest index than control and other treatments in comparison.

Bakhtiari *et al.* (2015) studied the effect of different concentration of Fe nano-oxide solution at five levels (0, 0.01, 0.02, 0.03 and 0.04 %) of wheat and reported that that significantly higher spike weight, 1000 grain weight, biological yield, and grain yield were achieved in plants treated with 0.04 percent Fe nano-oxide concentration and the lowest values were achieved in the control i.e. no application of Fe nano-oxide.

Benzon *et al*. (2015) reported synergistic effect of the nano-fertilizers on the efficacy of conventional fertilizer for better nutrient absorption by plant cells resulting to optimal growth plant parts and metabolic process such as photosynthesis leads to higher photosynthates accumulation and translocation to the economic parts of the plant, thus resulting in high yield which may be attributed to increased source (leaves) and sink (economic part) strength.

Dolatabadi *et al*. (2015) conducted an experiment in order to investigate the effect of exogenous application of nano-TiO_2 in annual medic (*Medicago scutellara L.)* with six concentrations of nano-TiO_2 (Control, 0.01, 0.02, 0.03, 0.04 and 0.06 %) and two stages of application i.e. pod stage and 10 percent flowering stage and reported that application of nano - TiO_2 resulted in significant increase in dry forage yield of the crop. Among the different stages of application of nano-fertilizers the seed yield of annual medic was significantly higher than yield at 10 percent flowering stage.

Farnia and Omidi (2015) showed that use of Zn nano fertilizer and nano biofertilizer treatment recorded significantly higher (17000 kg ha^{-1}) biomass yield and control treatment had the lowest (11000 kg ha^{-1}) biomass yield in maize. They also studied the comparison of the mean values of the grain yield for interaction between water stress and Zn nano fertilizer showed that 7 day irrigation period treatment with use of Zn nano fertilizer had the higher (10.5 t ha^{-1}) grain yield and nano application of Zn nano fertilizer in 21 day irrigation period treatment recorded lower grain yield (2.7 t ha^{-1}).

Kumar *et al.* (2015) reported that nano-ZnO and nano-Fe_2O_3 promoted root and shoot elongation of wheat at low concentration (up to 50 and 20 mg L^{-1}, respectively), then a drastic decrease occurred up to 100 mg L^{-1} nano particle concentration, and there after the growth was restricted. Fullerene nano particles didn’t show significant effects on root and shoot growth of wheat.

The experiment conducted by Yang *et al.* (2015), revealed at lower concentration of ZnO NPs, the germination of maize and rice seed was not affected. In spite of this the higher concentration of 2000 mg L^{-1} the root elongation was significantly inhibited by ZnO nano particles (50.45 % for maize and 66.75 % for rice). Later, they revealed that the phytotoxic effects of ZnO NPs (25 to 2000 mg L^{-1}) was dependent on concentration and it was not caused by the corresponding Zn^{2+}.

Zhao *et al.* (2015) showed that nano cerium oxide (CeO_2) and nano ZnO 400 and 800 mg kg^{-1} changed the concentration of calcium in kernels compared to control. In nano CeO_2 treated plants Cu, K, Mn and Zn were mainly localized at the insertion of kernels into cobs but Ca and Fe were distributed in other parts of the kernels. They also revealed that application of nano CeO_2 and nano ZnO reduced the corn yield and altered quality of corn.

The germination test carried out with ZnO NPs coated and uncoated seeds of maize results in better germination percentage (93-100 %) due to ZnO coating as compared to uncoated seeds (80 %). Pot culture experiment was conducted with coated seeds also indicated that the crop growth with ZnO coated seeds were similar to that observed with soluble Zn treatment applied as $ZnSO_4$ at 2.5 ppm Zn. The most important advantage of seed coating with ZnO NPs is that it did not exert any osmotic potential during time of germination of the seed. Hence, the total Zn requirement of the maize can be applied with the seed effectively through nano ZnO particles (Adhikari *et al.* 2016a).

Adhikari *et al.* (2016b) reported that the application of ZnO NPs at relatively lower level enhanced the growth of maize plant as compared to conventional Zn fertilizer i.e. $ZnSO_4$ under solution culture study.

ZnO NPs significantly influenced the growth, yield and Zn content of maize grains (Subbaiah *et al.* 2016).

On the other side, Cu being an essential micronutrient Cu NPs positively influence growth of maize plant by assimilating into the metabolic routes of plant and regulating the enzymatic activities. Apart from that, Mn and Fe nanoparticles delivery have been reported to display positive impacts on the seed germination and were also enhanced agronomic productivity (Adhikari *et al.* 2016b).

Mohsen *et al*. (2016) reported that zinc nano-chelate with nano TiO_2 (2000 ppm) as foliar spray could increase most of the important traits of barley such as thousand grain weight, grain yield, straw yield and harvest index and resulted in sustainable and high crop production with foliar application of nanoparticle.

Meena *et al.* (2017) revealed that among the different concentrations of nano zinc oxide 1000 and 1200 ppm recorded 100 per cent germination of maize seeds. However, 1200 ppm nano zinc oxide recorded higher root length (6.5 cm), shoot length (3.9 cm) and seed vigour index (1040) as compared to other concentrations. Lowest germination was recorded under 1600 nano zinc oxide treatment (40 %).

Beeresha (2018) opined that application of K_2O at 15 kg ha^{-1} and foliar application of 2500 ppm nano K_2O to the maize crop recorded significantly higher plant height (218 cm), number of leaves per plant (10.8), leaf area (3636 cm^2), chlorophyll content (64.82 µmol m^{-2}) and also yield attributes like cob length (17.9 cm), number of kernels per cob (41.3), test weight (34.80 g), kernel yield (9051 kg ha^{-1}), stover yield (11667 kg ha^{-1}) and harvest index (0.44).

Manikandan and Subramanian (2016) evaluated the response of maize plants to the zeolite based nitrogen nano-fertilizers and conventional fertilizers in two greenhouse experiments of two distinct soil textures (Inceptisol – Periyanayakkan palayam soil series – clay loam and Alfisols - regur soil series- sandy loam) and reported that, the grain yield of maize was significantly higher for nano-zeolite urea treatment than control (conventional urea treatment) in comparison.

Munir *et al*. (2018) reported that the application of ZnO NPs 100 mg L^{-1} in wheat improved stomatal conductance by 102% compared to control, transpiration rate was 62 percent higher than control treatment and also significantly increases in photosynthetic rate, stomatal resistance, intercellular CO_2 concentration.

Prajapati *et al*. (2018) showed that application of foliar application Nano zinc at 1000 ppm recorded maximum no. of tillers $plant^{-1}$ (9.30), plant height (93.60 cm) and length of spikelet (11.82 cm).

Rudani *et al.* (2018) concluded that zinc is plays a significant role in photosynthesis, cell membrane integrity, protein synthesis, pollen formation and chlorophyll within plant species.

2.5 Effect of Nano Fertilizers on Nutrient Uptake

Naik and Das (2007) observed the maximum Zn content of grain and straw (38.19 and 18.27 mg kg^{-1}) were found in the treatment receiving 1.0 kg Zn ha^{-1} as Zn-EDTA as basal application than that of 10 and 20 kg Zn ha^{-1} as inorganic $ZnSO_4$ application.

In the study carried out in a clay loamy soil, Du *et al.* (2011) investigated the effect of applying ZnO NPs on growth of wheat plants. The results indicated that Zn concentration of wheat tissue increased as a result of application of ZnO NPs to soil, however, no ZnO NPs were observed in primary root. Therefore, uptake of ZnO NPs may not be responsible for Zn accumulation in the plants and more likely it was dissolution of ZnO NPs during the 2 months incubation period which increased soil Zn availability.

Further they also reported that the titanium dioxide and zinc oxide nanoparticles were absorbed and accumulated in the tissues of wheat plants; particularly the zinc accumulation was significant, due to high dissolution rate of zinc oxide nanoparticles in the soil, when compared with that of titanium and control treatments.

Mahajan *et al.* (2011) observed that there was significant increase in zinc content in roots of mung and gram seedlings with the increase in nano ZnO applications indicating that the absorption and translocation of nanoparticles in the seedlings.

Fan *et al.* (2012) conducted an experiment to investigate the effects of combined application of nitrogen fertilizer and nano-carbon on nitrogen use of soil and rice yield to a rice cv. Changbai 10 and reported that the nitrogen uptake of plant was significantly increased owing to combined application of nitrogen fertilizer and nano-carbon fertilizers.

A significant increase in the zinc content of leaves and kernels by treating with nanoscale zinc oxide particles than that of chelated $ZnSO_4$ (Prasad *et al.* 2012) further they also found that the detrimental effects at higher concentrations of nano ZnO particles.

Ashrafi *et al.* (2013) conducted an experiment on soybean to evaluate the effect of nano-silver application and the results revealed that integrated use of compost, farmyard manure, nano-silver fertilizers and chemical fertilizers increased grain nitrogen, phosphorus and potassium uptake significantly than control and other treatments in comparison.

Jaberzadeh *et al.* (2013) through their studies on the wheat crop concluded that titanium dioxide nanoparticles under water deficit stress were able to increase the yield and yield components such as ear number, seed number per square meter, 1000 seed weight, highest biomass and harvest index as well as the more gluten and starch production.

Liang *et al*. (2013) used the flue-cured tobacco cultivar Zhongyan 100 in a pot experiment to examine the effects of the application of carbon Nano-particles (CNPs) in varying concentrations of 0, 25, 75 and 125 mg pot^{-1} and reported that, the application of CNPs increased the contents of nitrogen and potassium in tobacco plant organs. The potassium content of tobacco leaves increased by 21.05, 25.26 and 36.84 percent at the maturity stage, which was beneficial to quality improvement of tobacco.

Adhikari *et al*. (2014) conducted an experiment to evaluate the efficacy of different Nano RP at India Institute of Soil Science (IISS), Bhopal, taking maize as a test crop with five treatments (control, NK (100 %), NPK (100 %), NK (100 %) + 60 kg P_2O_5) Nano rock phosphate (Nano RP) through Udaipur Nano RP (34 % P_2O_5) and Udaipur Nano RP (31 % P_2O_5) and revealed that, the total P content and its uptake were higher (0.65 % and 40.29 kg/ha) in SSP treated plant, which was closely followed by Udaipur Nano RP 34 % (0.63 % and 38.29 kg/ha) over the control (0.60 % and 27.82 kg/ha). The SSP treated plants had significantly highest apparent P recovery (47.98 %) which was comparable to Udaipur Nano RP (34 % P_2O_5), whereas, the Udaipur Nano RP (31 % P_2O_5) had the lowest. The additional N and K uptake by the plant was also observed with application of P sources, which were ranged from 16.5 kg/ha to 37.2 kg/ha and 27.9 kg/ha to 64.7 kg/ha under different P treatments. These results showed that crop utilization of P from Nano RP was at par with that of P from SSP while yield response to P from Nano RP was marginally lower than to P from SSP but serve as a cheaper source.

Kumar *et al.* (2014) conducted on experiments at Pantnagar on effect of Nano-fertilizers of gypsum and rock phosphate at the rate of 3 kg/ha on the wheat and reported significant increase in nutrient uptake at 50 percent RDF with Nano-materials which was found to be at par with 100 percent RDF without Nano-materials.

Bakhtiari *et al*. (2015) results showed that Nano-Fe concentrations increased the highest values of spike weight (666.96 g), 1000 grain weight (37.96 g), biological yield (8895.0 kg ha^{-1}), grain yield (3776.5 kg ha^{-1}) and protein content (16.44 %) were achieved in 0.04 percent Nano-Fe concentration and the lowest values were achieved in the control.

Jhanzab *et al*. (2015) revealed silver nanoparticles in 25 ppm concentration have showed significant improvement in maximum leaf area and highest grain yield while 75 ppm concentration resulted in decrease in grain yield in wheat. Maximum number of grains per spike was recorded with 25 ppm followed by 50 ppm whereas maximum 100-grain weight was obtained for 25 and 125 ppm soil applied silver nanoparticles in wheat.

Liu *et al.* (2015) confirmed a high Zn bioavailability in ZnO NPs-spiked soil to maize as they observed significant positive correlations with ZnO NPs dose, indicating the Zn in plants is at least partly from ZnO NPs. Further, compared with bulk $ZnSO_4$, ZnO NPs produced similar plant Zn uptake or even higher shoot Zn concentration, indicating that the bioavailability of Zn released from ZnO NPs is similar to or higher than that from $ZnSO_4$. Another evidence was that soil DTPA- extractable Zn concentrations correlated significantly with ZnO NPs dose and Zn concentrations in plants, indicating ZnO NPs indeed released Zn ions other exchangeable forms into soil.

Recently, a review by Liu and Lal (2015) indicated that synthetic NPs had a great potential as fertilizers (including micronutrients) for increasing crop production and reduce adverse environmental impacts by excess nutrients from conventional fertilizer sources.

Watson *et al.* (2015) observed that phytotoxicity of ZnO NPs to young wheat seedlings was dependent on the soil properties. Phytotoxicity was observed in acid but not alkaline soils. However, although the extent of solubility of Zn from the NPs was a 100-fold less in the alkaline than the acid soil, an increased uptake of Zn into the shoots from the NPs occurred in the calcareous alkaline soil. These findings indicate that use of NPs such as ZnO NPs as a fertilizer or a pesticide would have to be tuned to the soil being treated to avoid phytotoxic effects yet retain beneficial Zn uptake.

On the contrary to these results mentioned above, ZnO NPs had also been reported to exhibit phytotoxicity in maize and cucumber (Zhang *et al*. 2015). However, the outcomes from many of the discrete studies of Zn-plant interactions suggest the potential use of commercial nanoparticles of ZnO as Zn sources in crops produced in Zn-deficient soils.

Chen *et al*. (2016) reported graphene oxide, a single atom thick and two dimensional sp^2 bonded carbon honeycomb lattice, was miscellaneously functionalized due to fascinating surface chemical characteristics, notably the large surface area and high-water solubility of graphene oxide nanosheets. GO is also commonly recognized as an important support material that can be hybridized with DNA, metal oxides, polymers and inorganic nanoparticles.

Manikandan and Subramanian (2016) evaluated the response of maize plants to the zeolite based nitrogen Nano-fertilizers and conventional fertilizers in two greenhouse experiments of two distinct soil textures and reported that, the nutrient uptake was significantly higher for Nano zeolite urea treatment than conventional urea.

Taheri *et al.* (2016) reported that the ZnO nanoparticles increased the shoot dry matter and leaf area indexes by 63.8 percent and 69.7 percent, respectively in mineral poor soils.

Skiba *et al.* (2020) mentioned zinc species affected Cu, Mn and Fe absorption and transport in pea plants at molecular and nanoscale levels. Significant reductions in Mn and Fe, as well as an increase in Cu, were found. The heavy metal uptake is influenced by nanoparticle-induced additive interactions, which also identify pathways for pollution movement in plants.

2.6 Effect of Nano Fertilizers on Quality Parameters

Qiang *et al*. (2008) conducted an experiment to evaluate performance of slow controlled release fertilizer made up of nano materials on quality of winter wheat and 18 summer corn and reported that application of these nano-fertilizers resulted in significant increase in protein content whereas soluble sugar content was found to be decreased in significantly by use of these fertilizers in comparison with conventional NPK chemical fertilizer.

Jian *et al*. (2008) conducted a research experiment to explore the application effect of nano-synergism fertilizer on winter wheat and reported that application of nano-synergism fertilizer resulted in decreased protein content of the wheat (7.52 %), whereas the fat content was increased significantly (33 %) upon application of these nano materials.

Ghafari and Razmjoo (2015) conducted an experiment to evaluate the effects of foliar application of nano-iron oxide (2 and 4 g/L), iron chelate (4 and 8 g/L) and iron sulphate (4 and 8 g/L) on quality of bread wheat (*Triticum aestivum* L.) and reported that significantly higher grain carbohydrate yield besides chlorophyll, grain protein and iron contents were observed with application of 8 g/L iron sulphate followed by application of 2 g/L of nano-iron oxide than control plots in comparison.

Nadi *et al*. (2013) conducted an experiment to study the effect of time and concentration of nano-Iron on yield and yield components of faba bean and reported that increase of nano-Iron concentration had a positive and significant effect on protein percent and chlorophyll content. Moreover, spraying at vegetation period had the lowest effect on grain protein percent. But, spraying at different periods had no significant effect on chlorophyll content.

Ramesh *et al*. (2014) reported significant increases of chlorophyll and protein content with low concentration nano-ZnO treated sample in wheat crop whereas and no changes was recorded w.r.t. bulk-ZnO and bulk and nano-TiO_2 treated samples.

Khater (2015) conducted an experiment to examine the effects of titanium dioxide nano particles reported that titanium dioxide (TiO_2) nano-particles (NPs) resulted in significant increase in amino acids, total sugars, total phenols, total indols and pigments in coriander.

Mir *et al*. (2015) conducted a research experiment to study the effect of nano and biological fertilizers on quality parameters viz. carbohydrate and chlorophyll content of forage sorghum and reported that the highest chlorophyll a (1.59 mg/g), chlorophyll b (5.31 mg/g), carotenoid (2.24 mg/g) and carbohydrate (3.24 mg/g) was achieved from combined use of bio-fertilizers (azetobarvar 1+ phosphorbarvar 2) + chelated nanofertilizers (Fe+k) treatments.

Manikandan and Subramanian (2016) evaluated the zeolite based nitrogen nanofertilizers on maize crop in two greenhouse experiments of two distinct soil textures (Inceptisol – Periyanayakkan palayam soil series – clay loam and Alfisols - Iregur soil series- sandy loam) and reported that the crude protein content of maize crop was significantly higher for nano-zeolite urea treatment in comparison to conventional urea.

Singh and Sindhu (2021) concluded that the application of 50 kg Zn ha^{-1} + 0.5 percent foliar spray at heading initiation and 100% heading significantly increased the β Carotene (4.23 ppm) over absolute control.

2.7 Effect of Nano Fertilizers on Nutrient Use Efficiency

As indicated by Royal Society, “Nanotechnology is the design, characterization, production and use of structures, devices and frameworks by controlling shape and size at nanometre scale” (Chinnamuthu and Boopathi, 2009). Currently nanotechnology is far from logical judgment concrete areas (Baruah and Dutta, 2009). For example, the progress of slow or controlled discharge of fertilizers, conditional release of pesticides and herbicides based on nanotechnology has turned out to be fundamentally significant to promote the development of sustainable and environment friendly agriculture. In reality, nanotechnology has given the plausibility of exploiting nanoscale or nanostructured materials as fertilizer carriers or controlled-release vectors for building of so-called “smart fertilizer” as new facilities to enhance nutrient use efficiency and diminish expenses of environmental protection (Chinnamuthu and Boopathi, 2009 and Cui *et al*. 2010).

Nano fertilizers consolidate nanodevices to synchronize the release fertilizer N and P with their uptake by crops, so averting undesirable nutrient losses to soil, water and air via direct internalization by crops so as to avoid the interaction of nutrients with soil, microorganisms, water, and air (De Rosa *et al*. 2010).

Encapsulation of fertilizers within a nanoparticle is one of these new systems are three different ways a) the nutrient can be encapsulated within the nano porous materials, b) actuated coated with thin polymeric film and c) as particles or emulsions nanometric scale of the measurements (Rai *et al*. 2012).

2.8 Effect of Nano Fertilizers on Yield and Economics

Khanda and Dixit (1996) opined that in rice, the highest returns per rupee investment was associated with alone foliar application of 0.5 percent $ZnSO_4$ twice at 25 and 35 DAT. Sharma *et al.* (1999) reported that the highest returns per rupee investment (19.52) were associated in rice with foliar application of 0.5 percent $ZnSO_4$ twice at 30 and 45 DAT on clay loam soil of Rajasthan. Similar results were observed by Chaphale and Badole (1999) by the soil application of 5 kg Zn ha^{-1} at Maharashtra.

Chaudary and Sinha (2007) reported that higher returns per rupee invested were obtained with the application of 25 kg $ZnSO_4$ ha^{-1} which was on par with 37.5 kg $ZnSO_4$ ha^{-1} on silty-clay soil of Pusa, Bihar.

Patel *et al*. (2008) stated that maximum net return was incurred due to 16 kg $ZnSO_4$ ha^{-1} and it was closely followed by application of 16 kg $ZnSO_4$ ha^{-1} at alternate year. A field experiment was conducted during the pre-kharif season of 2012 and 2013 at Varanasi to study the effect of nitrogen, phosphorus and potassium (NPK) (100% and 125% recommended dose of fertilizer), sulphur (0, 25 and 50 kg S ha^{-1}) and zinc (0, 5 and 10 kg Zn ha^{-1}) fertilization on growth, yield, economics and quality of baby corn. Results revealed that each increment of zinc application up to 10 kg Zn ha^{-1} correspondingly improved growth, yield attributes, cob yield, corn yield and green fodder yield as well as gross return, net return and the benefit: cost ratio (Kumar and Bohra, 2014).

A field experiment was conducted during the rabi season of the year 2009-10 at Pulse Research Station, Anand Agricultural University, Model Farm, Vadodara, Gujarat. Results revealed that highest B:C ratio was found to be significant under application of N_3 (160 kg N ha^{-1}), P_3 (80 kg P_2O_5 ha^{-1}) and Z_2 (5 kg Z ha^{-1}) over other treatments. The treatments which included zinc give higher B:C ratio than control and other treatments (Raskar *et al.* 2013).

Mehdi *et al*. (2012) reported that response of maize to applied nitrogen up to 120 kg ha^{-1} was linear in nature and the treatment combination N120: Zn10: seed rate 60 kg ha^{-1} fetched higher net returns (Rs. 26,460 and benefit cost ratio 1.53). The maximum yield (grain-4.66 and straw-5.44 kg ha^{-1}), harvest index (46.07), total nutrient uptake (N-123.19 kg ha^{-1}, K-90.86 kg ha^{-1} and Zn-327.74 g ha^{-1}), total carbohydrate (70.37 per cent), and higher net returns (1.40) was achieved by the application of 20 kg $ZnSO_4$ ha^{-1} with recommended NPK as compared to control and other treatments, while total P uptake declined with increasing levels of Zn.

Kumar *et al*. (2014) conducted an experiment at Pant Nagar on effect of nano-fertilizers of gypsum and rock phosphate at the rate of 3 kg ha^{-1} on the wheat and they reported that B: C ratio obtained at 50 % RDF with nano-materials was almost statically similar with 100 percent RDF without nano-materials.

3. MATERIALS AND METHODS

The experiment entitled “Effect of foliar application of Nano zinc on nutrient uptake, yield and quality of wheat on zinc deficient and sufficient soils of Inceptisol” was conducted in the field during *rabi* 2022-23. This chapter provides specifics on the material utilized and the methods used for the study.

3.1 Material

3.1.1 Experimental Site and Location

The field trial was conducted at Post Graduate Institute Research Farm of Department of Soil Science and Agricultural Chemistry, Mahatma Phule Krishi Vidyapeeth, Rahuri. The two experimental plots, one was zinc deficient and another zinc sufficient soils were leveled, uniform, medium deep black belonging to order of Inceptisol. Geographically the location of experimental site was $19^0$34’ N latitude and $74^0$64’ E longitude. The altitude was 513 meter above the mean sea level. This tract is lying on the Eastern side of Western Ghat Zone of Maharashtra.

3.1.1 Climate and Weather Condition

The climate in MPKV, Rahuri is considered to be a varied with respect to different climatic parameters and belongs to semi-arid tropical region with dry hot summers and cool winters and fall under the agroclimatic zone “Scarcity zone”. The 80 per cent rainfall received from June to September (South West Monsoon), while the remaining quantity is received in the months of October and November from north east monsoon. The climatic parameters during crop growth *viz*., average minimum varies from 13.2^0C to 18.5^0C and maximum temperature varies from 27.9^0C to 34.0^0C while, the average minimum and maximum rainfall varies from 0.8 mm to 12.8 mm, wind speed, bright sunshine hours, evaporation were recorded and presented in table 3.1.

3.1.3 Soil Characteristics

The topography of two experimental fields were uniformly leveled. The soils of the experimental sites are grouped under Inceptisol order belongs to family of fine montmorillonite isohyperthermic family of *Vertic Haplustept*. The texture of the soil was clayey with moderately alkaline pH, normal EC, low in nitrogen, medium in available phosphorus and organic carbon, very high in available potassium and with one plot selected was zinc sufficient and another was zinc deficient soil.

Table 3.1 Monthly average values of weather parameters during the experimental period

Week No.	Temperature (^{0}C)		Humidity (%)		Wind speed (km h^{-1})	Rainfall (mm)	Bright sunshine (hrs.)	Open pan evaporation (mm)
	Max.	Min.	RH-I	RH-II				
	November 2022							
45	31.0	17.2	76.9	27.3	1.0	0.0	9.4	5.8
46	30.1	15.6	84.6	33.7	1.3	0.0	8.9	6.8
47	27.9	14.7	77.9	31.9	0.9	0.0	8.6	5.2
48	30.1	16.2	81.4	36.3	0.6	0.0	7.6	5.2
	December 2022							
49	30.1	16.3	87.9	38.9	0.6	0.0	6.2	5.0
50	28.9	17.3	87.1	44.0	1.1	0.0	6.1	4.5
51	30.3	16.2	83.0	34.0	0.8	0.0	8.8	5.3
52	31.7	16.0	80.6	30.6	0.8	0.0	9.0	5.4
	January 2023							
1	28.1	15.1	82.9	48.0	1.1	0.0	6.4	4.6
2	28.3	13.5	84.5	37.5	0.9	0.0	7.5	4.7
3	30.0	13.2	83.5	29.7	0.7	0.0	9.1	5.1
4	29.7	15.5	78.3	40.1	1.4	0.8	7.7	5.1
5	28.9	15.8	79.3	36.6	1.8	0.0	7.7	4.9
	February 2023							
6	30.1	14.2	77.6	28.3	1.0	0.0	10.0	5.8
7	31.7	14.8	70.7	20.7	1.3	0.0	10.7	6.3
8	32.8	15.0	70.4	20.4	1.2	0.0	10.5	6.9
9	33.7	16.3	70.0	19.0	1.0	0.0	9.4	6.9
	March 2023							
10	31.7	17.4	79.4	29.3	1.3	12.8	6.7	6.2
11	30.7	18.5	77.1	33.7	1.3	4.0	5.7	5.2
12	30.0	17.3	85.1	33.1	1.6	7.2	7.6	5.7
13	34.0	19.2	72.7	23.9	1.8	0.0	9.5	7.4

Table 3.2 Initial properties of field experiment soils on Zn deficient and Zn sufficient

Sr. No.	Parameters	Values	
		Zn deficient	Zn sufficient
I	**Texture**	Clay	Clay
II	**Chemical properties**		
1.	pH (1: 2.5)	8.24	8.20
2.	EC (1:2.5) (dSm^{-1})	0.35	0.38
3.	Organic carbon (g kg^{-1})	4.9	5.4
4.	Calcium carbonate (%)	6.80	7.87
III	**Macronutrients**		
1.	Available N (kg ha^{-1})	159	166
2.	Available P (kg ha^{-1})	10.83	12.78
3.	Available K (kg ha^{-1})	467	490
IV	**DTPA micronutrients (mg kg^{-1})**		
1.	Fe	4.61	4.60
2.	Mn	8.30	9.80
3.	Zn	0.54	0.67
4.	Cu	1.35	1.52

3.2 Experiment Details

The two field experiments were conducted at Post Graduate Institute Research farm, Department of Soil Science and Agricultural Chemistry, Mahatma Phule Krishi Vidyapeeth, Rahuri.

The individual experiments on zinc deficient and sufficient soils were laid out in a randomized block design with eight treatments and three replications. The details of the experiments are given below:

3.2.1 Methodology

1.	**Location**	:	PGI Research Farm, Department of Soil Science and Agricultural Chemistry, MPKV, Rahuri (M.S.)
2.	**No. of experiments**	:	Field experiments (Two)
3.	**Crop**	:	Wheat
4.	**Variety**	:	Phule Samadhan
5.	**Season**	:	*Rabi* 2022
6.	**Spacing**	:	20 cm
7.	**Plot size**	:	Gross : 3.60 m x 4.20 m Net : 3.20 m x 3.80 m
8.	**Soil types**	:	Zinc deficient and sufficient soils of medium deep black soil (Inceptisols)
9.	**Source of zinc fertilizers**	:	Nano-ZnO (39.5% Zn)
10.	**Design**	:	Randomized Block Design (RBD)
11.	**Treatments**	:	08 (Eight)
12.	**Replications**	:	03 (Three)

3.2.2 Treatment Details

Tr. No.	Treatments
T_1	Absolute control
T_2	General Recommended Dose of Fertilizers (GRDF)
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.

Note: 1) GRDF is 120:60:40 kg ha^{-1} $N:P_2O_5:K_2O$ + 10 t ha^{-1} FYM for wheat.

2) Two foliar sprays of Nano Zn were given at crown root initiation (20 DAS) and at tillering stages (40 DAS)

3.2.3 Programme of research work

Table 3.3 Field operations adopted during experimentation (Zinc deficient and sufficient soils)

Sr. No.	Particulars	Frequencies (Two experimental plots)	Date of operation
1.	Ploughing	2	09/11/2022
2.	Harrowing	2	11/11/2022
3.	Preparation of field layout	2	18/11/2022
4.	Application of FYM	2	21/11/2022
5.	Application of dose of fertilizers	2	22/11/2022
6.	Sowing of seed	2	22/11/2022
7.	Gap filling	2	02/12/2022
8.	Application of $ZnSO_4.7H_2O$, Nano ZnO and Chelated zinc (as per treatments)	20	12/12/2022 30/12/2022
9.	Hand weeding	2	14/12/2022 15/12/2022
10.	Irrigations	10	22/11/2022 06/12/2022 23/12/2022 12/01/2023 03/02/2023
11.	Spraying of insecticide	2	23/01/2023
12.	Harvesting	2	20/03/2023
13.	Threshing	2	28/03/2023

3.2.4 Harvesting

Wheat was harvested after 115 days after sowing. The weight of grain and straw were recorded immediately and yield per hectare was calculated and reported.

3.3 Details of Laboratory Analysis

3.3.1 Glassware

The necessary glassware *viz.*, beakers, conical flasks, volumetric flasks, pipettes, burettes, funnels, measuring cylinders, digestion tubes, petri dishes, *etc.* were used for analytical work.

3.3.2 Equipments

The equipment's *viz.*, digestion and distillation unit, hot air oven, weighing balance, grinding machine, mechanical shaker, kel plus distillation unit, spectrophotometer, flame photometer, atomic absorption spectrophotometer, pH meter, conductivity meter, micro automatic pipette, hot plate *etc.* were used during the laboratory analysis.

3.3.3 Chemicals

High purity (AR grade) chemicals such as buffer tablet, sulphuric acid, sodium hydroxide, hydrogen peroxide, hydrochloric acid, potassium permanganate, sodium bicarbonate, ammonium acetate, ammonium molybdate, ammonium vanadate, boric acid, phenolphthalein, methyl red, bromocresol green, dipotassium hydrogen orthophosphate, potassium dihydrogen orthophosphate, *etc.* were used.

3.4 Methods

3.4.1 Soil Analysis

The representative soil samples were collected at initial and as per treatments at harvest stage and were analyzed for chemical properties by using the standard analytical methods as indicated in table 3.4.

3.4.2 Plant Analysis

The plant samples were collected from each net treatment plot at harvest stages of wheat. The collected plant samples were cleaned and air dried under shade and subsequently kept in hot air oven at 65 ± 2^0C till the sample gain constant weight and then ground well to maximum fineness. The processed plant samples were used for plant analysis as per standard methods as mentioned in table 3.4.

3.4.3 Physiological Studies

The physiological studies were done by using Portable photosynthesis system LI6400XT at 40 and 55 days after sowing with the following parameters,

A. Photosynthetic rate (μ moles m^{-2} s^{-1})

B. Stomatal conductance (μ moles m^{-2} s^{-1})

C. CO_2 concentration (μ moles CO_2 m^{-2} s^{-1})

D. Leaf temperature (^{0}C)

E. Transpiration rate (μ moles H_2O m^{-2} s^{-1})

Table 3.4 Standard methods of analysis

Sr. No.	Particulars	Method	Reference
A.	**Soil analysis**		
I.	**Chemical properties**		
1.	pH (1:2.5)	Potentiometry	Jackson (1973)
2.	EC (1:2.5) (dSm^{-1})	Conductometry	Jackson (1973)
3.	Organic carbon (g kg^{-1})	Wet oxidation	Nelson and Sommers (1982)
4.	Calcium carbonate (%)	Rapid titration	Piper (1966)
II.	**Macronutrients**		
5.	Available N (kg ha^{-1})	Alkaline permanganate (0.32% $KMnO_4$)	Subbiah and Asija (1956)
6.	Available P (kg ha^{-1})	Olsen method with 0.5 M $NaHCO_3$ (pH 8.5)	Watanabe and Olsen (1965)
7.	Available K (kg ha^{-1})	Neutral normal ammonium acetate (N *N* NH_4OAc)	Jackson (1973)
III.	**Micronutrients**		
8.	DTPA Fe, Mn, Zn and Cu (mg kg^{-1})	0.005 *M* DTPA	Lindsay and Norvell (1978)
B.	**Plant analysis**		
1.	Total N (%)	Kjeldahl (H_2O_2:H_2SO_4:: 1:1)	Parkinson and Allen (1975)
2.	Total P (%)	Vanado-Molybdate yellow colour in HNO_3 (HNO_3:$HClO_4$ 9:4)	Jackson (1973)
3.	Total K (%)	Flame photometery (HNO_3:$HClO_4$ 9:4)	Chapman and Pratt (1961)
4.	Total micronutrients (Fe, Mn, Zn, Cu)	Atomic Absorption Spectrophotometry (AAS)	Zososki and Burau (1977)
I.	**Quality parameter**		
1.	Crude protein (%)	Micro-kjeldahl	Jackson (1973)

3.4.4 Estimation of Chlorophyll

Soil plant analytical development (SPAD 502; Minolta company Ltd.) measures the greenness or relative chlorophyll content of the leaves. The third leaf from top was used for measuring chlorophyll, which was taken on one side of leaf blade, midway between the leaf base and tip. The readings were taken from five samples and from average further statistical analysis were done.

3.4.5 Yield Contributing Characters

3.4.5.1 Plant height (cm)

Five plants selected randomly from each net plot and which were tagged. Plant height at harvest was measured from the ground level to the uppermost portion of the ear head and mean values were presented in centimeters (cm). Average of all the five plants were taken for statistical analysis.

3.4.5.2 No. of tillers

The total number of tillers were recorded from the tagged plants at harvest. Average of it taken for statistical analysis.

3.4.5.3 Length of spikelet

Length of spikelet from the point of attachment of the lower most primary rachis to the tip of the panicle of five spikelets were collected randomly from the tagged plants and its length of the spikelet was measured in centimeters and the average of length of spikelet taken for statistical analysis.

3.4.5.4 No. of grains spikelet^{-1}

Total number of grains from the five randomly selected spikelets from the tagged plants of sampling rows were separately threshed, cleaned and were counted. The averages of all the ten spikes were calculated and were expressed as grains per ear head.

3.4.5.5 Grain yield plot^{-1}

From the individual plot, net plot area was harvested; sun dried for 3-4 days and was subsequently threshed (through thresher) and cleaned. The grain thus obtained, were weighed and expressed in quintals per hectare (q ha^{-1}).

3.4.5.6 Straw yield plot^{-1}

The total biological yield (grain + straw) from the net plot was recorded and straw yield was worked out by subtracting the grain yield from the biological yield and expressed in q ha^{-1}.

3.4.6 Apparent Nutrient Recovery Efficiency

Nutrient use efficiency is the response in grain yield per unit of fertilizer nutrient applied and it was calculated in per cent by using the following formula (Devasenapathy *et al.* 2008).

$$\text{Apparent nutrient recovery efficiency of nitrogen (\%)} = \frac{\text{Total uptake of N in treated treatment (kg ha}^{-1}\text{)} - \text{Total uptake of N in control treatment (kg ha}^{-1}\text{)}}{\text{Quantity of fertilizer N applied (kg ha}^{-1}\text{)}} \times 100$$

$$\text{Apparent nutrient recovery efficiency of phosphorus (\%)} = \frac{\text{Total uptake of P in treated treatment (kg ha}^{-1}\text{)} - \text{Total uptake in control treatment (kg ha}^{-1}\text{)}}{\text{Quantity of fertilizer P applied (kg ha}^{-1}\text{)}} \times 100$$

$$\text{Apparent nutrient recovery efficiency of potassium (\%)} = \frac{\text{Total uptake of K in treated treatment (kg ha}^{-1}\text{)} - \text{Total uptake in control treatment (kg ha}^{-1}\text{)}}{\text{Quantity of fertilizer K applied (kg ha}^{-1}\text{)}} \times 100$$

3.4.7 Nutrient Uptake

The uptake of major and micronutrients were worked out by multiplying dry matter accumulation to N, P, K, Fe, Mn, Zn and Cu concentration in wheat at harvest by using the following formulae:

$$\underset{\text{(kg ha}^{-1}\text{)}}{\text{Uptake of nutrient}} = \text{Total dry matter (q ha}^{-1}\text{)} \times \text{Concentration of element (\%)}$$

$$\underset{\text{(g ha}^{-1}\text{)}}{\text{Uptake of micronutrients}} = \frac{\text{Total dry matter (q ha}^{-1}\text{)} \times \text{Concentration of element (mg kg}^{-1}\text{)}}{10}$$

3.5 Crude Protein Content

The crude protein content in grain wheat was determined by multiplying total N concentration in grain with a factor of 5.81.

3.6 Gluten Content

Weigh 25 g sample into a dish and add about 15 mL of water to it and make it into a dough taking care that all the material is taken into the dough. Keep the dough gently in a beaker filled with water and let it stand for one hour. Remove the dough and place it in a piece of bolting silk cloth with an aperture of 0.16 mm and wash it with a gentle stream of water till water passing through the silk does not give a blue colour with a drop of iodine solution. Spread the silk tight on a porcelain plate to facilitate scraping. Collect the residue to form a ball, squeeze in the palms to remove excess water, transfer to a watch glass or petri dish and keep it in the oven at 105±1°C for drying. When partially dried, remove and cut into several pieces with a scissor and again keep in the oven to dry. Cool in a desiccators and weigh. Return it to the oven again for half hour, cool and weigh to ensure constant weight (Anonymous, 1968).

$$\text{Gluten on dry wt. basis (\%)} = \frac{\text{Weight of dry gluten (g)} \times 100 \times 100}{\text{Weight of sample (g)} \times \text{(100 – Moisture content (\%)}}$$

3.7 Economics

At harvest, economics were workout *viz.* cost of cultivation, gross and net monetary returns and B:C ratio.

3.8 Statistical Analysis

Two field experiments were (on zinc deficient and sufficient) conducted by using randomized block design (RBD). The data obtained were statistically analyzed as per the methods described by Panse and Sukhatme (1985).

4. RESULTS AND DISCUSSION

The present research work entitled, "Effect of foliar application of Nano zinc on nutrient uptake, yield and quality of wheat on zinc deficient and sufficient soils of Inceptisol" was conducted at the PGI Research Farm, Department of Soil Science and Agricultural Chemistry, Mahatma Phule Krishi Vidyapeeth, Rahuri during *Rabi* season 2022. The results of the investigation as per objectives of the study are exhibited and explored in this chapter under the given outline.

4.1 Effect of Foliar application of Different Sources of Zinc on the Yield Contributing Characteristics of Wheat
4.2 Effect of Foliar application of Different Sources of Zinc on Yield of Wheat
4.3 Effect of Foliar application of Different Sources of Zinc on Physiological Traits of Wheat
4.4 Effect of Foliar application of Different Sources of Zinc on Total uptake by Wheat
4.4.1 Effect of Foliar Application of Different Sources of Zinc on Total Macronutrient Uptake in Zinc Deficient and Sufficient Soil
4.4.2 Effect of Foliar Application of Different Sources of Zinc on Total Micronutrient Uptake in Zinc Deficient and Sufficient Soil
4.5 Effect of Foliar Application of Different Sources of Zinc on Quality Parameters of Wheat
4.6 Effect of Foliar application of Different Sources of Zinc on Chemical Properties of Soil at Harvest Stages of Wheat
4.7 Effect of Foliar Application of Different Sources of Zinc on Nutrient Use Efficiency on Wheat
4.8 Effect of Foliar Application of Different Sources of Zinc on Economics of Wheat

4.1 Effect of Foliar application of Different Sources of Zinc on the Yield Contributing Characteristics of Wheat

The growth attributes of wheat were significantly influenced by the different treatments which are reported in tables 4.1 to 4.4.

4.1.1 No. of Tillers Plant^{-1}

The no. of tillers as influenced by foliar application of different zinc sprays under zinc deficient and sufficient soil are reported in table 4.1 and depicted in fig 4.1. The results revealed that the number of tillers per plant was found significantly higher (8.66) in treatment T_3 (GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}) over T_1 and T_2 treatments, while treatments T_4, T_5, T_6, T_7 and T_8 (8.25, 8.42, 8.57, 8.21 and 8.58, respectively) were at par with treatment T_3 under zinc deficient soil.

However, under zinc sufficient soil, the no. of tillers plant^{-1} was found significantly higher (8.94 cm) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) over T_1, T_2 and T_3, while treatments T_4, T_5, T_7 and T_8 (8.45, 8.60, 8.52 and 8.74, respectively) were at par with treatment T_6.

The abundant growth of tillers occurred because the nano fertilizer enhanced the efficient use of nutrients, met the crop's nutrient needs, and boosted chloroplast activity reported by Hong *et al*. (2005) in wheat crop. Mustafa *et al*. (2011) also came across similar trends in wheat because of the enhancement of might be due to enzymatic activity and auxin metabolism in plants, which boosted tillering. It was also noticed that applying nano fertilizers during the active tillering stages led to a significant increase in the number of active tillers, primarily because it provided balanced nutrition to the crop.

Table 4.1 Effect of foliar application of different sources of zinc on no. of tillers plant^{-1} in zinc deficient and sufficient soil under wheat crop

Tr. No	Treatment	No. of tillers plant^{-1}	
		Zn deficient soil	Zn sufficient soil
T_1	Absolute control	5.36	6.02
T_2	General Recommended Dose of Fertilizers (GRDF)	8.10	8.08
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	8.66	8.20
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	8.25	8.45
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	8.42	8.60
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	8.57	8.94
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	8.21	8.52
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	8.58	8.74
	SE m±	**0.18**	**0.23**
	CD at 5%	**0.54**	**0.70**

4.1.2 Length of Spikelet

The significantly highest length of spikelet (cm) was found (8.76 cm) in treatment T_3 (GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}) over T_1 and T_2 treatments, while treatments T_4, T_5, T_6, T_7 and T_8 (6.11, 7.43, 8.16, 8.28, 8.46, 8.07 and 8.35 cm, respectively) were at par with treatment T_6, which are presented in table 4.2 and depicted in fig 4.2 under zinc deficient and sufficient soils.

On the contrary, while examining soils with a sufficient zinc content, there was a significant increase in the spikelet length (8.86 cm), particularly in treatment T_6. This treatment involved the application of GRDF along with two foliar sprays of Nano zinc @ 0.15%, done at 20 and 40 days after sowing (DAS). In comparison, treatments T_2, T_3, T_4, T_5, T_7, and T_8 exhibited spikelet lengths of 8.22, 8.26, 8.27, 8.31, 8.31, and 8.48 cm, respectively, which were statistically equivalent to the spikelet length observed in treatment T_6.

Table 4.2 Effect of foliar application of different sources of zinc on length of spikelet in zinc deficient and sufficient soil under wheat crop

Tr. No	Treatment	Length of spikelet (cm)	
		Zn deficient soil	**Zn sufficient soil**
T_1	Absolute control	6.11	4.99
T_2	General Recommended Dose of Fertilizers (GRDF)	7.43	8.22
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	8.76	8.26
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	8.16	8.27
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	8.28	8.31
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	8.46	8.86
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	8.07	8.31
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	8.35	8.48
	SE m±	**0.40**	**0.36**
	CD at 5%	**1.22**	**1.09**

The application of nano fertilizer during the spikelet initiation stage was observed to have a significant positive impact on spikelet length. Nano fertilizer application proved to be more effective in increasing spikelet length, primarily because it facilitated the controlled release of nutrients, including essential elements such as nitrogen, phosphorus, and potassium (NPK). This controlled release of chemical fertilizers played a key role in regulating plant growth and enhancing specific target activities, resulting in the observed spikelet length improvement. (De Rosa *et al*. 2010 and Nair *et al*. 2010). Furthermore, it is important to note that zinc plays a vital role in the synthesis of tryptophan, which serves as a precursor for the production of indole acetic acid (IAA) as highlighted by Spiegel-Roy and Goldschmidt (2008). Consequently, the presence of zinc may lead to a stimulative effect on plant growth by facilitating an increased synthesis of IAA, a pivotal growth-promoting hormone. The foliar application of zinc nano fertilizer on pearl millet had a notable effect, leading to a significant increase in shoot length, as observed in the study conducted by Tarafdar *et al*. (2014).

4.1.3 No. of Grains Spikelet^{-1}

Under conditions of zinc deficiency and sufficiency in the soil, the number of grains spikelet^{-1} significantly increased, up to (44.59) in treatment T_3. This treatment involved the application of GRDF in combination with soil application of $ZnSO_4.7H_2O$@ 20 kg ha^{-1}. On the other hand, treatments T_1, T_2, T_4, T_5, and T_7 showed lower grain counts per spikelet in comparison. Treatments T_6 and T_8, with grain counts of 42.42 and 41.54, respectively, were found to be statistically at par to treatment T_3 in terms of the number of grains per spikelet illustrated in table 4.3 and figure 4.3.

Table 4.3 Effect of foliar application of different sources of zinc on no. of grains spikelet^{-1} in zinc deficient and sufficient soil under wheat crop

Tr. No	Treatment	No. of grains spikelet^{-1}	
		Zn deficient soil	**Zn sufficient soil**
T_1	Absolute control	13.67	47.00
T_2	General Recommended Dose of Fertilizers (GRDF)	32.12	47.68
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	44.59	52.00
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	39.76	53.00
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	40.15	43.67
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	42.42	54.69
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	40.02	46.76
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	41.54	41.33
	SE m±	**1.39**	**1.24**
	CD at 5%	**4.18**	**3.73**

In contrast, in conditions where the soil had sufficient zinc levels, the number of grains spikelet^{-1} exhibited significant increase, upto 54.69, in treatment T_6. This treatment involved the application of GRDF in combination with two foliar sprays of Nano zinc @ 0.15%, administered at 20 and 40 (DAS). Treatment T_6 outperformed treatments T_1, T_2, T_5, T_7, and T_8, which showed lower grain counts per spikelet. Treatments T_3 and T_4, with grain counts of 52.00 and 53.00, respectively, were found to be statistically at par to treatment T_6 in terms of the number of grains spikelet^{-1}.

Nano fertilizers provide an advantage through their increased surface area, which enhances various metabolic functions within the plant system. This is attributed to the greater production of photosynthates, as noted by Kumar *et al.* in 2020. Also, many enzymatic events, including the creation of hormones and protein synthesis, zinc serves as a catalyst, which may explain the rise in the number of grains per panicle. Similar results were also supported by Prajapati *et al.* (2018).

4.1.4 Plant Height

The data regarding plant height with regards to zinc deficient and sufficient soils are provided in table 4.4 and illustrated in fig 4.4. Under zinc deficient soil, the plant height was found significantly higher (90.60 cm) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) over T_1, T_2 and T_3 treatments, while treatments T_4, T_5, T_7 and T_8 (85.20, 86.00, 83.93 and 86.87 cm, respectively) were at par with treatment T_6.

However, under zinc sufficient soil, plant height was found significantly higher (92.07 cm) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) over T_1 treatment, while treatments T_2, T_3, T_4, T_5, T_7 and T_8 (88.27, 88.40, 88.47, 89.07, 89.00 and 91.13 cm, respectively) were at par with treatment T_6.

Table 4.4 Effect of foliar application of different sources of zinc on plant height in zinc deficient and sufficient soil under wheat crop

Tr. No	**Treatment**	**Plant height (cm)**	
		Zn deficient soil	**Zn sufficient soil**
T_1	Absolute control	68.73	66.80
T_2	General Recommended Dose of Fertilizers (GRDF)	82.13	88.27
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	88.40	88.40
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	85.20	88.47
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	86.00	89.07
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	90.60	92.07
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	83.93	89.00
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	86.87	91.13
	SE m±	**2.35**	**1.45**
	CD at 5%	**7.05**	**4.37**

An elevation in plant height resulting from the application of NPK with nano nutrients has been documented in studies conducted by Mehta (2017), as well as in research by Munir *et al.* (2018) and Rizwan *et al.* (2019) when using nano zinc. This significant increase in plant height associated with nano nutrient application can be attributed to its capacity to stimulate both root and shoot growth, with a more pronounced effect observed in root development. The similar results observed by Benzon *et al.* (2015), the plant height was more enhanced when nano fertilizer was used along with conventional ones due to the reason that nano-fertilizer can either provide zinc for the plant or aid in the transport or absorption of available nutrients resulting in better crop growth.

Additionally, the improved plant height observed could be a result of increased nutrient uptake, improved source-to-sink relationships, and enhanced translocation of starch. These findings align with the research conducted by Lenka and Das (2019) in potato.

4.2 Effect of Foliar Application of Different Sources of Zinc on Yield of Wheat

4.2.1 Grain Yield

The application of fertilizers, regardless of the doses and sources of nutrients, led to a significant increase in grain yield compared to scenarios with no nutrient application, as evidenced by the data presented in table 4.5 and depicted in fig 4.5. Under zinc deficient and sufficient soils, the grain yield of wheat was found significantly higher (42.61 q ha^{-1}) in treatment T_3 (GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}) over T_1, T_2 and T_3 treatments, while, treatments T_4, T_5, T_6 and T_8 (40.65, 41.15, 41.56 and 42.07 q ha^{-1}, respectively) were at par with treatment T_3. Overall 9 percent increased grain yield of wheat found in treatment T_3 over GRDF treatment under zinc deficient soil.

Nevertheless, in the context of soil with sufficient zinc content, the grain yield was found significantly higher (44.15 q ha^{-1}) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) over T_1 and T_2 treatments, while, treatments T_3, T_4, T_5, T_7 and T_8 (41.18, 41.47, 42.76, 42.39 and 43.91 q ha^{-1}, respectively) were at par with treatment T_6. Which indicated that 8.61 percent increase in grain yield of wheat observed in treatment T_6 over T_2 (GRDF) treatment. In general, under Zn deficient soil, it is observed that the wheat crop is responding soil application of zinc, however, under zinc sufficient soil, the crop is responding for foliar application of Nano zinc @ 0.15% at 20 and 40 DAS.

Nano fertilizers, characterized by their extensive surface area and smaller particle size compared to the pores of plant roots and leaves, offer the potential to enhance nutrient penetration from the applied surface, thereby improving nutrient uptake and increasing wheat yields. As previously mentioned, nano fertilizers may influence these processes by facilitating the transport of nutrients, both in terms of penetration and movement within the plant. The significant increase in crop yields through the foliar application of nano fertilizers has been supported by research conducted by Tarafdar *et al*. (2012) and Benzon *et al*. (2015). Also, higher concentration of zinc played prominent significance in synthesis of carbohydrate and their transport to the site for grain production. Better absorption from the zinc treatment's foliar spray led to more efficient translocation to storage organs and, in turn, helped the photosynthetic activity, which may have accelerated the yield, Subbaiah *et al.* (2016) showed similar results.

Table 4.5 Effect of foliar application of different sources of zinc on grain yield in zinc deficient and sufficient soil under wheat crop

Tr. No	**Treatment**	**Grain yield (q ha^{-1})**	
		Zn deficient soil	**Zn sufficient soil**
T_1	Absolute control	9.75	10.27
T_2	General Recommended Dose of Fertilizers (GRDF)	39.09	40.65
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	42.61	41.18
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	40.65	41.47
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	41.15	42.76
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	41.56	44.15
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	39.96	42.39
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	42.07	43.91
	SE m±	**0.87**	**1.01**
	CD at 5%	**2.65**	**3.04**

4.2.2 Straw Yield

In the present investigation the straw yield of wheat presented in table 4.6 and depicted in fig 4.6 under zinc deficient and sufficient soils, was found significantly higher (60.14 q ha^{-1}) in treatment T_3 (GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}) over T_1, T_2 and T_4 treatments, while treatments T_5, T_6, T_7 and T_8 (57.60, 58.09, 56.11 and 58.66 q ha^{-1}, respectively) were at par with treatment T_3. Overall, 8.60 percent increased straw yield of wheat found in treatment T_3 over GRDF treatment, under zinc deficient soil.

In circumstances where the soil already contained sufficient zinc, the straw yield of wheat was found significantly higher (63.50 q ha^{-1}) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) over T_1 and T_2 treatments, while treatments T_3, T_4, T_5, T_7 and T_8 (59.40, 60.12, 61.98, 61.26 and 62.47 q ha^{-1}, respectively) were at par with treatment T_3. Under zinc sufficient soil 9.95 percent increase in straw yield in T_6 treatment over GRDF.

Incorporating nano fertilizers in conjunction with NPK (Nitrogen, Phosphorus, and Potassium) demonstrated a notable enhancement in crop yield compared to their individual application. The combined utilization of these components were found to establish a harmonious synergy in the context of chemical fertilizer application. This synergy facilitated the efficient uptake and translocation of essential nutrients from source to sink within the plant, consequently augmenting both crop productivity and straw yield. Consequently, this approach contributed to the achievement of consistent and sustainable crop yields, emphasizing the significance of judicious chemical fertilizer management. This outcome aligns with earlier findings reported by Gosavi and Bhagat (2009), Kumar *et al*. (2015) and Auwal and Amit (2017). The observed rise in straw yield following the foliar application of Nano zinc fertilizers can be attributed to the rapid uptake of these nano fertilizers by the plant alongwith other fertilizers. This increased absorption, in turn, stimulates a higher rate of photosynthesis and greater production of dry matter, ultimately leading to an elevated straw yield. These findings concur with those reported by Benzon *et al*. (2015) in the context of rice cultivation. Supplementing with zinc demonstrated favorable outcomes by promoting the production of Indole-3-acetic acid (IAA) and initiating the development of reproductive structures in plants. This, in turn, facilitated enhanced metabolic responses within the plants. Mohsen *et al*. (2016) similarly documented an increase in barley yield as a result of zinc supplementation.

Table 4.6 Effect of foliar application of different sources of zinc on straw yield in zinc deficient and sufficient soil under wheat crop

Tr. No	**Treatment**	**Straw yield (q ha^{-1})**	
		Zn deficient soil	**Zn sufficient soil**
T_1	Absolute control	13.54	14.22
T_2	General Recommended Dose of Fertilizers (GRDF)	55.38	57.75
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	60.14	59.40
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	56.25	60.12
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	57.60	61.98
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	58.09	63.50
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	56.11	61.26
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	58.66	62.47
	SE m±	**0.96**	**1.40**
	CD at 5%	**2.88**	**4.22**

The previously mentioned enhancement in vegetative growth parameters contributes to an efficient photosynthesis process due to the increased utilization of Nano particles. This advanced efficiency, in turn, leads to greater accumulation of dry matter in plant sinks and consequently results in improved yield parameters. Liu and Lal (2015) corroborate these findings in their research.

In the study conducted by Liu and Liao (2008), it was observed that the introduction of nano materials led to an elevation in water activity. This increase in water activity facilitated the absorption of essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K) by the plants. As a result of this enhanced nutrient uptake facilitated by increased water availability, there was a subsequent increase in dry matter production.

4.3 Effect of Foliar Application of Different Sources of Zinc on Physiological Traits of Wheat

4.3.1 Total Chlorophyll Content in Fresh Tissue (SPAD Value)

Total chlorophyll content in fresh tissue (SPAD value) of wheat under zinc deficient and sufficient soil at 40 and 55 DAS as influenced by different sources of zinc treatments are given in table 4.7 and depicted in fig 4.7, the total chlorophyll content in fresh tissue (SPAD value) at 40 DAS was found significantly higher (40.47 SPAD value) in treatment T_3 (GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}) over T_1 and T_2 treatments, while treatments T_4, T_5, T_6, T_7 and T_8 (38.97, 38.70, 39.33, 37.22 and 38.93 SPAD value, respectively) were at par with treatment T_3. The total chlorophyll content in fresh tissue (SPAD value) at 55 DAS was found significantly higher (42.40 SPAD value) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) over T_1, T_2, T_5 and T_7 treatments, while treatments T_3, T_4 and T_8 (41.14, 40.77 and 40.97 SPAD value, respectively).

In the context of a soil that already possessed with sufficient zinc content, the total chlorophyll content in fresh tissue (SPAD value) at 40 DAS was found significantly higher (42.27 SPAD value) in treatment T_3 (GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}) over T_1 and T_2 treatments, while, treatments T_4, T_5, T_6, T_7 and T_8 (41.73, 40.87, 41.13, 40.87 and 40.97 SPAD value, respectively) were at par with treatment T_3 and the total chlorophyll content in fresh tissue (SPAD value) at 55 DAS was found significantly higher (45.10 SPAD value) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) over T_1, T_2 and T_7 treatments, while, treatments T_3, T_5, T_4 and T_8 (44.32, 42.37, 42.33 and 43.40 SPAD value, respectively) were at par with treatment T_6.

Table 4.7 Effect of foliar application of different sources of zinc on total chlorophyll content in fresh tissue (SPAD value) in zinc deficient and sufficient soil under wheat crop

Tr. No	Treatment	Total Chlorophyll content in fresh tissue (SPAD Value)			
		Zn deficient soil		Zn sufficient soil	
		40 DAS	55 DAS	40 DAS	55 DAS
T_1	Absolute control	24.27	28.07	29.10	30.03
T_2	General Recommended Dose of Fertilizers (GRDF)	35.32	38.37	40.10	39.60
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	40.47	41.14	42.27	44.32
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	38.97	40.77	41.73	42.37
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	38.70	40.21	40.87	42.33
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	39.33	42.40	41.13	45.10
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	37.22	39.96	40.87	40.23
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	38.93	40.97	41.07	43.40
	SE m±	**0.76**	**0.71**	**0.70**	**0.99**
	CD at 5%	**2.28**	**2.13**	**2.10**	**2.99**

The impact of applying Nano fertilizer enriched with micronutrients is noteworthy due to its ability to increase the number of leaves and the overall leaf area. This effect has a direct influence on chlorophyll levels by enhancing biological activities and elevating enzymatic processes. Consequently, chlorophyll production is stimulated, and the activity of catalytic enzymes is intensified, leading to the inhibition of ethylene production and its detrimental effects. Ethylene is known to activate chlorophyllase, which can degrade chloroplasts. Therefore, the elements present in Nano fertilizer help sustain chloroplasts for extended periods, delaying the aging process. Additionally, Nano fertilizer promotes the activity of photosynthesis enzymes in tomato, as demonstrated in the research conducted by Siddiqui and Al-Whaibi (2014). These findings are in accordance with the outcomes reported by Nouraein (2019) for maize.

While, on the contrary the results reported by Tarafdar *et al*. (2014), the precise role of zinc in chlorophyll formation remains not entirely understood, it is recognized to function as a catalyst in a wide array of physiological and biochemical processes within plants, particularly in oxidation and reduction reactions.

4.3.2 Photosynthetic Rate

Photosynthesis serves as the cornerstone of crop production, and the rate of photosynthesis is a critical physiological parameter that directly impacts crop yield. The result revealed that there was significant effect of treatment T_3 (GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}). Which are given in table 4.8 and depicted in fig 4.8 under zinc deficient and sufficient soils, the photosynthetic rate (μ moles m^{-2} s^{-1}) at 40 DAS was found significantly higher (11.43 μ moles m^{-2} s^{-1}) in treatment T_3 over T_1 and T_2 treatments, while treatments T_4, T_5, T_6, T_7 and T_8 (10.50, 10.73, 11.40, 10.43 and 10.73 μ moles m^{-2} s^{-1}, respectively) were at par with treatment T_3. The photosynthetic rate (μ moles m^{-2} s^{-1}) at 55 DAS was found significantly higher (13.71 μ moles m^{-2} s^{-1}) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) over T_1 and T_2 treatments, while treatments T_3, T_4, T_5, T_6, T_7 and T_8 (12.18, 12.03, 11.75, 11.77 and 12.06 μ moles m^{-2} s^{-1}, respectively) were at par with treatment T_6.

Table 4.8 Effect of foliar application of different sources of zinc on photosynthetic rate in zinc deficient and sufficient soil under wheat crop

Tr. No	Treatment	Photosynthetic rate (μ moles m^{-2} s^{-1})			
		Zn deficient soil		Zn sufficient soil	
		40 DAS	55 DAS	40 DAS	55 DAS
T_1	Absolute control	7.53	8.13	9.97	9.76
T_2	General Recommended Dose of Fertilizers (GRDF)	10.19	10.74	11.93	12.54
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	11.43	12.18	11.87	13.69
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	10.50	12.03	12.43	13.31
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	10.73	11.75	12.93	13.09
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	11.40	13.71	13.47	14.31
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	10.43	11.77	11.53	12.94
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	10.73	12.06	11.50	13.53
	SE m±	**0.40**	**0.65**	**0.46**	**0.46**
	CD at 5%	**1.22**	**1.97**	**1.39**	**1.39**

Nevertheless, in the context of soil with sufficient zinc levels, the photosynthetic rate (µ moles m^{-2} s^{-1}) at 40 DAS was found significantly higher (13.47 µ moles m^{-2} s^{-1}) in treatment T_6 (GRDF + Two foliarsprays of Nano zinc @ 0.15% at 20 and 40 DAS) over T_1, T_2, T_3, T_7 and T_8 treatments, while treatments T_4 and T_5 (12.43 and 12.93 µ moles m^{-2} s^{-1}, respectively) were at par with treatment T_6. The photosynthetic rate (µ moles m^{-2} s^{-1}) at 55 DAS was found significantly higher (14.31 µ moles m^{-2} s^{-1}) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) over T_1 and T_2 treatments, while treatments T_3, T_4, T_5, T_7 and T_8 (13.69, 13.31, 13.09, 12.94 and 13.53 µ moles m^{-2} s^{-1}, respectively) were at par with treatment T_6.

The zinc oxide nanoparticles (ZnO-NPs) have a profound impact on plant photosynthesis, a vital yet delicate physiological process. These nanoparticles can either enhance or impede photosynthesis by affecting key parameters like photosynthetic efficiency, photochemical fluorescence, and quantum yield. Notably, NPs have the ability to augment essential photosynthetic enzymes such as Rubisco, PEP carboxylase, and carbonic anhydrase, in addition to increasing chlorophyll content and activity. This cumulative effect results in an elevated photosynthetic rate and ultimately leads to increased crop yield, as comprehensively reviewed by Kataria *et al*. (2019).

Indeed, Khan *et al*. (2019) have provided a comprehensive review of the various mechanisms through which nanoparticles (NPs) accelerate photosynthesis. NPs play a pivotal role in activating different steps and enzymes involved in photosynthesis, thereby enhancing photosynthetic efficiency. Specifically, NPs are known to inhibit the production of reactive oxygen species (ROS) while simultaneously promoting the electron transport chain within chloroplasts. They stimulate the activity of carbonic anhydrase enzyme and enhance the carboxylation process of Rubisco (Ribulose-1,5-bisphosphate carboxylase/oxygenase). NPs also contribute to increased pigment synthesis, light absorbance, and photophosphorylation, all of which collectively results in heightened CO_2 fixation and an increased photosynthetic capacity within plants.

The combined impact of nano fertilizers, when used alongside chemical fertilizers, results in a synergistic effect that enhances nutrient absorption by plant cells. This synergy leads to the optimal growth of various plant parts and promotes metabolic processes such as photosynthesis. As a consequence, there is an increased accumulation of photosynthates and their efficient translocation to the economically valuable parts of the plant. This heightened source-sink strength, as outlined by Benzon *et al*. (2015), ultimately contributes to a substantial increase in crop yield. Also, zinc is the essential constitute of carbonic anhydrase enzyme activity which enhances the rate of photosynthesis in plant, similar results also reported by Munir *et al*. (2018) in wheat crop and Rudani *et al*. (2018).

4.3.3 Stomatal Conductance

Stomatal conductance is a critical factor in assessing the efficiency of the stomatal apparatus and provides insights into the photosynthetic capabilities and respiratory activity of a given plant. The stomatal conductance was significantly influenced by various treatments, and the results are presented in table 4.9 under zinc deficient and sufficient soils, at 40 DAS it was found significantly higher (0.39 m moles m^{-2} s^{-1}) in treatment T_3 (GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}) over T_1, T_6 and T_2 treatments, while treatments T_4, T_5, T_7 and T_8 (0.36, 0.37, 0.36 and 0.36 m moles m^{-2} s^{-1}, respectively) were at par with treatment T_3. The photosynthetic rate (m moles m^{-2} s^{-1}) at 55 DAS was found significantly higher (0.57 m moles m^{-2} s^{-1}) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) over T_1, T_2 and T_4 treatments, while treatments T_3, T_5, T_7 and T_8 (0.51, 0.53, 0.51 and 0.52 m moles m^{-2} s^{-1}, respectively) were at par with treatment T_6.

Conversely, when considering soil with sufficient zinc content, the stomatal conductance (m moles m^{-2} s^{-1}) at 40 DAS was found significantly higher (0.37 m moles m^{-2} s^{-1}) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) over T_1, T_2 and T_4 treatments, while treatments T_3, T_5, T_7 and T_8 (0.36, 0.35, 0.35 and 0.36 m moles m^{-2} s^{-1}, respectively) were at par with treatment T_6. The stomatal conductance (m moles m^{-2} s^{-1}) at 55 DAS was found significantly higher (0.58 m moles m^{-2} s^{-1}) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) over T_1, T_2, T_4, T_5 and T_7 treatments, while treatments T_3 and T_8 (0.55 and 0.54 m moles m^{-2} s^{-1}, respectively) were at par with treatment T_6.

Physiological stress can significantly modify stomatal conductance, which, in turn, has a direct impact on the growth and quality of crop plants, Ahmed *et al*. (2021). Notably, plants treated with silver nanoparticles (AgNPs) exhibited the highest values for stomatal conductance. These findings are in line with reports from Mathur *et al*. (2019), Chanu and Upadhyaya (2019), and Khan and Upadhyaya (2019). The application of chitosan nanoparticles, characterized by their polycationic properties, may lead to an increase in the osmotic pressure of stomatal cells. This increase in osmotic pressure can result in a greater degree of stomatal cell opening and subsequently higher stomatal conductance. Furthermore, there is clear evidence that the application of chitosan nanoparticles affects the opening degree of stomatal cells in response to increased CO_2 concentration within integrated cells, as reported by Van *et al*. (2013). The water balance maintains in plant due to potassium, which having synergistic with zinc and applied zinc was accelerate the activity of potassium in plant and maintain the cooling effect in plant, Munir *et al*. (2018) also reported same results in wheat.

Table 4.9 Effect of foliar application of different sources of zinc on stomatal conductance in zinc deficient and sufficient soil under wheat crop

Tr. No	Treatment	Stomatal conductance (m moles m^{-2} s^{-1})			
		Zn deficient soil		Zn sufficient soil	
		40 DAS	55 DAS	40 DAS	55 DAS
T_1	Absolute control	0.26	0.31	0.28	0.34
T_2	General Recommended Dose of Fertilizers (GRDF)	0.32	0.43	0.32	0.41
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	0.39	0.51	0.36	0.55
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	0.36	0.50	0.34	0.53
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	0.37	0.53	0.35	0.52
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	0.38	0.57	0.37	0.58
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	0.36	0.51	0.35	0.50
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	0.36	0.52	0.36	0.54
	SE m±	**0.01**	**0.02**	**0.01**	**0.01**
	CD at 5%	**0.03**	**0.06**	**0.02**	**0.04**

4.3.4 Stomatal Resistance

Stomatal resistance is vital for a plant's ability to photosynthesize, maintain water balance, regulate gas exchange, control leaf temperature, and defend against environmental stressors, under zinc deficient and sufficient soils as influenced by different zinc treatments are reported in table 4.10. At 40 DAS it was found significantly higher (9.46 μ moles m^{-2} s^{-1}) in treatment T_3 (GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}) over T_1, T_2 and T_3 treatments, while treatments T_5, T_6, T_7 and T_8 (9.41, 9.43, 9.45 and 9.43 μ moles m^{-2} s^{-1}, respectively) were at par with treatment T_3. The stomatal resistance at 55 DAS was found significantly higher (16.21 μ moles m^{-2} s^{-1}) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) over T_1, T_2, T_5 and T_7 treatments, while treatments T_3, T_4 and T_8 (15.89, 15.47 and 15.68 μ moles m^{-2} s^{-1}, respectively) were at par with treatment T_6.

However, under zinc sufficient soil, the stomatal resistance at 40 DAS was found significantly higher (9.78 µ moles m^{-2} s^{-1}) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) over T_1, T_2, T_5 and T_7 treatments, while treatments T_3, T_4 and T_8 (9.74, 9.72 and 9.73 µ moles m^{-2} s^{-1}, respectively) were at par with treatment T_6. The stomatal resistance at 55 DAS was found significantly higher (16.03 µ moles m^{-2} s^{-1}) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) over T_1, T_2 and T_7 treatments, while treatments T_3 T_4, T_5 and T_8 (15.73, 15.61, 15.71 and 15.67 µ moles m^{-2} s^{-1}, respectively) were at par with treatment T_6.

Table 4.10 Effect of foliar application of different sources of zinc on stomatal resistance in zinc deficient and sufficient soil under wheat crop

Tr. No	**Treatment**	**Stomatal resistance (µ moles m^{-2} s^{-1})**			
		Zn deficient soil		**Zn sufficient soil**	
		40 DAS	**55 DAS**	**40 DAS**	**55 DAS**
T_1	Absolute control	8.89	9.95	9.12	10.29
T_2	General Recommended Dose of Fertilizers (GRDF)	9.17	13.66	9.38	12.65
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	9.46	15.89	9.74	15.73
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	9.36	15.47	9.72	15.61
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	9.41	15.32	9.68	15.71
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	9.43	16.21	9.78	16.03
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	9.45	15.29	9.66	14.28
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	9.43	15.68	9.73	15.67
	SE m±	**0.02**	**0.26**	**0.02**	**0.26**
	CD at 5%	**0.06**	**0.78**	**0.06**	**0.80**

The application of silicon nanoparticles (Si NPs) through plant spraying resulted in a noteworthy improvement in stomatal resistance values and a substantial reduction in transpiration rate, as reported by Mahmoud *et al.* (2017). The observed effects of NP silicon (Si) on stomatal behavior, such as the formation of a double layer of cuticular silicon, could explain the reduction in transpiration rate. Depending on the thickness of this double layer, it has the capacity to decrease the transpiration rate through the stomata. These mechanisms are in line with findings reported by Ma *et al.* (2001) and Gao *et al.*

(2006). The synergistic effect of zinc on potassium regulates the activity of opening and closing of stomata, the results are confirmed by Munir *et al.* (2018).

4.3.5 Intercellular CO_2 Concentration

The intercellular CO_2 concentration, also known as Ci (internal or chloroplastic CO_2 concentration), is a critical factor in photosynthesis and has several important implications for plant physiology and growth. In table 4.11 under zinc deficient and sufficient soils, the intercellular CO_2 concentration at 40 DAS was found significantly higher (123.57 μ moles CO_2 m^{-2} s^{-1}) in treatment T_3 (GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}) over T_1 and T_2 treatments, while treatments T_4, T_5, T_6, T_7 and T_8 (122.29, 122.83, 123.02, 122.84 and 122.93 μ moles CO_2 m^{-2} s^{-1}, respectively) were at par with treatment T_3. The intercellular CO_2 concentration at 55 DAS was found significantly higher (270.18 μ moles CO_2 m^{-2} s^{-1}) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) over T_1, T_2, T_5 and T_7 treatments, while treatments T_3, T_4 and T_8 (268.09, 267.11 and 267.81 μ moles CO_2 m^{-2} s^{-1}, respectively) were at par with treatment T_6.

However, under zinc sufficient soil, the intercellular CO_2 concentration at 40 DAS was found significantly higher (128.39 μ moles CO_2 m^{-2} s^{-1}) intreatment T_3 (GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}) over T_1 and T_2 treatments, while treatments T_4, T_5, T_6, T_7 and T_8 (125.30, 126.19, 127.75, 124.41 and 124.54 μ moles CO_2 m^{-2} s^{-1}, respectively) were at par with treatment T_3. The intercellular CO_2 concentration at 55 DAS was found significantly higher (272.46 μ moles CO_2 m^{-2} s^{-1}) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) over T_1, T_2, T_4, T_5 and T_7 treatments, while treatments T_3 and T_8 (269.97 and 267.34 μ moles CO_2 m^{-2} s^{-1}, respectively) were at par with treatment T_6.

Enhanced biological growth of crops was observed in the aforementioned treatments. This increase in crop growth necessitates a higher uptake of carbon dioxide (CO_2) for photosynthesis, consequently leading to elevated CO_2 concentrations within the crop. Additionally, zinc plays a pivotal role in the synthesis of the enzyme carbonic anhydrase, which aids in the transportation of CO_2 during the process of photosynthesis. Similar findings were reported in wheat crop by Munir *et al.* (2018). Nano fertilizers or nano-encapsulated nutrients, possess attributes that are highly advantageous for crops. These properties include the ability to deliver nutrients precisely when needed, controlled release of chemical fertilizers that can regulate CO_2 concentration and enhanced targeting of specific plant activities, as noted by Nair *et al.* (2010).

Table 4.11 Effect of foliar application of different sources of zinc on intercellular CO_2 concentration in zinc deficient and sufficient soil under wheat crop

Tr. No	Treatment	Intercellular CO_2 concentration (μ moles CO_2 m^{-2} s^{-1})			
		Zn deficient soil		Zn sufficient soil	
		40 DAS	55 DAS	40 DAS	55 DAS
T_1	Absolute control	115	245	116	242
T_2	General Recommended Dose of Fertilizers (GRDF)	119	258	123	256
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	124	268	128	270
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	122	267	125	265
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	123	266	126	263
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	123	270	128	272
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	123	266	124	262
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	123	268	125	267
	SE m±	**1.16**	**1.05**	**1.40**	**1.52**
	CD at 5%	**3.48**	**3.15**	**4.20**	**4.58**

4.3.6 Transpiration Rate

Canopy photosynthesis is contingent upon the total conductance, which in turn, is influenced by both stomatal frequency and the overall number of stomata per plant. In table 4.12 under zinc deficient and sufficient soils, the transpiration rate at 40 DAS was found significantly higher (2.28 μ moles H_2O m^{-2} s^{-1}) in treatment T_3 (GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}) over T_1 and T_2 treatments, while treatments T_4, T_5, T_6, T_7 and T_8 (2.22, 2.23, 2.25, 2.24 and 2.25 μ moles H_2O m^{-2} s^{-1}, respectively) were at par with treatment T_3. The transpiration rate at 55 DAS was found significantly higher (2.35 μ moles H_2O m^{-2} s^{-1}) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) over T_1, T_2, T_4, T_5, T_7 and T_8 treatments, while treatments T_3 (2.32 μ moles H_2O m^{-2} s^{-1}) was at par with treatment T_6.

However, under zinc sufficient soil, the transpiration rate at 40 DAS was found significantly higher (2.29 μ moles H_2O m^{-2} s^{-1}) in treatment T_3 (GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}) over T_1 and T_2 treatments, while treatments T_4, T_5, T_6, T_7 and T_8 (2.25, 2.28, 2.26, 2.23 and 2.22 µ moles H_2O m^{-2} s^{-1}, respectively) were at par with treatment T_3. The transpiration rate at 55 DAS was found significantly higher (2.38 µ moles H_2O m^{-2} s^{-1}) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) over T_1, T_2, T_4, T_5, T_7 and T_8 treatments, while treatments T_3 (2.35 µ moles H_2O m^{-2} s^{-1}) was at par with treatment T_6.

Table 4.12 Effect of foliar application of different sources of zinc on transpiration rate in zinc deficient and sufficient soil under wheat crop

Tr. No	**Treatment**	**Transpiration rate (µ moles H_2O m^{-2} s^{-1})**			
		Zn deficient soil		**Zn sufficient soil**	
		40 DAS	**55 DAS**	**40 DAS**	**55 DAS**
T_1	Absolute control	1.81	2.09	1.93	2.12
T_2	General Recommended Dose of Fertilizers (GRDF)	2.19	2.22	2.18	2.20
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	2.28	2.32	2.29	2.35
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	2.22	2.27	2.25	2.34
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	2.23	2.26	2.28	2.32
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	2.25	2.35	2.26	2.38
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	2.24	2.26	2.23	2.30
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	2.25	2.29	2.22	2.33
	SE m±	**0.02**	**0.01**	**0.02**	**0.01**
	CD at 5%	**0.07**	**0.04**	**0.06**	**0.04**

The application of zinc oxide nanoparticles (ZnO-NPs) led to a significant increase in the total chlorophyll content in leaves and had a positive impact on gas exchange characteristics, including the transpiration rate. These findings were reported by Ahmad *et al*. (2020). The effect of application of zinc on no. of tillers was found significant which was impacted on increasing rate of transpiration by their more foliage as tillers, same results denoted by Munir *et al*. (2018).

4.3.7 Leaf Temperature

The data in respect of leaf temperature as influenced by different treatments are reported in table 4.13 and found non significant at 40 and 55 DAS.

Table 4.13 Effect of foliar application of different sources of zinc on leaf temperature in zinc deficient and sufficient soil under wheat crop

Tr. No	Treatment	Leaf temperature (^{O}C)			
		Zn deficient soil		Zn sufficient soil	
		40 DAS	55 DAS	40 DAS	55 DAS
T_1	Absolute control	23.67	26.37	25.50	26.20
T_2	General Recommended Dose of Fertilizers (GRDF)	23.41	26.60	25.57	26.47
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	23.43	26.63	25.53	26.77
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	23.52	25.93	25.50	26.67
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	23.53	25.70	25.77	26.57
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	23.63	26.70	25.57	26.40
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	23.60	26.03	25.77	26.53
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	23.50	26.13	25.60	26.63
	SE m±	**0.19**	**0.18**	**0.20**	**0.14**
	CD at 5%	**NS**	**NS**	**NS**	**NS**

4.4 Effect of Foliar Application of Different Sources of Zinc on Nutrient Concentration and Total uptake by Wheat

4.4.1 Effect of Foliar Application of Different Sources of Zinc on Nutrient Concentration and Total Macronutrient Uptake in Zinc Deficient and Sufficient Soil

4.4.1.1 Total nitrogen uptake

The data about total uptake of nitrogen presented in table 4.15 and depicted in fig 4.9 under zinc deficient and sufficient soils, found significantly higher (141.09 kg ha^{-1}) in treatment T_3 (GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}) over T_1, T_2 and T_7 treatments, while treatments T_4, T_5, T_6 and T_8 (133.10, 135.78, 140.11 and 137.88 kg ha^{-1}, respectively) were at par with treatment T_3. In the context of zinc deficient soil, there was an observed increase of 11.37 per cent in the uptake of total nitrogen in treatment T_3 as compared to the GRDF treatment.

Nonetheless, in the case of soil with sufficient zinc level, the total uptake of nitrogen (kg ha^{-1}) was found significantly higher (147.22 kg ha^{-1}) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) over T_1 treatment, while treatments T_2, T_3, T_4, T_5, T_7 andT_8 (136.35, 136.77, 139.69, 140.72, 140.29 and 143.73 kg ha^{-1}, respectively) were at par with treatment T_6. In a zinc sufficient soil status, treatment T_6 exhibited an overall increase of 7.97 per cent in the uptake of total nitrogen in wheat as compared to the GRDF treatment.

Table 4.14 Effect of foliar application of different sources of zinc on concentration of nitrogen in grain and straw of wheat in zinc deficient and sufficient soil

Tr. No	**Treatment**	**Concentration of N in grain (%)**		**Concentration of N in straw (%)**	
		Zn deficient soil	**Zn sufficient soil**	**Zn deficient soil**	**Zn sufficient soil**
T_1	Absolute control	1.55	1.63	0.93	0.95
T_2	General Recommended Dose of Fertilizers (GRDF)	2.08	2.11	1.09	1.14
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	2.15	2.12	1.21	1.15
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	2.09	2.13	1.12	1.18
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	2.11	2.14	1.13	1.18
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	2.12	2.17	1.19	1.21
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	2.08	2.14	1.11	1.18
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	2.12	2.15	1.17	1.19
	SE m±	**0.018**	**0.02**	**0.018**	**0.03**
	CD at 5%	**NS**	**NS**	**NS**	**NS**

Table 4.15 Effect of foliar application of different sources of zinc total uptake of nitrogen by wheat in zinc deficient and sufficient soil

Tr. No	**Treatment**	**Total uptake of nitrogen (kg ha^{-1})**	
		Zn deficient soil	**Zn sufficient soil**
T_1	Absolute control	24.42	29.71
T_2	General Recommended Dose of Fertilizers (GRDF)	126.68	136.35
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	141.09	136.77
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	133.10	139.69
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	135.78	140.72
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	140.11	147.22
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	131.91	140.29
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	137.88	143.73
	SE m±	**2.88**	**2.74**
	CD at 5%	**8.64**	**8.23**

The enhanced absorption and uptake of nitrogen can be attributed to the activation of plant cells facilitated by zinc nanoparticles at their maximum concentration. Zinc plays a crucial role in chlorophyll formation in plants, which in turn may have indirectly improved the absorption of nitrogen within plant cells, ultimately benefiting the development of seed grains. These findings align with the results reported by Gerami *et al.* (2012) and White *et al.* (2017). The increased nitrogen uptake resulting from nano-based fertilizer formulations verifies the prolonged availability of nutrients. This extended nutrient availability is facilitated by the greater specific surface area and the higher number of particles per unit area present in the fertilizer, which enable enhanced nutrient penetration and uptake. These outcomes align with the research findings of Rahale (2011), who reported that the longevity of nutrients released by nano-based fertilizers exceeds 1000 hours, whereas conventional fertilizers release nutrients for less than 500 hours. Also, the zinc is essential constituent of carbonic anhydrase enzyme, which regulate the nitrogen metabolism in plant which reflect in the increased uptake of nitrogen, similar results concomitant by Fan *et al.* (2012).

4.4.1.2 Total phosphorus uptake

Total uptake of phosphorus by grain and straw of wheat are presented in table 4.17 and depicted in fig 4.10 under zinc deficient and sufficient soils, it was found significantly higher (23.67 kg ha^{-1}) in treatment T_3 (GRDF + Soil application of ZnSO4.7H2O @ 20 kg ha^{-1}) over T_1 treatment, while treatments T_2, T_4, T_5, T_6, T_7 and T_8 (21.38, 22.19, 22.59, 23.37, 21.46 and 22.81 kg ha^{-1}, respectively) were at par with treatment T_3. In the context of zinc deficient soil, it was observed that the uptake of total phosphorus by wheat crop increased by 10.71 per cent in treatment T_3 as compared to the T_2 treatment.

But in soil that has sufficient zinc, the total uptake of phosphorus was found significantly higher (24.80 kg ha^{-1}) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) over T_1 and T_2 treatment, while treatments T_3, T_4, T_5, T_7 and T_8 (23.40, 23.76, 24.04, 23.87 and 24.58 kg ha^{-1}, respectively) were at par with treatment T_6. In a zinc sufficient soil, treatment T_6 showed an observed increase of 20.15 per cent in the uptake of total phosphorus compared to the T_2 (GRDF) treatment.

Table 4.16 Effect of foliar application of different sources of zinc on concentration of phosphorus in grain and straw of wheat in zinc deficient and sufficient soil

Tr. No	Treatment	Concentration of P in grain (%)		Concentration of P in straw (%)	
		Zn deficient soil	Zn sufficient soil	Zn deficient soil	Zn sufficient soil
T_1	Absolute control	0.31	0.32	0.21	0.21
T_2	General Recommended Dose of Fertilizers (GRDF)	0.32	0.32	0.23	0.23
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	0.34	0.33	0.24	0.23
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	0.33	0.33	0.23	0.23
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	0.33	0.33	0.24	0.24
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	0.34	0.34	0.24	0.24
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	0.33	0.33	0.23	0.24
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	0.33	0.34	0.24	0.24
	SE m±	**0.02**	**0.004**	**0.003**	**0.0029**
	CD at 5%	**NS**	**NS**	**NS**	**NS**

Nano fertilizers have proven effective in sustaining phosphorus availability to plants through a gradual release over the necessary duration, as corroborated by the findings of Joseph *et al*. (2019). An interesting observation is that there was no negative interaction detected between the added zinc and phosphorus. This lack of negative interaction could be attributed to the unique characteristics of nano particles. In many research studies, simultaneous application of phosphorus and zinc has posed challenges due to metabolic abnormalities and the ionic nature of zinc, which can hinder the absorption of both nutrients by plants. However, when using chargeless nano zinc, the potential for interaction may be reduced, leading to improved phosphorus absorption within plant cells. This could explain the increased uptake of phosphorus observed in the study. These findings are in concerns with the research conducted by Subramanian and Gopalswamy (2012). This could be attributed to the fact that zinc was helpful for the uptake of phosphorus in plant when it was used at low concentration, similar results also reported by Liang *et al*. (2013).

Table 4.17 Effect of foliar application of different sources of zinc on total uptake of phosphorus by wheat in zinc deficient and sufficient soil

Tr. No	**Treatment**	**Total uptake of phosphorus (kg ha^{-1})**	
		Zn deficient soil	**Zn sufficient soil**
T_1	Absolute control	5.54	5.86
T_2	General Recommended Dose of Fertilizers (GRDF)	21.38	20.64
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	23.67	23.40
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	22.19	23.76
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	22.59	24.04
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	23.37	24.80
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	21.46	23.87
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	22.81	24.58
	SE m±	**1.12**	**0.52**
	CD at 5%	**3.38**	**1.57**

4.4.1.3 Total potassium uptake

The data pertaining to the total uptake of potassium presented in table 4.19 and depicted in fig 4.11 under zinc deficient and sufficient soils, was found significantly higher (93.87 kg ha^{-1}) in treatment T_3 (GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}) over T_1 and T_2 treatment, while treatments T_4, T_5, T_6 and T_8 (87.03, 89.70, 90.11 and 89.76 kg ha^{-1}, respectively) were at par with treatment T_3. There was a noticeable of 32.11 per cent increase in the uptake of total potassium in treatment T_3 as compared to the T_2 treatment in zinc deficient soil.

However, under zinc sufficient soil, the total uptake of potassium (kg ha^{-1}) was found significantly higher (97.34 kg ha^{-1}) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) over T_1 and T_2 treatment, while treatments T_3, T_4, T_5, T_7 and T_8 (91.85, 95.04, 96.19, 95.98 and 96.31 kg ha^{-1}, respectively) were at par with treatment T_6. Under zinc sufficient soil, treatment T_6 showed an uptake of total potassium that was 11.62 percent higher than treatment GRDF.

Ghahremani *et al*. (2014) provided insights into how nano fertilizers contribute to the gradual release of nutrients and enhance the efficiency of applied fertilizers. They observed that a prolonged absence of potassium (K) fertilization over a 10-year period led to a decline in K concentration within plants, a phenomenon also noted by Gaj *et al*. (2014). Rietra *et al*. (2017) explained that imbalanced fertilization practices can result in reduced nutrient uptake, which is closely associated with decreased growth and yield attributes in wheat crops. Moreover, the deficiency of potassium is exacerbated when nitrogen (N) is supplied in excess, further diminishing nutrient uptake. Nutrient uptake was observed to increase significantly with the foliar application of nano urea. This enhancement in nutrient uptake can be attributed to the large surface area of nano fertilizers and their particle size, which is smaller than the pore size of plant leaves. These characteristics facilitate greater penetration of nutrients from the applied surface into the plant, leading to improved nutrient uptake. These findings closely align with the research results reported by Patil *et al*. (2020) and Lahari *et al*. (2021) in the context of rice cultivation. Possible causes include to the synergistic effect of zinc on potassium was increased the concentration and also yield of crop which was reflect in the uptake of potassium and also the enhanced photosynthetic activity, vegetative development, cell activation and addition of chemical fertilization, finding was supported by Ladan *et al*. (2012) and Chen *et al*. (2016).

Table 4.18 Effect of foliar application of different sources of zinc on concentration of potassium in grain and straw of wheat in zinc deficient and sufficient soil

Tr. No	Treatment	Concentration of K in grain (%)		Concentration of K in straw (%)	
		Zn deficient soil	Zn sufficient soil	Zn deficient soil	Zn sufficient soil
T_1	Absolute control	1.18	1.18	0.59	0.88
T_2	General Recommended Dose of Fertilizers (GRDF)	1.27	1.27	0.79	0.84
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	1.48	1.32	0.91	0.9
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	1.33	1.33	0.85	0.88
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	1.36	1.39	0.88	0.91
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	1.46	1.48	0.90	0.59
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	1.32	1.36	0.84	0.85
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	1.39	1.46	0.88	0.79
	SE m±	**0.02**	**0.03**	**0.04**	**0.03**
	CD at 5%	**NS**	**NS**	**NS**	**NS**

Table 4.19 Effect of foliar application of different sources of zinc on total uptake of potassium by wheat in zinc deficient and sufficient soil

Tr. No	Treatment	Total uptake of potassium (kg ha^{-1})	
		Zn deficient soil	Zn sufficient soil
T_1	Absolute control	22.41	24.33
T_2	General Recommended Dose of Fertilizers (GRDF)	71.05	87.20
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	93.87	91.85
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	87.03	95.04
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	89.70	96.19
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	90.11	97.34
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	79.77	95.98
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	89.76	96.31
	SE m±	**2.19**	**2.89**
	CD at 5%	**6.58**	**8.68**

4.4.2 Effect of Foliar Application of Different Sources of Zinc on Micronutrient Concentration and Uptake in Zinc Deficient and Sufficient Soil

4.4.2.1 Total Iron uptake

The application of various zinc sources had a notable impact on the total uptake of iron under zinc deficient soil, it was found significantly higher (1498 g ha^{-1}) in treatment T_3 (GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}) over T_1, T_2, T_4, T_5 and T_7 treatment, while treatments T_6 and T_8 (1448 and 1419 g ha^{-1}, respectively) were at par with treatment T_3. When compared to the GRDF treatment, treatment T_3 uptake of total iron increased by 11.87 per cent in the circumstance of zinc deficient soil. The data were presented in table 4.21 and depicted in fig 4.12 for zinc deficient and sufficient soils.

However, under zinc sufficient soil, the total uptake of iron was found significantly higher (1665 g ha^{-1}) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) over T_1, T_2, T_3 and T_4 treatment, while treatments T_5, T_7 and T_8 (1590, 1578 and 1614 g ha^{-1}, respectively) were at par with treatment T_6. When compared to the GRDF treatment, treatment T_6 showed an overall increase in the uptake of total iron in wheat of 4.53 per cent in a soil condition where zinc sufficed.

Table 4.20 Effect of foliar application of different sources of zinc on concentration of iron in grain and straw of wheat in zinc deficient and sufficient soil

Tr. No	Treatment	Concentration of Fe in grain (mg kg^{-1})		Concentration of Fe in straw (mg kg^{-1})	
		Zn deficient soil	Zn sufficient soil	Zn deficient soil	Zn sufficient soil
T_1	Absolute control	140	152	188	203
T_2	General Recommended Dose of Fertilizers (GRDF)	140	157	192	205
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	145	157	198	205
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	143	158	193	205
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	143	162	195	208
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	143	162	197	212
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	142	160	192	207
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	143	162	195	210
	SE m±	**2.05**	**1.97**	**1.85**	**2.32**
	CD at 5%	**6.16**	**5.93**	**5.55**	**6.97**

Table 4.21 Effect of foliar application of different sources of zinc on total uptake of iron by wheat in zinc deficient and sufficient soil

Tr. No	Treatment	Total uptake of Fe (g ha^{-1})	
		Zn deficient soil	**Zn sufficient soil**
T_1	Absolute control	324	357
T_2	General Recommended Dose of Fertilizers (GRDF)	1339	1521
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	1498	1532
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	1371	1543
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	1410	1590
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	1448	1665
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	1353	1578
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	1419	1614
	SE m±	**28.06**	**30.10**
	CD at 5%	**84.18**	**90.31**

Nano fertilizers with particle sizes below 100 nanometers have been shown to enhance the plant's efficient utilization of fertilizers. They contribute to reduced pollution, are environmentally friendly, and exhibit improved solubility in water, thereby increasing their effectiveness in augmenting metabolic activities and enhancing the uptake of trace elements within plants, as observed by Joseph and Morrison (2006). Research studies have demonstrated that zinc enhances the absorption of iron nutrient by plants, as reported by Kheyri *et al.* (2018). Furthermore, the reduction in particle size results in an increased specific surface area and a higher number of particles per unit area of a fertilizer. This increased surface area and particle density provide more opportunities for contact with nano fertilizers, facilitating greater penetration and nutrient uptake, as demonstrated by Liscano *et al*. (2000). This might be as a result of the slow-release properties of nano particles shown positive impact on iron uptake by plants with sustained release benefits over the requirements of crops, the results are confirmed by Ghafari and Razmjoo (2015).

4.4.2.2 Total Manganese uptake

Total uptake of manganese presented in table 4.23 and depicted in fig 4.13 under zinc deficient and sufficient soils, was found to be significantly higher (901 g ha^{-1}) in treatment T_3 (GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}) over T_1, T_2, T_4 and T_7 treatment, while treatments T_5, T_6 and T_8 (838, 868 and 852 g ha^{-1}, respectively) were at par with treatment T_3. In the condition of zinc deficient soil, there was a discernible increase in the uptake of total manganese in treatment T_3 compared to the T_2 treatment of 12.34 per cent.

However, under zinc sufficient soil, the total uptake of manganese was found significantly higher (923 g ha^{-1}) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) over T_1, T_2, T_3 and T_4 treatment, while treatments T_5, T_7 and T_8 (906, 882 and 915 g ha^{-1}, respectively) were at par with treatment T_6, 10.27 per cent more total manganese was uptake in zinc sufficient soil in the T_6 treatment compared to treatment T_2 (GRDF).

This phenomenon may be attributed to the characteristic of nano fertilizers, which possess a relatively large surface area and particle size that is smaller than the pore size of plant leaves. This property enhances the penetration of nano fertilizers into the plant from the applied surface and subsequently improves the uptake of nano fertilizers, as reported by Kumar *et al.* (2014). This may be because the application of zinc showed positive interaction and uptake with distribution in the plant, Similar reported by Arunachalam *et al.* (2013).

Table 4.22 Effect of foliar application of different sources of zinc on concentration of manganese in grain and straw of wheat in zinc deficient and sufficient soil

Tr. No	**Treatment**	**Concentration of Mn in grain (mg kg^{-1})**		**Concentration of Mn in straw (mg kg^{-1})**	
		Zn deficient soil	**Zn sufficient soil**	**Zn deficient soil**	**Zn sufficient soil**
T_1	Absolute control	87	87	108	108
T_2	General Recommended Dose of Fertilizers (GRDF)	90	92	108	108
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	93	93	115	110
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	92	93	112	110
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	92	93	112	112
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	93	97	113	113
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	92	93	110	112
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	92	95	113	113
	SE m±	**2.17**	**2.22**	**2.27**	**2.66**
	CD at 5%	**6.51**	**6.66**	**6.81**	**7.98**

Table 4.23 Effect of foliar application of different sources of zinc on total uptake of manganese by wheat in zinc deficient and sufficient soil

Tr. No	**Treatment**	**Total uptake of Mn (g ha^{-1})**	
		Zn deficient soil	**Zn sufficient soil**
T_1	Absolute control	190	200
T_2	General Recommended Dose of Fertilizers (GRDF)	802	837
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	901	855
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	828	869
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	838	906
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	868	923
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	824	882
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	852	915
	SE m±	**22.84**	**14.44**
	CD at 5%	**68.53**	**43.34**

4.4.2.3 Total Zinc uptake

The data provided in table 4.25 and illustrated in fig. 4.14 under zinc deficient and sufficient soils, the total uptake of zinc was found significantly higher (419 g ha^{-1}) in treatment T_3 (GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}) over T_1, T_2, T_4, T_5, T_7 and T_8 treatment, while treatment T_6 (402 g ha^{-1}) were at par with treatment T_3. Under conditions of zinc deficiency, wheat cultivated in treatment T_3 showed a 15.10 per cent overall uptake in total zinc compared to wheat cultivated in treatment GRDF.

While in the case of zinc sufficient soil, the total uptake of zinc was found significantly higher (455 g ha^{-1}) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) over T_1, T_2 and T_3 treatment, while treatments T_4, T_5, T_7 and T_8 (427, 440, 435 and 446 g ha^{-1}, respectively) were at par with treatment T_6. In conditions where zinc was sufficient, wheat cultivated in treatment T_6 displayed an overall increase of 12.62 per cent in the uptake of total zinc compared to wheat cultivated in treatment GRDF.

Nano particles of zinc exhibit a remarkable ability to penetrate plant tissues through the leaf cuticle, epidermis, and stomatal openings more effectively than ionic or conventional particles. When applied as a foliar application, nano zinc acts as a site-specific agent and undergoes increased absorption in a sophisticated manner. This mechanism likely contributes to the improved uptake of zinc within the plant system through foliar application of nano zinc. These results are in concordant with the findings of Adress *et al*. (2017), Lopez *et al*. (2019) and Sadak and Bakri (2020). The increased uptake of zinc resulting from the application of nano zinc was similarly documented by Moghaddasi *et al*. (2017). Also, the slow-release pattern of nutrients has been recognized as a contributing factor to enhanced nutrient uptake, as advocated by Manikandan and Subramanian (2016). Foliar application stands as a rapid and efficient method for addressing plant nutrition. The result of zinc nanoparticles applied topically operate as site-specific agents and are also exposed to sophisticated methods of enhanced absorption, which may have improved zinc uptake in the plant system, Similar results are reported by Naik *et al*. (2007) and Du *et al*. (2011).

Table 4.24 Effect of foliar application of different sources of zinc on concentration of zinc in grain and straw of wheat in zinc deficient and sufficient soil

Tr. No	**Treatment**	**Concentration of Zn in grain (mg kg^{-1})**		**Concentration of Zn in straw (mg kg^{-1})**	
		Zn deficient soil	**Zn sufficient soil**	**Zn deficient soil**	**Zn sufficient soil**
T_1	Absolute control	40.00	40.33	47	52
T_2	General Recommended Dose of Fertilizers (GRDF)	40.67	40.83	50	55
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	41.33	40.83	55	57
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	41.17	40.83	52	58
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	41.17	41.00	53	58
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	41.33	41.83	53	62
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	40.67	41.00	52	58
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	40.33	41.67	53	58
	SE m±	**0.35**	**0.32**	**1.49**	**1.90**
	CD at 5%	**1.06**	**0.97**	**4.48**	**5.70**

Table 4.25 Effect of foliar application of different sources of zinc on total uptake of zinc by wheat in zinc deficient and sufficient soil

Tr. No	Treatment	Total uptake of Zn (g ha^{-1})	
		Zn deficient soil	**Zn sufficient soil**
T_1	Absolute control	85	95
T_2	General Recommended Dose of Fertilizers (GRDF)	364	404
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	419	423
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	378	427
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	394	440
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	402	455
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	371	435
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	399	446
	SE m±	**7.40**	**9.99**
	CD at 5%	**22.22**	**29.98**

4.4.2.4 Total Copper uptake

The data provided in table 4.27 and visualized in fig. 4.15 under zinc deficient and sufficient soils, the total uptake of copper was found significantly higher (59 g ha^{-1}) in treatment T_3 (GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}) over T_1 and T_2 treatments, while treatments T_4, T_5, T_6, T_7 and T_8 (56, 57, 58, 55 and 58 g ha^{-1}) were at par with treatment T_3. In soils characterized by zinc deficiency, treatment T_3 resulted in a 9.25% higher total copper uptake compared to the GRDF treatment.

However, under zinc sufficient soil, the total uptake of copper (g ha^{-1}) was found significantly higher (62 g ha^{-1}) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) and T_8 (GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS) over T_1 and T_2 treatments, while treatments T_3, T_4, T_5 and T_7 (58, 58, 60 and 59 g ha^{-1}, respectively) were at par with treatment T_6 and T_8. In a zinc sufficient soil environment, an overall increase of 8.77 per cent in the uptake of total copper in wheat was observed in both treatment T_6 and T_8 when compared to the GRDF treatment.

Table 4.26 Effect of foliar application of different sources of zinc on concentration of copper in grain and straw of wheat in zinc deficient and sufficient soil

Tr. No	Treatment	Concentration of Cu in grain (mg kg^{-1})		Concentration of Cu in straw (mg kg^{-1})	
		Zn deficient soil	Zn sufficient soil	Zn deficient soil	Zn sufficient soil
T_1	Absolute control	6.07	6.05	7.38	7.40
T_2	General Recommended Dose of Fertilizers (GRDF)	6.07	6.10	7.53	7.53
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	6.13	6.10	7.70	7.57
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	6.10	6.10	7.58	7.57
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	6.10	6.12	7.60	7.62
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	6.12	6.17	7.63	7.68
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	6.10	6.12	7.57	7.60
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	6.12	6.12	7.62	7.62
	SE m±	**0.04**	**0.04**	**0.07**	**0.07**
	CD at 5%	**0.12**	**0.13**	**0.21**	**0.23**

Table 4.27 Effect of foliar application of different sources of zinc on total uptake of copper by wheat in zinc deficient and sufficient soil

Tr. No	Treatment	Total uptake of Cu (g ha^{-1})	
		Zn deficient soil	Zn sufficient soil
T_1	Absolute control	13	14
T_2	General Recommended Dose of Fertilizers (GRDF)	54	57
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	59	58
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	56	58
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	57	60
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	58	62
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	55	59
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	58	62
	SE m±	**1.11**	**0.99**
	CD at 5%	**3.35**	**2.97**

This can be attributed to the beneficial effect of split nitrogen application, which has been observed to enhance the uptake of micronutrients, particularly copper. The heavy metal uptake is influenced by nanoparticle-induced additive interactions, which also identify pathways for pollution movement in plants, Similar results also reported by Skiba *et al.* (2020).

4.5 Effect of Foliar Application of Different Sources of Zinc on Quality Parameters of Wheat

4.5.1 Crude Protein

The data pertaining in table 4.28 and depicted in fig 4.16 under zinc deficient and sufficient soils, the crude protein was found significantly higher (12.51%) in treatment T_3 (GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}) over T_1, T_2, T_4 and T_7 treatments, while treatments T_5, T_6 and T_8 (12.28, 12.33 and 12.31%, respectively) were at par with treatment T_3.

However, under zinc sufficient soil, the crude protein was found significantly higher (12.60%) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS) over T_1 treatment, while treatments T_2, T_3, T_4, T_5, T_7 and T_8 (12.41, 12.47, 12.39, 12.28, 12.31 and 12.43%, respectively) were at par with treatment T_6.

Table 4.28 Effect of foliar application of different sources of zinc on crude protein content in wheat grain in zinc deficient and sufficient soil

Tr. No	Treatment	Crude protein (%)	
		Zn deficient soil	Zn sufficient soil
T_1	Absolute control	9.02	9.47
T_2	General Recommended Dose of Fertilizers (GRDF)	12.10	12.41
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	12.51	12.47
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	12.12	12.39
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	12.28	12.28
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	12.33	12.60
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	12.10	12.31
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	12.31	12.43
	SE m±	**0.11**	**0.13**
	CD at 5%	**0.32**	**0.40**

Prasad *et al*. (2012) observed that the controlled application of fertilizers in nanoform resulted in increased yield and protein content in peanuts. Similarly, Sharifi *et al*. (2016) found that the foliar application of nano zinc fertilizers led to higher crude protein content in forage corn compared to chemical forms of fertilizers. The zinc element played an additive role in protein formation, underscoring its significance in determining the protein content of plants, as highlighted by Safyan *et al*. (2012). It could be due to the in winter wheat grains, zinc is crucial for the production of protein and the process of nitrogen absorption. It may also have a role in controlling gene expression associated to proteins in seed grains, Similar findings were reported by Hadiat and Salama (2013), Gomez-Cornado *et al*. (2016).

4.5.2 Test Weight

The outcomes of various treatments involving chemical and Nano zinc fertilizers on the test weight (i.e 1000 grain) of wheat crop are presented in table 4.29 and depicted in fig 4.17 under zinc deficient and sufficient soils, it was found significantly higher (41.77 g) in treatment T_3 (GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}) over T_1, T_2, T_4 and T_7 treatments, while treatments T_5, T_6 and T_8 (12.28, 12.33 and 12.31%, respectively) were at par with treatment T_3. In the context of zinc deficient soil, treatment T_3 exhibited an observed increase of 3.64 per cent in the test weight of wheat compared to the GRDF treatment.

Table 4.29 Effect of foliar application of different sources of zinc on test weight of wheat grain in zinc deficient and sufficient soil

Tr. No	Treatment	Test weight (g) (1000 grains)	
		Zn deficient soil	Zn sufficient soil
T_1	Absolute control	32.93	34.52
T_2	General Recommended Dose of Fertilizers (GRDF)	40.30	40.34
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	41.77	39.42
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	39.83	39.41
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	40.40	43.37
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	40.02	39.72
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	39.87	39.80
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	40.68	38.98
	SE m±	**0.75**	**0.73**
	CD at 5%	**2.27**	**2.21**

However, under zinc sufficient soil, the test weight was found significantly higher (43.37 g) in treatment T_5 (GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS) over T_1 T_2, T_3, T_4, T_6, T_7 and T_8 treatments. When compared to the GRDF treatment, treatment T_5 exhibited an overall increase of 7.51 percent in the test weight of wheat in a soil where zinc was sufficient.

These observations can be attributed to nano fertilizers functioning as slow-release fertilizers, thereby reducing fertilizer losses, improving nutrient use efficiency, and promoting balanced crop nutrition. Nano fertilizers are known to gradually release nutrients over an extended period throughout the crop growth cycle, potentially enhancing crop yield without any associated negative effects. These findings align with the research conducted by previous scholars such as Maqsood *et al*. (2013), Gerdini (2016) and Gomaa *et al*. (2017). This could be due to the enhanced uptake of zinc accelerates the translocation of sugars and higher carbohydrate in grain, the results are confirmed by Jaberzadeh *et al*. (2013), Ghahremani *et al*. (2014), Harsini *et al*. (2014), Raezaei *et al*. (2014).

4.5.3 Gluten

The data pertaining in table 4.30 and depicted in fig 4.18 under zinc deficient and sufficient soils, the gluten content (on dry weight basis) was found significantly higher (7.11 %) in treatment T_5 (GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS) over T_1, T_2 and T_8 treatments, while treatments T_3, T_4, T_6 and T_7 (7.08, 7.08, 7.09 and 7.07%, respectively) were at par with treatment T_5.

Table 4.30 Effect of foliar application of different sources of zinc on gluten content wheat grain in zinc deficient and sufficient soil

Tr. No	Treatment	Gluten content (%) (on dry weight basis)	
		Zn deficient soil	Zn sufficient soil
T_1	Absolute control	6.98	7.00
T_2	General Recommended Dose of Fertilizers (GRDF)	7.00	7.06
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	7.08	7.05
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	7.08	7.06
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	7.11	7.09
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	7.09	7.04
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	7.07	7.05
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	7.05	7.06
	SE m±	**0.01**	**0.014**
	CD at 5%	**0.04**	**0.044**

However, under zinc sufficient soil, the gluten content (on dry weight basis) was found significantly higher (7.09 %) in treatment T_5 (GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS) over T_1, T_2, T_3, T_4, T_6, T_7 and T_8 treatments.

In general, under water stress conditions, the gluten content of wheat tends to decrease. However, the application of nano TiO_2 has been found to enhance these gluten contents. This improvement may be attributed to the positive correlation observed between titanium application and the rate of photosynthesis, as documented by Zhao *et al.* (2009) and Jaberzadeh *et al.* (2013). The ratio of monomeric gliadins to polymeric glutenins may be influenced by zinc nutrition, which in turn might change the quality of wheat dry gluten depends on their inherent chemical composition, which have a response function in various enzymatic activities in grain, similar findings were also reported by Niyigaba *et al.* (2019) and Maganti *et al.* (2020).

4.5.4 β Carotene

The data presented in table 4.31, for both zinc deficient and zinc sufficient soils, indicate that the β-carotene in wheat grain was not found to be statistically significant. The zinc plays an essential role in metabolism of starch formation and enzyme carbonic anhydrase which accelerate carbohydrate formation which was helpful for slight increase in β Carotene in wheat, similar results reported by Singh and Sandhu (2021).

Table 4.31 Effect of foliar application of different sources of zinc on β Carotene in wheat grain in zinc deficient and sufficient soil

Tr. No	Treatment	β Carotene (μg g^{-1})	
		Zn deficient soil	Zn sufficient soil
T_1	Absolute control	2.74	2.86
T_2	General Recommended Dose of Fertilizers (GRDF)	2.85	2.86
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	3.03	2.96
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	2.93	2.93
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	2.91	2.97
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	2.95	2.96
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	2.91	2.96
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	2.92	2.6
	SE m±	**0.02**	**0.017**
	CD at 5%	**NS**	**NS**

4.6 Effect of Foliar Application on Different Sources of Zinc on Soil Properties after Harvest

4.6.1 Soil Properties After Harvest

The data in table 4.32, considering both zinc deficient and sufficient soils conditions, revealed that the soil properties assessed after the harvest were not found to be statistically significant.

Table 4.32 Effect of foliar application on different sources of zinc on soil properties after harvest

Tr. No.	Treatment	Zn deficient soil				Zn sufficient soil			
		pH (1:2.5)	**EC (dS m^{-1})**	**$CaCO_3$ (%)**	**Organic carbon (g kg^{-1})**	**pH (1:2.5)**	**EC (dS m^{-1})**	**$CaCO_3$ (%)**	**Organic carbon (g kg^{-1})**
T_1	Absolute control	8.26	0.32	6.40	5.0	8.21	0.29	7.78	5.1
T_2	General Recommended Dose of Fertilizers (GRDF)	8.22	0.34	6.92	5.3	8.19	0.32	7.92	5.0
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	8.19	0.41	6.70	5.4	8.16	0.38	7.78	5.4
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS	8.20	0.38	6.80	5.2	8.20	0.35	7.9	5.2
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS	8.21	0.34	6.75	5.0	8.19	0.33	7.91	5.3
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS	8.21	0.35	6.72	5.0	8.18	0.34	7.94	5.3
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS	8.22	0.36	6.88	5.3	8.20	0.34	7.86	5.2
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS	8.21	0.35	6.9	5.2	8.19	0.36	7.84	5.4
	SE m±	**0.01**	**0.01**	**0.01**	**0.001**	**0.01**	**0.001**	**0.01**	**0.01**
	CD at 5%	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**
	Initial	**8.24**	**0.35**	**6.80**	**4.6**	**8.20**	**0.38**	**7.87**	**5.4**

4.6.2 Available Macronutrients in Zinc Deficient Soil

This data presented in table 4.33 and depicted in fig 4.19 under zinc deficient soil, available nitrogen content in soil was found significantly higher (170 kg ha^{-1}) in treatment T_2 (General Recommended Dose of Fertilizers) over T_1, T_3, T_4, T_5, T_6, T_7 and T_8 treatments, the available phosphorus content in soil was found significantly higher (13.24 kg ha^{-1}) in treatment T_2 (General Recommended Dose of Fertilizers) over T_1, T_3, T_5 and T_6 treatments, while treatments T_7 and T_8 (13.05 and 12.68 kg ha^{-1}, respectively) were at par with treatment T_2. Available potassium content in soil was found significantly higher (497 kg ha^{-1}) in treatment T_2 (GRDF) over T_1, T_3, T_4, T_5, T_6, and T_8 treatments, while treatment T_7 (496 kg ha^{-1}) was at par with treatment T_2.

The concurrent utilization of traditional fertilizers alongside nano fertilizers resulted in an augmented quantity of accessible macronutrients within the soil. Rajonee *et al.* (2016) noted that the slow-release characteristics of nano fertilizers led to higher levels of available nitrogen in post-harvest soil when compared to conventional fertilizers in the context of *Ipomoea aquatic* (kalmi). Furthermore, Astaneh *et al.* (2021) observed that the application of nano chelated nitrogen fertilizers resulted in increase in phosphorus content and also increase in potassium content as compared to conventional urea fertilizer.

Table 4.33 Effect of foliar application of different sources of zinc on soil available macronutrients in zinc deficient under wheat crop

Tr. No	**Treatment**	**Soil available macronutrients (kg ha^{-1})**		
		N	**P**	**K**
T_1	Absolute control	137	8.72	440
T_2	General Recommended Dose of Fertilizers (GRDF)	170	13.24	497
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	166	11.67	478
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS	165	13.05	482
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS	168	11.04	490
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS	169	11.67	491
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS	167	12.68	496
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS	168	13.05	478
	SE m±	**0.40**	**0.29**	**1.73**
	CD at 5%	**1.22**	**0.89**	**5.21**
	Initial	**159**	**10.83**	**467**

4.6.3 Available Macronutrients in Zinc Sufficient Soil

The data presented in table 4.34 and depicted in fig 4.20 under zinc sufficient soil, the available nitrogen content in soil was found significantly higher (191 kg ha^{-1}) in treatments T_4 (GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS) and T_7 (GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS) over T_1, T_2, T_3, T_5, T_6 and T_8 treatments. The available phosphorus content in soil was found significantly higher (12.90 kg ha^{-1}) in treatment T_2 (General Recommended Dose of

Fertilizers) over T_1, T_3, T_4, T_5, T_6, T_7 and T_8 treatments. Available potassium content in soil was found significantly higher (497 kg ha^{-1}) in treatment T_5 (GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS) over T_1, T_2, T_3, T_4, T_6, T_7 and T_8 treatments.

The application of nano fertilizers has been found to boost certain biogeochemical processes, specifically the nitrification process, which results in an increased availability of nitrogen within the soil. Nano fertilizers release humic acid and root exudates gradually as nutrients are released, subsequently elevating the nitrogen content. This nitrogen serves as a food source for soil microorganisms, as reported by Vande and Arai (2019). The application of nano fertilizer via foliar spraying is expected to not only diminish soil pollution but also augment soil fertility by enhancing the chemical attributes of the soil. This phenomenon can likely be attributed to the enhancement of nitrogen mineralization in the soil, potentially stemming from the addition of zinc, which may have further contributed to the observed improvements, Similar results was also reported by Grunes (1959), it also same for phosphorus and potassium availability in the soil may have increased as a results of biomass being incorporated into the soil by crops, the results are in conformity with the findings of Miao *et al*. (2010).

Table 4.34 Effect of foliar application of different sources of zinc on soil available macronutrients in zinc sufficient under wheat crop

Tr. No	**Treatment**	**Soil available macronutrients (kg ha^{-1})**		
		N	**P**	**K**
T_1	Absolute control	149	10.18	459
T_2	General Recommended Dose of Fertilizers (GRDF)	181	12.90	508
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	180	12.20	503
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS	191	12.54	517
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS	185	12.22	538
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS	186	12.37	519
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS	191	12.61	508
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS	187	12.11	504
	SE m±	**0.94**	**0.09**	**0.4**
	CD at 5%	**2.88**	**0.27**	**1.22**
	Initial	**166**	**12.78**	**490**

4.6.4 Available DTPA Micronutrients in Zinc Deficient in Soil

The data presented in table 4.35 and depicted in fig 4.21 under zinc deficient soil, available iron content in soil was found significantly higher (4.28 mg kg^{-1}) in treatments T_2 (General Recommended Dose of Fertilizers) over T_1, T_3, T_4, T_5, T_6, T_7 and T_8 treatments. Initially, soil was sufficient in available Fe hence post harvest status showed deficient in all the soils under treatment. Available manganese (mg kg^{-1}) was found significantly higher (8.49 mg kg^{-1}) in treatment T_4 (GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS) over T_3 treatment, while treatments T_1, T_2, T_5, T_6, T_7 and T_8 (8.25, 8.25, 8.25, 8.23, 8.17 and 8.19 mg kg^{-1}, respectively) was at par with treatment T_4. Initially, soil was deficient in available zinc under zinc deficient soil, but post-harvest status showed slightly higher status in treatment, which received zinc through $ZnSO_4$ through soil application as compared to the rest of the foliar treatments under study. Available zinc was found significantly higher (0.56 mg kg^{-1}) in treatment T_3 (GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}) over T_1, T_2, T_4, T_6, T_7 and T_8 treatments, while treatment T_5 (0.52 mg kg^{-1}) was at par with treatment T_3. Available copper content in soil was found non significantly at harvest of wheat.

Table 4.35 Effect of foliar application of different sources of zinc on soil available DTPA micronutrients in zinc deficient under wheat crop

Tr. No.	Treatment	Soil available micronutrients (mg kg^{-1})			
		Fe	Mn	Zn	Cu
T_1	Absolute control	4.07	8.25	0.46	1.34
T_2	General Recommended Dose of Fertilizers (GRDF)	4.28	8.25	0.48	1.39
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	4.16	8.32	0.56	1.35
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	4.13	8.49	0.46	1.36
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at20 and 40 DAS.	4.12	8.25	0.52	1.31
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	4.02	8.23	0.48	1.35
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15%at 20 and 40 DAS.	4.15	8.17	0.51	1.34
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	4.16	8.19	0.49	1.37
	SE m±	**0.02**	**0.06**	**0.012**	**0.01**
	CD at 5%	**0.07**	**0.20**	**0.038**	**NS**
	Initial	**4.61**	**8.30**	**0.54**	**1.35**

According to Jassim *et al*. (2019), the utilization of nano fertilizers has been observed to enhance the availability of essential micronutrients such as zinc (Zn), iron (Fe) and manganese (Mn) in the soil following the harvest of rice crop. Additionally, Sahar *et al*. (2020) concluded that the application of nano NPK fertilizers led to an increase in the availability of micronutrients in the soil after the harvest of soybean crops.

4.6.5 Available DTPA Micronutrients in Zinc Sufficient in Soil

The data presented in table 4.36 and depicted in fig 4.22 under zinc sufficient soil, available iron content in soil was found significantly higher (4.30 mg kg^{-1}) in treatment T_2 (General Recommended Dose of Fertilizers) over T_1, T_3, T_4, T_5, T_6, T_7 and T_8 treatments. Initially, the soil contained a sufficient amount of available iron (Fe); however, the post-harvest analysis indicated a deficiency of iron in all the soils subjected to treatment. Available manganese content in soil was found significantly higher (8.82 mg kg^{-1}) in treatment T_2 (General Recommended Dose of Fertilizers), while treatments T_1, T_3, T_4, T_5, T_6, T_7 and T_8 (8.64, 8.69, 8.60, 8.56, 8.62, 8.58 and 8.66 mg kg^{-1}, respectively) were at par with treatment T_3. Available zinc content in soil were sufficient and it was found significantly higher (0.65 mg kg^{-1}) in treatment T_3 **(**GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}**)** over T_1, T_3, T_4, T_5, T_6, T_7 and T_8 treatments, while treatmentT_3 (0.65 mg kg^{-1}) was at par with treatment T_3.

Table 4.36 Effect of foliar application of different sources of zinc on soil available DTPA micronutrients in zinc sufficient under wheat crop

Tr. No.	**Treatment**	**Soil available micronutrients (mg kg^{-1})**			
		Fe	**Mn**	**Zn**	**Cu**
T_1	Absolute control	4.09	8.64	0.60	1.41
T_2	General Recommended Dose of Fertilizers (GRDF)	4.30	8.82	0.64	1.70
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	4.29	8.69	0.65	1.51
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	4.17	8.60	0.61	1.46
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at20 and 40 DAS.	4.16	8.56	0.62	1.64
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	4.11	8.62	0.61	1.62
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15%at 20 and 40 DAS.	4.26	8.58	0.62	1.49
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	4.26	8.66	0.60	1.57
	SE m±	**0.03**	**0.10**	**0.01**	**0.07**
	CD at 5%	**0.09**	**0.31**	**0.03**	**0.21**
	Initial	**4.60**	**9.80**	**0.67**	**1.52**

At the outset, the soil possessed an proportionate supply of available zinc in the context of zinc-sufficient soil. Nevertheless, the post-harvest evaluation revealed a slightly elevated zinc status in treatments that received zinc from various sources, both via soil application and foliar application, as examined in the study and available copper (mg kg^{-1}) was found significantly higher (1.70 mg kg^{-1}) in treatment T_2 (General Recommended Dose of Fertilizers) over T_1 treatment, while treatments T_3, T_4, T_5, T_6, T_7 and T_8 (1.51, 1.46, 1.64, 1.62, 1.49 and 1.57 mg kg^{-1}, respectively) were at par with treatment T_2.

Thirunavukkarasu and Subramanian (2015) demonstrated that the slow-release mechanism of nano fertilizers has the capacity to improve the nutrient status of soil by mitigating leaching loss, fixation, atmospheric losses, and microbial conversion. These findings align with similar results reported by Rani *et al*. (2019) and Meena *et al*. (2021).

After application of nano zinc on leaves, there may have an increase in the mineralization of native iron and zinc, which led to better microbial activity in the soil due to gradual release of humic acid and root exudates and an increase in soil available iron and zinc. Similar results have also been reported by Mirzapor and Khashgoltermanesh (2013), Hassanpouraghdam and Vojad (2020).

4.7 Effect of Foliar Application of Different Sources of Zinc on Apparent Nutrient Recovery Efficiency of Macronutrients in Zinc Deficient Soil

The data of apparent nutrient recovery efficiency of N, P and K as influenced by different zinc sources treatments under zinc deficient and zinc sufficient soil are reported in table 4.37. The apparent nutrient recovery efficiency of nitrogen was found maximum (97%) in treatment T_3 (GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}). In respect of phosphorus, it was found maximum (13%) in treatments T_3 (GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}) and T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS). However, in respect of potassium it was found maximum (148%) in treatment T_3 (GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}). The percentage increase in apparent nutrient recovery efficiency for nitrogen (N), phosphorus (P), and potassium (K) in treatment T_3, as compared to the GRDF treatment, under zinc deficient soil conditions, which was found to be 14.11, 8.33, and 5.71%, respectively. This phenomenon could be attributed to the gradual increase in zinc availability to the plant over the course of the crop growth period.

However, under zinc sufficient soil, the apparent nutrient recovery efficiency of nitrogen was found maximum (98%) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.). In respect of phosphorus it was found maximum (14%) in treatments T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.)

However, in respect of potassium it was found maximum (152%) in treatment T_6 (GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.). In a condition of sufficient soil zinc levels, it was shown that treatment T_6 had an increase in apparent nutrient recovery efficiency for nitrogen (N), phosphorus (P), and potassium (K) of 6.52, 7.69, and 2.01%, respectively, when compared to the GRDF treatment.

Apparent nutrient recovery efficiency is a measure of the difference in nutrient uptake by the crop between the fertilized and unfertilized conditions, relative to the quantity of nutrient applied. An increase in apparent nutrient recovery, achieved with the recommended dose of fertilizer from inorganic sources, can be attributed to the fact that the crop takes up a greater quantity of nutrients compared to the amount applied. This can likely be attributed to the immediate supplementation provided through foliar spraying, which renders zinc beneficial to the plant's physiology and plays a pivotal role in plant metabolism. Similar findings were reported by Getinet (2022). Among the various nutrient management treatments examined, Sankar *et al.* (2020) reported that the highest apparent nutrient efficiency was observed in the treatments that involved the combination of NPK with nano fertilizers.

Table 4.37 Effect of foliar application of different sources of zinc on apparent nutrient recovery efficiency of macronutrients in zinc deficient soil under wheat crop

Tr. No.	**Treatment**	**ANR (%)**					
		Zn deficient soil			**Zn sufficient soil**		
		N	**P**	**K**	**N**	**P**	**K**
T_1	Absolute control	**-**	**-**	**-**	**-**	**-**	**-**
T_2	General Recommended Dose of Fertilizers (GRDF)	85	12	140	89	13	149
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	97	13	148	92	13	149
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	91	12	140	92	13	147
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	93	12	134	95	13	149
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	95	13	140	98	14	152
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	90	11	119	93	13	140
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	96	11	101	89	11	130

4.9 Effect of Foliar Application of Different Sources of Zinc on Economics of Wheat

The data in respect of cost of cultivation, gross monetary return, net monetary return and B:C ratio are presented in table 4.38 and 4.39.

Under zinc deficient soil, the lowest cost of cultivation Rs. 35948 /- was observed in T_1 i.e., absolute control followed by treatment T_2 (Rs. 54933/-). The gross monetary return (Rs. 94611/-) was recorded higher in T_3 i.e., GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1} followed by treatment T_8 (Rs. 93376 /-). The net monetary return (Rs. 38478 /-) was recorded higher in T_3 i.e., GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1} followed by treatment T_8 (32403/-) The per cent increase in net monetary returns was 20.66 over GRDF treatment. However, the highest B:C ratio (1.69) was recorded in T_3 treatment followed by treatment T_2 i.e GRDF (1.58).

Table 4.38 Effect of foliar application of different sources of zinc on economics of wheat in zinc deficient soil

Tr. No	Treatment	Cost of cultivation (Rs ha^{-1})	Gross monetary return (Rs ha^{-1})	Net monetary return (Rs ha^{-1})	B:C ratio
T_1	Absolute control	35948	21640	-14309	0.60
T_2	General Recommended Dose of Fertilizers (GRDF)	54933	86820	31887	1.58
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	56133	94611	38478	1.69
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	57873	90203	32330	1.56
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	59753	91345	31592	1.53
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	60843	92259	31416	1.52
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	59273	88720	29447	1.50
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	60973	93376	32403	1.53

Note- FYM- 1.20 Rs. kg^{-1}, N– 11.30 Rs. kg^{-1}, P– 56.25 Rs. kg^{-1}, K- 56.66 Rs. kg^{-1}, Chelated zinc- 170 Rs./100 g, $ZnSO_4.7H_2O$- 60 Rs. kg^{-1}, Nano zinc- 218 Rs/100 mL, Spraying charges- 40 Rs/15 L pumps Grains-2150 Rs. q^{-1}, Stover- 50 Rs. q^{-1}.

Table 4.39 Effect of foliar application of different sources of zinc on economics of wheat in zinc sufficient soil

Tr. No	Treatment	Cost of cultivation (Rs ha^{-1})	Gross monetary return (Rs ha^{-1})	Net monetary return (Rs ha^{-1})	B:C ratio
T_1	Absolute control	35948	22792	-13157	0.63
T_2	General Recommended Dose of Fertilizers (GRDF)	54933	90285	35352	1.64
T_3	GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}	56133	91507	35374	1.63
T_4	GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS.	57873	92167	34294	1.59
T_5	GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.	59753	95033	35280	1.59
T_6	GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.	60843	98098	37255	1.61
T_7	GRDF + Two foliar sprays of chelated zinc @ 0.15% at 20 and 40 DAS.	59273	94202	34929	1.59
T_8	GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS.	60973	97530	36557	1.60

Note- FYM- 1.20 Rs. kg^{-1}, N – 11.30 Rs. kg^{-1}, P – 56.25 Rs. kg^{-1}, K- 56.66 Rs. kg^{-1}, Chelated zinc- 170 Rs/100 g, $ZnSO_4.7H_2O$- 60 Rs. kg^{-1}, Nano zinc- 218 Rs/100 mL, Spraying charges- 40 Rs/15 L pumps Grains-2150 Rs. q^{-1}, Stover- 50 Rs. q^{-1}.

However, under zinc sufficient soil the lowest cost of cultivation Rs. 35948/- was observed in T_1 i.e., absolute control followed by treatment T_2 (Rs. 54933/-). The gross monetary return (Rs. 98098/-) was recorded higher in T_6 i.e., GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS followed by treatment T_8 (Rs. 97530/-). The net monetary return (Rs. 37255/-) was recorded higher in T_6 i.e., GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS followed by treatment T_8 (36557/-). The B:C ratio (1.64) of wheat crop in zinc sufficient soil was recorded higher in treatment T_2 i.e., General Recommended Dose of Fertilizers (GRDF) followed by treatment T_3 (1.63). There was very slight difference in net returns and B:C ratio in treatment T_3 over T_2. This outcome was made possible by the noteworthy increase in grain yield and the associated fertilizer costs across various treatments. This increase in grain yield at these levels is attributed to higher levels of productivity, resulting in elevated gross returns, net returns, and an improved benefit-to-cost ratio. According to Kumar *et al.* (2020), nano fertilizers have the capacity to enhance crop yields while concurrently reducing fertilizer wastage and minimizing the overall cost of cultivation. Similar results were also observed by Mehdi *et al.* (2012) and Kumar *et al.* (2014).

5. SUMMARY AND CONCLUSIONS

The research trials were implemented at Post Graduate Institute Research Farm, Department of Soil Science and Agricultural Chemistry, Mahatma Phule Krishi Vidyapeeth, Rahuri during *rabi* season 2022 entitled on “Effect of foliar application of Nano zinc on nutrient uptake, yield and quality of wheat on zinc deficient and sufficient soils of Inceptisol”. The findings acquired are outlined below, using suitable subheadings, and the summary and conclusions drawn are shaded in this chapter.

5.1 Summary

5.1.1 Effect of Foliar Application of Different Sources of Zinc on Growth Attributes and Yield Contributing Characters of Wheat Crop

No. of tillers per plant, Length of spikelet (cm) and No. of grains per spikelet under Zn deficient soil was found significantly higher in treatment T_3 - GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1} (8.66, 8.76 and 44.59, respectively). Plant height (cm) was found significant in T_6- GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS (90.60). However, No. of tillers per plant, length of spikelet (cm), no. of grains per spikelet and plant height (cm) under Zn sufficient soils were found significantly higher (8.94, 8.86, 54.69 and 92.07, respectively) in treatment T_6- GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.

5.1.2 Effect of Foliar Application of Different Sources of Zinc on Total Chlorophyll Content in Fresh Tissue of Wheat crop

Total chlorophyll content in fresh tissue (SPAD Values) under Zn deficient soil was found significantly higher (40.47) in treatment T_3 - GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1} at 40 DAS and it was significantly higher (42.40) in treatment T_6- GRDF + Two foliar sprays of Nano zinc @ 0.15% at 55 DAS. However, Total chlorophyll content in fresh tissue (SPAD Values) under Zn sufficient soil was found significantly higher (42.27) in treatment T_3 - GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1} at 40 DAS and it was significant (45.10) in treatment T_6 - GRDF + Two foliar sprays of Nano zinc @ 0.15% at 55 DAS.

5.1.3 Effect of Foliar Application of Different Sources of Zinc on Physiological Traits under Wheat Crop

Photosynthetic rate, stomatal conductance and stomatal resistance under Zn deficient soil was found significantly higher in treatment T_3- GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1} at 40 DAS (11.43 μ moles m^{-2} s^{-1}, 0.39 m moles m^{-2} s^{-1} and

9.46 µ moles m^{-2} s^{-1}, respectively) and it was significantly higher at 55 DAS in treatment T_6- GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS (13.71 µ moles m^{-2} s^{-1}, 0.57 m moles m^{-2} s^{-1} and 16.21 µ moles m^{-2} s^{-1} respectively). Photosynthetic rate, stomatal conductance and stomatal resistance under Zn sufficient soil was found significant in treatment T_6- GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS at 40 DAS (13.47 µ moles m^{-2} s^{-1}, 0.37 m moles m^{-2} s^{-1} and 9.78 µ moles m^{-2} s^{-1}, respectively) and at 55 DAS (14.31 µ moles m^{-2} s^{-1}, 0.58 m moles m^{-2} s^{-1} and 16.03 µ moles m^{-2} s^{-1}, respectively).

Intercellular CO_2 concentration and transpiration rate under Zn deficient soil was found significantly higher in treatment T_3- GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1} at 40 DAS (123.57 µ moles CO2 m^{-2} s^{-1} and 2.28 µ moles H_2O m^{-2} s^{-1}, respectively) and it was significant at 55 DAS in treatment T_6- GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 (270.18 57 µ moles CO_2 m^{-2} s^{-1} and 2.35 µ moles H_2O m^{-2} s^{-1}, respectively). Intercellular CO_2 concentration and transpiration rate in Zn sufficient soil was found significantly higher in treatment T_6- GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS at 40 DAS (128.39 µ moles CO_2 m^{-2} s^{-1} and 2.29 µ moles H_2O m^{-2} s^{-1}, respectively) and 55 DAS (272.46 µ moles CO_2 m^{-2} s^{-1} and 2.38 29 µ moles H_2O m^{-2} s^{-1}, respectively). Leaf temperature under Zn deficient and Zn sufficient soil were found non- significant.

5.1.4 Effect of Foliar Application of Different Sources of Zinc on Yield under Wheat Crop

The grain and straw yield (q ha^{-1}) under Zn deficient soil was found significantly higher 42.61 and 60.14 q ha^{-1}, respectively) in treatment T_3 - GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1}. However, under Zn sufficient soil, it was found significantly higher (44.15 and 63.50 q ha^{-1}, respectively) in treatment T_6- GRDF + Two foliar sprays of Nano zinc @ 0.15%. However, it was 9.0 and 8.61 per cent higher over GRDF treatment, respectively.

5.1.5 Effect of Foliar Application of Different Sources of Zinc on Total Uptake of Macronutrients under Wheat Crop

Total uptake of NPK by wheat under Zn deficient soil was found significantly higher in treatment T_3 - GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1} (141.09, 23.67 and 93.87 kg ha^{-1}, respectively). However, under Zn sufficient soil, the total uptake of NPK by wheat was found significantly higher in treatment T_6 - GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS (147.22, 24.80 and 97.34 kg ha^{-1}, respectively).

5.1.6 Effect of Foliar Application of Different Sources of Zinc on Total Uptake of Micronutrients under Wheat Crop

Total uptake of micronutrients by wheat under Zn deficient soil was significantly higher in treatment T_3 - GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1} (1498, 419, 901 and 59 mg kg^{-1}, respectively). However, total uptake of micronutrients by wheat under Zn sufficient soil was found significantly higher in treatment T_6 - GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS (1665, 455, 162 and 62 mg kg^{-1}, respectively) and total uptake of copper was found significantly higher in treatment T_8 - GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS (62 mg kg^{-1}).

5.1.7 Effect of Foliar Application of Different Sources of Zinc on Quality Parameters under Wheat Crop

The crude protein, test weight and β Carotene content in wheat grain under Zn deficient soil was found significantly higher in treatment T_3- GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1} (12.51%, 41.77 g and 3.03 μg g^{-1}, respectively) and gluten content (on dry weight basis) in wheat grain under Zn deficient soil was found significant in T_5- GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS (7.11%). However, under Zn sufficient soil crude protein content in wheat grain under Zn sufficient soil were found significant in T_6- GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS (12.60%) and test weight and gluten content in wheat grain (on dry weight basis) in were found significant in T_5- GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS (43.37 g, 7.09 μg g^{-1} and 2.97%, respectively).

5.1.8 Effect of Foliar Application of Different Sources of Zinc on Chemical Properties of Soil after Harvest

The soil chemical properties at harvest of wheat *viz.* pH, Electrical conductivity (dSm^{-1}), Calcium carbonate (%) and Organic carbon (g kg^{-1}) in Zn deficient and Zn sufficient soils were found non-significant.

The available N, P and K content under Zn deficient soil was found significantly higher in treatment T_2- GRDF (170, 13.24 and 497 kg ha^{-1}, respectively). However, in Zn sufficient soil, the available N content was found significantly higher in treatment T_4- GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS (191 kg ha^{-1}), available P content was found significantly higher in treatment T_2- GRDF (12.90 kg ha^{-1}) and available K content was found significant (538 kg ha^{-1}) in treatment T_5- GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS.

Available iron content under Zn deficient soil was found significantly higher in treatment T_2- GRDF (4.28 mg kg^{-1}), available zinc content was found significantly higher in treatment T_3- GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1} (0.56 mg kg^{-1}), available manganese content in Zn deficient soil was found significant in treatment T_4- GRDF + Two foliar sprays of $ZnSO_4.7H_2O$ @ 0.50% at 20 and 40 DAS (8.49 mg kg^{-1}) and copper content in Zn deficient soil was found non significant. However, available iron (Fe) content in Zn sufficient soil was found significant in treatment T_5- GRDF + Two foliar sprays of Nano zinc @ 0.10% at 20 and 40 DAS (4.30 mg kg^{-1}), available zinc was found significant in treatment T_3- GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1} (0.65 mg kg^{-1}), available manganese content was found significant in treatment T_2- General Recommended Dose of Fertilizers (8.82 mg kg^{-1}) and available copper content was found significant in treatment T_2- GRDF (1.70 mg kg^{-1}).

5.1.9 Effect of Foliar Application of Different Sources of Zinc on Apparent Nutrient Recovery Efficiency under Wheat Crop

The apparent nutrient recovery efficiency under Zn deficient soil for N was observed higher (97%) in treatment T_8- GRDF + Two foliar sprays of chelated zinc @ 0.20% at 20 and 40 DAS and for P and K in treatment T_3- GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1} (13 and 148 %, respectively). However, apparent nutrient recovery efficiency under Zn sufficient soil for N, P and K was observed higher (98, 14 and 152%, respectively) in treatment T_6- GRDF + Two foliar sprays of Nano zinc @ 0.15% at 20 and 40 DAS.

5.1.10 Effect of Foliar Application of Different Sources of Zinc on Economics under Wheat Crop

Maximum gross, net monetary returns and B:C ratio were recorded higher (Rs. 94611/-, Rs. 38478/- and 1.69, respectively) in treatment T_3- GRDF + Soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1} under Zn deficient soil. However, under Zn sufficient soil the maximum gross, net monetary returns and B:C ratio were recorded higher (Rs. 90285/-, Rs. 35352/- and 1.64, respectively) in treatment T_2- GRDF.

5.2 Conclusions

It can be concluded that, the application of General Recommended Dose of Fertilizers (120:60:40 kg ha^{-1} $N:P_2O_5:K_2O$ + 10 t ha^{-1} FYM) along with soil application of $ZnSO_4.7H_2O$ @ 20 kg ha^{-1} found beneficial under Zn deficient soil for increase in yield contributing characteristics, total chlorophyll, photosynthetic rate, stomatal conductance, stomatal resistance, intercellular CO_2 concentration, transpiration rate, , total uptake of macro as well as micronutrients, grain and straw yield, crude protein, test weight, B:C ratio of wheat as well as maintaining the Zn status in **zinc deficient** soil of Inceptisol. However, the treatment of GRDF + Two foliar sprays of nano zinc (0.15%) at 20 and 40 DAS found at par.

Further, application of General Recommended Dose of Fertilizers (120:60:40 kg ha^{-1} N:P_2O_5:K_2O + 10 t ha^{-1} FYM) along with Two foliar sprays of nano zinc @ 0.15% at 20 and 40 DAS found beneficial under **zinc sufficient** soil for increase in yield contributing characteristics, total chlorophyll, photosynthetic rate, stomatal conductance, stomatal resistance, intercellular CO_2 concentration, transpiration rate, total uptake of macro as well as micronutrients, grain and straw yield, test weight, gluten of wheat. However, the treatment of GRDF + Two foliar sprays of nano zinc (0.10%) at 20 and 40 DAS found at par.

Future line of research

1. It is need to confirm these results by conducting multilocational trials on farmers field for recommendation of foliar application Nano zinc in sufficient soil.
2. It is necessary to have research on specific particle size of Nano particles for use of different Nano particles in foliar as well as soil application.

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7. VITAE

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