

**“EFFECT OF ZINC FERTILIZATION ON GROWTH AND YIELD OF
FINGER MILLET (*Eleusine coracana* L. Gaertn.)”**

by

Mr. Bhojaraj Biradar

(Reg. No. 2023/016)

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

in partial fulfilment of the requirements for the degree

of

MASTER OF SCIENCE (AGRICULTURE)

in

AGRONOMY



**DEPARTMENT OF AGRONOMY
POST GRADUATE INSTITUTE
MAHATMA PHULE KRISHI VIDYAPEETH
RAHURI- 413 722, DIST.-AHILYANAGAR
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2025

CANDIDATE'S DECLARATION

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

Place : MPKV, Rahuri

Date : / / 2025

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CERTIFICATE

This is to certify that the thesis entitled, “**EFFECT OF ZINC FERTILIZATION ON GROWTH AND YIELD OF FINGER MILLET (*Eleusine coracana* L. Gaertn.)**” submitted to the Faculty of Agriculture, Mahatma Phule Krishi Vidyapeeth, Rahuri Dist. Ahilyanagar (Maharashtra) in partial fulfilment of the requirements for the award of the degree of **MASTER OF SCIENCE (AGRICULTURE)** in **AGRONOMY**, embodies the result of a piece of *bonafide* research work carried out by **Mr. BHOJARAJ BIRADAR**, 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

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Place : MPKV, Rahuri

Date : / /2025

(S. B. Kharbade)

ACKNOWLEDGEMENT

With ever regardful memories....

“Great discoveries and improvements invariably involve the cooperation of many minds. I may give credit for having blazed the trail but when I took at the subsequent developments, I feel credits is due to others rather than me.”

Gratitude cannot be seen or expressed; it can be felt deep in heart and is beyond description. Although ‘Thanks’ are poor expression of debt of gratitude one feel, yet there is no way to express it. First and foremost, I would like to thank Lord “Shri Rama” for giving me the strength, knowledge, ability and opportunity to undertake this research study and to persevere and complete it satisfactorily. Without his blessings, this achievement would not have been possible.

*This research study owes a lot of gratitude to a number of individuals who selflessly contributed their ideas and time to bring this research study to its birth and fruition. I am really fortunate for getting an opportunity to work under the dynamic and able guidance of **Dr. R. M. Gethe** Professor, Department of Agronomy, MPKV, Rahuri who has provided constant encouragement, constructive criticism and sympathetic attitude throughout the course of investigation and preparation of this manuscript. Without his able guidance, this thesis would not have been possible and I shall eternally be grateful to him for his assistance.*

*I extend my sincere and deepest thanks to **Dr. S. R. Gadakh**, Honorable Vice Chancellor, MPKV Rahuri, **Dr. V. S. Shirke**, Director of research, MPKV, Rahuri, **Dr. D. D. Pawar**, Dean Faculty of Agriculture and Director of Instructions, MPKV, Rahuri and **Dr. S.B. Kharbade**, Associate Dean, Post Graduate Institute, MPKV, Rahuri for his directives and valuable guidance during the experimentation of research work.*

*It is great privilege for me to express my profound sense of gratitude to **Dr. P. S. Bodake**, Head, Department of Agronomy for his valuable suggestions, technical guidance, thought provoking ideas and support during the tenure of my research and studies.*

*On the path to search knowledge, one needs the complementary guidance and this task was performed by the members of my advisory committee. I avail this opportunity to express my sincere thanks to my committee members **Dr. U. S. Surve**, Professor of Agronomy, **Dr. Y. G. Ban**, Breeder (Asstt. Prof. of Agril. Botany), AICRP on Small Millets, ZARS, Kolhapur, **Dr. S. R. Shelke**, Assistant professor of Soil Science, **Dr. M.R. Patil**, Head, Department of Agricultural Statistics, MPKV, Rahuri for their valuable guidance, kind co-operation, inspiration and support for the successful conduct of my studies.*

*It takes a large ground crew to help even a small book to blast off. So, extend my gratitude to **Dr. A. G. Durgude**, **Dr. N. J. Danawale**, **Dr. S. S. Illhe**, Professors, and **Dr. B. T. Sinare**, Associate professor, Department of Agronomy and other staff members for providing me the facilities of research material and uncountable practical suggestions to complete the research work. I sincerely express my thanks to Mr. D.M. Chavan and G.B. Gaikwad, Agril. Assistants, Department of Agronomy, H.D Jawale, Clerk, Department of Agronomy, Kavane mama and other workers on field and in laboratory etc. for their assistance in the field and laboratory work.*

*There are many who are instrumental in making me that I am today; so, my regards to **Dr. M. R. Patil**, University Librarian, MPKV, Rahuri and his staff for providing online e-journal facilities and help in procuring references from other universities time-to-time during my research work.*

Though inadequate, I would like to thank my seniors Abhijeeth Dhanwade, Dr. Kashinath Teli, Dr. Pushpalatha, Dr. Vairavan, Ganesh, Shruthi, Megharaj, Praveen, Nidhesh, Mahesh, Nagbhushan, Tarunkumar, Ram, Dnyaneshwar, Niharika, Girish, Soundarya, Pavan, Vivek, Badal, Yogesh, and my all classmates Yashaswini, Priyanka, Indrakumar, Sharanbasu, Basavannappa, Sadashiv, Priyanshu, Sathiya, Sivamari, Satyabrata, Saurav, Rohan, Nayan, Abhishek, Gaurav, Harshal, Prathmesh, Rushikesh, Hariom, Divya, Shrutika, Aarti, Pallavi, Mayuri, Samiksha and my all Juniors Mahesh, Niranjana, Mrutyunjay, Jeetendra, Manoj, Dileep, Bharath, Pulkit, AnnaRam, Sawailal, Swapnil, Shritam specially to my friends Ganesh, Sushma, Sharanu, Nagaraj, Chetan, Pandurang, Pavan, Vishal, Yashodha, Srushti, Hrithik, Muheet, Ganiyar, Laxmikanth, Shreedhar, Shrikanth, Dayanand, Ajay, Akash, Babu, Arun, Harsha, Varun, Narendra, Karthik, Suman, Puneet, Somnath, Raju, Prasad, Sangayya, Sangamesh, Beeresh, Ramesh, Saiman, Bheemrao, Shivu, Sudarshan for helping me directly or indirectly, selfless encouragement throughout the bright and dark phase of research work and ensuring that the fire keeps burning and being at times when I required motivation and propelling me on the course of this thesis and for assisting me in collection of data for my research work.

My acknowledgement would be incomplete without thinking the biggest source of my strength, my family. I express my heartiest gratitude and deep indebtedness to my mother Smt. Kavita and father Shri. Sharanappa Biradar and my family members Gouramma, Gurunath, Saraswathi, Jayashree, Avvamma, Siddhu, Shivkumar, Kiran, Bhagyashree, Rajkumar, Renuka, Basavaraj, Sauravi, Basavasai who always stood like lighthouse for illumination in the pathway of every success and their sacrifice in moulding me and building up my educational career. I cannot imagine if I could do anything without them. They remain the pillars of all sources for me since beginning of my life.

I am highly obliged to the scientists, past and present, whose contribution was the great source of information helped to undertake the present investigation. While travelling on the path of life and education, many hands pushed me forth, learned hearts put me on the right path, enlighten by their knowledge and experience. I ever remain thankful to them all.

I express my deep sense of gratitude and indebtedness to Indian Council of Agricultural Research (ICAR), New Delhi for providing financial assistance to me in the form of “National Testing Service” for the completion of my M.Sc. degree programme.

To my friends, this would have been a much more difficult feat without you. Thank you all for your unwavering support.

THANK YOU ONE AND ALL.....

Place : MPKV, Rahuri

Date : / / 2025

(Bhojaraj Biradar)

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LIST OF ABBREVIATIONS AND SYMBOLS

%	:	Per cent
/	:	Per
@	:	At the rate of
⁻¹	:	Per
°C	:	Degree Celsius
acre ⁻¹	:	Per acre
B:C	:	Benefit cost ratio
CHO	:	Carbohydrate
CF	:	Crude fibre
CV	:	Co-efficient of Variation
cm	:	Centimeter
DAS	:	Days after sowing
day ⁻¹	:	Per day
dm ²	:	Decimeter square
dsm ⁻¹	:	Deci siemen per meter
EC	:	Electrical conductivity
<i>et al.</i>	:	and others (etalli)
etc	:	et cetera
Even.	:	Evening
Fig.	:	Figure
FYM	:	Farm Yard Manure
g	:	Gram
GRDF	:	General Recommended Dose of Fertilizer
ha	:	Hectare
ha ⁻¹	:	Per hectare
hrs	:	Hours
<i>i.e.</i>	:	Id est (that is)
K	:	Potassium
K ₂ O	:	Potassium Oxide
kg	:	Kilo gram
kg ha ⁻¹	:	Kilo gram per hectare
Lit ⁻¹	:	Per litre
m	:	Meter
m ²	:	Meter square

m^{-2}	:	Per meter square
max.	:	Maximum
mg	:	Milligram
M ha	:	Million hectares
min.	:	Minimum
mm	:	Millimeter
MOP	:	Muriate of potash
Morn.	:	Morning
N	:	Nitrogen
No.	:	Number
NS	:	Non-significant
OC	:	Organic carbon
P	:	Phosphorus
pH	:	Puissance de hydrogen
P_2O_5	:	Phosphorus penta oxide
ppm	:	Parts per million
q	:	Quintal
$q\ ha^{-1}$	:	Quintal per hectare
RDF	:	Recommended Dose of Fertilizer
RH	:	Relative humidity
₹	:	Indian rupee
S.E.m	:	Standard error of mean
Sr. No.	:	Serial number
SSP	:	Single Super Phosphate
t	:	Tonne (s)
Temp.	:	Temperature
Tr. No.	:	Treatment number
<i>viz.</i> ,	:	Videlicet (Namely)
<i>wt.</i>	:	Weight
$year^{-1}$	:	Per year
ZnO	:	Zinc Oxide

ABSTRACT

“EFFECT OF ZINC FERTILIZATION ON GROWTH AND YIELD OF FINGER MILLET (*Eleusine coracana* L. Gaertn.)”

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2025

Research Guide	:	Dr. R. M. Gethe
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Department	:	Agronomy
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A field investigation entitled “Effect of zinc fertilization on growth and yield of finger millet (*Eleusine coracana* L. Gaertn.)” was conducted in *kharif* season of 2024 at Instructional Farm, Post Graduate Institute, Mahatma Phule Krishi Vidyapeeth, Rahuri, Dist. Ahilyanagar (M.S.).

The experiment consisted of ten treatments *viz.*, T₁: Absolute control; T₂: RDF (Recommended dose of fertilizer); T₃: GRDF (General recommended dose of fertilizer); T₄: T₃ + Seed treatment of ZnSO₄ @ 2.5 g kg⁻¹ of seeds; T₅: T₃ + Seed treatment of Nano-ZnO @ 1000 ppm; T₆: T₃ + Seed treatment of Chelated Zn @ 1 g kg⁻¹ of seeds; T₇: T₃ + Two foliar sprays of ZnSO₄ @ 0.5 %; T₈: T₃ + Two foliar sprays of Nano-ZnO @ 0.15 %; T₉: T₃ + Two foliar sprays of Chelated Zn @ 0.20 %; T₁₀: T₃ + Soil application of ZnSO₄ @ 20 kg ha⁻¹.

The experiment was laid out in randomized block design (RBD) with three replications. The soil was clay in texture, low in available nitrogen (184.85 kg ha⁻¹), high in available phosphorus (18.87 kg ha⁻¹) and very high amount of potassium (386.07 kg ha⁻¹). The soil was showed slightly alkaline in reaction (pH 8.19) with an electrical conductivity of 0.29 dS m⁻¹. The sowing was done manually by line sowing with the help of labour to ensure proper plant to plant distance and uniform seed placement. The distance was kept 30 cm x 10 cm.

The Phule Nachani variety seeds were line sown at spacing of 30 cm x 10 cm. At the time of sowing, 5 tons of FYM and the recommended fertilizer dosage (60:30:30 N: P₂O₅: K₂O kg ha⁻¹) were applied as a basal dose using urea, SSP and MOP. Seed treatment, soil application and foliar sprays of different zinc sources were applied as per the treatments.

The results revealed that treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % exhibited significantly higher growth attributes *viz.*, plant height (116.7 cm), number of functional leaves (50.5), leaf area (11.45 dm²) and dry accumulation per plant (23.16 g), which was at par with treatment T₉ *i.e.* GRDF + Two foliar sprays of Chelated zinc @ 0.2 % with plant height (111.8 cm), number of functional leaves (48.2), leaf area (10.88 dm²) and dry accumulation per plant (22.32 g) and treatment T₇ *i.e.* GRDF + Two foliar sprays of Zinc sulphate @ 0.5 % with plant height (110.3 cm), number of functional leaves (47.8), leaf area (10.84 dm²) and dry accumulation per plant (22.02 g).

Similarly, yield attributes *viz.*, number of fingers earhead⁻¹ (8.1), number of grains finger⁻¹ (358), grain weight plant⁻¹ (8.68 g) and finger length (8.8 cm) at harvest were highest

under treatment T₈ GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % and at par results were obtained with treatment T₉ *i.e.* GRDF + Two foliar sprays of Chelated zinc @ 0.20 % with number of fingers earhead⁻¹ (7.7), number of grains finger⁻¹ (334), grain weight plant⁻¹ (8.28 g) and finger length (8.4 cm) and treatment T₇ *i.e.* GRDF + Two foliar sprays of Zinc sulphate @ 0.5 % with number of fingers earhead⁻¹ (7.4), number of grains finger⁻¹ (323), grain weight plant⁻¹ (8.12 g) and finger length (8.2 cm).

Significantly, the highest grain yield (27.41 q ha⁻¹), straw yield (43.46 q ha⁻¹), biological yield (70.87 q ha⁻¹) and harvest index (38.75 %) was obtained with treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %, which was at par with treatment T₉ *i.e.* GRDF + Two foliar sprays of Chelated zinc @ 0.20 % with grain yield (25.43 q ha⁻¹), straw yield (42.19 q ha⁻¹), biological yield (67.62 q ha⁻¹) and harvest index (37.59 %) and treatment T₇ *i.e.* GRDF + Two foliar sprays of Zinc sulphate @ 0.5 % with grain yield (24.97 q ha⁻¹), straw yield (41.74 q ha⁻¹), biological yield (66.71 q ha⁻¹) and harvest index (37.43 %).

Crude protein content, crude fibre content, carbohydrate and ash content were remained unaffected among the treatments, but the crude protein content (7.55 %), carbohydrates (70.23 %) and ash content (2.29 %) were numerically higher in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %.

Significantly highest total uptake of nitrogen (62.90 kg ha⁻¹), phosphorus (27.27 kg ha⁻¹) and potassium (91.14 kg ha⁻¹) was with treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %, which was at par with treatment T₉ *i.e.* GRDF + Two foliar sprays of Chelated zinc @ 0.20 % with total uptake of nitrogen (57.95 kg ha⁻¹), phosphorus (24.84 kg ha⁻¹) and potassium (85.51 kg ha⁻¹) and treatment T₇ *i.e.* GRDF + Two foliar sprays of Zinc sulphate @ 0.5 % with total uptake of nitrogen (56.59 kg ha⁻¹), phosphorus (23.97 kg ha⁻¹) and potassium (83.32 kg ha⁻¹).

Similarly, the total micronutrient uptake *i.e.* Fe (236.69 g ha⁻¹), Mn (172.02 g ha⁻¹), Cu (46.07 g ha⁻¹) and Zn (149.71 g ha⁻¹) were significantly highest under treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %, which was at par with treatment T₉ *i.e.* GRDF + Two foliar sprays of Chelated zinc @ 0.20 % with total uptake of Fe (221.02 g ha⁻¹), Mn (162.27 g ha⁻¹), Cu (43.35 g ha⁻¹) and Zn (141.36 g ha⁻¹) and treatment T₇ *i.e.* GRDF + Two foliar sprays of Zinc sulphate @ 0.5 % with total uptake of Fe (216.74 g ha⁻¹), Mn (158.31 g ha⁻¹), Cu (42.23 g ha⁻¹) and Zn (138.18 g ha⁻¹).

The highest gross monetary returns (₹ 1,40,453), net monetary returns (₹ 75,523) and B:C ratio (2.16) were obtained significantly in the treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %, which was at par with the treatment T₉ *i.e.* GRDF + Two foliar sprays of Chelated zinc @ 0.20 % with gross monetary returns (₹ 1,30,579), net monetary returns (₹ 69,247) and B:C ratio (2.13) and treatment T₇ *i.e.* GRDF + Two foliar sprays of Zinc sulphate @ 0.5 % with gross monetary returns (₹ 1,28,264), net monetary returns (₹ 67,396) and B:C ratio (2.11).

Based on one season experiment, GRDF (5 ton FYM + 60:30:30 N: P₂O₅: K₂O kg ha⁻¹) + Two foliar sprays of Nano-ZnO @ 0.15 % at tillering and flowering stages or GRDF (5 ton FYM + 60:30:30 N: P₂O₅: K₂O kg ha⁻¹) + Two foliar sprays Chelated zinc @ 0.20 % to finger millet crop found beneficial for increase in growth attributes, yield attributes, grain yield, nutrient uptake and economic returns.

1. INTRODUCTION

Milletts have been termed as “nutri-cereals” because millets are free of gluten and contain a lot of micronutrients, such as minerals and B-complex vitamins. Furthermore, millets can be used as nutritious meals and are rich in phytochemicals that aid in health. Millets are climate change-compliant crops because they are C₄ crops. Their ability to adapt to a wide range of climatic conditions, their lower requirement for irrigation, their enhanced growth and productivity under low nutrient input conditions, their diminished dependence on synthetic fertilizers, and their reduced susceptibility to environmental stress are just some of their climate-resilient traits. These characteristics highlight millets as the desired crop for the global population in spite of the rising climate change issues. The United Nations announced 2023 as the “International Year of Millets” in recognition of the significance of millets.

India is the world's largest producer of finger millet, making up over 60 per cent of global production. 9 per cent protein, 76.3 per cent carbohydrates, 2.2 per cent minerals, 1.3 per cent fat, 3.9 per cent ash, and vitamins A and B are all present in finger millet. The grains are the richest source of calcium (410 mg 100 g⁻¹ grain), which is a particularly crucial supplement for developing children and the elderly. They are also rich in phosphorus, potassium, and amino acids (Tomar *et al.* 2011). Finger millet is grown on 1.04 million hectares of land in India, yielding 1.39 million tons of grain annually, or an average productivity of 1,661 kg ha⁻¹ (Anonymous, 2023-24). It is grown on 72,000 hectares of land in Maharashtra, yielding 81,000 tons and 1,120 kg ha⁻¹ of productivity (Anonymous, 2024).

After sorghum and pearl millet, finger millet (*Eleusine coracana* L. Gaertn.), a nutri-cereal, comes in third place among the nation's important millets. Of all the nutri-cereals grown in our nation, it produces the most. Finger millet's resilience and capacity to tolerate weather variations when cultivated on soils with little water-holding capacity are the characteristics that have made it a significant dryland crop. Millions of people throughout the world's arid and semi-arid tropics rely on it as their main source of nutrition. The poorest of the poor, who have the greatest need for these nutrients, may get affordable proteins, minerals, and vitamins through finger millet grains, which are more nutritious than rice and wheat. Ragi is essential to provide the human race high-quality nutrients. Ragi's protein is recognized as “biologically complete”. Finger millet's protein composition has a relatively high biological value, which is necessary for the body's nitrogen homeostasis to be maintained.

For diabetics, finger millet is thought to be particularly healthful for diabetics. The high levels of calcium (0.38 per cent), protein (6–13 per cent), dietary fiber (18 per cent), carbohydrates (65–75 per cent), minerals (2.5–3.5 per cent), phytates (0.48 per cent), tannins (0.61 per cent), phenolic compound (0.3–3%), and trypsin are what give finger millet its nutritional value.

Additionally, it has more minerals than maize, including calcium, iron, manganese, and copper (National Research Council, 1996). Whole finger millet seeds have a calcium concentration of 0.34 per cent, while other main grains have a calcium content of 0.01 to 0.06 per cent (Kumar *et al.* 2016). According to Mbithi-Mwikya *et al.* (2002), finger millet comprises high concentrations of potassium (408 mg 100 g⁻¹), magnesium (137 mg 100 g⁻¹), copper (0.47 mg 100 g⁻¹), sodium (11 mg 100 g⁻¹), and phosphorus (283 mg 100 g⁻¹). Water-soluble and lipo-soluble vitamins are both present in finger millet. Thiamine (0.2 mg 100 g⁻¹), riboflavin (0.1 mg 100 g⁻¹), and niacin (0.1 mg 100 g⁻¹) are all suitably abundant in it. It is regarded as a nutriceal due to its abundance of phytochemicals (Singh and Raghuvanshi, 2012). Finger millet is an important cereal for community-based health care programs and children's feeding schemes in rural institutions in poor nations because of its high nutritional value, which also provides it some therapeutic benefit.

Along with deficiencies in vitamin A, iodine, iron, and selenium, zinc insufficiency is regarded globally as one of the “big five silent killers” of humans. Particularly in underdeveloped nations, these micronutrient shortages result in both economic losses and weakened health. Zinc is a cross-cutting essential micronutrient that is crucial to human, animal, and plant physiology and structure. Accordingly, a sustained recommended intake (RDI) of zinc (8.0-20.5 mg of per day) is necessary to reduce the prevalence of zinc insufficiency (Connorton and Balk, 2019).

Zinc is currently considered to be the fourth most important nutrient that limits production in India, after potassium (K), phosphorus (P), and nitrogen (N). Pollen function, fertilization, germination, and chlorophyll production all depend on zinc. According to Kaya and Higgs (2002), zinc is crucial for the production of agricultural biomass. Zinc and manganese are two micronutrients that can influence a plant's vulnerability to drought-related stress (Cakmak, 2000; Khan *et al.* 2003 and Pandey *et al.* 2006).

In the plant system, zinc is essential for a number of enzymatic and physiological functions. In addition to transforming carbohydrates, chlorophyll, and protein production, it carries out a variety of catalytic tasks in the plant (Wasim *et al.* 2016). A drop in the carbonic anhydrase enzyme occurs when zinc levels are low, which lowers the rate of net photosynthesis. Zinc is used to improve the overall quality of seed production, as well as the quantity of zinc and protein in seeds and pneumatic organs. Zinc is essential for around 300 enzymes in the human body, which promote cell division and proliferation (Sharma *et al.* 2017).

Numerous health issues, including anemia, an increased risk of abortion, skeletal abnormalities, disorders of learning, delayed healing of wounds, poor immune functions, and an increased risk of digestive tract infections and diarrhea, particularly in children and pregnant women, have been linked to low dietary zinc consumption (Burke *et al.* 2015; Subbaiah *et al.* 2016). It is

becoming more and more crucial to develop solutions that aid in the production of plants with high zinc concentrations in context of zinc insufficiency.

The finger millet plant (shoot) typically contains 2.3 mg of zinc per 100 g⁻¹ (Barbeau and Hilu, 1993). The plant can better absorb and use zinc if nutrients are applied properly. The most effective technique for increasing crop productivity among the many approaches is foliar spraying. This method of applying nutrients is quick and easy, and it improves the nutritional status of finger millet plants. Because foliar spray is applied directly to the leaves, its effectiveness can be explained simply. But zinc can also be sprayed straight into the soil. While foliar spraying zinc fertilizer increases the concentration of zinc in grain, soil-applied zinc is efficient in increasing grain yield (Tariq *et al.* 2014).

Because of their ease of handling and low amount requirements, nano fertilizers have become more popular recently than conventional fertilizers. Foliar-applied fertilizers encounter a number of structural obstacles because the nutrients (cations and anions) are salt-based and may find it difficult to enter the interior plant tissue because the cells' pores are smaller than those of the fertilizer particles. As a result, nanoparticles aggregate with a diameter smaller than the plant cell wall's pore size, making it easier for them to pass through the wall and reach the plasma membrane. Applying nano fertilizer shows promise for effectively transferring nutrients to the targeted plant sections (Mahil and Kumar, 2019).

Through efficient soil nutrient management, nanotechnology—which has been dubbed the "next great frontier of agricultural research"—plays a significant part in transforming agriculture and food production. One emerging field in agriculture that could revolutionize long-term food grain production is nanotechnology. Nanotechnology has not yet been fully applied in agriculture since it has been fully employed in other fields. Nanotechnology is a distinct branch of study that deals with atom-by-atom modification to create techniques and technologies that have the potential to transform conventional farming into precision agriculture. Typically, nanoparticles are 10⁻⁹ m in size (Subramanian and Tarafdar, 2011).

One promising method to improve the quality and production of valued crops is to treat seeds before they are sown (Acharya *et al.* 2020). According to Ellouzi *et al.* (2017), it is among the sustainable ways to rapidly improve seed establishment and quality attributes that lead to better plant growth. According to numerous research, seed treatment improves germination rate, emergence, and growth, protects seeds during storage, and changes physiological states including nutrient uptake, water use efficiency, and tolerance to biotic and abiotic stressors.

Based on analysis of plant and soil samples, 49% of Indian soils are believed to be zinc deficient (Singh, 2008). Improving the re-mobilization of absorbed and deposited zinc to grain is a research goal because Maharashtra's soils are also zinc deficient and finger millet's grain Zn

content needs to be increased for nutritional purposes. According to Ramegowda *et al.* (2016), zinc application has also been shown to raise the content of grain iron (Fe) in finger millet.

Aiming at evaluating the “Effect of zinc fertilization on growth and yield of finger millet”, which can be sustained in Maharashtra's soil type and climate, experiments were planned in *Kharif* 2024 with following objectives;

1. To study the effect of different sources of Zn on growth and yield of finger millet
2. To study the effect of Zn fertilization on nutrient uptake and quality parameters of finger millet
3. To study the economics of different treatments

2. REVIEW OF LITERATURE

An attempt has been made in this chapter to review the work done in India as well as abroad with respect to studying the effect of zinc fertilization on growth and yield of finger millet and other crops. The review of literature is divided into different segments as per the objectives of the present investigation.

2.1 Effect of Different Sources of Zn on Growth and Yield of Finger millet

Babu *et al.* (2001) from Bengaluru, Karnataka explored the integrated use of macro and micronutrients in finger millet. They found that Zn application notably enhanced grain yield by improving photosynthetic activity and enzyme function.

Sridhara *et al.* (2003) reported that application of RDF (50 kg N, 37.5 kg P₂O₅ and 25 kg K₂O ha⁻¹) along with zinc sulphate @ 10 kg ha⁻¹ recorded a greater number of ear heads plant⁻¹ in finger millet compared with application of RDF alone during *kharif* in red sandy loam soils of Shimoga, Karnataka.

Pandey *et al.* (2010) revealed that there is positive response of chickpea Seeds treated with ZnO NPs on germination and root growth observed a positive response with seed germination and root growth. The effect of these ZnO NPs on the reactivity of phytohormones, especially indole acetic acid (IAA) involved in the phyto stimulatory actions was also observed. Due to oxygen vacancies the oxygen deficient, *i.e.*, zinc-rich ZnO NPs increased the level of IAA in roots (sprouts) which in turn indicate the increase in the growth rate of plants as Zn is an essential nutrient for plants.

Kumar *et al.* (2012) reported that length of the earhead was the highest with basal application of 20 kg ha⁻¹ ZnSO₄ over application of 10 kg ZnSO₄ as basal + 0.5 per cent foliar spray of ZnSO₄ at 30 days after sowing in a field experiment conducted at CCS Haryana Agricultural University, Hisar in pearl millet.

Kumar *et al.* (2012) conducted an experiment in sandy loam soils of CCS Haryana Agricultural University, Hisar during *kharif* seasons for two years in pearl millet and observed that basal application of 20 kg ha⁻¹ ZnSO₄ increased the grain yield (4053 kg ha⁻¹) compared to application of 10 kg ZnSO₄ as basal + 0.5 per cent as foliar spray 30 days after sowing (3972 kg ha⁻¹).

Prasad *et al.* (2012) also noticed that priming groundnut seeds with nanoscale ZnO particles with a concentration of 1000 ppm was significantly increases the germination, shoot length, root length and vigour index of groundnut seeds when compared to the other concentrations of the same material and varying concentrations of another material (chelated zinc sulphate) tested.

Davoody *et al.* (2013) conducted field experiment by at the Agricultural Research Center of Islamic Azad University, Birjand branch, Iran revealed that with the foliar application of nano ZnO @ 500 ppm significantly increased the panicle length in fox-tail millet over the control.

Mehta *et al.* (2013) at Udaipur, Rajasthan observed that the combination of 5 kg Zn/ha with two foliar sprays of 0.5 % ZnSO₄ resulted in the highest grain yield and improved zinc content in grains during the *kharif* season.

Durgude *et al.* (2014) reported that total uptake of Fe and Mn were significantly higher in treatment graded recommended dose of fertilizer + soil application of FeSO₄ + ZnSO₄ each of two stages *i.e.* 7536 and 1222 g ha⁻¹ Fe and Mn, respectively. The total uptake of Zn was also significantly higher in same treatment (852 g ha⁻¹) followed by soil application of Fe-EDTA @ 2.5 kg ha⁻¹ + Zn-EDTA @ 2.5 kg ha⁻¹ (836 g ha⁻¹) and soil application of ZnSO₄ @ 20 kg ha⁻¹ cow dung at two stages (821 g ha⁻¹). The highest maize grain yield in hybrid maize (79.4 q ha⁻¹) was significantly increased in the treatment of graded recommended dose of fertilizer + soil application of FeSO₄ + ZnSO₄ each of two stages followed by soil application of Fe-EDTA @ 2.5 kg ha⁻¹ + Zn-EDTA @ 2.5 kg ha⁻¹ treatment, where Fe and Zn source were added in soil as a sulphate and chelated form respectively.

Prasad *et al.* (2014) observed the highest number of tillers plant⁻¹ (1.72) with soil application of 60 kg N ha⁻¹ and 10 kg Zn ha⁻¹ over the treatment 60 kg N ha⁻¹ of nitrogen and no zinc treatment in a field experiment conducted at Mirzapur, Uttar Pradesh during *kharif* season in pearl millet.

Rani and Patro (2014) Soil application of ZnSO₄ @ 12.5 kg ha⁻¹ at the time of sowing recorded the highest grain yield (466.4 g m⁻²) as reported in a field experiment conducted on finger millet in red sandy loam soils of Agricultural Research Station, Vizianagaram, Andhra Pradesh.

Shinde *et al.* (2014) studied the effect of foliar zinc application on finger millet in Rahuri, Maharashtra. Their results revealed a significant increase in finger length and number of grains per earhead with 0.5 % ZnSO₄ foliar spray during booting and flowering stages.

Tarafdar *et al.* (2014) conducted experiment on Development of Zinc Nano fertilizer to Enhance Crop Production in Pearl Millet. Results indicate that synthesized nanoparticle size ranged between 15 and 25 nm. A significant improvement in shoot length (15.1 per cent), root length (4.2 per cent), root area (24.2 per cent), chlorophyll content (24.4 per cent), total soluble leaf protein (38.7 per cent), plant dry biomass (12.5 per cent), and enzyme activities of acid phosphatase (76.9 per cent), alkaline phosphatase (61.7 per cent), phytase (322.2 per cent), and dehydrogenase (21 per cent) were observed over control in 6 weeks old plants. The grain yield at crop maturity was improved by 37.7 per cent due to application of zinc nano fertilizer.

Chaudhari *et al.* (2015) conducted field experiments in Navsari, Gujarat. They observed that soil application of ZnSO₄ @ 25 kg/ha along with FYM significantly enhanced biological yield in finger millet by improving soil fertility and microbial activity.

Jha *et al.* (2015) evaluated the effect of Zn fertilization on maize in Ranchi, Jharkhand. They reported that foliar Zn application at 0.5 % significantly improved grain weight and test weight by enhancing cell division during the grain-filling stage.

Shankar *et al.* (2015) observed higher leaf dry, stem dry weight and total dry matter, higher grain (4626 kg ha^{-1}), straw yield (5589 kg ha^{-1}), thousand seed weight (3.32 g), ear head length (8.48 cm), number of finger ear head⁻¹ (6.95), seed germination (100 per cent), shoot and root dry weight (5.9 mg), vigour index (590) registered with application of FYM @ 10 t ha^{-1} + Zn @ 2.50 kg ha^{-1} followed by of FYM @ 5 t ha^{-1} + Zn @ 2.50 kg ha^{-1} compared to control in finger millet.

Janmohammadi *et al.* (2016) conducted experiment on Impact of foliar application of nano micronutrient fertilizers and titanium dioxide nanoparticles on the growth and yield components of barley under supplemental irrigation. Barley plants were separately treated with of chelated nano-scale zinc oxide (ZnO) and ferric oxide (Fe_2O_3) suspensions during tillering stage, booting and milky stages. Results revealed that days to anthesis and maturity significantly increased after application of both nano fertilizers. Furthermore, a considerable improvement was observed in grain mass, spike length number of the grains per spike, chlorophyll content, grain yield and harvest index by application of nano-fertilizer.

Kumar *et al.* (2016) studied the effect of zinc on test weight and quality of wheat in Hisar, Haryana. They found that application of 5 kg Zn ha^{-1} increased thousand grain weight due to better nutrient remobilization and filling efficiency.

Sawant *et al.* (2016) conducted research in Parbhani, Maharashtra, and reported that foliar application of ZnSO_4 enhanced straw and biological yield in sorghum. The increase was due to better vegetative growth and nutrient use efficiency.

Verma and Jat (2016) carried out a study in Jaipur, Rajasthan, and concluded that foliar zinc application improved harvest index in wheat by enhancing grain production relative to total biomass.

Verma *et al.* (2016) studied the effect of zinc fertilization on wheat in Ludhiana, Punjab. Their results showed that foliar application of Zn at reproductive stages significantly improved grain number and seed setting due to enhanced pollen viability and enzyme activity.

Kumar and Kubsad (2017) reported that soil application of ZnSO_4 @ 16 kg ha^{-1} followed by foliar sprays of 0.5 per cent ZnSO_4 at 35 and 45 days after sowing recorded the highest dry matter accumulation (14.7 Mg ha^{-1}) over control (10.1 Mg ha^{-1}) in a study conducted on sorghum crop during *rabi*, on clay loam soils at Dharwad.

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 per cent).

Prashantha and Chikkaramappa (2017) observed that application of FYM @ 10 t + 100 kg N + 50 kg P₂O₅ + 50 kg K₂O + ZnSO₄ @ 15 kg ha⁻¹ to finger millet crop recorded significantly higher thousand grain weight during *kharif* in sandy clay loam soils of Gutthikatte, Karnataka.

Prashantha and Chikkaramappa (2017) noticed that RDF + FYM with ZnSO₄ @ 15 kg ha⁻¹ and Borax @ 12.5 kg ha⁻¹ recorded significantly higher plant height (113.81 cm) in finger millet compared to control during *kharif* in sandy clay loam soils of Gutthikatte, Karnataka.

Rameshraddy *et al.* (2017) conducted a study in Bengaluru, Karnataka to assess the impact of zinc and iron nutrition on finger millet. They reported that application of ZnSO₄ at 25 kg/ha significantly enhanced grain yield. The increase in yield was attributed to improved growth attributes such as plant height and dry matter accumulation due to adequate zinc nutrition.

Rameshraddy *et al.* (2017) reported that foliar application of ZnO-Nano particles (500 ppm) recorded a greater number of tillers plant⁻¹ of finger millet over the control at GKVK Bengaluru.

Rameshraddy *et al.* (2017) reported that foliar application of zinc oxide nano particles 500 ppm recorded the highest shoot biomass (63 gm plant⁻¹) over the control (41.6 gm plant⁻¹) in finger millet at the college farm, Bengaluru.

Rani *et al.* (2017) reported that application of RDF along with 0.5 per cent ZnSO₄ foliar spray recorded more number productive tillers per plant in finger millet when compared with control during *kharif* in sandy loam soils of Vizianagaram, Andhra Pradesh.

Reddy *et al.* (2017) conducted a field experiment in Hyderabad, Telangana, to evaluate the effect of foliar application of micronutrients on finger millet. Their results indicated that foliar application of ZnSO₄ at 0.5 % significantly increased the number of fingers per earhead and grain yield, which was attributed to better spikelet differentiation and nutrient use efficiency.

Saraswathi *et al.* (2017) reported that foliar application of nano scale zinc oxide particle @ 500 ppm registered significantly higher grain yield over soil application of ZnSO₄ in finger millet.

Beeresha (2018) carried out an M.Sc. thesis study at UAS, Dharwad, Karnataka to study nutrient management in finger millet. Soil application of ZnSO₄ along with foliar sprays increased the grain yield and protein content, highlighting the effectiveness of combined nutrient application strategies.

Fulpagare *et al.* (2018) reported that application of RDF + Soil application of 25 kg ha⁻¹ FeSO₄ + 20 kg ha⁻¹ ZnSO₄ recorded highest straw yield in pearl millet when compared with other treatments during *kharif*.

Kulkarni *et al.* (2018) in Dharwad, Karnataka, reported that the integration of zinc with organic manure resulted in significantly higher biological yield of finger millet, likely due to synergistic effects on nutrient availability and uptake.

Patel *et al.* (2018) conducted a study in Anand, Gujarat on pearl millet and found that foliar application of 0.5 % ZnSO₄ during flowering increased grain number and yield. The improvement was due to increased enzyme activity and assimilate transport during the reproductive phase.

Tripathi *et al.* (2018) conducted field trials during *Kharif* in Rewa, Madhya Pradesh. Application of 25 kg ZnSO₄/ha along with a 0.5 % foliar spray significantly improved yield attributes, attributed to increased Zn uptake and better plant vigour.

Akshay (2019) reported that the test weight of sorghum was significantly high compared to control due to the application of ZnSO₄ 25 kg ha⁻¹ + foliar spray @ 0.5 per cent ZnSO₄ at flowering and dough stages compared to control during *rabi* season at Vasantrya Naik Marathwada Krishi Vidyapeeth, Parbhani.

Akshay (2019) reported that the grain yield of sorghum was significantly high compared to control due to the application of ZnSO₄ 25 kg ha⁻¹ + foliar spray @ 0.5 per cent ZnSO₄ at flowering and dough stages during *rabi* season.

Chowdary and Patra (2019) observed that the integrated application of recommended FYM @ 2.5 t ha⁻¹ + 75 per cent RDF + foliar spray of ZnSO₄ @ 0.5 per cent + borax @ 0.5 foliar spray in finger millet significantly increased the straw yield over absolute control during spring season in sandy clay loam soils of Raghunathpur, Purulia West Bengal.

Garg, (2019) observed that the harvest index was found significantly superior with application of treatment nitrogen + phosphorus + zinc indicating an increase of 33.2 per cent in finger millet and 26.4 per cent in pearl millet over control in S.K.N. College of Agriculture, Jobner (Rajasthan) during *kharif* in loamy sand soils.

Kadam *et al.* (2019) reported that a field experiment was conducted for two years at the National Agricultural Research Project, Aurangabad in summer with pearl millet and stated that the treatment combination of recommended dose of fertilizer 120 kg N + 45 kg P₂O₅ + 45 kg K₂O + 20 kg ZnSO₄ ha⁻¹ recorded the higher straw yield of pearl millet which was significantly superior over RDF @ 120:45:45 kg ha⁻¹ NPK.

Kadam *et al.* (2019) reported that a field experiment was conducted for two years at the National Agricultural Research Project, Aurangabad in summer with pearl millet and stated that the treatment combination of recommended dose of fertilizer 120 kg N + 45 kg P₂O₅ + 45 kg K₂O + 20 kg ZnSO₄ ha⁻¹ recorded the highest grain yield and higher number of tillers plant⁻¹ (4.0) and (4.1) which was on a par with application of RDF @ 120:45:45 kg ha⁻¹ NPK.

Kolencik *et al.* (2019) conducted trials in Slovakia to investigate the influence of zinc fertilization on cereals. Their study demonstrated that Zn application improved micronutrient content and grain quality, which was linked to the role of Zn in enzymatic activation and metabolic regulation.

Mahil and Kumar (2019) conducted a review on Foliar application of nano fertilizers in agricultural crops stated that foliar spray of nano ZnO increased the grain weight per earhead in finger millet.

Poornima and Koti (2019) reported that foliar application of nano ZnO and bulk ZnSO₄ were significantly superior to seed priming with nano ZnO and bulk ZnSO₄ in terms of plant height, Leaf area index, yield attributes, grain yield and grain zinc content in sorghum.

Prashantha *et al.* (2019) reported that highest grain yield was registered by the application of RDF + FYM + ZnSO₄ @ 15 kg ha⁻¹ + borax @ 12.5 kg ha⁻¹ in finger millet compared with control under irrigated conditions during *kharif*.

Prashantha *et al.* (2019) reported that application of RDF + FYM + ZnSO₄ @ 15 kg ha⁻¹ + borax @ 12.5 kg ha⁻¹ recorded significantly highest test weight in finger millet compared with control under irrigated conditions during *kharif*.

Saraswathi *et al.* (2019) conducted a pot culture experiment on effect of Nano ZnO on Growth and Yield of Finger Millet (*Eleusine coracana* L. Garten.). Results revealed that foliar application of nano scale zinc oxide particle at lower rate dose compared to the chelated zinc sulphate recommended and they recorded higher grain yield (9.60 g plant⁻¹) and straw yield (15.87 g plant⁻¹) in the treatment which receives nano ZnO @ 500 ppm ha⁻¹ as foliar spray, compared to chelated zinc sulphate.

Saroja *et al.* (2019) reported that a field experiment conducted during *kharif* on loamy sand soils of S.K.N. College of Agriculture, Jobner (Rajasthan), recorded highest harvest index in pearl millet with RDF + soil application of ZnSO₄ @ 6 kg ha⁻¹ than lower levels of zinc.

Sathisha *et al.* (2019) conducted an experiment on foxtail millet at ARS, Hagari on medium black soils during *rabi*, and reported that the treatment RDF + soil application of ZnSO₄ at 15 kg ha⁻¹ and FeSO₄ at 10 kg ha⁻¹ + foliar application of 0.5 per cent ZnSO₄ and FeSO₄ each at 30 DAS recorded significantly higher number of tillers plant⁻¹ (4.21).

Sathisha *et al.* (2019) reported that 100 per cent RDF along with soil application of zinc sulphate @ 15 kg ha⁻¹ and foliar application of 0.5 per cent ZnSO₄ at 30 DAS recorded highest grain yield in foxtail millet compared with application of RDF alone during *rabi* in medium black soils of Hagari, Karnataka.

Sharanappa *et al.* (2019) reported that significantly higher grain and stover yield of pearl millet was obtained in soil application of ZnSO₄ @ 15 kg ha⁻¹ and FeSO₄ @ 10 kg ha⁻¹ + foliar

application of 0.5 per cent ZnSO_4 and FeSO_4 in pearl millet compared to control during *kharif* in medium black soils of Raichur, Karnataka.

Sharma and Singh (2019) conducted a study in Kota, Rajasthan and found that foliar application of ZnSO_4 significantly increased grain weight in wheat. The improved results were linked to better photosynthate partitioning to reproductive organs.

Thakur *et al.* (2019) evaluated the impact of micronutrient sprays on pearl millet in Durg, Chhattisgarh. They found that 0.5 % ZnSO_4 foliar application increased biomass production and straw yield, attributed to enhanced chlorophyll synthesis and root proliferation.

Dutta *et al.* (2020) conducted trials in Bhagalpur, Bihar to evaluate the impact of foliar micronutrients on pearl millet. They reported that 0.5 % foliar Zn application significantly improved spike length and grain weight, likely due to enhanced auxin activity and assimilate translocation.

Gaikwad *et al.* (2020) conducted a field trial in Akola, Maharashtra, to evaluate the effect of nano-zinc fertilization on small millets. The foliar application of 0.5 % nano- ZnO significantly increased grain and straw yield due to improved metabolic efficiency and nutrient absorption.

Sathisha *et al.* (2020) reported that a field experiment conducted during *rabi* on medium black soils of Hagari (Karnataka), recorded highest harvest index in foxtail millet with RDF + soil application of ZnSO_4 @ 15 kg ha⁻¹ and FeSO_4 @ 10 kg ha⁻¹ + foliar application of 0.5 per cent ZnSO_4 and FeSO_4 each at 30 DAS compared to control.

Singh *et al.* (2020) reported from Pantnagar, Uttarakhand, that foliar application of zinc at booting and milking stages enhanced harvest index in finger millet. Improved partitioning of assimilates toward grain yield was credited for this enhancement.

Vijaykumar *et al.* (2020) reported that application of NPK along with ZnSO_4 (0.5 per cent) + FeSO_4 (1 per cent) + citric acid (0.1 per cent) spray twice at vegetative and flowering stages recorded higher grain yield compared to all other treatments in finger millet during *kharif* in red sandy loam soils of Paiyur, Tamil Nadu.

Bhosale *et al.* (2021) conducted research in Kolhapur, Maharashtra and found that foliar sprays of Zn improved grain quality and test weight in finger millet. They attributed the improvements to enhanced protein synthesis and cellular expansion.

Rajput *et al.* (2021) carried out research in Udaipur, Rajasthan to evaluate the influence of micronutrients on finger millet. The foliar application of 0.5 % ZnSO_4 showed a marked increase in yield attributes like ear length, grain yield, and test weight. The improvement was associated with enhanced enzyme activity and photosynthetic efficiency.

Khardia *et al.* (2022) conducted field experiments during the *kharif* season in Jabalpur, Madhya Pradesh. They observed that the application of 25 kg ZnSO_4 ha⁻¹ along with two foliar sprays

of 0.5 % ZnSO₄ significantly improved plant height, tiller number, and grain yield. The combined approach maximized nutrient availability and uptake efficiency.

Kruthika *et al.* (2023) conducted field experiment to determine the “Effect of nano zinc and foliar application of boron on growth and yield of finger millet (*Eleusine coracana* L.)”. The experiment was laid out in Randomized Block Design comprising of 10 treatments which include of three levels of (Nano zinc 300 ppm, 600 ppm, 900 ppm) and three levels of foliar application of Boron at (0.1 per cent, 0.3 per cent and 0.5 per cent), whose effect is observed in finger millet. The results revealed that the treatment with application of Nano zinc 900 ppm + Boron at 0.5 per cent recorded higher plant height, number of tillers plant⁻¹ plant dry weight, CGR, RGR and yield parameter test weight, seed yield, stover yield and harvest index.

2.2 Effect of Zn Fertilization on Nutrient Uptake and Quality Parameters of Finger millet

Hossain *et al.* (2008) from Jessore (Bangladesh) reported that Zn application increased grain Zn concentration in maize by 73 per cent and in rice by 141 per cent. The actual values (mg Zn kg⁻¹ grain) for maize were 28.4 for Zn fertilized (@ 4 kg ha⁻¹) crop as against 16.5 for control (no zinc). Similarly, the grain Zn concentration (mg Zn kg⁻¹ grain) in rice was 50.0 for Zn fertilized (@ 2 kg Zn ha⁻¹) crop as against 20.7 for no Zn treatment.

Ramegowda *et al.* (2013) concluded that external application of Zn resulted in improved Zn concentration in different plant parts; in particular there was a significant increase in seed Zn concentration in all genotypes. Apart from that, Zn application increased the seed iron (Fe) concentration with no or minimal effect on copper (Cu) concentration in finger millet.

Prasad *et al.* (2014) reported 31.47 per cent improvement in grain yield of pearl millet with 10 kg Zn ha⁻¹ as compared to 0 kg Zn ha⁻¹. However, due to synergistic interaction between nitrogen and Zn, highest grain zinc content (26.1 mg kg⁻¹) was attained with 20 kg N with 5 kg Zn ha⁻¹, while the zinc content in control (N₀Zn₀) was found as 8.6 mg kg⁻¹. The agronomic efficiency, partial factor productivity and apparent recovery efficiency (nitrogen and zinc) diminished as nitrogen and zinc rates increased.

Rani and Patro (2014) reported that the treatment, foliar sprays of ZnSO₄ @ 0.5 per cent each at flowering and 20 days after flowering recorded the highest Zn content in grain (3.45 mg 100 g⁻¹) over soil application of ZnSO₄ @ 12.5 kg ha⁻¹ at the time of sowing (3.41 mg 100 g⁻¹) as reported from a field experiment conducted in red sandy loam soils at Vizianagaram in finger millet.

Shukla *et al.* (2014) in Kanpur, Uttar Pradesh observed that nano-zinc application improved crude protein content in wheat grain by enhancing nitrogen metabolism and enzymatic activities like nitrate reductase and ribonuclease.

Yadav *et al.* (2014c) conducted field experiment at Hisar (Haryana), revealed that there is an improvement in total uptake of N, P, K and Zn by both grain and straw of pearl millet due to application of 125-62.5-40 kg N, P_2O_5 and K_2O along with 25 kg $ZnSO_4$ ha⁻¹ during *kharif* in sandy loam soils.

Patil *et al.* (2015) evaluated the effect of zinc and iron on nutrient content and quality of finger millet in Dharwad, Karnataka. They observed that application of zinc improved ash content and mineral density in grains due to better translocation of micronutrients.

Ramesh and Bharathi (2015) investigated the effect of balanced nutrient application on millet crops in Coimbatore, Tamil Nadu. They found that higher protein content was inversely related to crude fiber, as nutrients were directed more toward metabolic products than structural tissues.

Shankar *et al.* (2015) opined that uptake of N, P, K and Zn of finger millet were found to be higher with the application of Zn @ 5 kg ha⁻¹ along with RDF compared to control during *kharif* at Bengaluru, Karnataka.

Upadhyay and Yadav (2015) from Varanasi, Uttar Pradesh reported that application of 5 kg Zn ha⁻¹ significantly increased biomass and Zn uptake in finger millet. This was mainly due to the involvement of Zn in auxin production and root development.

Mishra *et al.* (2016) studied the impact of zinc fertilization on rice in Faizabad, Uttar Pradesh. They observed that foliar application of $ZnSO_4$ improved carbohydrate content in grains due to enhanced photosynthesis and increased activity of carbonic anhydrase and starch-synthesizing enzymes.

Pradhan *et al.* (2016) reported that the application of 8 kg Zn ha⁻¹ as $ZnSO_4$ as deep placement at sowing by drill significantly recorded the highest Zn content in grain (4.91 mg) over control (2.92 mg) as observed in a field experiment conducted on finger millet for two years at Jagdalpur.

Shankaranarayan *et al.* (2016) conducted research in Coimbatore, Tamil Nadu, evaluating the effect of nano-fertilizers on nutrient dynamics in cereals. They observed that nano-zinc application improved crop productivity and micronutrient uptake with minimal residual accumulation in soil, confirming high absorption efficiency.

Yamunarani *et al.* (2016) reported that external supply of Zn significantly increased the seed Zn concentration compared to that occurring under control irrespective of genotype. In addition, Zn application increased seed Fe concentration with no or minimal effect on Cu concentration in finger millet grain.

Joshi *et al.* (2017) carried out pot experiments in Bhopal, Madhya Pradesh, and found that foliar application of nano-ZnO increased protein content in cereals. The improvement was linked to elevated nitrogen assimilation and amino acid synthesis.

Kumar *et al.* (2017) reported that a treatment combination of soil application of zinc @ 16 kg ha⁻¹ followed by foliar sprays of 0.5 per cent ZnSO₄ at 35 and 45 days after sowing in pearl millet recorded the highest crude protein (7.1 per cent) over control (6.3 per cent).

Mathur *et al.* (2017) reported that significant improvement in Zn, (47.90, 18.32 per cent) Fe (30.20, 16.11 per cent) and B (25.60, 19.75 per cent) uptake were noticed with soil + foliar and (Fe + Zn + B) over control in sorghum.

Rameshraddy *et al.* (2017) reported that seed priming and foliar application of ZnO nano @ 500 ppm had significantly enhanced leaf and seed zinc content of finger millet than Zn gluconate and ZnSO₄ under control and water stress conditions.

Rani *et al.* (2017) reported that the highest Zn and Fe uptake by plant was observed with 150 per cent RDF + ZnSO₄ @ 0.5 per cent foliar spray + FeSO₄ @ 0.2 per cent foliar spray over 100 per cent RDF (60-40-30 kg ha⁻¹ of N, P₂O₅ and K₂O) in a field experiment conducted on finger millet during *Kharif*, at Vizianagaram in sandy loam soils.

Sandhya Rani *et al.* (2017) reported higher grain and straw yield (78.1q ha⁻¹ and 33.7q ha⁻¹ respectively) of finger millet with application of 150 per cent RDF + ZnSO₄ @ 0.5 per cent Foliar spray + FeSO₄ @ 0.2 per cent. Highest available soil macronutrients and uptake of macronutrients was also found with the same treatment. Highest available zinc in the soil was found with the treatment applied with 150 per cent RDF + ZnSO₄ soil application + FeSO₄ 0.2 per cent Foliar spray (3.32 ppm) and the highest.

Singh *et al.* (2017) carried out an experiment at Banaras Hindu University, Barkachha during *kharif* season, in pearl millet and concluded that the highest Zn content in plant was recorded with the application of 20 kg P₂O₅ + 30 kg Zn ha⁻¹ (54.66 ppm) over control (24.88 ppm).

Fulpagare *et al.* (2018) reported that maximum N, P and K content of soil in treatment receiving RDF + soil application of 25 kg ha⁻¹ FeSO₄ and 20 kg ha⁻¹ ZnSO₄ followed by RDF + soil application of 20 kg ha⁻¹ ZnSO₄. Maximum iron content and zinc contents were observed with RDF + soil application of 25 kg ha⁻¹ FeSO₄ and RDF + 20 kg ha⁻¹ ZnSO₄ respectively followed by RDF + combined soil application of 25 kg ha⁻¹ FeSO₄ and 20 kg ZnSO₄.

Meena *et al.* (2018) observed that highest Fe content in fresh leaves of pearl millet (15.1 mg kg⁻¹ dry weights) and mustard (23.1 mg kg⁻¹ dry wt.) was estimated with 5 kg Zn + 10 kg Fe + 10 t FYM ha⁻¹, which was significantly higher than control treatment at 50 days after sowing of crops.

Meena *et al.* (2018) in Jaipur, Rajasthan evaluated foliar zinc application in wheat and found that it significantly improved nitrogen uptake and efficiency. The improved response was linked to better enzymatic activity and chlorophyll synthesis.

Rakesh *et al.* (2018) in Dharwad, Karnataka found that nano-zinc foliar spray significantly increased grain yield and micronutrient content in little millet. The improvement was due to higher uptake efficiency and better distribution within the plant system.

Sawarkar *et al.* (2018) conducted field trials in Nagpur, Maharashtra. They reported that the application of zinc fertilizers led to a significant increase in carbohydrate content in soybean and wheat, attributed to enhanced enzymatic functions and better source-sink balance.

Akshay (2019) reported that the protein and iron content in grains of sorghum was significantly high compared to control due to the application of ZnSO_4 25 kg ha⁻¹ + foliar spray @ 0.5 per cent ZnSO_4 at flowering and dough stages during *rabi* season.

Akshay (2019) reported that the grain zinc content of sorghum was significantly high compared to control due to the application of ZnSO_4 25 kg ha⁻¹ + foliar spray @ 0.5 per cent ZnSO_4 at flowering and dough stages during *rabi* season at Vasantao Naik Marathwada Krishi Vidyapeeth, Parbhani.

Mahil and Kumar (2019) conducted field experiment on foliar application of nano fertilizers in agricultural crops stated that the foliar application of nano forms of iron and zinc fertilizers increased the phosphorus concentration, biomass, and crude protein and soluble carbohydrate concentration in forage corn over chemical forms of fertilizers.

Poornima and Koti (2019) observed that the grain Zn content was 5.6 per cent higher with 500 ppm of nano ZnO foliar spray as compared to 1000 ppm of bulk ZnSO_4 foliar spray. Zinc content in grain improved with both nano and bulk treatments as compared to control, but the per cent increase over control was higher with nano ZnO (18 per cent) than bulk ZnSO_4 (11 per cent) in sorghum.

Rizwan *et al.* (2019) found that the seed priming with 25, 50, 75 and 100 mg L⁻¹ ZnO NPs had increased grain zinc concentrations by 105 per cent, 33 per cent, 58 per cent and 102 per cent respectively relative to control in wheat. Similarly, Fe concentrations in wheat grains were increased by 20 per cent, 59 per cent, 89 per cent and 121 per cent when seeds were primed with 5, 10, 15 and 20 mg L⁻¹ Fe NPs respectively compared to control.

Kumar *et al.* (2020a) reported highest uptake of N, P, K, Fe in finger millet with RDF + foliar application of FeSO_4 @ 0.5 per cent twice at 30 and 60 DAS followed by RDF + foliar application of Fe-humate twice at 30 and 60 DAS. The highest uptake of Zn in crop was obtained in treatment receiving RDF + Zn Humate foliar spray @ 0.25 per cent twice at 30 and 60 DAS followed by RDF + Zn Humate soil application.

Vijayakumar *et al.* (2020) reported highest nutrient uptake of N, P, K and Fe with the treatment receiving NPK + ZnSO₄ (0.5 per cent) + FeSO₄ (1 per cent) + citric acid (0.1 per cent) spray twice at vegetative and flowering stages of finger millet and it was on par with NPK + ZnSO₄ (12.5 kg ha⁻¹) and FeSO₄ (25 kg ha⁻¹) as enriched FYM. The higher Zn uptake was recorded in the treatment receiving NPK + ZnSO₄ (12.5 kg ha⁻¹) + FeSO₄ (25 kg ha⁻¹).

Gaikwad *et al.* (2021) in Akola, Maharashtra studied the impact of nano zinc fertilization on nutritional quality of finger millet. They found that Zn application significantly increased ash and mineral content in grains by improving nutrient uptake and accumulation.

Umar *et al.* (2021) conducted an experiment on Synthesis, characterization and application of ZnO nanoparticles for improved growth and Zn biofortification in maize. Pot and field experiments were conducted to evaluate the effect of ZnO nanoparticles in comparison with conventional Zn fertilizer (ZnSO₄) on growth and grain Zn contents of maize. Maximum Zn concentration (~80 mg kg⁻¹) was observed in young leaves at vegetative growth stage in treatments receiving ZnO nanoparticles. Foliar applied ZnO NPs showed maximum increase in grain Zn concentration (82 per cent).

2.3 To Study the Economics of Different Treatments

Gupta *et al.* (2001) reported that application of 40 kg N + 20 kg P₂O₅ + 20 kg ZnSO₄ ha⁻¹ in pearl millet resulted in higher gross returns.

Sridhara *et al.* (2003) reported maximum benefit-cost ratio with recommended NPK + azotobacter + zinc sulphate + gypsum (2.48) followed by NPK + gypsum + azotobacter (2.42) and NPK + zinc sulphate + azotobacter (2.39), while the lowest benefit-cost ratio was recorded with recommended NPK alone (2.16) in finger millet.

Parihar *et al.* (2010) reported that the integrated application of recommended FYM @ 7.5 t ha⁻¹ + 40 kg N + 20 kg P₂O₅ + 10 kg K₂O + ZnSO₄ @ 12.5 kg ha⁻¹ in little millet recorded the net income of 1866 ha⁻¹ and benefit-cost ratio of 1.23 during *kharif* in sandy loam soils of Rewa, Madhya Pradesh.

Shinde *et al.* (2014) conducted a study in Rahuri, Maharashtra, where they reported that foliar application of ZnSO₄ at 0.5 % during critical growth stages significantly improved economic returns in finger millet. The treatment recorded higher gross and net returns, and a better B:C ratio, due to increased grain and straw yield.

Yadav *et al.* (2014b) conducted field experiment at Hisar, Haryana recorded the highest gross and net returns and benefit-cost ratio due to the application of 125 kg N + 62.5 kg P₂O₅ + 40 kg K₂O + 25 kg ZnSO₄ ha⁻¹ + bio mix to pearl millet during *kharif* in sandy loam soils.

Choudhary *et al.* (2016) reported that application of 5 kg Zn ha⁻¹ along with RDF (60 kg N, 40 kg P₂O₅ and 40 kg K₂O ha⁻¹) recorded significantly higher net returns and benefit-cost ratio

as compared to RDF alone from pearl millet in pearl millet-chickpea cropping sequence on sandy loam soils of New Delhi.

Naseeruddin (2016) reported higher gross returns and net returns with RDF+ foliar application of nanoscale ZnO + CaO + MgO at 40 and 60 DAS (Rs.1,01,450/- and Rs.69,980/- respectively), whereas the benefit cost ratio was highest with RDF + nano ZnO at 40 and 60DAS (3.38) and RDF + nano MgO at 40 and 60 DAS (3.29). The lowest gross income (Rs.69,843/-), net income (Rs.45,017/-) and B:C ratio (2.81) were observed with RDF alone in sweet sorghum.

Shankar *et al.* (2016b) reported that higher benefit-cost ratio was obtained with soil application of 50 kg N + 40 kg P₂O₅ + 25 kg K₂O + 12.5 kg ZnSO₄ ha⁻¹ compared to application of RDF alone during *kharif* in finger millet – finger millet crop rotation system at University of Agricultural Sciences, Bengaluru, Karnataka.

Verma and Jat (2016) in Jaipur, Rajasthan evaluated the economics of zinc fertilization in wheat. Their findings showed that soil application of ZnSO₄ along with foliar sprays yielded maximum net returns and a favorable B:C ratio, due to enhanced grain yield relative to the additional cost of micronutrient inputs.

Chand and Susheela (2017) registered higher gross return (₹ 1,39,886 ha⁻¹), net return (₹ 93,340 ha⁻¹) and benefit cost ratio (3.00) in baby corn crop with foliar spray of ZnSO₄ @ 0.2 % at 25 DAS and 40 DAS along with soil application of ZnSO₄ @ 25 kg ha⁻¹.

Thuyavanan and Kandasamy (2017) from their work on maize in the Experimental Farm, Annamalai University, Annamalainagar, during summer stated that application of zinc @ 5 kg ha⁻¹ as basal along with 150 per cent recommended dose of fertilizers shows higher net return (₹ 55186 ha⁻¹) and benefit cost ratio (2.21).

Arshewar *et al.* (2018) reported that the application of zinc @ 15 kg ha⁻¹ in pearl millet generated 13.0 per cent, 13.8 per cent and 2.5 per cent higher gross monetary return, net monetary return and B:C ratio respectively over 5 kg ha⁻¹ of zinc in pearl millet.

More *et al.* (2018) conducted field research in Rahuri, Maharashtra to assess the cost-effectiveness of nano-zinc application in cereals. The results indicated that foliar application of nano-ZnO not only improved yield but also resulted in superior net returns and B:C ratio, attributed to the lower cost and higher efficiency of nano-formulations.

Nandan *et al.* (2018) reported that amongst the zinc and iron fortification treatments, highest gross returns, net returns and B: C ratio was realized with treatment RDF + Zn (0.5 per cent) + Fe (0.05 per cent) through foliar application, which was closely followed by RDF + seed treatment + soil application of ZnSO₄ @ 25 kg ha⁻¹ and RDF + soil application of ZnSO₄ @ 25 kg ha⁻¹ (recommended practice). However, the lowest net returns were obtained with RDF alone treatment in chickpea.

Patel *et al.* (2018) carried out an economic analysis of micronutrient application on finger millet in Anand, Gujarat. Their study revealed that the foliar application of 0.5 % ZnSO_4 recorded the highest net returns and benefit-cost ratio (B:C ratio). This was attributed to improved yield coupled with marginal increases in input costs, thereby maximizing profitability.

Pruthviraj and Chandrashekara (2019) reported that seed treatment with nano ZnO in combination with foliar application of nano ZnO @ 1000 ppm recorded significantly higher seed cotton yield ($\text{₹ } 3221 \text{ kg ha}^{-1}$), gross returns ($\text{₹ } 1,56,241 \text{ ha}^{-1}$), net returns ($\text{₹ } 88,128 \text{ ha}^{-1}$) and B:C ratio (2.3) than recommended practices.

Uma *et al.* (2019) reported that seed priming with 800 ppm of nano zinc oxide for 30 minutes and foliar application of nano ZnO at 500 ppm along with RDF (FYM @ 10 t + 150 kg N + 75 kg P_2O_5 and 37.5 kg $\text{K}_2\text{O ha}^{-1}$) recorded higher kernel yield (8750 kg ha^{-1}) and stover yield (11136 kg ha^{-1}), higher gross returns ($\text{₹ } 1,33,636 \text{ ha}^{-1}$) and net returns ($\text{₹ } 84,777 \text{ ha}^{-1}$). Whereas, higher B:C ratio of 3.45 was recorded in the seed treated with 800 ppm of nano zinc oxide for 30 minutes with recommended dose of fertilizer.

Soumya *et al.* (2020) reported that the effect of nano zinc and silicon on the performance of wetland paddy (*Oryza sativa* L.) and reported that higher gross returns ($\text{₹ } 1,38,294 \text{ ha}^{-1}$), net returns ($\text{₹ } 98,631 \text{ ha}^{-1}$) and B:C ratio (2.5) were observed by foliar application of zinc and silicon (40 ppm) at 40 DAT with the tune of 34.95 per cent higher than conventional foliar sources (ZnSO_4 EDTA and potassium silicate).

Divya *et al.* (2021) reported that the effect of foliar application of iron and zinc on the yield and economics of finger millet (var MR-1). Results revealed that the application of 0.6 % ZnSO_4 + 0.5 % FeSO_4 resulted in the highest grain yield (3.93 t ha^{-1}) and stover yield (6.03 t ha^{-1}) compared to other treatments. Economic analysis showed maximum gross returns (INR 87,573.33), net returns (INR 56,639.08), and a B:C ratio of 1.83 for the treatment of 0.6 % ZnSO_4 + 0.5 % FeSO_4 .

Rajesh *et al.* (2021) conducted a field experiment during *rabi* 2020-21 at ICAR-KVK, UAS, Raichur with an objective to assess the effect of foliar sprays of nano N and nano Zn on growth and yield of sweet corn crop. There were thirteen different nutrient treatments consisting of chemical nano nitrogen, chemical nano zinc and green nano zinc along with two recommended doses of fertilizer and absolute control treatment. They reported that treatment involving in 75 % N, 100 % P and K + foliar application of chemically synthesized nano N @ 4 ml/l and chemically synthesized nano Zn @ 2 ml/l at 25 and 50 DAS, respectively recorded a significantly higher gross returns ($126503 \text{ Rs ha}^{-1}$), Net returns (77928 Rs ha^{-1}) and B:C ratio (2.60) respectively.

Choudhary *et al.* (2022) conducted a field experiment during two consecutive *Kharif* seasons of 2020 and 2021 at Udaipur to evaluate the effect of foliar application of zinc based nano fertilizer and different fertility levels on yield and economics of maize in Southern Rajasthan.

Significantly higher net returns (₹ 82,956 ha⁻¹) and BC ratio (3.04) were recorded by spraying Zn chitosan nano particles (0.1 %) at both the stages of knee height and at 50 % tasseling stage over control (₹ 69.373 ha⁻¹ and 2.71, respectively).

Deepak Sathyan (2022) conducted research at the research fields of school of agriculture Department of Agronomy, Lovely Professional University, Phagwara (Punjab) during *rabi* season in the year 2021-2022. The objective of the study was to evaluate “Effect of nano nutrients on pea growth and yield *Pisum sativum* L.”. The experiment consists of 7 treatments and replicated thrice. Results indicated that among various treatments, treatment involving in 0.1 % Nano Zinc + 0.2 % Nano Urea at 30 DAS showed a significantly higher gross returns, net returns and B:C ratio.

3. MATERIAL AND METHODS

A field experiment entitled “Effect of zinc fertilization on growth and yield of finger millet (*Eleusine coracana* L. Gaertn.)” has been conducted during *kharif* 2024 at Instructional Farm, Post Graduate Institute, MPKV, Rahuri. The details of experimental procedures, materials used, and benchmarks adopted for treatment evaluation during the course of research are described in this chapter.

3.1 Details of Experimental Material

3.1.1 Location of the Experimental Site

The experiment was conducted at the Instructional Farm, PGI, Mahatma Phule Krishi Vidyapeeth, Rahuri, Dist. Ahilyanagar, Maharashtra (India). The selection of the site was considered on the basis of the suitability of the land for the cultivation of finger millet. Geographically, Instructional Farm is situated between 19° 33' N and 19° 48' N latitudes and between 74° 65' E and 74° 90' E longitudes. The altitude above mean sea level is about 513 metres.

3.1.2 Soil Characteristics of the Experimental Site

The topography of the experimental plot was uniform and level. The soil in the experimental area was well drained. In order to know the physical and chemical properties of soil, representative composite soil samples from 0-30 cm depth were collected from randomly drawn spots on the experimental plot with the help of a screw auger before the start of the experiment. The sample was air dried under shade. The composite soil sample was analyzed following standard methods, which are presented along with references (Table 3.1).

The soil texture of the experimental site was found to be clayey in mixture. The chemical composition according to criteria laid out by Muhr *et al.* (1965) indicated that soil was low in available nitrogen (184.85 kg ha⁻¹), moderate in available phosphorus (18.87 kg ha⁻¹) and very high in potassium (386.07 kg ha⁻¹). The soil available micronutrients were Fe (4.12 mg kg⁻¹), Mn (3.20 mg kg⁻¹), Cu (0.41 mg kg⁻¹) and Zn (0.55 mg kg⁻¹). The soil was alkaline in reaction (pH 8.19) with a low electrical conductivity of 0.29 dS m⁻¹ and organic carbon of 0.55% (Table 3.1).

3.1.3 Climate and Weather Condition

In terms of climate, the experimental unit is located in a semi-arid region and subtropical zone with annual rainfall ranges between 307 to 619 mm. The average annual rainfall is about 520 mm, which is overall intense during the monsoon months from June to September. Over most of the area, rainfall and its distribution are unpredictable and variable. The average annual maximum temperature varies from 23.2 °C to 39.8 °C, on the other side, the annual mean minimum temperature ranges from 9.4 °C to 26.9 °C, along with this, the mean morning and evening relative humidity varies from 59 to 99 % and 19 to 93 %, respectively. Argo-climatically, an experimental region is located in the scarcity zone of Maharashtra.

Table 3.1 Physico-chemical properties of soil and methods used for soil analysis

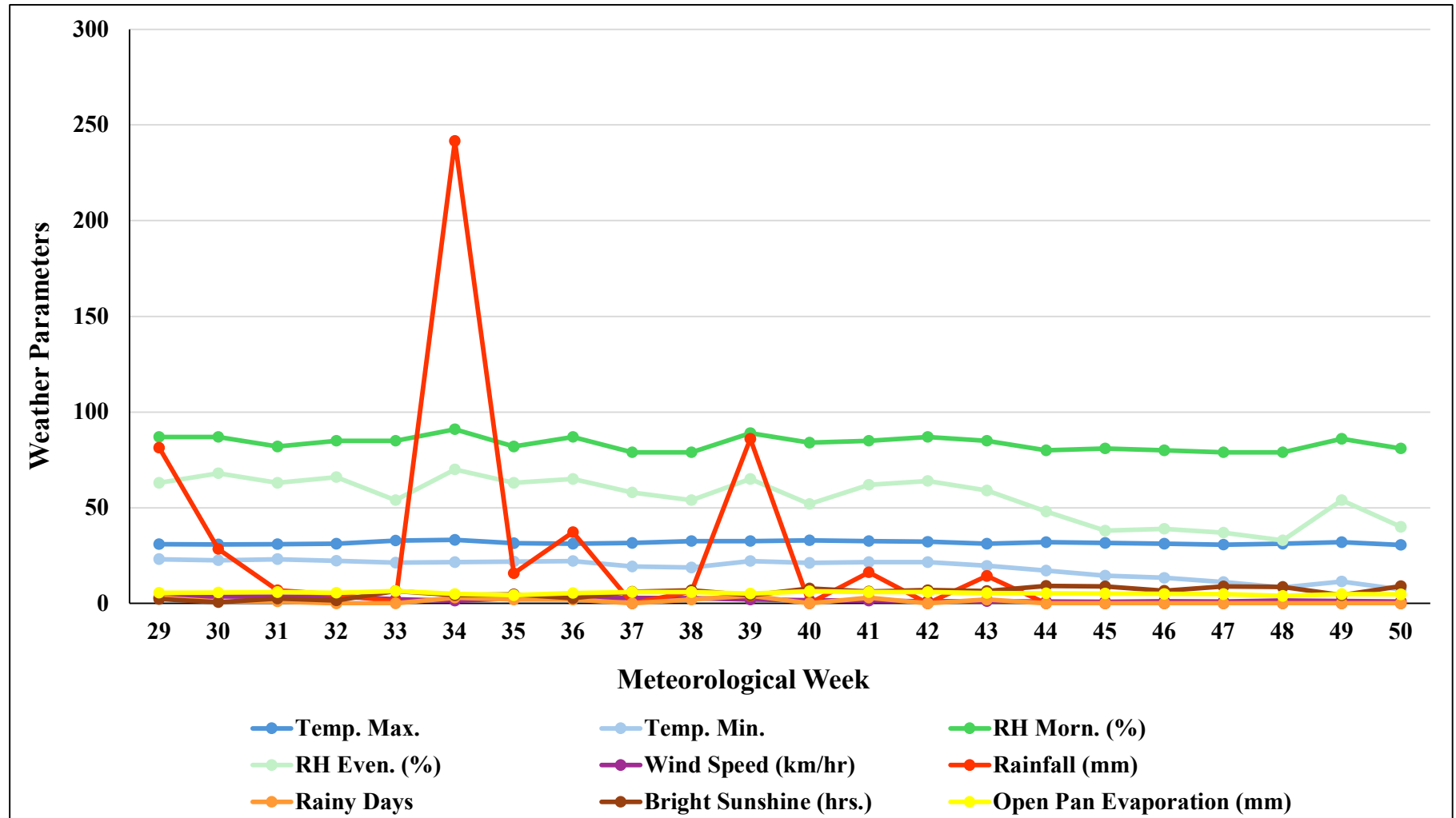
Sr. No.	Characteristics	Composition	Method used	References
A.	Physical properties			
1.	Coarse sand (%)	6.71	International pipette method	Piper (1966)
2.	Fine sand (%)	12.52		
3.	Silt (%)	28.47		
4.	Clay (%)	51.77		
5.	Textural class	Clay		
B.	Chemical properties			
1.	Soil pH (1:2.5 soil: water)	8.19	Potentiometric method	Jackson (1973)
2.	EC (dS m ⁻¹)	0.29	Conductometric method	Jackson (1973)
3.	Organic carbon (%)	0.55	Wet oxidation method Walkey and Black	Nelson and Sommer (1982)
4.	Available N (kg ha ⁻¹)	184.85	Alkaline permanganate method	Subbiah and Asija (1956)
5.	Available P ₂ O ₅ (kg ha ⁻¹)	18.87	Olsen method 0.5M NaHCO ₃ (pH 8.5)	Olsen <i>et al.</i> (1964)
6.	Available K ₂ O (kg ha ⁻¹)	386.07	Flame photometry N N NH ₄ OAc (pH 7.0)	Knudsen and Perterson (1982)
7.	DTPA Fe (mg kg ⁻¹)	4.12	DTPA extraction	Lindsey and Norvell (1978)
8.	DTPA Mn (mg kg ⁻¹)	3.20		
9.	DTPA Cu (mg kg ⁻¹)	0.41		
10.	DTPA Zn (mg kg ⁻¹)	0.55		

3.1.4 Nature of Season During Experimental Period

The Mahatma Phule Krishi Vidyapeeth's meteorological observatory at Rahuri recorded meteorological data on important weather parameters during the crop growing cycle for the year 2024-25, as presented in Table 3.2. During the crop growth season of 2024-25, the weekly maximum and minimum temperatures ranged between 30.6 to 33.2 °C and 7.3 to 23.1 °C, respectively. The mean weekly morning relative humidity ranged between 79 and 91 %, and the evening humidity ranged between 33 and 70 %. The total rainfall received of 23 rainy days during the field trial was 539.6 mm. The maximum bright sunshine hours of 9.2 was recorded in 44 MW. The highest wind speed of 3.6 km hr⁻¹ was recorded in 30 MW while lowest wind velocity of 0.9 km hr⁻¹ was recorded in 45 MW. The experimental plot was irrigated at regular intervals, depending on the moisture condition of the soil. Generally, weather conditions were quite favourable for the growth of the finger millet crop.

Table 3.2 Meteorological data recorded during experimental period (*Kharif* 2024)

Met. Week	Date	Temperature (°C)		Relative humidity (%)		Wind speed (km hr ⁻¹)	Rain fall (mm)	No. of Rainy days	Sunsh ine (hrs.)	Open pan evaporati on (mm)
		Max.	Min.	Morn.	Even.					
July, 2024										
29	14-20	31.0	23.1	87	63	3.0	81.4	3	2.3	5.6
30	21-27	30.8	22.5	87	68	3.6	28.4	1	0.6	5.7
31	28-03	31.0	23.1	82	63	3.5	6.8	1	2.5	6.0
August, 2024										
32	04-10	31.2	22.3	85	66	3.5	4.6	0	1.6	5.6
33	11-17	32.8	21.3	85	54	2.2	1	0	6.4	6.5
34	18-24	33.2	21.5	91	70	1.4	241.6	3	4.3	4.9
35	25-31	31.4	21.9	82	63	2.6	15.8	2	4.7	4.3
September, 2024										
36	01-07	31.2	22.1	87	65	2.6	37.2	2	2.7	5.4
37	08-14	31.6	19.3	79	58	2.8	0	0	6.1	6.0
38	15-21	32.6	18.7	79	54	2.7	6.2	2	6.8	6.0
39	22-28	32.6	22.1	89	65	2.1	86	4	4.2	5.2
October, 2024										
40	29-05	33.0	21.1	84	52	1.7	0	0	7.8	6.3
41	06-12	32.6	21.5	85	62	1.4	16.2	3	6.2	5.9
42	13-19	32.2	21.5	87	64	1.2	0	0	7.0	6.0
43	20-26	31.2	19.7	85	59	1.2	14.4	2	6.5	5.5
44	27-02	32.0	17.1	80	48	1.1	0	0	9.2	5.3
November, 2024										
45	03-09	31.6	14.5	81	38	0.9	0	0	8.8	5.2
46	10-16	31.2	13.3	80	39	1.2	0	0	6.6	4.9
47	17-23	30.7	11.1	79	37	1.1	0	0	8.8	4.8
48	24-30	31.2	8.3	79	33	1.5	0	0	8.6	3.9
December, 2024										
49	01-07	32.0	11.5	86	54	1.3	0	0	4.3	4.8
50	08-14	30.6	7.3	81	40	1.0	0	0	9.0	4.7
Avg.		31.7	18.4	83.6	55.2	1.9	-	5.2	5.68	5.38



3.1.5 Previous Cropping History

The information regarding the crops grown on the experimental plot during the previous three years of investigation presented in Table 3.3.

Table 3.3 Cropping history of experimental field

Sr. No.	Year	Crops grown in previous year		
		<i>Kharif</i>	<i>Rabi</i>	Summer
1.	2023 - 2024	Soybean	Wheat	fallow
2.	2024 - 2025	Present investigation		-

3.1.6 Varietal Characters of Phule Nachani

Phule Nachani approved for cultivation in Maharashtra's finger millet growing areas, boasts a combination of desirable traits. It offers high yield potential within a late maturity group, typically maturing in 115 to 120 days. With its dwarf plant stature, the variety resists lodging while producing abundant tillers. Plant habit is erect, dark green colour leaf, flag leaf angle curved at tip, no pigmentation and semi drooping leaf angle, brown grain colour complemented by strong culm strength, semi-loose ear and easy threshability. Notably, Phule Nachani displays strong resistance to leaf blast and neck blast, common diseases affecting finger millet crops.

3.2 Details of the Experimental Methods

3.2.1 Experimental Details

The field experiment was laid out in “Randomized Block Design” with ten treatment and three replications. The treatment details are presented in Table 3.5 and plan of layout is depicted in Fig 3.2.

Table 3.4 Experimental details

Crop	Finger millet
Variety	Phule Nachani
Design	Randomized Block Design
Treatment combinations	10
Replications	3
Gross plot size	4.00 x 3.60 m ²
Net plot size	3.60 x 3.00 m ²
Number of plots	30
Method of sowing	Line sowing
Spacing	30 cm x 10 cm
Season	<i>Kharif</i> , 2024
Manure	5 t FYM ha ⁻¹
GRDF	5 t FYM + 60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹
Seed rate	10 kg ha ⁻¹
Location of experiment	PGI farm, MPKV, Rahuri

3.2.2 Plan and Layout of Experiment

The experiment was laid out in Randomized Block Design with ten treatments and three replications. Each experimental plot was with gross plot size of 4.00 x 3.60 m² and net plot size of 3.60 x 3.00 m². The treatment randomization was as per the plan of layout shown in Fig. 3.2

Table 3.5 Treatments details

Treatment No.	Treatment details
T ₁	Absolute control
T ₂	RDF (60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)
T ₃	GRDF (5 ton FYM + 60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)
T ₄	T ₃ + Seed treatment of ZnSO ₄ @ 2.5 g kg ⁻¹ of seeds
T ₅	T ₃ + Seed treatment of Nano-ZnO @ 1000 ppm
T ₆	T ₃ + Seed treatment of Chelated Zn @ 1 g kg ⁻¹ of seeds
T ₇	T ₃ + Two foliar sprays of ZnSO ₄ @ 0.5 %
T ₈	T ₃ + Two foliar sprays of Nano-ZnO @ 0.15 %
T ₉	T ₃ + Two foliar sprays of Chelated Zn @ 0.20 %
T ₁₀	T ₃ + Soil application of ZnSO ₄ @ 20 kg ha ⁻¹

Note: 1. Soil application – at the time of sowing as basal dose
 2. Two foliar sprays given at tillering and flowering stage
 3. GRDF is common to all treatments except T₁ and T₂

3.3 Field Operations

The details of the cultural operations carried out on experimental plots during the period of investigation are presented in Table 3.6.

3.3.1 Preparation of Land and Planting Layout

After completion of preparatory tillage operations, the experimental layout was done with a gross plot size of 4.00 x 3.60 m². The treatments are allotted to different plots with the help of random processes in all replications.

3.3.2 Seeds and Sowing

For sowing 10 kg ha⁻¹ seed of Finger millet (Phule Nachani) was used. Crop was sown on 23, July, 2024. Seeds were mixed dried vermicompost and sown manually. The direction of sowing in line was East-West for getting maximum amount of sunlight. After sowing the seeds were covered with a thin layer of soil firmly and field was irrigated immediately.

3.3.3 Fertilizer Application

The finger millet crop was fertilized with RDF at 60:30:30 NPK kg ha⁻¹ + 5 tonnes FYM ha⁻¹. Out of which FYM was applied before harrowing, a full dose of N, P and K was applied

at sowing as a basal dose. The details of fertilizer applied to the experiment crop are presented in Table 3.5.

Table 3.6 Schedule of cultural operations carried out during the experimental period

Sr. No.	Field operations	Frequency	Date of operations
A.	Pre sowing operations		
1.	Ploughing	1	15/07/2024
2.	Harrowing	1	20/07/2024
3.	Preparation of layout	1	21/07/2024
4.	Application of FYM	1	08/07/2024
5.	Seed treatment and basal dose of fertilizer application as per treatments	1	23/07/2024
6.	Sowing	1	23/07/2024
B.	Post sowing operations		
1.	Thinning and gap filling	1	02/08/2024
2.	Weeding	2	20/08/2024, 05/09/2024
3.	Irrigation	6	03/08/2024, 14/09/2024 01/10/2024, 18/10/2024 05/11/2024, 21/11/2024
4.	Spraying	2	13/09/2024, 07/10/2024
5.	Harvesting	1	12-13/12/2024
6.	Threshing	1	23/12/2024

3.3.4 Hand Weeding

Two common weeding was given to all treatments at 25 DAS and another one hand weeding at 45 DAS in order to keep plots weed free. (Table 3.6)

3.3.5 Foliar Spray of Zinc Fertilizers

Two foliar sprays were carried out at tillering and flowering stage as per treatment details.

3.3.6 Irrigation

The first irrigation was given immediately after sowing for uniform germination. Subsequent irrigations were given as per the crop requirement based on the soil moisture content and rain fall.

3.3.7 Harvesting

The crop was harvested on 12th, 13th December 2024. The fingers were dried in the sun for two weeks. After threshing, the grains were cleaned, and weight was recorded at 14 to 15 %

moisture content and expressed in $q\text{ ha}^{-1}$. The stover from each individual plot was harvested and sun-dried. The weighed stover was expressed in $q\text{ ha}^{-1}$.

3.4 Collection of Experimental Data

3.4.1 Biometric Observation

The details of observations recorded during the course of the investigation are presented in Table 3.7.

3.4.1.1 Initial plant count

Accuracy of treatment comparison is directly related to uniform plant population. So, the total number of plants emerged in each net plot was counted and recorded as a mean emergence count in per centage.

3.4.1.2 Final plant count

The final plant count of plant population from each net plot was taken up just before harvesting of crop and it is expressed in per centage.

3.4.2 Sampling Technique

The various biometric observations of five randomly selected and tagged plants in each net plot were recorded

3.4.3 Observations on Growth Parameters

The various growth parameters such as plant height, number of tillers hill^{-1} number of leaves plant^{-1} , leaf area plant^{-1} and dry matter production plant^{-1} were recorded from five randomly selected and labelled plants at different growth stages of crop.

3.4.4 Growth Parameters

3.4.4.1 Plant height (cm)

The plant height was measured in cm from the ground level of the main centre of the stem to the tips of the last fully opened leaf until the stage of finger emergence. Thereafter, the periodical plant height was measured from ground level to the base of the finger in cm up to harvest.

3.4.4.2 No. of functional leaves plant^{-1}

The total number of fully opened green leaves of five plants was counted, and their average was taken as the number of leaves per plant.

3.4.4.3 Leaf area plant^{-1} (dm^2)

The plants taken for the dry matter study were used for measuring leaf area per plant. The leaf area was measured with the help of a leaf area meter. The leaf area metre recorded a direct reading of leaf area when the leaves were put on the screen and expressed it as dm^2 per plant.

3.4.4.4 No. of tillers plant^{-1}

The total number of fully developed tillers having functional leaves from five plants was counted, and their average was taken as the number of tillers per plant.

Table 3.7 Biometric observations recorded during crop experimentation

Sr. No.	Parameter	Frequency	Sample size	Period
A.	Plant count			
1.	Initial	1	All plants	15 DAS
2.	Final	1	All plants	At harvest
B.	Growth parameter			
1.	Plant height (cm)	4	5 plants	30,60,90 DAS and at harvest
2.	No of tillers plant ⁻¹	4	5 plants	30 and 60 DAS
3.	Dry matter production plant ⁻¹ (g)	4	2 plants	30,60,90 DAS and at harvest
4.	No. of functional leaves plant ⁻¹	4	5 plants	30,60,90 DAS and at harvest
5.	Leaf area plant ⁻¹ (dm ²)	4	5 plants	30,60,90 DAS and at harvest
C.	Yield attributes			
1.	No. of fingers earhead ⁻¹	1	5 earheads	At harvest
2.	No. of grains finger ⁻¹	1	5 earheads	At harvest
3.	Length of finger (cm)	1	5 earheads	At harvest
4.	Grain weight plant ⁻¹ (g)	1	5 earheads	At harvest
5.	Thousand grain weight (g)	1	Sample from net plot	At harvest
D.	Yield studies			
1.	Grain yield (q ha ⁻¹)	1	Net plot	At harvest
2.	Straw yield (q ha ⁻¹)	1	Net plot	At harvest
3.	Biological yield (q ha ⁻¹)	1	Net plot	At harvest
4.	Harvest index (%)	1	-	At harvest
E.	Chemical parameters of soil			
1.	Initial fertility status (pH, EC, OC and Available N, P, K and micronutrients)	1	Composite	Before sowing
2.	Final fertility status (pH, EC, OC and Available N, P, K and micronutrients)	1	Sample from net plot	At harvest
F.	Physical parameters of soil			
1.	Coarse sand (%)	1	Composite	Before sowing
2.	Fine sand (%)	1	Composite	Before sowing
3.	Silt (%)	1	Composite	Before sowing
4.	Clay (%)	1	Composite	Before sowing
5.	Textural class	1	Composite	Before sowing

G.	Uptake by crop			
1.	Nitrogen uptake (%)	1	Sample from net plot	At harvest
2.	Phosphorous uptake (%)	1	Sample from net plot	At harvest
3.	Potassium uptake (%)	1	Sample from net plot	At harvest
4.	Micronutrients (Zn, Mn, Fe, Cu)	1	Sample from net plot	At harvest
H.	Quality parameters			
1.	Crude protein content (%)	1	Sample from net plot	At harvest
2.	Crude fibre content (%)	1	Sample from net plot	At harvest
3.	Carbohydrates (%)	1	Sample from net plot	At harvest
4.	Ash (%)	1	Sample from net plot	At harvest
I.	Economic studies			
1.	Gross monetary returns (₹ ha ⁻¹)	-		
2.	Cost of cultivation (₹ ha ⁻¹)	-		
3.	Net monetary returns (₹ ha ⁻¹)	-		
4.	Benefit: cost ratio	-		

3.4.4.5 Dry matter production plant⁻¹ (g)

Total dry matter production in leaf, stem, and finger was recorded at 30, 60, and 90 DAS and at harvest. Samples were dried at 65 °C to attain a constant weight, and the average dry weight was calculated and expressed in grammes per plant.

3.4.5 Post-Harvest Studies

3.4.5.1 Length of fingers (cm)

The length of the finger was measured using a linear scale from the base to the tip of the ear head and expressed in centimeters.

3.4.5.2 No. of fingers earhead⁻¹

The total number of fingers present in each ear head obtained from tagged plants was counted, and the average was taken as the number of fingers ear head⁻¹.

3.4.5.3 No. of grains finger⁻¹

The total number of grains present in each finger obtained from tagged plants was counted, and the average was taken as the number of grains finger⁻¹.

3.4.5.4 Grain weight plant⁻¹ (g)

From each plot, earheads of five plants were selected randomly at harvest. Samples were dried at 70 + 2 °C in hot air oven until it attains constant weight. Mean dry weight was recorded as grain weight per plant and expressed in grams (g).

3.4.5.5 Thousand grain weight (g)

The weight of thousand grains from the tagged plants were considered the test weight and expressed in grammes (g).

3.4.5.6 Grain yield (q ha⁻¹)

Treatment-wise, grains were harvested from a net plot. Then the grains were sun dried, cleaned, separated manually, weighted with an electric balance separately, and expressed in q ha⁻¹.

3.4.5.7 Straw yield (q ha⁻¹)

After treatment-wise separating the ear head from the plants, the plants were cut from the bottom and left in the field for sun drying. Then plants were weighted with the help of a hand weighing balance and expressed as stover weight per plot in q ha⁻¹.

3.4.5.8 Biological yield (q ha⁻¹)

After the complete drying of plants in the sun, the biological yield (grain + straw) from each net plot was recorded and converted on a hectare basis.

3.4.5.9 Harvest index (%)

The harvest index was calculated by using the formula as below

$$\text{Harvest Index (\%)} = \frac{\text{Economical yield}}{\text{Biological yield}} \times 100$$

3.4.6 Soil Analysis

The analytical work was done in the laboratory of the Department of Agronomy, Soil Science and Agricultural Chemistry, Post Graduate Institute, Mahatma Phule Krishi Vidyapeeth, Rahuri during the academic year 2024-2025.

3.4.6.1 Soil sampling

The soil samples were collected before sowing (composite sample) and after harvest of the crop from each plot separately. Soil samples were collected at 0-15 cm depth and was air dried in shade, gently ground using wooden pestle and mortar and passed through 2 mm sieve except for organic carbon where 0.5 mm sieve was used. The sieved samples were used for further analysis of pH (1:2.5), EC (dS m⁻¹), organic carbon (%), available nitrogen, phosphorus, potassium and micronutrients by adopting standard procedures.

3.4.6.2 Soil pH

Hydrogen ion activity expressed as pH was determined by pH meter using 1:2.5 soil water suspension (Jackson, 1973).

3.4.6.3 Electrical conductivity (dS m⁻¹)

The clear supernatant extract obtained from soil water suspension used for pH was utilized for the EC measurement using a conductivity bridge (Jackson, 1973).

3.4.6.4 Organic carbon (%)

Walkley and Black Wet oxidation method as described by Nelson and Sommers (1982) was used to determine organic carbon.

3.4.6.5 Available nitrogen (kg ha^{-1})

Ten grammes of soil sample were distilled with 25 ml of 0.32 per cent KMnO_4 and 25 ml of 2.5 per cent sodium hydroxide (NaOH). The released ammonia was trapped in 4 per cent boric acid, which contained a mixed indicator, and titrated against 0.02 per cent sulfuric acid solution (Subbiah and Asija, 1956).

3.4.6.6 Available phosphorus (kg ha^{-1})

The available phosphorus in the soil samples was extracted with Olsen's reagent (0.5 N NaHCO_3). Phosphorus in the extracts was determined by ascorbic acid reductant method using spectrophotometer at 660 nm (Olsen *et al.* 1965) (expressed as kg ha^{-1} and interpreted as, low, medium and high).

3.4.6.7 Available potassium (kg ha^{-1})

The available potassium in the soil was extracted with neutral, normal ammonium acetate, and the potassium content of the extract was determined by using a flame photometer as described by Knudsen and Peterson (1982).

3.4.6.8 DTPA- Micronutrients (mg kg^{-1})

DTPA- Fe, Mn, Zn and Cu determined from soil extract with atomic absorption spectrophotometer as described by Lindsay and Norvell (1978).

3.4.7 Plant Analysis

3.4.7.1 Collection and preparation of plant samples

The collected plant samples at the time of harvest were dried at $65 \pm 20^\circ\text{C}$ in a hot air oven, powdered using a grinder fitted with stainless steel blades and preserved in polythene covers for further analysis (Jackson, 1967). These samples after digesting were analyzed for nitrogen, phosphorus and potassium and micronutrients concentration by adopting standard procedures.

3.4.7.2 Nitrogen (%)

Nitrogen content in plant samples was estimated by modified Microkjeldahl method (Piper, 1966) after digesting the organic matter by H_2SO_4 and H_2O_2 and expressed in per cent.

3.4.7.3 Phosphorus (%)

In the digested extract, phosphorus content was determined by Vanado-molybdo phosphoric yellow color method as described by Piper (1966) using Spectrophotometer at 420 nm and P content was expressed as per cent.

3.4.7.4 Potassium (%)

Potassium content in the triacid digest was determined using flame photometer (Piper, 1966) and expressed as per cent.

3.4.7.5 Micronutrients (Zn, Fe, Mn, Cu) (mg kg⁻¹)

The micronutrient content in the triacid digest were estimated using Atomic Absorption Spectrophotometer. (Lindsay and Norvell, 1978).

The nutrient uptake was computed using the formula

$$\text{N, P, K uptake (kg ha}^{-1}\text{)} = \frac{\text{Nutrient content (\%)} \times \text{Dry matter (kg ha}^{-1}\text{)}}{100}$$

$$\text{Micronutrient uptake (g ha}^{-1}\text{)} = \frac{\text{Micronutrient content (mg kg}^{-1}\text{)} \times \text{Dry matter (kg ha}^{-1}\text{)}}{1000}$$

3.4.8 Quality Analysis

Plant samples from each treatment were collected at harvest, oven dried, powdered and used for the analysis of quality parameters. All the oven dried samples were powdered in willey mill using 2 mm sieve for crude protein, carbohydrate and ash content, while 1 mm sieve for crude fibre analysis.

3.4.8.1 Crude protein content (%)

Protein content in finger millet was calculated by multiplying total nitrogen content (%) with 6.25 and it was expressed in per cent.

3.4.8.2 Crude fibre content (%)

Crude fibre (CF) content in the grain was estimated by acid-alkali digestion method. The crude fibre was calculated by using the following formula and expressed in per centage (AOAC, 2005).

$$\text{CF (\%)} = \frac{\text{wt. of sample after ashing (g)} - \text{wt. of sample before ashing (g)}}{\text{wt. of the dried sample taken (g)}} \times 100$$

3.4.8.3 Carbohydrates (%)

Carbohydrates (CHO) content was calculated by using following formula and expressed in per centage (AOAC, 2005).

$$\text{CHO (\%)} = 100 - [\text{Crude protein (\%)} + \text{CF (\%)} + \text{Fat (\%)} + \text{Ash (\%)} + \text{Moisture (\%)}]$$

3.4.8.4 Ash content (%)

5 grams of oven dried sample grounded in Willey mill using 2 mm sieve was desmoked on a heater and ignited at 550 °C in muffle furnace for 5 hours and cooled in desiccator. The weight of residual ash in previously weighed crucible was taken as total mineral. The mineral content was calculated and expressed in per cent as follows (AOAC, 2005).

$$\text{Ash content (\%)} = \frac{\text{wt. of ash (g)}}{\text{wt. of sample taken for ashing (g)}} \times 100$$

3.4.9 Economic Studies

The economic evaluation in terms of gross and net monetary returns, cost of cultivation and B:C ratio was computed treatment wise. For calculation of gross monetary returns and cost of cultivation, the prices mentioned in Appendix-I and II were considered.

3.4.9.1 Cost of cultivation

The cost of cultivation (₹ ha⁻¹) of each treatment was worked out by considering the actual amount incurred for the purchase of required input and the amount spent on the labour charges and machinery power required for land preparation.

3.4.9.2 Gross monetary returns

The treatment-wise gross monetary returns (₹ ha⁻¹) were worked out by considering the prevailing prices of the produce during the year of experimentation.

3.4.9.3 Net monetary returns

Net monetary returns (₹ ha⁻¹) were worked out by subtracting the cost of cultivation from gross monetary returns.

3.4.9.4 Benefit: Cost ratio

The benefit-cost ratio was worked out by using the following formula:

$$\text{B: C ratio} = \frac{\text{Gross monetary returns (₹ ha}^{-1}\text{)}}{\text{Cost of cultivation (₹ ha}^{-1}\text{)}}$$

3.5 Statistical Analysis for Interpretation of Data

The experimental data collected on growth and yield components, yield, and nutrient uptake of plants were subjected to Fisher's method of "Analysis of Variance" (ANOVA) as outlined by Panse and Sukhatme (1985). Wherever the F-test was significant, for comparison among the treatment means, an appropriate value of the critical difference (C.D.) was worked out. If the F-test found to be non-significant, against C.D. values, NS (non-significant) was indicated. All the data were analyzed, and the results were presented and discussed at a probability level of five %.

4. RESULTS AND DISCUSSION

The experiment on “Effect of Zinc Fertilization on Growth and Yield of Finger Millet (*Eleusine coracana* L. Gaertn)” was conducted at Instructional Farm, Post Graduate Institute, MPKV, Rahuri during *kharif*, 2024.

The data include various parameters *viz.*, growth attributes, yield attributes and yield, nutrient content, uptake and status after harvest of finger millet were statistically analyzed to test significance of results. A field trial was conducted in which different method of application and various zinc sources involved.

The following details of biometric and other observations recorded during experiment is as follows:

4.1 Plant Population

4.2 Growth Studies

4.3 Yield Attributes

4.4 Yield Studies

4.5 Quality Parameters

4.6 Soil Chemical Analysis

4.7 Nutrient Uptake

4.8 Economic Studies

4.1 Plant Population Studies

Data regarding the mean initial plant population at 15 DAS and final plant population at harvest as well as the percentage of ideal plant population were presented in Table 4.1. From data in Table 4.1 it was observed that mean initial plant population of finger millet was 3,25,164 ha⁻¹ which was 97.55 per cent of the theoretical plant population. This indicated that the plant population was uniform and optimum throughout the experimental period.

Data presented in Table 4.1 revealed that mean final plant population of finger millet at harvest was 3,22,023 ha⁻¹ which was 96.61 per cent. Plant population did not differ significantly due to different treatments. Application of different zinc sources with different application method did not affect on plant population of finger millet significantly at harvest.

4.2 Growth Studies

4.2.1 Plant Height (cm)

Data on plant height affected by various zinc fertilization treatments at 30, 60, 90 DAS, and harvest are shown in Table 4.2 and Fig. 4.1. The height of the finger millet plants increased gradually over the trial. Different zinc fertilization treatments had a substantial impact on plant height at 60, 90 DAS, and harvest, according to data analysis. At 30, 60, 90 DAS, and harvest, the average heights were 40.1 cm, 62.2 cm, 92.2 cm, and 99.5 cm, respectively.

Table 4.1 Effect of zinc fertilization on plant population in finger millet

Tr. No.	Treatment	Plant population (15 DAS)		Plant population (At harvest)	
		Per ha	Per cent	Per ha	Per cent
T ₁	Absolute control	324300	97.29	321177	96.35
T ₂	RDF (60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	324755	97.43	321411	96.42
T ₃	GRDF (5 ton FYM + 60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	324866	97.46	322011	96.60
T ₄	T ₃ + Seed treatment of ZnSO ₄ @ 2.5 g kg ⁻¹ of seeds	325033	97.51	322455	96.74
T ₅	T ₃ + Seed treatment of Nano-ZnO @ 1000 ppm	325877	97.76	321922	96.58
T ₆	T ₃ + Seed treatment of Chelated Zn @ 1 g kg ⁻¹ of seeds	325700	97.71	321889	96.57
T ₇	T ₃ + Two foliar sprays of ZnSO ₄ @ 0.5 %	325244	97.57	322422	96.73
T ₈	T ₃ + Two foliar sprays of Nano-ZnO @ 0.15 %	324866	97.46	322433	96.73
T ₉	T ₃ + Two foliar sprays of Chelated Zn @ 0.20 %	324700	97.41	321800	96.54
T ₁₀	T ₃ + Soil application of ZnSO ₄ @ 20 kg ha ⁻¹	326300	97.89	322711	96.81
	SE (m) ±	416.38	0.125	413.48	0.124
	CD at 5 %	NS	NS	NS	NS
	General Mean	325164	97.55	322023	96.61

At 30 DAS, there was no significant change in finger millet plant height among the treatments using seed treatment of different zinc sources and soil application of zinc sulphate.

At 60 DAS, significantly highest plant height (72.1 cm) was recorded with treatment T₁₀ *i.e.* GRDF + Soil application of ZnSO₄ @ 20 kg ha⁻¹, but which was at par with treatment T₅ *i.e.* GRDF + seed treatment of Nano-ZnO @ 1000 ppm (67.5 cm). Among all the treatments, lowest plant height (54.4 cm) was recorded in treatment T₁ *i.e.* Absolute control.

At 90 DAS and during harvest, treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % exhibited significantly the highest plant height (105.3 cm and 116.7 cm at 90 DAS and at harvest respectively), But it was at par with the plant height observed in treatment T₉ *i.e.* GRDF + Two foliar sprays of Chelated Zn @ 0.20 % (102.1 cm and 111.8 cm at 90 DAS and at harvest respectively) and in treatment T₇ *i.e.* GRDF + Two foliar sprays of ZnSO₄ @ 0.5 % (101 cm and 110.3 cm at 90 DAS and at harvest respectively). Out of all the treatments, treatment T₁ *i.e.* Absolute control exhibited the lowest plant height, measuring 76.6 cm and 81.8 cm at 90 DAS and at harvest respectively.

Table 4.2 Effect of zinc fertilization on plant height at different growth stages in finger millet

Tr. No.	Treatment	Plant height (cm)			
		30 DAS	60 DAS	90 DAS	At Harvest
T ₁	Absolute control	34.5	54.4	76.6	81.8
T ₂	RDF (60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	37.9	58.4	81.8	87.4
T ₃	GRDF (5 ton FYM + 60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	39.2	60.6	85.1	91.1
T ₄	T ₃ + Seed treatment of ZnSO ₄ @ 2.5 g kg ⁻¹ of seeds	40.8	63.7	88.7	94.8
T ₅	T ₃ + Seed treatment of Nano-ZnO @ 1000 ppm	43.9	67.5	92.6	99.1
T ₆	T ₃ + Seed treatment of Chelated Zn @ 1 g kg ⁻¹ of seeds	42.5	64.3	89.6	95.9
T ₇	T ₃ + Two foliar sprays of ZnSO ₄ @ 0.5 %	38.7	60.2	101.0	110.3
T ₈	T ₃ + Two foliar sprays of Nano-ZnO @ 0.15 %	38.8	60.3	105.3	116.7
T ₉	T ₃ + Two foliar sprays of Chelated Zn @ 0.20 %	38.9	60.4	102.1	111.8
T ₁₀	T ₃ + Soil application of ZnSO ₄ @ 20 kg ha ⁻¹	45.8	72.1	99.3	106.3
	SE (m) ±	3.76	1.99	1.85	2.42
	CD at 5 %	NS	5.91	5.49	7.18
	General Mean	40.1	62.2	92.2	99.5

The results indicated a significant improvement in plant height with zinc application, particularly through soil and foliar routes. The superior performance of treatment T₁₀ *i.e.* GRDF + Soil application of ZnSO₄ @ 20 kg ha⁻¹ and treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % may be attributed to enhanced enzymatic activity, improved chlorophyll synthesis, and better hormonal regulation facilitated by the zinc nutrient. Foliar application, especially using Nano-ZnO, likely ensured more efficient absorption and utilization of zinc during key vegetative stages. The steady increase in height with time across treatments reflects cumulative nutrient uptake and vegetative growth.

Similar findings were reported by Rameshraddy *et al.* (2017), who observed that foliar application of nano zinc oxide increased plant height significantly in finger millet. Rajput *et al.* (2021) also demonstrated that chelated and nano-form zinc applications enhanced plant growth by improving metabolic and physiological functions of the crop.

4.2.2 Number of Tillers Plant⁻¹

Data on the total number of tillers at 30 and 60 days after sowing, impacted by different zinc sources and treatment methods, are shown in Table 4.3 and Fig. 4.2. The total number of finger millet tillers ascended consistently over the trial. Data analysis showed that the total number of tillers at 30 and 60 DAS was considerably altered by different zinc sources and application methods. At 30 and 60 DAS, the average total number of tillers was 2.7 and 3.8 respectively.

At 30 DAS, treatment T₁₀ *i.e.* GRDF + Soil application of ZnSO₄ @ 20 kg ha⁻¹ recorded significantly higher number of tillers plant⁻¹ (3.5) which was significantly on par with treatment T₅ *i.e.* GRDF + Seed treatment of Nano-ZnO @ 1000 ppm (3.2). Significantly minimum number of tillers plant⁻¹ was recorded in treatment T₁ *i.e.* Absolute control (2.1).

Table 4.3 Effect of zinc fertilization on number of tillers at different growth stages in finger millet

Tr. No.	Treatment	No. of tillers plant ⁻¹	
		30 DAS	60 DAS
T ₁	Absolute control	2.1	2.9
T ₂	RDF (60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	2.3	3.3
T ₃	GRDF (5 ton FYM + 60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	2.6	3.6
T ₄	T ₃ + Seed treatment of ZnSO ₄ @ 2.5 g kg ⁻¹ of seeds	2.7	4.0
T ₅	T ₃ + Seed treatment of Nano-ZnO @ 1000 ppm	3.2	4.5
T ₆	T ₃ + Seed treatment of Chelated Zn @ 1 g kg ⁻¹ of seeds	2.7	4.1
T ₇	T ₃ + Two foliar sprays of ZnSO ₄ @ 0.5 %	2.6	3.6
T ₈	T ₃ + Two foliar sprays of Nano-ZnO @ 0.15 %	2.7	3.7
T ₉	T ₃ + Two foliar sprays of Chelated Zn @ 0.20 %	2.6	3.6
T ₁₀	T ₃ + Soil application of ZnSO ₄ @ 20 kg ha ⁻¹	3.5	5.0
	SE (m) ±	0.16	0.20
	CD at 5 %	0.48	0.60
	General Mean	2.7	3.8

Treatment T₁₀ *i.e.* GRDF + Soil application of ZnSO₄ @ 20 kg ha⁻¹ resulted in a significantly higher number of tillers plant⁻¹ (5.0) at 60 DAS, which was significantly comparable to

treatment T₅ *i.e.* GRDF + Seed treatment of Nano-ZnO @ 1000 ppm (4.5). In contrast, treatment T₁ *i.e.* Absolute control showed a lower number of tillers plant⁻¹ (2.9).

Zinc plays a vital role in cell division and hormonal balance, which directly influences the initiation and development of tillers in cereals. The results showed that application of zinc, especially in the form of soil-applied ZnSO₄ in treatment T₁₀ *i.e.* GRDF + Soil application of ZnSO₄ @ 20 kg ha⁻¹ and seed-treated Nano-ZnO in treatment T₅ *i.e.* GRDF + Seed treatment of Nano-ZnO @ 1000 ppm significantly increased tillering. The increased tillering in treatment T₁₀ *i.e.* GRDF + Soil application of ZnSO₄ @ 20 kg ha⁻¹ may be due to the higher zinc availability in the rhizosphere throughout the early vegetative phase, while in treatment T₅ *i.e.* GRDF + Seed treatment of Nano-ZnO @ 1000 ppm, the nanoform ensured rapid seedling vigor and establishment.

The effect of zinc in enhancing tiller production has been corroborated by Khardia *et al.* (2022), who reported improved tillering in millets with zinc fertilization. Similar findings were reported by Rameshraddy *et al.* (2017). As the application of zinc improves the source to sink relation which leading to production of higher number of tillers in the crop.

4.2.3 Dry Matter Accumulation Plant⁻¹ (g)

Table 4.4 and Fig. 4.3 exhibited data on the accumulation of dry matter in finger millet at various stages of development as influenced by different treatments. These data demonstrate the significant effect of the numerous treatments that were tried in the experiment at different phases of the finger millet crop. It is also evident that as the crop turned older, the accumulation of dry matter increased gradually. The mean dry matter accumulation were 3.06 g, 9.00 g, 16.86 g and 20.33 g at 30, 60, 90 DAS and at harvest respectively.

At 30 DAS there were no significant difference in terms of dry matter accumulation in finger millet among treatments. However, higher dry matter accumulation was observed with treatment T₁₀ *i.e.* GRDF + Soil application of ZnSO₄ @ 20 kg ha⁻¹ (3.83 g plant⁻¹).

At 60 DAS, significantly higher dry matter accumulation per plant (11.37 g) was recorded with treatment T₁₀ *i.e.* GRDF + Soil application of ZnSO₄ @ 20 kg ha⁻¹, which was on par with treatment T₅ *i.e.* GRDF + Seed treatment of Nano-ZnO @ 1000 ppm (10.80 g). In contrast, lower dry matter accumulation (6.13 g plant⁻¹) was observed with treatment T₁ *i.e.* Absolute control.

At 90 DAS and at harvest, significantly higher dry matter accumulation per plant (18.96 g and 23.16 g at 90 DAS and at harvest respectively) was recorded with treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %, which was on par with treatment T₉ *i.e.* GRDF + Two sprays of Chelated Zn @ 0.20 % (18.32 g and 22.32 g at 90 DAS and at harvest respectively) and treatment T₇ *i.e.* GRDF + Two foliar sprays of ZnSO₄ @ 0.5 % (18.22 g and 22.02 g at 90 DAS and at harvest respectively). In contrast, lower dry matter accumulation per plant was observed with treatment T₁ *i.e.* Absolute control (12.25 g and 14.75 g at 90 DAS and at harvest respectively).

Table 4.4 Effect of zinc fertilization on dry matter accumulation at different growth stages in finger millet

Tr. No.	Treatment	Dry matter plant ⁻¹ (g)			
		30 DAS	60 DAS	90 DAS	At Harvest
T ₁	Absolute control	2.53	6.13	12.25	14.75
T ₂	RDF (60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	2.66	7.39	14.76	17.26
T ₃	GRDF (5 ton FYM + 60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	2.96	8.58	16.44	19.74
T ₄	T ₃ + Seed treatment of ZnSO ₄ @ 2.5 g kg ⁻¹ of seeds	3.18	9.99	16.99	20.49
T ₅	T ₃ + Seed treatment of Nano-ZnO @ 1000 ppm	3.31	10.80	17.51	21.11
T ₆	T ₃ + Seed treatment of Chelated Zn @ 1 g kg ⁻¹ of seeds	3.23	10.02	17.20	20.75
T ₇	T ₃ + Two foliar sprays of ZnSO ₄ @ 0.5 %	2.95	8.51	18.22	22.02
T ₈	T ₃ + Two foliar sprays of Nano-ZnO @ 0.15 %	2.91	8.56	18.96	23.16
T ₉	T ₃ + Two foliar sprays of Chelated Zn @ 0.20 %	3.00	8.67	18.32	22.32
T ₁₀	T ₃ + Soil application of ZnSO ₄ @ 20 kg ha ⁻¹	3.83	11.37	17.92	21.72
	SE (m) ±	0.45	0.36	0.33	0.46
	CD at 5 %	NS	1.09	0.98	1.37
	General Mean	3.06	9.00	16.86	20.33

The increase in dry matter accumulation due to zinc fertilization can be attributed to improved physiological functions like enhanced photosynthesis, better root development, and increased nutrient uptake. The foliar application of Nano-ZnO in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % ensured better translocation and availability of zinc during active vegetative and reproductive phases, resulting in consistently higher biomass accumulation. Meanwhile, soil application in treatment T₁₀ *i.e.* GRDF + Soil application of ZnSO₄ @ 20 kg ha⁻¹ also provided a steady zinc supply, promoting robust early growth.

Nano zinc oxide, due to its high surface area and better absorption, has shown promising effects on biomass build-up, as also observed by Kolencik *et al.* (2019), who reported that foliar sprays of nano zinc increased dry matter in millets. Furthermore, Babu *et al.* (2001) confirmed that the combination of organic manure with zinc fertilization promotes higher biomass accumulation due to synergistic nutrient interactions.

4.2.4 Number of Functional Leaves Plant⁻¹

In Table 4.5 and Fig. 4.4, the total number of functional leaves per plant at 30, 60, and 90 DAS and at harvest, are presented. The data shows the effect of different method of application of various zinc sources. The study revealed a consistent increase in the total number of functional leaves per finger millet plant throughout the experiment. Statistical analysis of the data indicated that the various fertilizer treatments had a significant impact on the total number of functional leaves per plant at 60 and 90 DAS, as well as at harvest. The average number of functional leaves per plant were 22.2, 30.3, 44.6 and 40.1 30, 60, 90 DAS and at harvest respectively.

Table 4.5 Effect of zinc fertilization on number of functional leaves at different growth stages in finger millet

Tr. No.	Treatment	No. of functional leaves plant ⁻¹			
		30 DAS	60 DAS	90 DAS	At Harvest
T ₁	Absolute control	19.9	24.9	32.9	28.5
T ₂	RDF (60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	20.8	27.8	36.8	32.6
T ₃	GRDF (5 ton FYM + 60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	21.3	29.3	39.3	34.9
T ₄	T ₃ + Seed treatment of ZnSO ₄ @ 2.5 g kg ⁻¹ of seeds	22.7	30.7	42.7	37.0
T ₅	T ₃ + Seed treatment of Nano-ZnO @ 1000 ppm	24.5	33.0	45.5	39.7
T ₆	T ₃ + Seed treatment of Chelated Zn @ 1 g kg ⁻¹ of seeds	23.3	31.3	43.3	38.5
T ₇	T ₃ + Two foliar sprays of ZnSO ₄ @ 0.5 %	21.5	29.5	51.5	47.8
T ₈	T ₃ + Two foliar sprays of Nano-ZnO @ 0.15 %	21.5	29.5	55.0	50.5
T ₉	T ₃ + Two foliar sprays of Chelated Zn @ 0.20 %	21.3	29.3	51.8	48.2
T ₁₀	T ₃ + Soil application of ZnSO ₄ @ 20 kg ha ⁻¹	25.4	37.4	47.4	43.7
	SE (m) ±	1.90	1.89	1.90	1.89
	CD at 5 %	NS	5.64	5.63	5.64
	General Mean	22.2	30.3	44.6	40.1

At 30 DAS, there is no significant difference in number of functional leaves per plant among the treatments. At 60 DAS, significantly highest number of functional leaves per plant (37.4) was recorded with treatment T₁₀ *i.e.* GRDF + Soil application of ZnSO₄ @ 20 kg ha⁻¹, which was at par with treatment T₅ *i.e.* GRDF + seed treatment of Nano-ZnO @ 1000 ppm (33.0). In contrast, significantly lowest number of functional leaves (24.9 per plant) was observed with treatment T₁ *i.e.* Absolute control.

At 90 DAS and at harvest significantly the highest number of functional leaves was noted in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % (55.0 and 50.5 leaves at respective stages), which was at par with treatment T₉ *i.e.* GRDF + Two sprays of Chelated Zn @ 0.20 % (51.8 and 48.2 leaves at respective stages) and treatment T₇ *i.e.* GRDF + Two foliar sprays of ZnSO₄ @ 0.5 % (51.5 and 47.8 leaves at respective stages). Significantly the minimum number of functional leaves was observed in treatment T₁ *i.e.* Absolute control with 32.9 and 28.5 leaves per plant at the respective stages.

Zinc plays a vital role in chlorophyll synthesis and enzyme activation, both of which contribute to leaf expansion and retention. The superior performance of foliar-applied zinc sources, especially Nano-ZnO in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %, could be attributed to better zinc absorption, which enhances leaf initiation and delays senescence. The higher number of functional leaves observed in treatments of foliar application of different zinc sources indicates that nano ZnO, chelated zinc and zinc sulphate applications help in maintaining leaf health for a longer period, facilitating better photosynthetic efficiency and assimilate production.

These results are supported by the findings of Beeresha (2018). He reported that foliar application of nano-ZnO compared to all other treatments increased the number of leaves per plant and resulted in larger leaf area. Adequate supply of Nano-ZnO at appropriate concentrations contributes to more leaf production, resulting in greater leaf area, due to less competition for nutrients between plants.

4.2.5 Leaf Area Plant⁻¹ (dm²)

In Table 4.6 and Fig. 4.5, leaf area per plant at 30, 60, and 90 days after sowing (DAS), and at harvest, are presented. The data shows the effect of different method of application of various zinc sources. The study revealed a consistent increase in leaf area per plant in finger millet throughout the experiment. The mean leaf area per plant were 3.74, 6.36, 10.44 and 9.20 dm² at 30, 60, 90 DAS and at harvest.

At 30 DAS, there is no significant difference in leaf area per plant among the treatments. At 60 DAS, significantly higher leaf area per plant (7.80 dm²) was recorded with treatment T₁₀ *i.e.* GRDF + Soil application of ZnSO₄ @ 20 kg ha⁻¹, which was at par with treatment T₅ *i.e.* GRDF + seed treatment of Nano-ZnO @ 1000 ppm (7.18 dm²). In contrast, significantly lowest leaf area of 5.53 dm² per plant was observed with treatment T₁ *i.e.* Absolute control.

At 90 DAS and at harvest the highest leaf area was noted in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %, with 12.49 dm² and 11.45 dm² at respective stages. This was at par with treatment T₉ *i.e.* GRDF + Two sprays of Chelated Zn @ 0.20 % (12.04 and 10.88 dm² at respective stages) and treatment T₇ *i.e.* GRDF + Two foliar sprays of ZnSO₄ @ 0.5 % (11.98 and 10.84 dm² leaf area at respective stages). Significantly the lowest leaf area was observed in the

treatment T₁ *i.e.* Absolute control, with 8.22 dm² and 7.12 dm² leaf area per plant at the respective stages.

Table 4.6 Effect of zinc fertilization on leaf area per plant at different growth stages in finger millet

Tr. No.	Treatment	Leaf area plant ⁻¹ (dm ²)			
		30 DAS	60 DAS	90 DAS	At Harvest
T ₁	Absolute control	3.24	5.53	8.22	7.12
T ₂	RDF (60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	3.59	6.04	9.19	7.94
T ₃	GRDF (5 ton FYM + 60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	3.71	6.11	9.37	8.13
T ₄	T ₃ + Seed treatment of ZnSO ₄ @ 2.5 g kg ⁻¹ of seeds	3.85	6.27	9.94	8.40
T ₅	T ₃ + Seed treatment of Nano-ZnO @ 1000 ppm	3.99	7.18	10.35	8.83
T ₆	T ₃ + Seed treatment of Chelated Zn @ 1 g kg ⁻¹ of seeds	3.88	6.39	10.08	8.76
T ₇	T ₃ + Two foliar sprays of ZnSO ₄ @ 0.5 %	3.69	6.15	11.98	10.84
T ₈	T ₃ + Two foliar sprays of Nano-ZnO @ 0.15 %	3.68	6.08	12.49	11.45
T ₉	T ₃ + Two foliar sprays of Chelated Zn @ 0.20 %	3.65	6.10	12.04	10.88
T ₁₀	T ₃ + Soil application of ZnSO ₄ @ 20 kg ha ⁻¹	4.08	7.80	10.78	9.65
	SE (m) ±	0.27	0.40	0.45	0.45
	CD at 5 %	NS	1.19	1.34	1.34
	General Mean	3.74	6.36	10.44	9.20

The significant enhancement in leaf area due to zinc fertilization may be attributed to improved cell division and elongation, leading to better leaf expansion. Treatments with foliar-applied Nano-ZnO in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % and chelated Zn in treatment T₉ *i.e.* GRDF + Two sprays of Chelated Zn @ 0.20 % resulted in broader leaves with increased photosynthetic surface area, which directly contributes to better dry matter accumulation and overall crop productivity. Soil application of ZnSO₄ in treatment T₁₀ *i.e.* GRDF + Soil application of ZnSO₄ @ 20 kg ha⁻¹ also proved effective, particularly in early crop stages, by ensuring a continuous supply of zinc through root uptake.

These findings align with reports by Tripathi *et al.* (2018), who observed increased leaf area index in millets under nano zinc and chelated zinc application. Also, Upadhyay and Yadav (2015) noted that zinc applications improve membrane integrity and chloroplast structure, ultimately increasing leaf expansion and area.

4.3 Yield Attributes

4.3.1 Number of Fingers per Earhead

Data presented in Table 4.7 and Fig. 4.6 show significant variation in the number of fingers per earhead among treatments. The overall general mean fingers per earhead was 6.9. Significantly the maximum number of fingers was observed under treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %, which recorded 8.1 fingers, which was at par with treatment T₉ *i.e.* GRDF + Two sprays of Chelated Zn @ 0.20 % (7.7) and treatment T₇ *i.e.* GRDF + Two foliar sprays of ZnSO₄ @ 0.5 % (7.4), all statistically at par. Significantly the minimum number of fingers (6.0) was noted in the treatment T₁ *i.e.* Absolute control.

The increase in number of fingers under treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % might be attributed to improved floral primordia development and enhanced auxin activity influenced by zinc, which promotes spikelet differentiation and development.

These results are consistent with the findings of Mehta *et al.* (2013) and Reddy *et al.* (2017), who reported increased number of fingers per earhead in millets due to foliar application of micronutrients, especially zinc.

4.3.2 Number of Grains per Finger

Significant differences in the number of grains per finger were recorded among the treatments. The general mean was 285 grains per finger. Treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % produced significantly highest number of grains (358), which was at par with treatment T₉ *i.e.* GRDF + Two sprays of Chelated Zn @ 0.20 % (334) and treatment T₇ *i.e.* GRDF + Two foliar sprays of ZnSO₄ @ 0.5 % (323). Significantly lowest number of grains (221) was recorded in the treatment T₁ *i.e.* Absolute control.

The enhancement in grain number under treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % may be due to better translocation of photosynthates to the reproductive organs and improved pollen viability facilitated by foliar application of Nano-ZnO.

Similar outcomes were reported by Verma and Jat (2016) and Patel *et al.* (2018), who observed that zinc plays a key role in seed set and grain development when applied during reproductive stages.

4.3.3 Grain Weight per Plant (g)

The grain weight per plant was significantly affected by the zinc treatments, with a general mean of 7.38 g. The highest grain weight per plant was recorded in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % (8.68 g), which was at par with treatment T₉ *i.e.* GRDF + Two sprays of Chelated Zn @ 0.20 % (8.28 g) and treatment T₇ *i.e.* GRDF + Two foliar sprays of ZnSO₄ @ 0.5 % (8.12 g), all significantly superior to the control. The significantly lowest grain weight per plant (4.91 g) was noted in the treatment T₁ *i.e.* Absolute control.

The increase in grain weight under treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % could be attributed to improved grain filling and better carbohydrate partitioning to seeds, facilitated by zinc-enhanced enzymatic and hormonal activity in the plant system.

These results are in agreement with the findings of Jha *et al.* (2015) and Sharma and Singh (2019), who reported increased grain weight in zinc-treated cereals.

Table 4.7 Effect of zinc fertilization on no. of fingers, no. of grains, grain weight, finger length and thousand grain weight at harvest in finger millet

Tr. No.	Treatment	Yield attributes				
		No. of fingers earhead ⁻¹	No. of grains finger ⁻¹	Grain weight plant ⁻¹ (g)	Finger length (cm)	Thousand grain weight (g)
T ₁	Absolute control	6.0	221	4.91	6.7	2.84
T ₂	RDF (60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	6.2	236	6.32	7.1	2.91
T ₃	GRDF (5 ton FYM + 60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	6.5	257	7.02	7.3	2.95
T ₄	T ₃ + Seed treatment of ZnSO ₄ @ 2.5 g kg ⁻¹ of seeds	6.7	268	7.33	7.5	2.97
T ₅	T ₃ + Seed treatment of Nano-ZnO @ 1000 ppm	6.9	281	7.67	7.9	3.00
T ₆	T ₃ + Seed treatment of Chelated Zn @ 1 g kg ⁻¹ of seeds	6.8	271	7.49	7.6	2.98
T ₇	T ₃ + Two foliar sprays of ZnSO ₄ @ 0.5 %	7.4	323	8.12	8.2	3.09
T ₈	T ₃ + Two foliar sprays of Nano-ZnO @ 0.15 %	8.1	358	8.68	8.8	3.19
T ₉	T ₃ + Two foliar sprays of Chelated Zn @ 0.20 %	7.7	334	8.28	8.4	3.14
T ₁₀	T ₃ + Soil application of ZnSO ₄ @ 20 kg ha ⁻¹	7.1	299	7.92	8.0	3.02
	SE (m) ±	0.29	15.22	0.34	0.39	0.14
	CD at 5 %	0.87	45.23	1.02	1.16	NS
	General Mean	6.9	285	7.38	7.7	3.01

4.3.4 Finger Length (cm)

The average finger length across treatments was 7.7 cm. The significantly longest finger length was recorded under treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % (8.8 cm), which was at par with treatment T₉ *i.e.* GRDF + Two sprays of Chelated Zn @ 0.20 % (8.4 cm) and treatment T₇ *i.e.* GRDF + Two foliar sprays of ZnSO₄ @ 0.5 % (8.2 cm). The shortest finger length (6.7 cm) was recorded in the treatment T₁ *i.e.* Absolute control.

The improved finger length under treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % is likely due to enhanced cell elongation and vascular differentiation in the spikelet axis, facilitated by better nutrient uptake and translocation with nano-form zinc application.

A similar increase in finger length was observed by Shinde *et al.* (2014) and Dutta *et al.* (2020) in finger millet and pearl millet, respectively, under foliar zinc treatments.

4.3.5 Thousand Grain Weight (g)

Although statistically non-significant, thousand grain weight showed numerical improvement across treatments. The overall mean was 3.01 g. Treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % recorded the numerically highest thousand grain weight (3.19 g). The numerically lowest weight was noted in the treatment T₁ *i.e.* Absolute control (2.84 g).

The observed trend suggests better grain filling under foliar nano-zinc application, possibly due to improved assimilate translocation and hormone regulation during the grain development stage.

These observations are supported by Kumar *et al.* (2016) and Bhosale *et al.* (2021), who found improved test weight in cereals under foliar zinc application.

4.4 Yield Studies

4.4.1 Grain Yield (q ha⁻¹)

Grain yield of finger millet was significantly influenced by zinc fertilization treatments (Table 4.8 and Fig. 4.7). The mean grain yield was 22.69 q ha⁻¹. Significantly the maximum grain yield was recorded in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % (27.41 q ha⁻¹), which was at par with treatment T₉ *i.e.* GRDF + Two sprays of Chelated Zn @ 0.20 % (25.43 q ha⁻¹) and treatment T₇ *i.e.* GRDF + Two foliar sprays of ZnSO₄ @ 0.5 % (24.97 q ha⁻¹), which were statistically on par. The minimum grain yield was observed under treatment T₁ *i.e.* Absolute control (14.21 q ha⁻¹).

The increased grain yield under treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % may be due to enhanced reproductive efficiency, better nutrient uptake, and improved physiological functions resulting from Nano-ZnO foliar application.

Similar findings were reported by Rakesh *et al.* (2018) and Gaikwad *et al.* (2020), who found significant improvement in grain yield of small millets due to foliar zinc nutrition, particularly in nano form.

4.4.2 Straw Yield (q ha⁻¹)

The straw yield varied significantly among the treatments, with a general mean of 39.15 q ha⁻¹. The highest straw yield was recorded in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % (43.46 q ha⁻¹), which was at par with treatment T₉ *i.e.* GRDF + Two sprays of Chelated Zn @ 0.20 % (42.19 q ha⁻¹) and treatment T₇ *i.e.* GRDF + Two foliar sprays of ZnSO₄ @

0.5 % (41.74 q ha⁻¹). The minimum straw yield was observed in treatment T₁ *i.e.* Absolute control (29.52 q ha⁻¹).

Table 4.8 Effect of zinc fertilization on grain yield, % increase in yield over GRDF, straw yield, biological yield and HI (%) at harvest in finger millet

Tr. No.	Treatment	Yield studies				
		Grain yield (q ha ⁻¹)	% increase in yield over GRDF	Straw yield (q ha ⁻¹)	Biological yield (q ha ⁻¹)	HI (%)
T ₁	Absolute control	14.21	-	29.52	43.73	32.56
T ₂	RDF (60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	18.54	-	34.93	53.48	34.67
T ₃	GRDF (5 ton FYM + 60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	22.23	-	38.25	60.48	36.75
T ₄	T ₃ + Seed treatment of ZnSO ₄ @ 2.5 g kg ⁻¹ of seeds	22.68	2.02	39.59	62.27	36.47
T ₅	T ₃ + Seed treatment of Nano-ZnO @ 1000 ppm	23.71	6.66	40.46	64.17	37.00
T ₆	T ₃ + Seed treatment of Chelated Zn @ 1 g kg ⁻¹ of seeds	23.15	4.13	39.91	63.06	36.71
T ₇	T ₃ + Two foliar sprays of ZnSO ₄ @ 0.5 %	24.97	12.33	41.74	66.71	37.43
T ₈	T ₃ + Two foliar sprays of Nano-ZnO @ 0.15 %	27.41	23.31	43.46	70.87	38.75
T ₉	T ₃ + Two foliar sprays of Chelated Zn @ 0.20 %	25.43	14.39	42.19	67.62	37.59
T ₁₀	T ₃ + Soil application of ZnSO ₄ @ 20 kg ha ⁻¹	24.54	10.39	41.46	66.00	37.11
	SE (m) ±	0.89	-	0.61	1.41	0.45
	CD at 5 %	2.65	-	1.81	4.22	1.36
	General Mean	22.69	-	39.15	61.84	35.51

Higher straw yield in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % can be attributed to improved vegetative growth and biomass accumulation due to efficient nutrient assimilation and prolonged green leaf duration.

These results are supported by Sawant *et al.* (2016) and Thakur *et al.* (2019), who observed increased biomass and straw yield under foliar application of micronutrients, especially zinc.

4.4.3 Biological Yield (q ha⁻¹)

Biological yield, the sum of grain and straw yield, was significantly influenced by zinc treatments. The mean biological yield was 61.84 q ha⁻¹. The maximum biological yield was obtained

in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % (70.87 q ha⁻¹), which was at par with treatment T₉ *i.e.* GRDF + Two sprays of Chelated Zn @ 0.20 % (67.62 q ha⁻¹) and treatment T₇ *i.e.* GRDF + Two foliar sprays of ZnSO₄ @ 0.5 % (66.71 q ha⁻¹). The minimum was recorded in treatment T₁ *i.e.* Absolute control (43.73 q ha⁻¹).

Enhanced biological yield in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % may be attributed to overall improvement in growth and yield traits due to increased nutrient availability and metabolic efficiency of Nano-ZnO.

Similar enhancement in biological yield due to zinc fertilization has been reported by Chaudhari *et al.* (2015) and Kulkarni *et al.* (2018).

4.4.4 Harvest Index (%)

Harvest index was significantly affected by zinc fertilization treatments. The overall mean was 35.51%. Treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % recorded the highest Harvest Index (38.75 %), which was at par with treatment T₉ *i.e.* GRDF + Two sprays of Chelated Zn @ 0.20 % (37.59 %) and treatment T₇ *i.e.* GRDF + Two foliar sprays of ZnSO₄ @ 0.5 % (37.43 %). The lowest Harvest Index was recorded in the control treatment T₁ *i.e.* Absolute control (32.56 %).

The higher Harvest Index under treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % suggest better partitioning of photosynthates toward grain production, likely facilitated by improved reproductive physiology under nano-zinc treatment.

These results are in line with the findings of Verma and Jat (2016) and Singh *et al.* (2020), who observed enhanced Harvest Index with zinc nutrition due to better biomass conversion to economic yield.

4.5 Quality Parameters

4.5.1 Crude Protein Content (%)

In Table 4.9 showed that the crude protein content in finger millet was not significantly influenced by zinc fertilization treatments. The general mean protein content was 7.38 %. Treatment T₈ *i.e.* GRDF + two foliar sprays of Nano-ZnO @ 0.15 % recorded the numerically higher protein content (7.55 %). The numerically lowest protein content was observed in treatment T₁ *i.e.* Absolute control (7.21 %).

The slight increase in protein content under treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % may be due to improved nitrogen uptake and its efficient assimilation into amino acids and protein structures. Zinc enhances the activity of enzymes like ribonuclease and peptidase, which play a key role in protein synthesis.

These findings are supported by Shukla *et al.* (2014) and Joshi *et al.* (2017), who reported that zinc nutrition, particularly in nano form, facilitates nitrogen metabolism and protein accumulation in cereal grains.

Table 4.9 Effect of zinc fertilization on crude protein, crude fibre, carbohydrates and ash content in finger millet

Tr. No.	Treatment	Crude protein content (%)	Crude fibre content (%)	Carbohydrate content (%)	Ash (%)
T ₁	Absolute control	7.21	3.50	68.93	1.95
T ₂	RDF (60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	7.26	3.48	68.98	1.99
T ₃	GRDF (5 ton FYM + 60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	7.30	3.44	69.01	2.00
T ₄	T ₃ + Seed treatment of ZnSO ₄ @ 2.5 g kg ⁻¹ of seeds	7.34	3.40	69.03	2.05
T ₅	T ₃ + Seed treatment of Nano-ZnO @ 1000 ppm	7.40	3.36	69.06	2.10
T ₆	T ₃ + Seed treatment of Chelated Zn @ 1 g kg ⁻¹ of seeds	7.36	3.38	69.04	2.09
T ₇	T ₃ + Two foliar sprays of ZnSO ₄ @ 0.5 %	7.48	3.30	69.15	2.27
T ₈	T ₃ + Two foliar sprays of Nano-ZnO @ 0.15 %	7.55	3.24	69.23	2.29
T ₉	T ₃ + Two foliar sprays of Chelated Zn @ 0.20 %	7.50	3.28	69.18	2.26
T ₁₀	T ₃ + Soil application of ZnSO ₄ @ 20 kg ha ⁻¹	7.44	3.33	69.10	2.25
	SE (m) ±	0.26	0.10	1.42	0.08
	CD at 5 %	NS	NS	NS	NS
	General Mean	7.38	3.37	69.07	2.13

4.5.2 Crude Fibre Content (%)

Crude fibre content was not significantly influenced by the treatments, with an overall mean of 3.37 %. However, a declining trend in fibre content was observed with increasing zinc availability. The numerically lowest fibre content (3.24 %) was recorded in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %. The numerically highest fibre content (3.50 %) was noted under treatment T₁ *i.e.* Absolute control.

The marginal reduction in fibre under treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % may be attributed to a higher partitioning of assimilates towards grain reserves like protein and carbohydrates rather than structural components like cellulose and lignin.

A similar inverse trend between protein and fibre accumulation under balanced nutrient supply was observed by Ramesh and Bharathi (2015) in millets and small grains.

4.5.3 Carbohydrate Content (%)

Carbohydrate content was not significantly altered among treatments, though a slight increase was observed under zinc-enriched foliar sprays. The general mean carbohydrate content was 69.07 %. Treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % recorded the numerically highest value (69.23 %). The treatment T₁ *i.e.* Absolute control recorded the numerically lowest carbohydrate content (68.93 %).

The improvement in carbohydrate content under treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % may be linked to enhanced photosynthesis and carbohydrate translocation efficiency due to zinc-mediated activation of carbonic anhydrase and other enzymes.

These results are in line with observations by Mishra *et al.* (2016) and Sawarkar *et al.* (2018), who reported increased carbohydrate content in zinc-treated cereals due to improved enzymatic activities and source-sink dynamics.

4.5.4 Ash Content (%)

Ash content, an indicator of total mineral content, remained statistically unaffected across treatments but showed a gradual increase with foliar zinc application. The overall mean was 2.13 %. The numerically highest ash content was recorded in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % (2.29 %). The numerically lowest ash content was recorded in treatment T₁ *i.e.* Absolute control (1.95%).

The increase in ash content in zinc-treated plots could be attributed to higher uptake and translocation of essential minerals, including Zn, Fe, Cu, and Mn, into the grain.

These findings agree with Patil *et al.* (2015) and Gaikwad *et al.* (2021), who reported that zinc fertilization enhances the mineral density and ash content in the grains of finger millet and similar crops.

4.6 Soil Chemical Analysis

4.6.1 Soil pH, EC (dS m⁻¹) and OC (%)

The chemical properties of soil such as pH, electrical conductivity, and organic carbon (%) were evaluated after harvest to assess the residual effect of different zinc fertilization treatments (Table 4.10). The initial soil pH, EC, and OC were 8.19, 0.29 dS m⁻¹, and 0.53 %, respectively.

Post-harvest analysis revealed that soil pH ranged from 8.07 in treatment T₁ *i.e.* Absolute control to 8.28 in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %, with a general mean of 8.17. All values remained within the slightly alkaline range, and differences among treatments were statistically non-significant. EC values ranged narrowly between 0.27 to 0.29 dS m⁻¹, with a mean of 0.28 dS m⁻¹, showing no significant build-up of soluble salts. Organic carbon content ranged from 0.52 % to 0.55 %, with a mean of 0.54 %. The lowest was OC found in T₁₀ (0.52%).

Table 4.10 Effect of zinc fertilization on soil chemical properties in finger millet after harvest

Tr. No.	Treatment	Soil studies		
		pH (1:2.5)	EC (dS m ⁻¹)	OC (%)
T ₁	Absolute control	8.07	0.28	0.53
T ₂	RDF (60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	8.16	0.29	0.54
T ₃	GRDF (5 ton FYM + 60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	8.12	0.28	0.54
T ₄	T ₃ + Seed treatment of ZnSO ₄ @ 2.5 g kg ⁻¹ of seeds	8.15	0.27	0.55
T ₅	T ₃ + Seed treatment of Nano-ZnO @ 1000 ppm	8.16	0.28	0.54
T ₆	T ₃ + Seed treatment of Chelated Zn @ 1 g kg ⁻¹ of seeds	8.16	0.27	0.55
T ₇	T ₃ + Two foliar sprays of ZnSO ₄ @ 0.5 %	8.13	0.29	0.54
T ₈	T ₃ + Two foliar sprays of Nano-ZnO @ 0.15 %	8.28	0.29	0.55
T ₉	T ₃ + Two foliar sprays of Chelated Zn @ 0.20 %	8.21	0.28	0.54
T ₁₀	T ₃ + Soil application of ZnSO ₄ @ 20 kg ha ⁻¹	8.27	0.28	0.52
	SE (m) ±	0.21	0.01	0.02
	CD at 5 %	NS	NS	NS
	General Mean	8.17	0.28	0.54
	Initial Value	8.19	0.29	0.55

The slight reduction in pH in organic and foliar applied zinc treatments might be attributed to enhanced microbial activity and production of organic acids due to FYM and zinc interactions. However, since zinc doses were low and organic sources were common across treatments (except treatment T₁ *i.e.* Absolute control and treatment T₂ *i.e.* RDF (60:30:30 N: P₂O₅: K₂O kg ha⁻¹)), the overall influence on soil pH and EC remained minimal. A marginal improvement in organic carbon content in treated plots may be due to residual FYM and higher biomass turnover from greater crop growth.

These observations are in agreement with the findings of Sharma *et al.* (2015) and Patel and Solanki (2017), who reported that integrated nutrient management and foliar micronutrient application caused negligible changes in soil pH and EC but tended to enhance soil organic carbon through improved crop residue return and microbial activity.

4.6.2 Soil Available N, P₂O₅ and K₂O (kg ha⁻¹)

Table 4.11 and Fig. 4.8 illustrate the post-harvest soil available nitrogen (N), phosphorus (P₂O₅), and potassium (K₂O) levels as influenced by different zinc fertilization

treatments. The initial soil test values were 184.85 kg ha⁻¹ N, 18.87 kg ha⁻¹ P₂O₅, and 386.07 kg ha⁻¹ K₂O.

Table 4.11 Effect of zinc fertilization on soil available nutrients of finger millet after harvest

Tr. No.	Treatment	Available nutrients (kg ha ⁻¹)		
		N	P ₂ O ₅	K ₂ O
T ₁	Absolute control	164.55	14.56	368.70
T ₂	RDF (60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	189.33	24.60	372.78
T ₃	GRDF (5 ton FYM + 60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	196.45	25.03	382.85
T ₄	T ₃ + Seed treatment of ZnSO ₄ @ 2.5 g kg ⁻¹ of seeds	187.03	23.26	372.32
T ₅	T ₃ + Seed treatment of Nano-ZnO @ 1000 ppm	183.17	21.12	367.97
T ₆	T ₃ + Seed treatment of Chelated Zn @ 1 g kg ⁻¹ of seeds	185.64	21.82	369.42
T ₇	T ₃ + Two foliar sprays of ZnSO ₄ @ 0.5 %	177.01	18.36	361.02
T ₈	T ₃ + Two foliar sprays of Nano-ZnO @ 0.15 %	167.26	17.01	354.77
T ₉	T ₃ + Two foliar sprays of Chelated Zn @ 0.20 %	171.50	17.20	357.85
T ₁₀	T ₃ + Soil application of ZnSO ₄ @ 20 kg ha ⁻¹	178.59	18.99	364.69
	SE (m) ±	6.30	1.05	5.03
	CD at 5 %	18.69	3.11	14.93
	General Mean	180.05	20.30	367.23
	Initial value	184.85	18.87	386.07

The mean soil available nitrogen after harvest was 180.05 kg ha⁻¹. Significantly maximum available N (196.45 kg ha⁻¹) was recorded in treatment T₃ *i.e.* GRDF (5 ton FYM + 60:30:30 N: P₂O₅: K₂O kg ha⁻¹), which received FYM + RDF, which was at par with treatment T₂ *i.e.* RDF (60:30:30 N: P₂O₅: K₂O kg ha⁻¹) (189.33 kg ha⁻¹). Among zinc treatments, moderate levels were observed in T₄–T₁₀, with the lowest being in treatment T₁ *i.e.* Absolute control (164.55 kg ha⁻¹).

The slightly reduced nitrogen availability in zinc applied treatment like treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % and similar treatments may be attributed to higher plant uptake due to enhanced biomass production, leaving less residual N in the soil. Meanwhile, treatments with organic sources like FYM helped maintain or enhance available nitrogen through mineralization.

Available phosphorus content in soil after harvest varied significantly with treatments, with a general mean of 20.30 kg ha⁻¹. The significantly highest P₂O₅ (25.03 kg ha⁻¹) availability was

found in T₃ *i.e.* GRDF (5 ton FYM + 60:30:30 N: P₂O₅: K₂O kg ha⁻¹), which was at par with treatment T₂ *i.e.* RDF (60:30:30 N: P₂O₅: K₂O kg ha⁻¹) (24.60 kg ha⁻¹). Among zinc treatments, lower phosphorus availability was recorded in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % (17.01 kg ha⁻¹) and treatment T₉ *i.e.* GRDF + Two sprays of Chelated Zn @ 0.20 % (17.20 kg ha⁻¹), indicating more uptake by plants under those treatments. Significantly lowest P₂O₅ availability was found in treatment T₁ *i.e.* Absolute control (14.56 kg ha⁻¹).

This trend reflects that while FYM and mineral phosphorus improved soil P levels, high-performing zinc treatments like treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % led to significant phosphorus use by the crop, especially during reproductive stages.

Post-harvest available K₂O in soil ranged from 354.77 kg ha⁻¹ in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % to 382.85 kg ha⁻¹ in T₃ *i.e.* GRDF (5 ton FYM + 60:30:30 N: P₂O₅: K₂O kg ha⁻¹), with an average of 367.23 kg ha⁻¹. As observed for N and P, T₃ *i.e.* GRDF (5 ton FYM + 60:30:30 N: P₂O₅: K₂O kg ha⁻¹) maintained the significantly highest residual potassium due to the contribution of FYM, while treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % showed the lowest residual potassium (354.77 kg ha⁻¹), likely due to higher crop removal through increased yield.

Reduction in available K under treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % may be ascribed to enhanced root activity and higher nutrient uptake, resulting in efficient use of soil K for grain and biomass production.

Post-harvest reduction in soil available nutrients, especially in high-yielding treatments like treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %, may be due to increased plant uptake supported by improved zinc-mediated metabolic activities. Studies by Babu *et al.* (2015), More *et al.* (2018), and Dixit and Shukla (2022) confirmed that while zinc treatments enhance yield and nutrient use, they may lead to lower residual soil nutrients due to increased plant demand and utilization efficiency.

4.6.3 Post-Harvest Soil Micronutrient Availability (mg kg⁻¹)

The influence of various zinc fertilization treatments on soil available micronutrients (iron, manganese, copper, and zinc) after the harvest of finger millet is presented in Table 4.12 and Fig. 4.9. The initial soil values were 4.12, 3.20, 0.41, and 0.55 mg kg⁻¹ Fe, Mn, Cu and Zn respectively.

Soil available iron content ranged from 3.76 mg kg⁻¹ in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % to 4.11 mg kg⁻¹ in treatment T₁ *i.e.* Absolute control, with a general mean of 3.94 mg kg⁻¹. The lowest values were recorded in the treatments with high crop uptake, such as treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % (3.76 mg kg⁻¹) and treatment T₉ *i.e.* GRDF + Two sprays of Chelated Zn @ 0.20 % (3.79 mg kg⁻¹). This indicates

that zinc application, particularly in nano and chelated forms, may indirectly enhance iron uptake by the plant, reducing residual iron in soil.

Table 4.12 Effect of zinc fertilization on soil available micronutrients in finger millet after harvest

Tr. No.	Treatment	Available micronutrients (mg kg ⁻¹)			
		Fe	Mn	Cu	Zn
T ₁	Absolute control	4.11	3.13	0.40	0.55
T ₂	RDF (60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	4.08	3.11	0.39	0.53
T ₃	GRDF (5 ton FYM + 60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	4.06	3.08	0.37	0.53
T ₄	T ₃ + Seed treatment of ZnSO ₄ @ 2.5 g kg ⁻¹ of seeds	4.01	3.06	0.36	0.53
T ₅	T ₃ + Seed treatment of Nano-ZnO @ 1000 ppm	3.93	3.02	0.35	0.52
T ₆	T ₃ + Seed treatment of Chelated Zn @ 1 g kg ⁻¹ of seeds	3.98	3.03	0.35	0.52
T ₇	T ₃ + Two foliar sprays of ZnSO ₄ @ 0.5 %	3.80	2.96	0.34	0.53
T ₈	T ₃ + Two foliar sprays of Nano-ZnO @ 0.15 %	3.76	2.94	0.32	0.51
T ₉	T ₃ + Two foliar sprays of Chelated Zn @ 0.20 %	3.79	2.99	0.33	0.52
T ₁₀	T ₃ + Soil application of ZnSO ₄ @ 20 kg ha ⁻¹	3.84	3.00	0.35	0.59
	SE (m) ±	0.09	0.04	0.04	0.01
	CD at 5 %	NS	NS	NS	0.03
	General Mean	3.94	3.03	0.36	0.53
	Initial value	4.12	3.20	0.41	0.55
	Critical limit	4.50	2.00	0.20	0.60

The manganese content in soil ranged from 2.94 mg kg⁻¹ in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % to 3.13 mg kg⁻¹ in treatment T₁ *i.e.* Absolute control, with a mean of 3.03 mg kg⁻¹. All treatments showed a slight decline compared to the initial value, suggesting increased uptake by the plant. However, levels remained above the critical limit (2.00 mg kg⁻¹), indicating that no deficiency is expected in subsequent crops.

Soil copper availability after harvest varied slightly across treatments, with values ranging from 0.32 mg kg⁻¹ in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % to 0.40 mg kg⁻¹ treatment T₁ *i.e.* Absolute control, and a general mean of 0.36 mg kg⁻¹. The minimal differences suggest that zinc treatments had limited direct effect on Cu solubility in soil. Nevertheless,

slightly lower Cu in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % may reflect higher crop uptake due to enhanced growth and biomass.

Soil available zinc content ranged from 0.51 mg kg⁻¹ to 0.59 mg kg⁻¹, with a mean of 0.53 mg kg⁻¹. Significantly the highest zinc availability (0.59 mg kg⁻¹) was observed under treatment T₁₀ *i.e.* GRDF + Soil application of ZnSO₄ @ 20 kg ha⁻¹ due to soil application. Significantly the lowest zinc availability was observed under treatment T₁ *i.e.* Absolute control (0.51 mg kg⁻¹).

Post-harvest soil micronutrient availability reflects both the nutrient input and the degree of crop uptake. Treatments involving nano and chelated zinc showed efficient utilization of nutrients with minimal residual buildup. Similar findings were reported by Dhoke *et al.* (2011), Shankaranarayan *et al.* (2016), and Meena *et al.* (2020), who observed that nano-zinc applications can meet crop requirements without causing excessive soil accumulation.

4.7 Nutrient Uptake

4.7.1 Nitrogen Uptake (kg ha⁻¹)

Table 4.13 Effect of zinc fertilization on nitrogen uptake by grain and straw of finger millet after harvest

Tr. No.	Treatment	Nitrogen uptake (kg ha ⁻¹)		
		Grain	Straw	Total
T ₁	Absolute control	14.35	15.06	29.41
T ₂	RDF (60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	19.65	18.86	38.52
T ₃	GRDF (5 ton FYM + 60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	24.01	21.42	45.43
T ₄	T ₃ + Seed treatment of ZnSO ₄ @ 2.5 g kg ⁻¹ of seeds	24.95	22.96	47.91
T ₅	T ₃ + Seed treatment of Nano-ZnO @ 1000 ppm	27.27	24.27	51.54
T ₆	T ₃ + Seed treatment of Chelated Zn @ 1 g kg ⁻¹ of seeds	26.16	23.15	49.31
T ₇	T ₃ + Two foliar sprays of ZnSO ₄ @ 0.5 %	30.71	25.88	56.59
T ₈	T ₃ + Two foliar sprays of Nano-ZnO @ 0.15 %	35.09	27.82	62.90
T ₉	T ₃ + Two foliar sprays of Chelated Zn @ 0.20 %	31.79	26.16	57.95
T ₁₀	T ₃ + Soil application of ZnSO ₄ @ 20 kg ha ⁻¹	29.69	25.29	54.99
	SE (m) ±	1.52	0.71	2.13
	CD at 5 %	4.56	2.14	6.41
	General Mean	26.37	23.09	49.45

The nitrogen uptake by finger millet was significantly influenced by different zinc fertilization treatments (Table 4.13 and Fig. 4.10). The general mean of total nitrogen uptake was 49.45 kg ha^{-1} . Treatment T_8 *i.e.* GRDF + two foliar sprays of Nano-ZnO @ 0.15 % recorded the highest nitrogen uptake of 62.90 kg ha^{-1} , which was at par with treatment T_9 *i.e.* GRDF + Two sprays of Chelated Zn @ 0.20 % (57.95 kg ha^{-1}) and treatment T_7 *i.e.* GRDF + Two foliar sprays of ZnSO_4 @ 0.5 % (56.59 kg ha^{-1}), which were statistically at par. The lowest uptake (29.41 kg ha^{-1}) was observed under treatment T_1 *i.e.* Absolute control.

The increase in nitrogen uptake under treatment T_8 *i.e.* GRDF + two foliar sprays of Nano-ZnO @ 0.15 % might be due to better root growth and enhanced enzyme activity (like nitrate reductase) supported by zinc, especially in nano form, which improves N metabolism and its efficient utilization by the plant. The application of ZnO NPs enhanced the absorption of N, P and K compared with the control. This was mainly caused by the following reasons. Firstly, the application of ZnO NPs increased the content of available N, P and K in the soil by increasing the microbial population and activity in the rhizosphere and soil enzymes such as urease or phosphatase activity.

The improved N uptake due to zinc fertilization is in agreement with the findings of Patel *et al.* (2015) and Meena *et al.* (2018), who reported that foliar zinc application enhances nitrogen use efficiency in cereals.

4.7.2 Phosphorus Uptake (kg ha^{-1})

In Table 4.14 and Fig. 4.11 showed that the phosphorus uptake by grain and straw was significantly affected by the application of different zinc sources. The mean total phosphorus uptake was 21.23 kg ha^{-1} . The highest uptake was observed in treatment T_8 *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % (27.27 kg ha^{-1}), which was significantly superior to other treatments. It was which was at par with treatment T_9 *i.e.* GRDF + Two sprays of Chelated Zn @ 0.20 % (24.84 kg ha^{-1}) and treatment T_7 *i.e.* GRDF + Two foliar sprays of ZnSO_4 @ 0.5 % (23.97 kg ha^{-1}). The lowest P uptake (13.36 kg ha^{-1}) was recorded in treatment T_1 *i.e.* Absolute control.

The increased P uptake under treatment T_8 *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % might be attributed to improved root morphology and exudation of organic acids that enhance phosphorus solubility and availability in the rhizosphere under zinc nutrition.

It has shown that nanoparticles get into plant cells through either stomatal or vascular system. Stomatal pathway is highly capacitive because of its large size exclusion limit and its high transport velocity. These scientific reports support the present hypothesis of nanoparticle penetration in the plant cell through stomatal opening and natural nanopore which may enhance plant cell metabolic activities that lead to higher crop production. The better response of zinc nano fertilizer might be due to its essentiality as trace nutrient element.

Table 4.14 Effect of zinc fertilization on phosphorus uptake by grain and straw of finger millet after harvest

Tr. No.	Treatment	Phosphorus uptake (kg ha ⁻¹)		
		Grain	Straw	Total
T ₁	Absolute control	5.68	7.68	13.36
T ₂	RDF (60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	7.60	9.31	16.91
T ₃	GRDF (5 ton FYM + 60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	9.11	10.19	19.31
T ₄	T ₃ + Seed treatment of ZnSO ₄ @ 2.5 g kg ⁻¹ of seeds	9.53	10.81	20.33
T ₅	T ₃ + Seed treatment of Nano-ZnO @ 1000 ppm	10.43	11.57	22.00
T ₆	T ₃ + Seed treatment of Chelated Zn @ 1 g kg ⁻¹ of seeds	9.95	11.16	21.11
T ₇	T ₃ + Two foliar sprays of ZnSO ₄ @ 0.5 %	11.49	12.48	23.97
T ₈	T ₃ + Two foliar sprays of Nano-ZnO @ 0.15 %	13.43	13.84	27.27
T ₉	T ₃ + Two foliar sprays of Chelated Zn @ 0.20 %	11.95	12.89	24.84
T ₁₀	T ₃ + Soil application of ZnSO ₄ @ 20 kg ha ⁻¹	11.04	12.13	23.17
	SE (m) ±	0.71	0.46	1.21
	CD at 5 %	2.14	1.39	3.63
	General Mean	10.02	11.21	21.23

Similar results were reported by Dixit *et al.* (2014) and Maurya *et al.* (2020), who observed that application of zinc particularly in nano form facilitates greater P uptake due to enhanced root proliferation and mobilization of phosphorus.

4.7.3 Potassium Uptake (kg ha⁻¹)

In Table 4.15 and Fig. 4.12 showed that the potassium uptake varied significantly due to zinc fertilization. The general mean of total K uptake was 74.02 kg ha⁻¹. The highest total uptake was recorded in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % (91.14 kg ha⁻¹), which was at par with treatment T₉ *i.e.* GRDF + Two sprays of Chelated Zn @ 0.20 % (85.51 kg ha⁻¹) and treatment T₇ *i.e.* GRDF + Two foliar sprays of ZnSO₄ @ 0.5 % (83.32 kg ha⁻¹), which were on par. The lowest K uptake was found in treatment T₁ *i.e.* Absolute control (47.23 kg ha⁻¹).

The improvement in potassium uptake with treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % can be associated with enhanced metabolic activity and translocation of potassium within the plant, possibly due to improved plant water status and membrane integrity maintained by sufficient zinc supply.

Table 4.15 Effect of zinc fertilization on potassium uptake by grain and straw of finger millet after harvest

Tr. No.	Treatment	Potassium uptake (kg ha ⁻¹)		
		Grain	Straw	Total
T ₁	Absolute control	11.51	35.72	47.23
T ₂	RDF (60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	15.76	43.32	59.08
T ₃	GRDF (5 ton FYM + 60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	19.56	48.96	68.52
T ₄	T ₃ + Seed treatment of ZnSO ₄ @ 2.5 g kg ⁻¹ of seeds	20.64	51.87	72.51
T ₅	T ₃ + Seed treatment of Nano-ZnO @ 1000 ppm	22.52	55.02	77.55
T ₆	T ₃ + Seed treatment of Chelated Zn @ 1 g kg ⁻¹ of seeds	21.53	53.08	74.61
T ₇	T ₃ + Two foliar sprays of ZnSO ₄ @ 0.5 %	24.47	58.85	83.32
T ₈	T ₃ + Two foliar sprays of Nano-ZnO @ 0.15 %	27.69	63.45	91.14
T ₉	T ₃ + Two foliar sprays of Chelated Zn @ 0.20 %	25.18	60.33	85.51
T ₁₀	T ₃ + Soil application of ZnSO ₄ @ 20 kg ha ⁻¹	23.56	57.22	80.78
	SE (m) ±	1.11	1.61	2.71
	CD at 5 %	3.34	4.84	8.14
	General Mean	21.24	52.78	74.02

These findings are consistent with the reports of Kundu *et al.* (2016) and Verma *et al.* (2021), who highlighted the role of zinc in facilitating potassium transport and uptake in cereal crops.

4.7.4 Micronutrient Uptake (Fe, Mn, Cu, Zn)

In Table 4.16, 4.17 and Fig. 4.13 showed that the total iron uptake by finger millet ranged from 115.39 g ha⁻¹ in treatment T₁ *i.e.* Absolute control to 236.69 g ha⁻¹ in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %. The general mean was 193.96 g ha⁻¹. Significantly highest Fe uptake (236.69 g ha⁻¹) recorded in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %, which was at par with treatment T₉ *i.e.* GRDF + Two sprays of Chelated Zn @ 0.20 % (221.02 g ha⁻¹), and treatment T₇ *i.e.* GRDF + Two foliar sprays of ZnSO₄ @ 0.5 % (216.74 g ha⁻¹). Significantly lowest Fe uptake (115.39 g ha⁻¹) with treatment T₁ *i.e.* Absolute control.

This enhanced uptake may be due to the improved metabolic activity and root development associated with Nano-ZnO application.

Table 4.16 Effect of zinc fertilization on iron and manganese content and total uptake by finger millet

Tr. No.	Treatment	Fe			Mn		
		Content (mg kg ⁻¹)		Total uptake (g ha ⁻¹)	Content (mg kg ⁻¹)		Total uptake (g ha ⁻¹)
		Grain	Straw		Grain	Straw	
T ₁	Absolute control	35.33	22.08	115.39	25.81	14.79	80.34
T ₂	RDF (60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	38.22	24.52	156.52	28.51	16.23	109.56
T ₃	GRDF (5 ton FYM + 60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	40.27	25.36	186.52	30.28	17.48	134.17
T ₄	T ₃ + Seed treatment of ZnSO ₄ @ 2.5 g kg ⁻¹ of seeds	40.35	25.83	193.78	30.32	17.84	139.40
T ₅	T ₃ + Seed treatment of Nano-ZnO @ 1000 ppm	41.03	26.37	203.97	31.03	18.42	148.10
T ₆	T ₃ + Seed treatment of Chelated Zn @ 1 g kg ⁻¹ of seeds	40.56	26.01	197.70	30.79	18.03	143.23
T ₇	T ₃ + Two foliar sprays of ZnSO ₄ @ 0.5 %	42.12	26.73	216.74	31.69	18.97	158.31
T ₈	T ₃ + Two foliar sprays of Nano-ZnO @ 0.15 %	43.41	27.08	236.69	31.98	19.41	172.02
T ₉	T ₃ + Two foliar sprays of Chelated Zn @ 0.20 %	42.25	26.92	221.02	31.84	19.27	162.27
T ₁₀	T ₃ + Soil application of ZnSO ₄ @ 20 kg ha ⁻¹	41.25	26.54	211.27	31.17	18.72	154.11
	SE (m) ±	2.63	1.67	7.11	2.08	1.47	5.16
	CD at 5 %	NS	NS	21.34	NS	NS	15.50
	General Mean	40.48	25.75	193.96	30.34	17.92	140.15

Manganese uptake was highest under treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % (172.02 g ha⁻¹), which was at par with treatment T₉ *i.e.* GRDF + Two sprays of Chelated Zn @ 0.20 % (162.27 g ha⁻¹) and treatment T₇ *i.e.* GRDF + Two foliar sprays of ZnSO₄ @ 0.5 % (158.31 g ha⁻¹). The lowest Mn uptake was found in the treatment T₁ *i.e.* Absolute control with 80.34 g ha⁻¹. The mean uptake across treatments was 140.15 g ha⁻¹. Enhanced manganese uptake could be attributed to better root health and micronutrient mobilization promoted by zinc nutrition.

Total Cu uptake ranged from 24.74 g ha⁻¹ in treatment T₁ *i.e.* Absolute control to 46.07 g ha⁻¹ in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %. The mean copper uptake was 37.92 g ha⁻¹. Significantly the highest Cu uptake (46.07 g ha⁻¹) was observed in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %, which was at par with treatment T₉ *i.e.* GRDF + Two sprays of Chelated Zn @ 0.20 % (43.35 g ha⁻¹) and treatment T₇ *i.e.* GRDF + Two foliar sprays of ZnSO₄ @ 0.5 % (42.23 g ha⁻¹). Zinc-induced activation of transport proteins and increased chelation could have supported the enhanced Cu uptake in these treatments. Significantly

the lowest Cu uptake (24.74 g ha^{-1}) with treatment T_1 *i.e.* Absolute control.

Table 4.17 Effect of zinc fertilization on copper and zinc content and total uptake by finger millet

Tr. No.	Treatment	Cu			Zn		
		Content (mg kg^{-1})		Total uptake (g ha^{-1})	Content (mg kg^{-1})		Total uptake (g ha^{-1})
		Grain	Straw		Grain	Straw	
T ₁	Absolute control	5.92	5.53	24.74	18.6	16.42	74.91
T ₂	RDF (60:30:30 N: P ₂ O ₅ : K ₂ O kg ha^{-1})	6.04	5.69	31.08	20.85	17.56	100.00
T ₃	GRDF (5 ton FYM + 60:30:30 N: P ₂ O ₅ : K ₂ O kg ha^{-1})	6.16	5.74	35.65	21.56	17.89	116.36
T ₄	T ₃ + Seed treatment of ZnSO ₄ @ 2.5 g kg^{-1} of seeds	6.23	5.82	37.17	22.41	18.37	123.56
T ₅	T ₃ + Seed treatment of Nano-ZnO @ 1000 ppm	6.45	5.98	39.49	22.75	18.98	130.73
T ₆	T ₃ + Seed treatment of Chelated Zn @ 1 g kg^{-1} of seeds	6.31	5.89	38.11	22.62	18.72	127.08
T ₇	T ₃ + Two foliar sprays of ZnSO ₄ @ 0.5 %	6.53	6.21	42.23	23.16	19.25	138.18
T ₈	T ₃ + Two foliar sprays of Nano-ZnO @ 0.15 %	6.69	6.38	46.07	23.73	19.48	149.71
T ₉	T ₃ + Two foliar sprays of Chelated Zn @ 0.20 %	6.61	6.29	43.35	23.42	19.39	141.36
T ₁₀	T ₃ + Soil application of ZnSO ₄ @ 20 kg ha^{-1}	6.48	6.13	41.32	22.93	19.07	135.34
	SE (m) $\pm$	0.33	0.31	1.35	1.75	1.47	4.11
	CD at 5 %	NS	NS	4.06	NS	NS	12.31
	General Mean	6.34	5.97	37.92	22.20	18.51	123.72

Zinc uptake showed a clear response to the applied treatments. Significantly the highest zinc uptake (149.71 g ha^{-1}) was observed in treatment T_8 *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %, which was at par with treatment T_9 *i.e.* GRDF + Two sprays of Chelated Zn @ 0.20 % (141.36 g ha^{-1}) and treatment T_7 *i.e.* GRDF + Two foliar sprays of ZnSO₄ @ 0.5 % (138.18 g ha^{-1}). The treatment T_1 *i.e.* Absolute control recorded the lowest uptake (74.91 g ha^{-1}). The increased uptake under foliar nano-zinc treatment is a direct result of its enhanced availability, surface reactivity, and mobility within plant tissues.

The increased uptake of micronutrients under nano-zinc foliar spray treatment T_8 *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % is supported by its high bioavailability and ability to enhance the absorption and translocation of other nutrients. Similar findings were reported by More *et al.* (2018), and Meena *et al.* (2020), who highlighted the synergistic role of zinc in improving the

efficiency of micronutrient uptake in cereals.

4.8 Economic Studies

4.8.1 Gross Monetary Returns (₹ ha⁻¹)

Gross monetary returns showed significant variation due to zinc fertilization treatments (Table 4.18 and Fig. 4.15 and 4.16). The overall mean gross return was ₹ 1,16,723 ha⁻¹. The highest return was recorded in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % with ₹ 1,40,453 ha⁻¹, which was at par with treatment T₉ *i.e.* GRDF + Two sprays of Chelated Zn @ 0.20 % (₹ 1,30,579 ha⁻¹) and treatment T₇ *i.e.* GRDF + Two foliar sprays of ZnSO₄ @ 0.5 % (₹ 1,28,264 ha⁻¹), all of which were significantly superior to the other treatments. The lowest gross return of ₹ 73,863 ha⁻¹ was observed in the treatment T₁ *i.e.* Absolute control.

The increase in gross returns under treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % can be directly attributed to the significantly higher grain and straw yields achieved under this treatment, aided by enhanced nutrient uptake and productivity due to efficient zinc utilization in nano form.

4.8.2 Cost of Cultivation (₹ ha⁻¹)

The cost of cultivation across treatments ranged from ₹ 38,567 ha⁻¹ in treatment T₁ *i.e.* Absolute control to ₹ 65,537 ha⁻¹ in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %, with a mean of ₹ 57,324 ha⁻¹. The highest cost was incurred under treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % due to the expense of Nano-ZnO, foliar sprays, and associated labor. Treatment T₉ *i.e.* GRDF + Two sprays of Chelated Zn @ 0.20 % (₹ 61,734) and treatment T₁₀ *i.e.* GRDF + Soil application of ZnSO₄ @ 20 kg ha⁻¹ (₹ 61,273) also showed elevated costs. Treatment T₁ *i.e.* Absolute control had the lowest cost (₹ 38,567), owing to the absence of any fertilizer or zinc input.

Despite the higher cost under treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %, the increased productivity more than offset the investment, resulting in better economic returns.

4.8.3 Net Monetary Returns (₹ ha⁻¹)

Net returns followed the trend of gross returns. The mean net monetary return was ₹ 59,398 ha⁻¹. Treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % recorded the maximum net return of ₹ 75,523 ha⁻¹, which was at par with treatment T₉ *i.e.* GRDF + Two sprays of Chelated Zn @ 0.20 % (₹ 69,247 ha⁻¹) and treatment T₇ *i.e.* GRDF + Two foliar sprays of ZnSO₄ @ 0.5 % (₹ 67,396 ha⁻¹). The treatment T₁ *i.e.* Absolute control yielded the minimum return of ₹ 34,787 ha⁻¹.

The superior net returns under treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % are a result of significantly higher yields with only moderately increased input cost, proving the economic viability of Nano-ZnO foliar application.

Table 4.18 Effect of zinc fertilization on Gross monetary returns, cost of cultivation, net monetary returns and B:C ratio of finger millet

Tr. No.	Treatment	Gross monetary returns (₹ ha ⁻¹)	Cost of cultivation (₹ ha ⁻¹)	Net monetary returns (₹ ha ⁻¹)	B:C ratio
T ₁	Absolute control	73863	38567	34787	1.89
T ₂	RDF (60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	95831	46535	45979	1.92
T ₃	GRDF (5 ton FYM + 60:30:30 N: P ₂ O ₅ : K ₂ O kg ha ⁻¹)	114353	58240	55728	1.95
T ₄	T ₃ + Seed treatment of ZnSO ₄ @ 2.5 g kg ⁻¹ of seeds	116754	58630	57983	1.99
T ₅	T ₃ + Seed treatment of Nano-ZnO @ 1000 ppm	121918	59259	62533	2.05
T ₆	T ₃ + Seed treatment of Chelated Zn @ 1 g kg ⁻¹ of seeds	119088	58767	60166	2.02
T ₇	T ₃ + Two foliar sprays of ZnSO ₄ @ 0.5 %	128264	61095	67396	2.11
T ₈	T ₃ + Two foliar sprays of Nano-ZnO @ 0.15 %	140453	65537	75523	2.16
T ₉	T ₃ + Two foliar sprays of Chelated Zn @ 0.20 %	130579	61734	69247	2.13
T ₁₀	T ₃ + Soil application of ZnSO ₄ @ 20 kg ha ⁻¹	126122	61273	64642	2.05
	SE (m) ±	4014.6	-	4014.6	-
	CD at 5 %	12045	-	12045	-
	General Mean	116723	57324	59398	2.03

4.8.4 Benefit: Cost (B:C) Ratio

The B:C ratio is a crucial index of profitability and was numerically influenced by the treatments. The average B:C ratio was 2.03. The maximum value of 2.16 was observed in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15. The lowest B:C ratio of 1.89 was observed in treatment T₁ *i.e.* Absolute control.

A higher B:C ratio in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % indicates that every rupee invested returned ₹ 2.16, making it the most cost-effective treatment. Despite higher input cost, the enhanced grain and straw yield under Nano-ZnO foliar application ensured higher profitability.

The improvement in gross returns, net returns, and B:C ratio under treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % is supported by enhanced yield performance and nutrient uptake efficiency due to foliar application of Nano-ZnO. Previous findings by Charishma *et al.* (2022) and Shinde *et al.* (2014) also reported that application of nano-form and zinc fertilizers increased the profitability of cereal-based cropping systems by improving yield and nutrient use efficiency.

5. SUMMARY AND CONCLUSION

5.1 SUMMARY

A field experiment entitled “Effect of zinc fertilization on growth and yield of finger millet (*Eleusine coracana* L. Gaertn.)” was conducted during *Kharif* season of 2024-2025 at the Instructional Farm, Post Graduate Institute, Mahatma Phule Krishi Vidyapeeth, Rahuri. The experiment consists of ten treatments viz., T₁: Absolute control; T₂: RDF (Recommended dose of fertilizer); T₃: GRDF (General recommended dose of fertilizer); T₄: T₃ + Seed treatment of ZnSO₄ @ 2.5 g kg⁻¹ of seeds; T₅: T₃ + Seed treatment of Nano-ZnO @ 1000 ppm; T₆: T₃ + Seed treatment of Chelated Zn @ 1 g kg⁻¹ of seeds; T₇: T₃ + Two foliar sprays of ZnSO₄ @ 0.5 %; T₈: T₃ + Two foliar sprays of Nano-ZnO @ 0.15 %; T₉: T₃ + Two foliar sprays of Chelated Zn @ 0.20 %; T₁₀: T₃ + Soil application of ZnSO₄ @ 20 kg ha⁻¹.

The experiment was laid out in randomized block design (RBD) with three replications. The soil was clay in texture, low in available nitrogen (184.85 kg ha⁻¹), high in available phosphorus (18.87 kg ha⁻¹) and very high amount of potassium (386.07 kg ha⁻¹). The soil was showed slightly alkaline in reaction (pH 8.19) with an electrical conductivity of 0.29 dS m⁻¹.

The Phule Nachani variety seeds were line sown at spacing of 30 cm x 10 cm. At the time of sowing, 5 tons of FYM and the recommended fertilizer dosage (60: 30: 30 kg N, P₂O₅, K₂O ha⁻¹) were applied as a basal dose using urea, SSP, and MOP. Seed treatment, soil application and foliar sprays of different zinc sources were applied as per the treatments.

Periodic assessments of growth traits, grain production, straw yield, and other parameters impacting yield at harvest time were carried out during the study. Measurements were made of the grain and straw's nitrogen, phosphorus, potassium, and micronutrient contents as well as their overall concentrations. Additionally, the soil's available nitrogen, phosphorus, potassium, and micronutrient content were evaluated both prior to and following crop harvest. Furthermore, quality parameters and the economic analysis of different method of application of various zinc sources was conducted based on input and output data.

The key outcomes resulting from the treatments in this experiment are summarized as below.

5.1.1 Effect of Zinc Fertilization on Growth and Yield of Finger millet

Plant population did not differ significantly among the treatments. Growth attributes such as plant height, number of tillers, number of functional leaves, leaf area, and dry matter accumulation showed significant improvement due to zinc fertilization. The treatment T₈ i.e. GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %, consistently resulted in significantly higher values across multiple growth parameters. It included maximum plant height (116.7 cm), number of functional leaves plant⁻¹ (50.5), leaf area plant⁻¹ (11.45 dm²) and dry matter accumulation (23.16 g

plant⁻¹) at harvest, which was at par with treatment T₉ *i.e.* GRDF + Two foliar sprays of Chelated zinc @ 0.2 %, it included plant height (111.8 cm), number of functional leaves plant⁻¹ (48.2), leaf area plant⁻¹ (10.88 dm²) and dry matter accumulation (22.32 g plant⁻¹) and treatment T₇ *i.e.* GRDF + Two foliar sprays of Zinc sulphate @ 0.5 %, it included plant height (110.3 cm), number of functional leaves plant⁻¹ (47.8), leaf area plant⁻¹ (10.84 dm²) and dry matter accumulation (22.02 g plant⁻¹).

Yield contributing characters such as number of fingers earhead⁻¹ (8.1), number of grains finger⁻¹ (358), grain weight plant⁻¹ (8.68), finger length (8.8 cm) and thousand grain weight (3.19 g) were recorded maximum under treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %, which was at par with treatment T₉ *i.e.* GRDF + Two foliar sprays of Chelated zinc @ 0.2 % (7.7 fingers earhead⁻¹, 334 grains finger⁻¹, 8.28 g grain weight plant⁻¹, 8.4 cm finger length and 3.14 g thousand grain weight) and treatment T₇ *i.e.* GRDF + Two foliar sprays of Zinc sulphate @ 0.5 % (7.4 fingers earhead⁻¹, 323 grains finger⁻¹, 8.12 g grain weight plant⁻¹, 8.2 cm finger length and 3.09 g thousand grain weight).

Grain yield was significantly influenced by zinc fertilization. The highest grain yield (27.41 q ha⁻¹) was obtained with treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % which was at par with treatment T₉ *i.e.* GRDF + Two foliar sprays of Chelated zinc @ 0.2 % (25.43 q ha⁻¹) and treatment T₇ *i.e.* GRDF + Two foliar sprays of Zinc sulphate @ 0.5 % (24.97 q ha⁻¹). Straw yield was also significantly highest in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % (43.46 q ha⁻¹), which was at par with treatment T₉ *i.e.* GRDF + Two foliar sprays of Chelated zinc @ 0.2 % (42.19 q ha⁻¹) and treatment T₇ *i.e.* GRDF + Two foliar sprays of Zinc sulphate @ 0.5 % (41.74 q ha⁻¹). The biological yield was maximum in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % (70.87 q ha⁻¹) and harvest index recorded significantly higher value (38.75 %) under treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %, which was at par with treatment T₉ *i.e.* GRDF + Two foliar sprays of Chelated zinc @ 0.2 % (37.59 %) and treatment T₇ *i.e.* GRDF + Two foliar sprays of Zinc sulphate @ 0.5 % (37.43 %).

5.1.2 Effect of Zinc Fertilization on Nutrient Uptake and Quality of Finger millet

Regarding nutrient uptake, total nitrogen uptake was maximum in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % (62.90 kg ha⁻¹), which was at par with treatment T₉ *i.e.* GRDF + Two foliar sprays of Chelated zinc @ 0.2 % (57.95 kg ha⁻¹) and treatment T₇ *i.e.* GRDF + Two foliar sprays of Zinc sulphate @ 0.5 % (56.59 kg ha⁻¹). Similarly, total phosphorus uptake peaked in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % (27.27 kg ha⁻¹), which was at par with treatment T₉ *i.e.* GRDF + Two foliar sprays of Chelated zinc @ 0.2 % (24.84 kg ha⁻¹) and treatment T₇ *i.e.* GRDF + Two foliar sprays of Zinc sulphate @ 0.5 % (23.97 kg ha⁻¹). Potassium uptake also followed this trend, with treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % (91.14 kg ha⁻¹) being highest, which was at par with treatment T₉ *i.e.* GRDF + Two

foliar sprays of Chelated zinc @ 0.2 % (85.51 kg ha⁻¹) and treatment T₇ *i.e.* GRDF + Two foliar sprays of Zinc sulphate @ 0.5 % (83.32 kg ha⁻¹).

Micronutrient uptake (Fe, Mn, Zn, Cu) increased significantly with zinc fertilization. Maximum uptake was recorded in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % for all micronutrients - Fe (236.69 g ha⁻¹), Mn (172.02 g ha⁻¹), Cu (46.07 g ha⁻¹) and Zn (149.71 g ha⁻¹), which was at par with treatment T₉ *i.e.* GRDF + Two foliar sprays of Chelated zinc @ 0.2 % (GRDF + Two foliar sprays of Chelated zinc @ 0.2 %) for all micronutrients - Fe (221.02 g ha⁻¹), Mn (162.27 g ha⁻¹), Cu (6.29 g ha⁻¹) and Zn (141.36 g ha⁻¹) and T₇ *i.e.* GRDF + Two foliar sprays of Zinc sulphate @ 0.5 % for all micronutrients - Fe (216.74 g ha⁻¹), Mn (158.31 g ha⁻¹), Cu (42.23 g ha⁻¹) and Zn (138.18 g ha⁻¹).

While crude protein content, crude fibre content, carbohydrates and ash content remained statistically similar across the treatments. However, T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %) showed numerically highest crude protein content (7.55 %), carbohydrates (69.23 %) and ash content (2.29 %) and lowest crude fibre content (3.24 %).

5.1.3 Economics of Different Treatments

Significantly maximum gross monetary returns (₹ 1,40,453 ha⁻¹), net monetary returns (₹ 75,523 ha⁻¹) and B:C ratio (2.16) were obtained in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %, which was at par with treatment T₉ *i.e.* GRDF + Two foliar sprays of Chelated zinc @ 0.2 % with gross monetary returns (₹ 1,30,579 ha⁻¹), net monetary returns (₹ 69,247 ha⁻¹) and B:C ratio (2.13) and treatment T₇ *i.e.* GRDF + Two foliar sprays of Zinc sulphate @ 0.5 % with gross monetary returns (₹ 1,28,264 ha⁻¹), net monetary returns (₹ 67,396 ha⁻¹) and B:C ratio (2.11).

5.2 Conclusion

Based on the findings of the present experiment, the following key conclusions can be drawn;

1. Among different zinc sources and different methods of application, treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % exhibited significantly higher growth attributes *viz.*, plant height, number of functional leaves, leaf area, number of tillers and dry accumulation per plant, which was at par with treatment T₉ *i.e.* GRDF + Two foliar sprays of Chelated zinc @ 0.2 % and treatment T₇ *i.e.* GRDF + Two foliar sprays of Zinc sulphate @ 0.5 %.
2. Yield attributes *viz.*, number of fingers earhead⁻¹, number of grains finger⁻¹, grain weight plant⁻¹ and finger length at harvest were highest under treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 % and comparable results were obtained with treatment T₉ *i.e.* GRDF + Two foliar sprays of Chelated zinc @ 0.20 % and treatment T₇ *i.e.* GRDF + Two foliar sprays of Zinc sulphate @ 0.5 %.

3. Grain yield, straw yield, biological yield, and harvest index were significantly higher with treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %, which was at par with the treatment T₉ *i.e.* GRDF + Two foliar sprays of Chelated zinc @ 0.20 % and treatment T₇ *i.e.* GRDF + Two foliar sprays of Zinc sulphate @ 0.5 %.
4. Total uptake of nitrogen, phosphorus, potassium, and micronutrients was maximum with treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %, which was at par with the treatment T₉ *i.e.* GRDF + Two foliar sprays of Chelated zinc @ 0.20 % and treatment T₇ *i.e.* GRDF + Two foliar sprays of Zinc sulphate @ 0.5 %.
5. Crude protein content, crude fibre content, carbohydrate and ash content were remained unaffected among the treatments, but the crude protein content, carbohydrates and ash content were numerically higher in treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %.
6. The gross monetary returns, net monetary returns and B:C ratio were obtained highest in the treatment T₈ *i.e.* GRDF + Two foliar sprays of Nano-ZnO @ 0.15 %, which was at par with the treatment T₉ *i.e.* GRDF + Two foliar sprays of Chelated zinc @ 0.20 % and treatment T₇ *i.e.* GRDF + Two foliar sprays of Zinc sulphate @ 0.5 %.

Based on one year field experiment it can be concluded that treatments included General recommended dose of fertilizer + Two foliar sprays of Nano-ZnO @ 0.15 % at tillering and flowering stages or General recommended dose of fertilizer + Two foliar sprays of Chelated zinc @ 0.20 % at tillering and flowering stages is suggestive to over come zinc deficiency in finger millet formed beneficial for increase in growth attributes, yield attributes, nutrient uptake, grain yield and monetary returns.

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7. APPENDICES

Appendix I. Prevailing market prices of input and output

Sr. No.	Particulars	Unit	Price (₹)
1.	Hired human labour	Male	day ⁻¹
		Female	day ⁻¹
2.	Land preparation		
I	Ploughing (Tractor)	acre ⁻¹	2500
II	Rotavator (Tractor)	ha ⁻¹	2000
III	Sowing	ha ⁻¹	2500
3.	Fertilizers		
I	FYM (tonne ⁻¹)	m ⁻³	1500
II	Urea	kg ⁻¹	6
III	SSP	kg ⁻¹	15
IV	MOP	kg ⁻¹	33
V	Zinc sulphate	kg ⁻¹	100
VI	Chelated zinc	kg ⁻¹	400
VII	Nano zinc oxide	kg ⁻¹	2400
4.	Sowing		
I	Seed	kg ⁻¹	57
5.	Inter cultivation operation		
I	Gap filling	day ⁻¹	397
II	Weeding	day ⁻¹	397
III	Irrigation	day ⁻¹	397
6.	Spraying	day ⁻¹	397
7.	Output		
I	Grain	kg ⁻¹	48.86
II	Straw	kg ⁻¹	1.5
8.	Land revenue	Year ⁻¹	800

Appendix II. Details of cost of cultivation in different treatment. (₹ ha⁻¹)

Sr. No.	Particulars	T ₁	T ₂	T ₃	T ₄	T ₅	T ₆	T ₇	T ₈	T ₉	T ₁₀
1.	Land preparation										
i.	Ploughing	6250	6250	6250	6250	6250	6250	6250	6250	6250	6250
ii.	Rotavator	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
iii.	Layout preparation	3970	3970	3970	3970	3970	3970	3970	3970	3970	3970
2.	Seed and sowing	4540	4540	4540	4540	4540	4540	4540	4540	4540	4540
3.	Manure										
i.	FYM			10000	10000	10000	10000	10000	10000	10000	10000
ii.	Fertilizer		6037	6037	6037	6037	6037	6037	6037	6037	6037
4.	Inter cultivation operation										
i.	Gap filling	794	794	794	794	794	794	794	794	794	794
ii.	Weeding	7940	7940	7940	7940	7940	7940	7940	7940	7940	7940
5.	Seed treatment/ soil application/ foliar spray				3	24	4	500	3600	800	2000
6.	Spraying charge							794	794	794	
7.	Irrigation	2382	2382	2382	2382	2382	2382	2382	2382	2382	2382
8.	Harvesting	3970	3970	3970	3970	3970	3970	3970	3970	3970	3970
9.	Threshing	4263	5562	6669	6804	7362	6945	7491	8223	7629	7362
10.	Cost A (working capital)	36109	43445	54552	54690	55269	54832	56668	60500	57106	57269
11.	Land revenue	800	800	800	800	800	800	800	800	800	800
12.	Interest on working capital	2167	2607	3273	3281	3316	3290	3400	3630	3426	3438
13.	Cost B (11+12)	2967	3407	4073	4081	4116	4090	4200	4430	4226	4238
	Cost of cultivation (Cost A + Cost B)	39076	49852	58625	58771	59385	58922	60868	64930	61332	61497

8. VITAE

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