

**NANO ZINC NUTRITION IN RICE BASED CROPPING
SYSTEMS IN HIGH PHOSPHORUS SOILS**

by

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(2020-21-046)

THESIS

**Submitted in partial fulfilment of the requirement for the degree of
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Kerala Agricultural University



DEPARTMENT OF AGRONOMY

COLLEGE OF AGRICULTURE

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KERALA, INDIA

2025

DECLARATION

I, hereby declare that this thesis entitled “**Nano zinc nutrition in rice based cropping systems in high phosphorus soils**” is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title, of any other University or Society.

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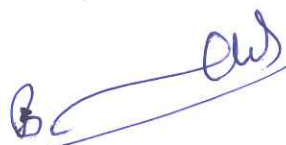
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TABLE OF CONTENTS

Sl. No.	Particulars	Page No.
1.	INTRODUCTION	1-5
2.	REVIEW OF LITERATURE	7-34
3.	MATERIALS AND METHODS	35-58
4.	RESULTS	59-186
5.	DISCUSSION	187-212
6.	SUMMARY	213-221
7.	REFERENCES	223-249
8.	APPENDICES	
9.	ABSTRACT	

LIST OF TABLES

Table No.	Title	Page No.
1.	Mechanical composition of initial soil sample of the experimental site	35
2.	Chemical properties of initial soil sample of the experimental field	36
3.	Basic procedure for the analysis of soil samples	52
4.	Standard analytical procedure adopted for the plant analysis	53
5a.	Effect of nano zinc nutrition on plant height at different stages of <i>virippu</i> rice, cm	60
5b.	Effect of nano zinc nutrition on plant height at different stages of <i>mundakan</i> rice, cm	61
6a.	Effect of nano zinc nutrition on tillers m ⁻² at different stages of <i>virippu</i> rice	63
6b.	Effect of nano zinc nutrition on tillers per m ⁻² at different stages of <i>mundakan</i> rice	64
7a.	Effect of nano zinc nutrition on leaf area per hill at different stages of <i>virippu</i> rice and leaf area index (LAI) at panicle initiation stage	66
7b.	Effect of nano zinc nutrition on leaf area per hill at different stages of <i>mundakan</i> rice and leaf area index (LAI) at panicle initiation stage	67
8a.	Effect of nano zinc nutrition on dry matter production at harvest, days to 50 % flowering, sterility % of <i>virippu</i> rice	71
8b.	Effect of nano zinc nutrition on dry matter production at harvest, days to 50 % flowering, sterility % of <i>mundakan</i> rice	72
9a.	Effect of nano zinc nutrition on productive tillers per hill, no. of grains per panicle, grain weight per panicle, thousand grain weight of <i>virippu</i> rice	74
9b.	Effect of nano zinc nutrition on productive tillers per hill, no. of grains per panicle, grain weight per panicle, thousand grain weight of <i>mundakan</i> rice	75
10a.	Effect of nano zinc nutrition on grain yield, straw yield and harvest index of <i>virippu</i> rice	77
10b.	Effect of nano zinc nutrition on grain yield, straw yield and harvest index of <i>mundakan</i> rice	78
10c.	Effect of nano zinc nutrition on pooled mean of grain yield and straw yield of rice, kg ha ⁻¹	80

11a.	Effect of nano zinc nutrition on nitrogen uptake by different parts of rice plant at panicle initiation stage in <i>virippu</i> , kg ha ⁻¹	82
11b.	Effect of nano zinc nutrition on nitrogen uptake by different parts of rice plant at panicle initiation stage in <i>mundakan</i> , kg ha ⁻¹	83
12a.	Effect of nano zinc nutrition on nitrogen uptake by different parts of rice plant at harvest stage in <i>virippu</i> , kg ha ⁻¹	85
12b.	Effect of nano zinc nutrition on nitrogen uptake by different parts of rice plant at harvest stage in <i>mundakan</i> , kg ha ⁻¹	86
13a.	Effect of nano zinc nutrition on phosphorus uptake by different parts of rice plant at panicle initiation stage in <i>virippu</i> , kg ha ⁻¹	88
13b.	Effect of nano zinc nutrition on phosphorus uptake by different parts of rice plant at panicle initiation stage in <i>mundakan</i> , kg ha ⁻¹	89
14a.	Effect of nano zinc nutrition on phosphorus uptake by different parts of rice plant at harvest stage in <i>virippu</i> , kg ha ⁻¹	91
14b.	Effect of nano zinc nutrition on phosphorus uptake by different parts of rice plant at harvest stage in <i>mundakan</i> , kg ha ⁻¹	92
15a.	Effect of nano zinc nutrition on potassium uptake by different parts of rice plant at panicle initiation stage in <i>virippu</i> , kg ha ⁻¹	94
15b.	Effect of nano zinc nutrition on potassium uptake by different parts of rice plant at panicle initiation stage in <i>mundakan</i> , kg ha ⁻¹	95
16a.	Effect of nano zinc nutrition on potassium uptake by different parts of rice plant at harvest stage in <i>virippu</i> , kg ha ⁻¹	96
16b.	Effect of nano zinc nutrition on potassium uptake by different parts of rice plant at harvest stage in <i>mundakan</i> , kg ha ⁻¹	97
17a.	Effect of nano zinc nutrition on calcium uptake by different parts of rice plant at panicle initiation stage in <i>virippu</i> , kg ha ⁻¹	99
17b.	Effect of nano zinc nutrition on calcium uptake by different parts of rice plant at panicle initiation stage in <i>mundakan</i> , kg ha ⁻¹	100
18a.	Effect of nano zinc nutrition on calcium uptake by different parts of rice plant at harvest stage in <i>virippu</i> , kg ha ⁻¹	102
18b.	Effect of nano zinc nutrition on calcium uptake by different parts of rice plant at harvest stage in <i>mundakan</i> , kg ha ⁻¹	103
19a.	Effect of nano zinc nutrition on zinc uptake by different parts of rice plant at panicle initiation stage in <i>virippu</i> , kg ha ⁻¹	105
19b.	Effect of nano zinc nutrition on zinc uptake by different parts of rice plant at panicle initiation stage in <i>mundakan</i> , kg ha ⁻¹	106
20a.	Effect of nano zinc nutrition on zinc uptake by different parts of rice plant at harvest stage in <i>virippu</i> , kg ha ⁻¹	108
20b.	Effect of nano zinc nutrition on zinc uptake by different parts of rice plant at harvest stage in <i>mundakan</i> , kg ha ⁻¹	109
21a.	Effect of nano zinc nutrition on agronomic efficiency, physiological efficiency and apparent recovery efficiency in <i>virippu</i> , kg kg ⁻¹	111

21b.	Effect of nano zinc nutrition on agronomic efficiency, physiological efficiency and apparent recovery efficiency in <i>mundakan</i> , kg kg ⁻¹	112
22a.	Effect of nano zinc nutrition on soil reaction (pH), electrical conductivity (EC) and organic carbon (OC) content of the soil after <i>virippu</i> rice experiment.	115
22b.	Effect of nano zinc nutrition on soil reaction (pH), electrical conductivity (EC) and organic carbon (OC) content of the soil after <i>mundakan</i> rice experiment	116
23a.	Effect of nano zinc nutrition on available nitrogen, phosphorus and potassium in soil after <i>virippu</i> rice experiment, kg ha ⁻¹	118
23b.	Effect of nano zinc nutrition on available nitrogen, phosphorus and potassium in soil after <i>mundakan</i> rice experiment, kg ha ⁻¹	119
24a.	Effect of nano zinc nutrition on available calcium and zinc in soil after <i>virippu</i> rice experiment, mg kg ⁻¹	121
24b.	Effect of nano zinc nutrition on available calcium and zinc in soil after <i>mundakan</i> rice experiment, mg kg ⁻¹	122
25a.	Effect of nano zinc nutrition on dehydrogenase enzyme activity and phosphatase enzyme activity in soil of <i>virippu</i> rice	124
25b.	Effect of nano zinc nutrition on dehydrogenase enzyme activity and phosphatase enzyme activity in soil of <i>mundakan</i> rice	125
26.	Effect of nano zinc nutrition on economics of rice	127
27.	Effect of residual nutrient status of soil on plant height of cowpea, cm	129
28.	Effect of residual nutrient status of soil on number of branches per plant of cowpea	129
29.	Effect of residual nutrient status of soil on dry matter production at harvest, days to 50 per cent flowering, number of pods per plant, 100 seed weight of cowpea	129
30.	Effect of residual nutrient status of soil on seed yield per plant, seed yield ha ⁻¹ , haulm yield per plant, haulm yield ha ⁻¹ of cowpea	130
31.	Effect of residual nutrient status of soil on plant height of bhindi, cm	132
32.	Effect of residual nutrient status of soil on number of branches per plant of bhindi	133
33.	Effect of residual nutrient status of soil on dry matter production at harvest, days to 50 per cent flowering, number of fruits per plant, fruit weight of bhindi	133
34.	Effect of residual nutrient status of soil on fruit yield per plant, fruit yield ha ⁻¹ , haulm yield per plant, haulm yield ha ⁻¹ of bhindi	134
35.	Rice equivalent yield of cowpea and bhindi, kg ha ⁻¹	134

36a.	Effect of residual nutrient status and crop sequence on chemical properties of soil after the experiment.	138
36b.	Interaction effects of residual nutrient status and crop sequence on chemical properties of soil after the experiment.	139
37a.	Effect of residual nutrients and crop sequences on available nutrient status of N, P, K and Ca in the soil after the experiment	141
37b.	Interaction effect of residual nutrients and crop sequences on available nutrient status of N, P, K and Ca in the soil after the experiment	142
38a.	Effect of residual nutrients and crop sequences on available nutrient status of Zn, Fe and B in the soil after the experiment, mg kg ⁻¹	145
38b.	Interaction effect of residual nutrients and crop sequences on available nutrient status of Zn, Fe and B in the soil after the experiment, mg kg ⁻¹	146
39a.	Effect of residual nutrients and crop sequences on soil enzyme activity after the experiment	148
39b.	Interaction effect of residual nutrients and crop sequences on soil enzyme activity after the experiment	149
40a.	Effect of residual nutrients and crop sequences on system yield and system productivity	151
40b.	Interaction effect of residual nutrients and crop sequences on system yield and system productivity	152
41a.	Effect of residual nutrients and crop sequences on energy efficiency and specific energy	154
41b.	Interaction effect of residual nutrients and crop sequences on energy efficiency and specific intensity	155
42a.	Effect of residual nutrients and crop sequences on energy productivity and energy intensity	157
42b.	Interaction effect of residual nutrients and crop sequences on energy productivity and energy intensity	158
43a.	Effect of nano zinc nutrition on N balance sheet of rice-rice-cowpea system, kg ha ⁻¹	160
43b.	Effect of nano zinc nutrition on N balance sheet of rice-rice-bhindi system, kg ha ⁻¹	161
43c.	Effect of nano zinc nutrition on N balance sheet of rice-rice-fallow system, kg ha ⁻¹	162
44a.	Effect of nano zinc nutrition on P balance sheet of rice-rice-cowpea system, kg ha ⁻¹	163
44b.	Effect of nano zinc nutrition on P balance sheet of rice-rice-bhindi system, kg ha ⁻¹	164
44c.	Effect of nano zinc nutrition on P balance sheet of rice-rice-fallow system, kg ha ⁻¹	165

45a.	Effect of nano zinc nutrition on K balance sheet of rice-rice-cowpea system, kg ha ⁻¹	169
45b.	Effect of nano zinc nutrition on K balance sheet of rice-rice-bhindi system, kg ha ⁻¹	170
45c.	Effect of nano zinc nutrition on K balance sheet of rice-rice-fallow system, kg ha ⁻¹	171
46a.	Effect of nano zinc nutrition on Ca balance sheet of rice-rice-cowpea system, kg ha ⁻¹	172
46b.	Effect of nano zinc nutrition on Ca balance sheet of rice-rice-bhindi system, kg ha ⁻¹	173
46c.	Effect of nano zinc nutrition on Ca balance sheet of rice-rice-fallow system, kg ha ⁻¹	174
47a.	Effect of nano zinc nutrition on Zn balance sheet of rice-rice-cowpea system, kg ha ⁻¹	175
47b.	Effect of nano zinc nutrition on Zn balance sheet of rice-rice-bhindi system, kg ha ⁻¹	176
47c.	Effect of nano zinc nutrition on Zn balance sheet of rice-rice-fallow system, kg ha ⁻¹	177
48a.	Effect of nano zinc nutrition on Fe balance sheet of rice-rice-cowpea system, kg ha ⁻¹	178
48b.	Effect of nano zinc nutrition on Fe balance sheet of rice-rice-bhindi system, kg ha ⁻¹	179
48c.	Effect of nano zinc nutrition on Fe balance sheet of rice-rice-fallow system, kg ha ⁻¹	180
49a.	Effect of nano zinc nutrition on B balance sheet of rice-rice-cowpea system, kg ha ⁻¹	181
49b.	Effect of nano zinc nutrition on B balance sheet of rice-rice-bhindi system, kg ha ⁻¹	182
49c.	Effect of nano zinc nutrition on B balance sheet of rice-rice-fallow system, kg ha ⁻¹	183
50a.	Effect of residual nutrients and crop sequences on economics of rice based cropping system	185
50b.	Interaction effect of residual nutrients and crop sequences on economics of rice based cropping system	186

LIST OF FIGURES

Fig. No.	Title	Between pages
1a.	Standard week wise temperature during <i>virippu</i> (2022-2023)	38-39
1b.	Standard week wise relative humidity during <i>virippu</i> (2022-2023)	38-39
1c.	Standard week wise rainfall during <i>virippu</i> (2022-2023)	38-39
2a.	Standard week wise temperature during <i>mundakan</i> (2022-2023)	38-39
2b.	Standard week wise relative humidity during <i>mundakan</i> (2022-2023)	38-39
2c.	Standard week wise rainfall during <i>mundakan</i> (2022-2023)	38-39
3a.	Standard week wise temperature during <i>puncha</i> (2022-2023)	38-39
3b.	Standard week wise relative humidity during <i>puncha</i> (2022-2023)	38-39
3c.	Standard week wise rainfall during <i>puncha</i> (2022-2023)	38-39
4a.	Layout plan of experiment during <i>virippu</i> and <i>mundakan</i>	40-41
4b.	Layout plan of experiment during <i>puncha</i>	40-41
5.	Effect of nano zinc nutrition on leaf area index (LAI) at panicle initiation stage during <i>virippu</i> and <i>mundakan</i> rice	188-189

6.	Effect of nano zinc nutrition on dry matter production at harvest during <i>virippu</i> and <i>mundakan</i> rice	188-189
7.	Effect of nano zinc nutrition on pooled mean of grain and straw yield of rice, kg ha ⁻¹	190-191
8.	Effect of nano zinc nutrition on nutrient uptake in rice at panicle initiation stage during <i>virippu</i> , kg ha ⁻¹	192-193
9.	Effect of nano zinc nutrition on nutrient uptake in rice at panicle initiation during <i>mundakan</i> , kg ha ⁻¹	192-193
10.	Effect of nano zinc nutrition on nutrient uptake in rice at harvest stage during <i>virippu</i> , kg ha ⁻¹	194-195
11.	Effect of nano zinc nutrition on nutrient uptake in rice at harvest stage during <i>mundakan</i> , kg ha ⁻¹	194-195
12.	Interaction effect of residual nutrients and crop sequences on available zinc status of the soil after the experiment	200-201
13.	Interaction effect of residual nutrients and crop sequences on phosphatase activity after the experiment	200-201
14.	Interaction effect of residual nutrients and crop sequences on available phosphorus and calcium status of the soil after the experiment	202-203
15.	Effect of residual nutrients and crop sequences on N balance sheet, kg ha ⁻¹	204-205
16.	Effect of residual nutrients and crop sequences on P balance sheet, kg ha ⁻¹	204-205
17.	Effect of residual nutrients and crop sequences on K balance sheet, kg ha ⁻¹	206-207
18.	Effect of residual nutrients and crop sequences on Zn balance sheet, kg ha ⁻¹	206-207
19.	Effect of residual nutrients and crop sequences on energy efficiency and specific energy	208-209

20.	Effect of residual nutrients and crop sequences on energy productivity and energy intensity	210-211
21.	Interaction effect of residual nutrients and crop sequences on system yield and system productivity	212-213
22.	Effect of residual nutrients and crop sequences on economics of rice based cropping system	212-213

LIST OF PLATES

Plate No.	Title	Between pages
1.	General view of the experiment during <i>virippu</i>	42-43
2.	General view of the experiment during <i>mundakan</i>	42-43
3.	General view of the experiment during <i>puncha</i>	42-43
4.	Different growth stages of the <i>virippu</i> rice	44-45
5.	Different growth stages of the <i>mundakan</i> rice	44-45
6.	Comparison of treatments at maximum tillering stage during <i>virippu</i>	188-189
7.	Comparison of treatments at maximum tillering stage during <i>mundakan</i>	188-189
8.	Comparison of treatments at panicle initiation stage during <i>virippu</i>	190-191
9.	Comparison of treatments at panicle initiation stage during <i>mundakan</i>	190-191
10.	Comparison of treatments at flowering stage during <i>virippu</i>	196-197
11.	Comparison of treatments at flowering stage during <i>mundakan</i>	196-197
12.	Comparison of treatments at harvest stage during <i>virippu</i>	198-199
13.	Comparison of treatments at harvest stage during <i>mundakan</i>	198-199

LIST OF APPENDICES

Sl. No.	Title	Appendix No.
1.	Weather data during <i>virippu</i>	Ia
2.	Weather data during <i>mundakan</i>	Ib
3.	Weather data during <i>puncha</i>	Ic
4.	Average input cost and market price of produce	II
5.	Standard energy equivalent per unit values for inputs and outputs	III
6.	Fixed energy input (MJ ha ⁻¹) of <i>virippu</i> rice	IVa
7.	Variable energy input (MJ ha ⁻¹) of <i>virippu</i> rice	IVb
8.	Fixed energy input (MJ ha ⁻¹) of <i>mundakan</i> rice	Va
9.	Variable energy input (MJ ha ⁻¹) of <i>mundakan</i> rice	Vb
10.	Energy input (MJ ha ⁻¹) of <i>puncha</i> grain cowpea	VI
11.	Energy input (MJ ha ⁻¹) of <i>puncha</i> bhindi	VII

ABBREVIATIONS AND SYMBOLS

%	Per cent
@	At the rate of
₹	Rupee
₹ ha ⁻¹	Rupees per Hectare
AE	Agronomic Efficiency
AEU	Agro Ecological Unit
AICRP	All India Co-ordinated Research Project
ANOVA	Analysis of Variance
ARE	Apparent Recovery Efficiency
B	Boron
BCR	Benefit Cost Ratio
BD	Bulk Density
Ca	Calcium
CD (0.05)	Critical Difference at 5 % Level
cm	Centi Meter
cm ²	Square Centi Meter
CO ₂	Carbon Dioxide
CTCRI	Central Tuber Crops Research Institute
CTR	Conventional Transplanting
DAP	Days After Planting
DAP	Diammonium Phosphate
DAS	Days After Sowing
DAT	Days After Transplanting
DSR	Direct-Seeded Rice
DTPA	Diethylene Triamine Penta Acetic Acid
EC	Electrical Conductivity
EC	Emulsifiable Concentrate
EDTA	Ethylene Diamine Tetra Acetic Acid
eg.,	For example
<i>et al.</i>	Co-workers/ Co-authors
etc.	Et cetera
Fe	Iron
FFP	Farmers' Fertilization Practice
Fig.	Figure
FS	Foliar spray
FYM	Farm yard manure
g	Gram
g ⁻¹	Per gram
GoI	Government of India
ha ⁻¹	Per Hectare

<i>i.e.</i>	That is
IARI	Indian Agricultural Research Institute
ICAR	Indian Council of Agricultural Research
IFFCO	Indian Farmers Fertilizer Co-operative Ltd.
IFS	Integrated Farming System
IFSRS	Integrated Farming System Research Station
K	Potassium
KAU	Kerala Agricultural University
kg	Kilogram
kg ha ⁻¹	Kilogram per Hectare
kg kg ⁻¹	Kilogram per Kilogram
kg MJ ⁻¹	Kilogram per Mega Joule
m ⁻²	Per Square Meter
mg	Milligram
mg L ⁻¹	Milligram per Litre
ml L ⁻¹	Millilitre per Litre
Mg	Magnesium
mg g ⁻¹	Milligram per Gram
mg kg ⁻¹	Milligram per Kilogram
mha	Million Hectares
MJ ₹ ⁻¹	Mega Joules per Rupee
MJ ha ⁻¹	Mega Joules per Hectare
mm	Millimeter
MOP	Muriate of Potash
MSPE	Micro and Secondary Nutrients and Pollutant Elements in Soils and Plants
mt	Million Tonnes
MT	Maximum Tillering
N	Nitrogen
NFs	Nanofertilizers
nm	Nano Meter
NP	Nutri Priming
NPs	Nanoparticles
NR	Nutrient Response
NS	Not-Significant
NUE	Nutrient Use Efficiency
OC	Organic Carbon
°C	Degree Celsius
°E	Degree East
°N	Degree North
P	Phosphorus

PE	Physiological Efficiency
pH	Potenz Hydrogen
PI	Panicle Initiation
POP	Package of Practices
ppm	Parts Per Million
PU	Prilled Urea
PudTR	Puddled Transplanted Rice
q ha ⁻¹	Quintal per Hectare
RBCS	Rice-Based Cropping Systems
RCBD	Randomized Complete Block Design
RDN	Recommended Dose of Nutrients
REY	Rice Equivalent Yield
RH	Relative Humidity
SA	Soil Application
SC	Suspension Concentrate
SEm	Standard Error of mean
SGM	Summer Green Manuring
SHM	Soil Health Management
SRI	System of Rice Intensification
t	Tonnes
t ha ⁻¹	Tonnes per Hectare
USDA	United States Department of Agriculture
<i>viz.</i>	Namely
w/v	Weight per Volume
ZEU	Zinc-Enriched Urea
Zn	Zinc
ZnCU	Zinc-Coated Urea
ZnO	Zinc oxide

INTRODUCTION

1. INTRODUCTION

Rice (*Oryza sativa* L.) is a vital cereal crop which serves as the staple food for major parts of the world. Rice as a staple food serves more than half of the world's population. It is predominantly cultivated and consumed in Asian continent accounting for more than 90 per cent of the world's production. India is the second major producer of rice after China, with the contribution of 26 per cent to the world's rice production (USDA, 2024). In India, rice is grown on 47.83 mha, with a production of 137.82 mt and productivity of 2.88 t ha⁻¹ (INDIASTAT, 2024). Rice's remarkable adaptability to diverse climatic conditions and its versatile cultivation methods make it an ideal crop to meet global food demands. This adaptability not only ensures food security but also enhances economic profitability, particularly in developing countries.

Rice-based cropping systems are integral to Indian agriculture, significantly contributing to food security, economic stability and sustainable farming practices. Rice-based cropping systems are highly versatile, adaptable to diverse ecological zones and suitable for both irrigated and rainfed conditions. These systems involve the rotation or combination of rice with other crops such as cereals, pulses, oilseeds and vegetables, tailored to the diverse agro-climatic zones across the country. In India, the rice-based cropping system allocates the largest area to the rice-wheat system, spanning approximately 10.38 mha. Uttar Pradesh contributes the most to this system, covering 4.12 mha, followed by Punjab with a significant share of 2.10 mha. The rice-rice system is another prominent cropping practice, primarily found in southern states such as Tamil Nadu (2.15 mha), Andhra Pradesh (1.39 mha), Assam (1.13 mha), Karnataka (0.68 mha), Gujarat (0.26 mha), Kerala (0.13 mha) and Odisha (0.14 mha), collectively accounting for 5.89 mha (Shahid *et al.*, 2024). In southern parts of the country where rice-rice cropping system is majorly followed, crops like vegetables and pulses in rotation during summer season will improve profitability as well as the soil health.

Nutrient management across different seasons is crucial for maximizing the productivity of cropping systems. Micronutrients are essential in boosting the yield potential of various cropping patterns (Deep *et al.*, 2018). In India, zinc (Zn) has emerged as the fourth most significant nutrient limiting crop yields. The prevalence of zinc deficiency in Indian soils is projected to rise from 42 to 63 per cent by the year 2025 (Sharma *et al.*, 2021). Cakmak (2008) emphasized that nearly half of the agricultural land worldwide suffers from a low concentration of bioavailable zinc (Zn), a critical micronutrient necessary for optimizing crop yields and enhancing the nutritional quality of grains. This deficiency is a growing concern in many countries, as both soils and plants often exhibit insufficient Zn levels. One of the primary reasons for this widespread issue is that, despite the presence of adequate total zinc in the soil, its solubility is extremely low, limiting its availability to plants. This lack of accessible Zn hinders crop productivity and can lead to nutritional deficiencies in the food supply, highlighting the need for improved soil and crop management strategies to address this challenge effectively.

Phosphorus (P) fertilization plays a critical role in soil fertility and crop growth, but its interaction with zinc (Zn) significantly influences nutrient uptake by plants. These two nutrients exhibit antagonistic behavior in plant nutrition, where high levels of P can interfere with Zn absorption resulting in P induced Zn deficiency (Watts-Williams *et al.*, 2014; Zhang *et al.*, 2012). Excessive P fertilization was particularly detrimental to Zn uptake in cereal crops like rice, where Zn deficiency can impair plant growth, yield and grain quality (Sánchez-Rodríguez *et al.*, 2017).

Zinc is an essential micronutrient for plants, required in minimal quantities but crucial for numerous physiological and biochemical processes vital to their growth and development (Mousavi *et al.*, 2011; Cabot *et al.*, 2019). It is integral to synthesizing cytochromes, nucleic acids and activating enzymes involved in carbohydrate metabolism, oxidation reactions, and revival mechanisms in plants (Alloway, 2008b). Zn serves as a

cofactor for enzymes like rubisco, which is critical for photosynthesis and chlorophyll synthesis, and it also plays a critical role in protein biosynthesis (Das *et al.*, 2018). Furthermore, it supports membrane stability, seed and stalk maturation, and auxin production, which drives plant growth (Barman *et al.*, 2018). Zinc also contributes to enhancing stress tolerance, strengthening the plant immune system and defending against pathogens (Nandal and Solanki, 2021).

Zinc deficiency, a widespread micronutrient disorder, negatively affects photosynthetic activity in cereal crops and leads to leaf yellowing, commonly referred to as chlorosis (Sharma *et al.*, 2021; Sharma *et al.*, 2013). On the other hand, both excessive and deficient levels of Zn can lead to the generation of reactive oxygen species, damaging plant cells (Cabot *et al.*, 2019). Therefore, Zn plays a fundamental role in maintaining plant health, improving productivity and building resilience to environmental stresses. Lack of sufficient zinc content in food grains would also lead to deficiency in humans. Approximately 60 to 70 per cent of people in Asia and Sub-Saharan Africa are at risk of insufficient zinc (Zn) consumption (Prasad *et al.*, 2014). Globally, one-third of the population faces the threat of Zn deficiency, with children under five being particularly vulnerable due to their higher Zn requirements for growth and development (Cakmak and Kutman, 2018).

Zinc is supplied to crops through various methods such as soil application, foliar spraying, seed priming, or a combination of these techniques (Khan *et al.*, 2003). The effectiveness of these methods varies. Soil application is the most commonly used approach, and its success depends on factors like soil pH, moisture levels, the presence of competing nutrients, and the plant's ability to absorb Zn *etc.* (Rehman *et al.*, 2015). Conversely, foliar application depends on the plant's ability to absorb and efficiently transport zinc to the grains. Since different crops respond uniquely to various zinc application methods, it becomes important to carefully select the approach that best meets the nutritional requirements of the specific crop (Praharaj *et al.*, 2021).

Foliar application of zinc has been recognized as an effective approach to mitigate challenges associated with zinc immobilization and fixation in soils (Pandey *et al.*, 2013). This method has also been shown to enhance zinc concentration in grains more effectively than conventional soil application (Hidoto *et al.*, 2017). Additionally, seed priming with zinc fertilizers can contribute to improved crop productivity by promoting root development, which in turn enhances the plant's ability to absorb nutrients and water more efficiently (Pereira *et al.*, 2021).

Conventional fertilizer application often leads to excessive use, posing environmental risks due to the need for larger quantities to deliver adequate nutrients. Environmentalists and consumers advocate reducing synthetic fertilizers to minimize pollution, residue effects, and protect agro-ecosystems. Sustainable crop production requires alternative nutrient sources and improved nutrient delivery methods. Nanotechnology has brought significant advancements to agriculture, transforming various practices. In the last decade, the use of nano-fertilizers has contributed to increased crop productivity, lowered production costs and enhanced production stability (Kashyap *et al.*, 2016; Kashyap *et al.*, 2017).

Nanotechnology, using materials smaller than 100 nm, offers a promising solution by enhancing nutrient absorption, efficiency and minimizing losses. Nanomaterials, due to their reduced size, exhibit a high surface to volume ratio, increased reactivity and unique properties compared to their bulk or ionic forms (Ahmed *et al.*, 2021). These properties enable nano materials to fortify plants, enhance abiotic stresses tolerance and strengthen plant defenses against pathogens (Elmer and White, 2018; Etesami *et al.*, 2021). Nano-fertilizers are developed through nutrient encapsulation, thin nanomaterial coatings, or nano-sized emulsions. Their uptake is facilitated by nano-pores and stomatal openings, improving nutrient use efficiency (NUE). Enhanced transport through plasmodesmata (50-60 nm channels) further boosts delivery, resulting in 6-17 per cent higher productivity and improved crop quality (Kumar *et al.*, 2021).

Nano zinc fertilizers formulated with zinc oxide (ZnO) nanoparticles have shown considerable potential in boosting cereal crop productivity. These fertilizers present an effective approach for correcting soil zinc deficiencies, thereby improving both the yield and quality of crop production (Azam *et al.*, 2022). Zinc oxide nanoparticles are estimated to be absorbed by plants 15-20 times more efficiently than traditional zinc salts. Unlike zinc salts, which are highly water-soluble and prone to nutrient leaching, zinc nanoparticles exhibit lower solubility, reducing nutrient loss and improving overall nutrient use efficiency (Srivastav *et al.*, 2016).

Considering the above scenario, for a better understanding of response of rice crop to nano zinc nutrition in high P soils, the present study is proposed. The primary objectives of the research were

- To evaluate the response of rice to nano zinc in high P soils
- To study the residual effect of nano zinc nutrition on growth and yield of succeeding crops
- To study the P - Zn interactions
- To identify promising crop sequence in terms of system productivity and profitability

REVIEW OF LITERATURE

2. REVIEW OF LITERATURE

Rice (*Oryza sativa* L.) being a key food source, sustains more than half of the global population. Rice-based cropping systems are essential for Indian agriculture, contributing to food security, economic stability, and environmental sustainability (Upadhaya *et al.*, 2022). Diversifying these systems with legumes, vegetables, pulses, oilseeds, fodder, and medicinal crops enhances productivity, optimizes resource use, and reduces reliance on chemical fertilizers. Crop diversification has proven to be an effective strategy for improving farm income, mitigating weather related risks, and addressing food and nutritional insecurity (Dalal and Shankar, 2022). Legumes, in particular, support sustainable agriculture by fixing atmospheric nitrogen, benefiting both the main and subsequent crops. Additionally, integrating vegetable crops within these systems has been shown to increase farmers' net profitability.

In rice based cropping systems the productivity and profitability of the system can be improved to the best by adopting the effective technologies of production which can overcome the factors restricting productivity. Nutrient management is a critical factor in enhancing both the productivity and profitability of agricultural systems. Micronutrients in particular, play a vital role in boosting the productivity of cropping systems (Deep *et al.*, 2018). In India, zinc (Zn) has emerged as the fourth most important nutrient limiting crop yields. The prevalence of zinc deficiency in Indian soils is expected to rise significantly, from 42 to 63 per cent, by 2025 (Sharma *et al.*, 2021).

In rice, zinc deficiency is more prominent compared to other field crops especially in high P soils and also the grains are very poor in zinc content. Zinc and phosphate ions have an affinity for each other, leading to the formation of chemical bonds either within the soil or the plant. This interaction can result in a phosphorus-induced zinc deficiency.

This chapter provides a detailed review of research on zinc nutrition in rice-based cropping systems under high-phosphorus soils, with a focus on the effects of nano and

conventional fertilizers and various methods of their application. It examines their influence on the growth and yield of succeeding crops, phosphorus-zinc interactions, system productivity, and overall profitability.

2.1 ZINC AND PHOSPHORUS STATUS OF SOILS IN INDIA AND KERALA

Zinc (Zn) deficiency is a significant issue in Indian soils, impacting crop productivity and food quality. A comprehensive soil health management (SHM) initiative, carried out by the Indian government from 2015 to 2019, analyzed more than 30 million soil samples. The findings indicated that 39 per cent of Indian soils are deficient in zinc, with levels falling below the threshold of 0.6 mg kg^{-1} (GoI, 2019).

Zinc deficiency is a significant concern in Indian agricultural soils, affecting crop productivity and nutritional quality. A large-scale study analyzing 2,42,827 surface soil samples from 615 districts across 28 states revealed that Zn deficiency affects 51.2 per cent of soils. More than 50 per cent of soils in 131 districts were deficient in available Zn, highlighting its widespread occurrence. Additionally, Zn deficiency often coexists with other nutrient deficiencies, with notable instances of Zn+B (8.7 per cent), Zn+Fe (5.8 per cent), Zn+Mn (3.4 per cent), and Zn+Cu (2.8 per cent) deficiencies. The findings emphasize the urgent need for targeted Zn fertilization strategies to enhance crop yield, improve soil health, and address nutritional deficiencies in both plants and humans (Shukla *et al.*, 2021).

Zinc (Zn) deficiency is a major limitation to crop production in the Southern Laterites (AEU 8) of Kerala, as observed in the wetlands of Chenkal panchayat, Parassala block, Thiruvananthapuram. The study found that widespread deficiencies of Zn, along with calcium, magnesium, sulphur, and boron, necessitating external inputs of secondary and micronutrients for improved crop productivity. Balanced fertilization, including appropriate micronutrient mixtures, is recommended to enhance rice yield and nutrient use efficiency in this region (Sheeba *et al.*, 2019). Aparna *et al.* (2023) conducted a soil survey to identify the soil fertility status of the AEU 8, Thiruvananthapuram. Soil samples

were collected by geo referenced soil sampling method and were analysed for soil fertility status. Results indicated that there is sufficient amount of the zinc in soils, unless there is a high phosphorus situation, stating to the deficiency of zinc in soils prevailed in high phosphorus containing soils as a effect of phosphorus induced zinc deficiency.

The All India Coordinated Research Project on Micro and Secondary Nutrients and Pollutant Elements in Soils and Plants (AICRP-MSPE), under the Indian Council of Agricultural Research (ICAR), reported that approximately 38 per cent of Indian soils are deficient in zinc. These findings emphasize the need for better micronutrient mapping and targeted Zn fertilization to boost crop yields and nutrition (Khokhar *et al.*, 2024).

A permanent manurial trial at ICAR-CTCRI, conducted over 14 years in tuber crops with various combinations of N, P and K both individually and with FYM, highlighted the necessity of maintaining soil Zn levels. The lowest Zn concentrations were observed in treatments with phosphorus alone and those lacking FYM and K (John, 2024).

2.2 ZINC AND PHOSPHORUS NUTRITION IN RICE BASED CROPPING SYSTEMS

Shivay *et al.* (2018) conducted a field experiment over two years to evaluate the impact of zinc-enriched urea (ZEU) on the productivity, Zn uptake, and use efficiency in an aromatic rice-wheat cropping system. Eight treatments included prilled urea (PU) and ZEU at 0.5 per cent to 3.5 per cent, using ZnO (80 per cent Zn) for enrichment. Growth, yield, Zn concentration, uptake, and economic parameters were analyzed. Results showed that 3.5 per cent ZEU recorded the highest yield and Zn uptake (1,168-1,353 g ha⁻¹). Wang *et al.* (2014) conducted an experiment in an intensive rice production system to evaluate the effects of different Zn fertilization sources, specifically ZnSO₄ and Zn-EDTA, on grain yield and Zn accumulation in rice grains. The study found that Zn application significantly enhanced both yield and grain Zn content compared to treatments without Zn fertilization. Grain yield increased by 29.6 per cent with ZnSO₄

application and by 19.9 per cent with Zn-EDTA compared to control, demonstrating the beneficial impact of Zn fertilization on rice productivity and nutritional quality.

Amanullah *et al.* (2020) studied a rice-wheat cropping system for assessing the individual and combined effects of phosphorus and zinc fertilization on rice productivity and concluded that the combined application of 80 kg P ha⁻¹ and 10 kg Zn ha⁻¹ resulted in the highest grain yield of 7.8 t ha⁻¹. This treatment also showed significant improvement in various growth parameters compared to other nutrient combinations. A study conducted by Shahane *et al.* (2020) demonstrated that the application of 5 kg Zn ha⁻¹ through ZnSO₄.7H₂O along with the complementary microbial consortia of N fixing and P solubilising microorganisms improved soil DTPA-extractable Zn levels by 4.025-4.836 g ha⁻¹, representing a 20-24 per cent increase after two rice wheat cropping cycles. Thus integrating Zn fertilization with microbial inoculation can optimize Zn use efficiency, enhance soil fertility, and improve nutrient uptake in rice wheat cropping system.

Lakshmi *et al.* (2021) conducted a six-year study in rice-wheat cropping system to evaluate different Zn fertilization strategies. The study tested three application frequencies of Zn such as application only in the first year, every alternate year, and annually and at four Zn rates such as 2.5, 5.0, 7.5 and 10 kg ha⁻¹ per year. Zn forms such as water-soluble, exchangeable, and complexed Zn correlated significantly with yield and Zn uptake. The most effective strategy was 10 kg ha⁻¹ applied biennially, while 7.5 kg ha⁻¹ applied annually also yielded comparable results. Choudhary *et al.* (2022) evaluated the system of rice intensification (SRI) in comparison to conventional transplanting (CTR) across three nutrient management strategies: farmers' fertilization practice (FFP), which included FYM at 5 t ha⁻¹ along with N:P₂O₅:K₂O at 50:40:20 kg ha⁻¹; recommended dose of fertilizers (RDF) with FYM at 10 t ha⁻¹ and N:P₂O₅:K₂O at 90:40:40 kg ha⁻¹; and RDF supplemented with zinc fertilization through ZnSO₄ at 25 kg ha⁻¹. The application of RDF combined with zinc notably enhanced grain and straw yields relative to FFP, while also contributing to greater zinc enrichment in grains and increased zinc uptake compared to RDF alone. Moreover, this nutrient management approach

improved nutrient harvest index, partial factor productivity of NPK, and zinc use efficiency.

A study conducted at Pattambi, Kerala, investigated the interactive effects of phosphorus (P) and zinc (Zn) nutrition on the growth and yield of lowland rice (Rinthal, 2021). The experiment comprised 16 treatment combinations, involving four phosphorus application rates (0, 25, 50, and 100 mg kg⁻¹ as KH₂PO₄) and four zinc levels (0, 5, 10, and 15 mg kg⁻¹ as ZnSO₄·7H₂O). The combined application of 100 mg kg⁻¹ phosphorus and 10 mg kg⁻¹ zinc produced the highest grain and straw yields, while also significantly enhancing key growth parameters, indicating a synergistic effect of balanced P and Zn nutrition on rice performance.

Shankar *et al.* (2021a) conducted an experiment in an intensive rice-rice cropping system under a subtropical climate in the red and lateritic belt of western West Bengal. The study reported that applying zinc along with the recommended dose of fertilizers significantly improved growth and yield in both the *Kharif* (5.6 t ha⁻¹) and *Boro* (6.6 t ha⁻¹) seasons compared to the control treatment without Zn application.

In a 16-year long-term fertilizer study, various combinations of nutrients were tested to assess their effects on soil health and rice yield. Among the 12 treatments, those involving zinc (Zn) and phosphorus (P) - particularly 100% NPK + Zn, 100% NPK + Zn + S, and 100% NPK + Zn + B were crucial in understanding nutrient interactions and their influence on rice productivity. The treatments with combined Zn and recommended doses of phosphorus (as part of NPK) demonstrated notable improvements in soil biological and chemical attributes, which correlated with increased rice yield (Garnaik *et al.*, 2022).

Long-term assessment of Zn fertilization and FYM impact on soil properties in rice-based cropping systems (RBCS) in calcareous soils of Northern Bihar with four fertility levels (control, 50%, 100%, and 150% RDF) were tested in two cropping systems: Rice-Wheat-Sorghum (R-W-S) and Rice-Mustard-Moong (R-M-M). After ten

cycles, Zn deficiency was noted in 150% RDF treatments, prompting Zn and FYM amendments in alternate years. Treatments included 10 kg Zn ha⁻¹ alone, Zn with 5-10 t FYM ha⁻¹, and FYM alone. Soil analysis showed that 10 kg Zn ha⁻¹ with 10 t FYM ha⁻¹ significantly improved organic carbon, available Zn, and micronutrients. The study highlighted Zn fertilization with FYM as a sustainable strategy for maintaining Zn balance and soil fertility in long-term RBCS (Man *et al.*, 2024).

2.3 EFFECT OF NANO ZINC NUTRITION IN RICE BASED CROPPING SYSTEM

The application of nano zinc, through both soil and foliar routes, has demonstrated superior performance in enhancing crop yield (Apoorva *et al.*, 2017). Beyond yield improvement, zinc nanoparticles (Zn NPs) have also shown potential in managing key rice diseases. Zeinab *et al.* (2016) reported that foliar spraying of ZnO nanoparticles five days prior to inoculation effectively suppressed rice blast disease (caused by *Pyricularia grisea*), while application two days before inoculation was effective in controlling rice brown spot disease (*Helminthosporium oryzae*). Furthermore, Brijbooshan *et al.* (2018) observed that the recommended dose of fertilizers (RDF), combined with two foliar sprays of nano ZnO at 1000 ppm, significantly improved yield attributes-including panicle number, panicle length and weight, grain number per panicle, test weight, and overall grain and straw yield. This treatment performed comparably with RDF plus two foliar applications of ZnSO₄.7H₂O at 0.5 per cent and nano ZnO at 1500 ppm.

NPK along with nano zinc has improved the yields by 24 per cent owing to the high surface area and reactivity with the soil colloids nano zinc resulted in less nutrient loss, hence increased the zinc use efficiency, zinc harvest index and plant uptake efficiency index (Pal *et al.*, 2018).

Improvement in growth of pot grown rice plants in terms of plant height, chlorophyll content, biomass, tiller number and yield was observed with application of Zn oxide NP compared to ZnSO₄ (Rameshraddy *et al.*, 2017). Zinc NP is not only

effective in remediation but helps in Zn fortification in rice cultivated under low soil Zn concentration. Foliar application of Zn NP @ 5.0 g L⁻¹ was found to improve growth and yield parameters significantly and was also observed to report high dehydrogenase activity (Bala *et al.*, 2019). Treatment including fertilization with Zn nano particles along with basal application of ZnSO₄ was found to report good agronomic and physiological features which inturn resulted in higher yield and nutrient - enriched rice grains (Elshayb *et al.*, 2021).

Ghasemi *et al.* (2017) investigated the effect of foliar application of nano zinc oxide on key agronomic traits in rice using a split-plot design comprising five levels of ZnO treatments. The study demonstrated that foliar application of 20 ppm and 40 ppm ZnO during the panicle initiation and full heading stages significantly enhanced plant height, spikelets per panicle, biological yield, grain yield, and straw yield. Moreover, the highest number of tillers per hill was recorded under treatments involving foliar application of 20 ppm and 40 ppm ZnO during mid-tillering and panicle initiation, as well as 40 ppm during panicle initiation and full heading. The application of 40 ppm ZnO at panicle initiation and full heading also resulted in the greatest 1000-grain weight (27.58 g), while application at mid-tillering and panicle initiation produced the longest panicles (28.98 cm). These findings highlight the potential of stage-specific foliar application of nano zinc oxide to improve multiple yield-contributing parameters in rice.

Aswathy (2018) conducted a study to perceive the influence of nano zinc sources and application methods on zinc uptake and productivity in a rice–maize cropping system under alfisol conditions during *Kharif* season involved sixteen treatments with soil application and foliar spray methods during key growth stages of rice. The results revealed that nano-based formulations performed superior over traditional sources like zinc sulphate and zinc oxide in terms of yield and zinc uptake efficiency. Despite lower zinc content in nano formulations compared to zinc sulphate, their efficiency was higher,

making them promising alternatives for enhancing crop productivity and nutrient use efficiency in rice-maize systems.

Nano-fertilizers have emerged as valuable inputs in modern agriculture, contributing to enhanced crop yield, quality, and nutrient use efficiency. These formulations enable precise and timely delivery of nutrients aligned with the crop's developmental stages, thereby ensuring sustained nutrient availability throughout the plant growth cycle (Hayyawi, 2021).

A controlled pot experiment was undertaken to investigate the influence of varying dosages of zinc oxide nanoparticles (ZnO NPs) - 0.3, 0.6, 1.2, 2.4, and 4.8 g Zn pot⁻¹ on the yield attributes and grain quality of rice. The results demonstrated that ZnO NPs markedly enhanced biomass accumulation, grain yield, and zinc enrichment in rice grains. Application of ZnO NPs led to significant improvements in key yield components, including an increase in panicle number (4.83-13.14 per cent), spikelets per panicle (4.81-10.69 per cent), filled grain percentage (0.28-2.36 per cent), and thousand-grain weight (3.82-6.62 per cent), relative to the control. Additionally, the application positively influenced grain quality indicators such as brown rice recovery, milled rice percentage, and nutritional constituents including amylose and protein content. Notably, ZnO NP treatments substantially elevated zinc concentration in polished rice grains, highlighting their potential as an agronomically efficient approach for enhancing both yield and nutritional quality in rice cultivation systems Zhang *et al.* (2021).

Kumar and Singaravel (2022) revealed that the zinc oxide nanoparticles (ZnO NPs) in seed priming was superior. In experiments involving four rice varieties (ADT-50, ADT-45, ADT-43, and CR-1009), ZnO NPs at concentrations ranging from 200 to 2000 ppm were tested. Notably, priming with 1000 ppm ZnO NPs significantly enhanced shoot length, root length, vigour index, and germination percentage. The highest values were observed in the ADT-50 variety, with a shoot length of 12.94 cm, root length of 10.96 cm, vigour index of 2390, and 100 per cent germination rate. Mi *et al.* (2023) studied the

effectiveness of zinc oxide nanoparticles (ZnO NPs) as a novel fertilizer in enhancing rice yield and quality. Field trials conducted over two years demonstrated that ZnO NPs significantly increased rice grain yield by 3.24 to 5.12 per cent and improved rice quality by boosting the head milling rate and reducing chalky grains. Additionally, ZnO NPs application substantially increased zinc content in both milled and brown rice, with increases ranging from 18.11 to 48.30 per cent. The optimal dosage for these benefits was found to be between 7.5 kg and 30 kg ha⁻¹.

Foliar application of phosphorus and zinc nano particles has shown positive effects on the growth and yield of rice in rice production systems. The application of two-third of the recommended NPK dose combined with 50 ppm zinc nanoparticles (Zn50NPs) significantly improved grain yield (10.05 t ha⁻¹) and straw yield (13.68 t ha⁻¹) compared to the full recommended dose of fertilizers NPK (165:36:60) applied through soil (Elekhtyar and AL-Huqail, 2023).

Parashar *et al.* (2023) studied the use of ZnO NPs and ZnSO₄ to enhance rice growth and zinc biofortification. The results showed that ZnO NPs significantly improved plant growth, yield, and zinc content in grains, even at low concentrations. Compared to ZnSO₄, ZnO NPs increased spikelet numbers by over 50 per cent, plant height by 25 per cent, and grain per spike by 19 per cent. Additionally, ZnO NPs boosted zinc content in grains by 55 per cent, making them a promising tool for efficient and safe biofortification in rice cultivation

A two years field experiment by Wang *et al.* (2023) demonstrated that foliar spraying of ZnO NPs significantly improved rice's breakdown and taste values by 31.0-41.7 per cent and 8.2-13.0 per cent, respectively, compared to the control treatment. Additionally, ZnO NPs increased zinc content and accumulation in grains by 33.6-65.1 per cent and 37.8-74.7 per cent, respectively. The application also elevated nitrogen content and enhanced the aroma compound 2-acetyl-1-pyrroline by 6.1-21.4 per cent. While ZnO NPs reduced Fe and Cu content in grains, they effectively enriched zinc in

edible parts and increased its bioavailability. Overall, ZnO NPs offer a promising method for improving rice quality, zinc enrichment, and aroma enhancement.

Poddar *et al.* (2025) emphasizing the pressing issue of soil degradation, due to rapid urbanization and industrialization, emphasizing the potentials of nanofertilizers (NFs) as a sustainable alternative to traditional chemical fertilizers. NFs offer a controlled release mechanism that enhances nutrient absorption efficiency, reducing waste and promoting soil health. The focus on optimal soil management through nanomaterials is promising for improving agricultural productivity, crop quality and soil microbial activity. The use of nanofertilizers in modern agriculture, aiming to balance productivity with environmental stewardship.

2.4 EFFECT OF DIFFERENT FERTILIZER APPLICATION METHODS OF ZINC ON GROWTH AND YIELD PARAMETERS OF RICE

Seed priming in 0.5 per cent (w/v) zinc solution increased the yield by ≤ 5 per cent. Zn concentration in whole grain increased from 22 (control) to 29 mg kg⁻¹ when applied as soil along with foliar spray and also increased the grain yields (Imran *et al.*, 2015). Seed priming with NP can increase the productivity of many crop species, due to the positive effects of NP on plant metabolism and development, increased root development leads to increased potential of the plant to access nutrients and water, consequently larger leaf area and use of light energy by plants for its growth (Pereira *et al.*, 2021). Seed priming with ZnO nanoparticles (ZnO NPs) did not show significant effects on seed germination; however, it notably enhanced seedling growth. This improvement was attributed to enhanced physiological and biochemical responses, including increased zinc concentration and ZnO NPs uptake in the seedlings, as well as the modulation of other metabolic pathways in the rice seedlings (Li *et al.*, 2021).

Foliar application of zinc during reproductive phase, from heading to early milk stage resulted in higher grain zinc concentration (Fang *et al.*, 2008). Kheyri *et al.* (2019) in his experiment found that application of nano zinc at 300 g ha⁻¹ and soil application @

9 kg Zn ha⁻¹ increased the yield components, yield and nutrient accumulation in rice plant tissue.

Zulfiqar (2021) highlighted zinc (Zn) deficiency as a critical abiotic constraint affecting rice productivity and a significant nutritional challenge for human health. The study evaluated four Zn application strategies under two rice cultivation systems-puddled transplanted rice (PudTR) and direct-seeded rice (DSR): zinc seed coating (2 g Zn/kg seed), zinc seed priming (0.25 M Zn solution), basal soil application (10 kg Zn ha⁻¹), and foliar spraying (0.5 per cent Zn solution). Positive controls included hydro-priming and foliar water application, alongside a no-zinc control. Across both systems, Zn application markedly improved grain Zn concentration and yield. Over a two-year period, seed priming produced the highest yield enhancement (23 per cent), followed by foliar spray and basal application (both 18 per cent), and seed coating (13 per cent). The maximum grain Zn concentration was achieved with seed priming in PudTR (33 per cent increase) and basal application in DSR (45 per cent increase). Overall, zinc seed priming emerged as the most efficient and cost-effective approach to enhance both rice yield and Zn biofortification.

Kandil *et al.* (2022) investigated the impact of varying concentrations of foliar-applied zinc (Zn) on multiple agronomic, yield-related, and grain quality parameters in rice. The results demonstrated that foliar Zn application significantly influenced plant height, grain yield, straw yield, biological yield, harvest index, 1,000-grain weight, panicle length, protein content, and grain Zn concentration. A pronounced effect of Zn supplementation was evident across all measured plant attributes. Notably, higher rates of foliar Zn application (up to 2,500 mg L⁻¹) consistently enhanced yield components, nutrient content, and grain quality traits across both growing seasons. The study recommended foliar Zn application at a concentration of 2,000 mg L⁻¹ as an effective strategy to optimize rice productivity and grain nutritional quality while supporting environmental and human health considerations.

In order to assess how different zinc (Zn) administration techniques and combinations of Zn formulations affected rice development and yield, Patel *et al.* (2022) were found that productivity was greatly boosted by applying RDF in conjunction with root dipping in 2 per cent ZnO and RDF with soil application of 5.0 kg Zn ha⁻¹. Furthermore, compared to RDF, the postharvest soil's DTPA-extractable Zn level increased 1.78 times after 10 kg Zn ha⁻¹ was applied.

Nandy *et al.* (2023) reported the impact of combining inorganic and organic nutrients with nano zinc foliar spray on rice growth in Inceptisols. The recommended dose of nitrogen 60 kg ha⁻¹ and the applied FYM (0.53% N, 0.17% P, 0.56% K and 1.81µg g⁻¹ Zn). The results showed that a combination of 75 per cent recommended nitrogen dose from chemical fertilizers, 25 per cent from farmyard manure, and nano zinc spray @ 10 mg L⁻¹ yields the highest grain yield at 5.06 t ha⁻¹ by increasing the number of panicles per m⁻² and grains per panicle, surpassing the yield from 100 per cent of recommended dose of nitrogen.

Ramaiyan *et al.* (2023) studied comparison of zinc (Zn) application methods (soil-applied ZnSO₄ vs. ZnO nanoparticle seed priming ± foliar spray) and fortified organic manures (farmyard manure/rice residue compost) across three rice systems: transplanted (TPR), direct-seeded (DSR), and aerobic (AR). ZnO nanoparticles + fortified rice residue compost maximized the soil health and sustainability AR systems outperformed over TPR and DSR in soil quality with 11.3 per cent higher organic carbon 21.96 per cent increase in dehydrogenase activity (microbial health) and 17.31 per cent more microbial biomass carbon. Besides this it also enhanced the Zn use efficiency in TPR and DSR along with the AR system. AR systems increased the DTPA-Zn (bioavailable soil Zn) by 10.57 per cent.

Sharma *et al.* (2023) evaluated the impact of Nano N and Nano Zn on rice (HPR 2795 variety) in mid-hill conditions. The study tested 14 nitrogen management strategies, combining conventional N (100, 75, or 50 per cent of 60 kg ha⁻¹) with foliar sprays of

Nano N (4 ml L⁻¹) and/or Nano Zn (2 ml L⁻¹). The results demonstrated that the treatment 100 per cent N + single combined spray of Nano N and Nano Zn achieved the highest grain yield (34.9 q ha⁻¹ in 2021; 33.9 q ha⁻¹ in 2022), closely followed by 75 per cent N + double combined sprays of Nano N and Nano Zn (33.5 q ha⁻¹ in 2021; 32.5 q ha⁻¹ in 2022). Plant height at all growth stages was significantly higher in 100 per cent N + single combined spray of Nano N and Nano Zn, though statistically comparable to 75 per cent N + double combined sprays of Nano N and Nano Zn. Developmental parameters (e.g., tillering, panicle initiation) were unaffected by treatments.

Yogi *et al.* (2023) assessed various zinc (Zn) fertilization approaches for upland (rainfed) rice cultivation in north-eastern India, with a focus on enhancing Zn-use efficiency, grain biofortification, and yield performance. The study demonstrated that foliar application of zinc sulfate was the most effective strategy, resulting in notable increases in grain yield (16.3 per cent), straw yield (18.8 per cent), and grain Zn concentration (37.9 mg kg⁻¹), representing a 29 per cent improvement over the untreated control. Furthermore, foliar Zn supplementation positively influenced rice processing qualities, leading to improved hulling efficiency (79 per cent), milling recovery (67.9 per cent), and head rice recovery (57.6 per cent). These findings highlight the potential of foliar Zn application as a viable agronomic practice to enhance both productivity and nutritional quality in upland rice systems.

Hossain *et al.* (2025) evaluated the effect of foliar application of zinc (Zn) and boron (B) on wheat growth and yield. The study having varying application methods and rates of Zn included soil application as well as foliar applications at different stages and concentrations. Treatment N₁₄₀P₂₅K₁₁₀S₁₆ kg ha⁻¹ with twice foliar application of Zn @ 2 kg ha⁻¹ along with boron @ 1 kg ha⁻¹ at 35 DAS and 50 DAS, showed the most significant improvement in wheat growth and yield attributes. This suggests that repeated foliar application of zinc can enhance plant performance.

Muthukumararaja *et al.* (2025) has reported the critical role of zinc in enhancing rice growth and yield in zinc-deficient soils. The experiment compared four zinc sources (Zinc Lysinate, Zinc HEDP, Zinc oxide, Zinc sulphate) and four application levels (Zn0-0, Zn1- 2.5, Zn2- 5, Zn3- 7.5 kg Zn ha⁻¹). Among the tested formulations, zinc Lysinate emerged as the most effective, delivering yields comparable to zinc sulfate. The optimal results were achieved with soil application of zinc at 5 kg ha⁻¹, particularly when combined with zinc Lysinate. These findings underscore the importance of selecting suitable zinc sources and application rates to sustainably improve rice productivity in Zn stressed soil conditions.

2.5 EFFECT OF RESIDUAL NUTRIENT STATUS ON SUMMER CROPS IN RICE BASED CROPPING SYSTEM

Transitioning from anaerobic conditions in flooded rice cultivation to aerobic conditions during subsequent dry season crops has been shown to enhance zinc (Zn) availability in the soil and improve Zn uptake by crops (Abdullah, 2015). These combined influences likely contribute to the sustained residual benefits of Zn application within rice-based cropping systems.

Kumar *et al.* (2020) evaluated the residual effects of Zn fertilization on rapeseed in a rice-rapeseed cropping sequence in acidic soils of Northeast India. Results showed that Zn fertilization applied to the preceding rice crop significantly improved rapeseed productivity, except for foliar Zn application alone. The treatment combining Zn at 10 kg ha⁻¹ with a 0.5 per cent foliar spray (two times-panicle initiation and booting stages) yielded the highest plant height (48.9 cm), siliqua per plant (24.8), seeds per siliqua (14.4), seed yield (692 kg ha⁻¹) and biological yield (2390 kg ha⁻¹). This combination was identified as the most profitable option for enhancing rapeseed productivity in the region under the rice-rapeseed sequence.

The experiments, conducted during the *rabi* seasons of 2018-19 and 2019-20, investigated the combined effects of recommended fertilizer doses with or without nano

zinc on lentils under residual soil conditions from preceding rice crops. Foliar application of nano zinc significantly improved lentil growth and yield attributes. It increased the number of branches per plant by 19.57 per cent and the number of filled pods per plant by 5.49 per cent, leading to a 10.17 per cent increased seed yield compared to treatments without nano zinc (Nandy *et al.*, 2025). Accordingly, the use of nano zinc enhanced total zinc uptake by 11.34 per cent, along with increases in nitrogen (7.83 per cent) and potassium (8.26 per cent) uptake by lentil which has proceeded by rice crop. It also positively affected soil health by increasing dehydrogenase enzyme activity, a marker of microbial activity, by 1.75 and 1.42 per cent at 30 and 60 days after sowing, respectively.

The study conducted at ICAR-IARI, during 2020 and 2021, evaluated the effects of summer green manuring (SGM) and various fertilization strategies on basmati rice – wheat cropping system in Indo Gangetic Plain. The experiment revealed that incorporating *Sesbania aculeata* as green manure significantly boosted rice grain yield by 13.2 per cent and 12.3 per cent compared to fallow plots. Fertilization strategies integrating zinc with urea further enhanced yield, with a 9.56-10.5 per cent increase relative to urea alone and a remarkable 33.7-33.8 per cent improvement over sole zinc application. The study also highlighted the nutritional benefits of SGM, which increased micronutrient content (Zn, Cu, Mn, Fe) in milled rice by up to 25 per cent in 2020 and 23.75 per cent in 2021 compared to fallow plots. Combining zinc-coated urea with SGM improved Zn and Fe content in rice by approximately 2.99 mg kg⁻¹ and 2.62 mg kg⁻¹ in the first year and slightly less in the second year. Among fertilization methods, the application of *Sesbania* with 1 per cent bulk ZnO-coated prilled urea yielded superior results for grain yield, micronutrient acquisition, and protein content. However, plots treated with *Sesbania* combined with 0.2 per cent nano ZnO-coated urea showed statistically comparable outcomes. Additionally, nano ZnO-coated urea reduced zinc usage by 20 per cent, offering a cost-effective and sustainable alternate for farmers (Baral *et al.*, 2023a).

2.6 EFFECT OF DIFFERENT FERTILIZER APPLICATION METHODS OF ZINC ON NUTRIENT USE EFFICIENCY, NUTRIENT BALANCE AND SOIL HEALTH

Bana *et al.* (2022) investigated the effects of zinc fertilization on biofortification and nutrient use efficiency of basmati rice in the Himalayan foothill region. Among the zinc management strategies, the combined application of 4.0 per cent zinc-coated urea (ZnCU) with a 0.2 per cent foliar zinc spray ($\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$) resulted in the highest grain (3.46 t ha^{-1}) and straw (7.93 t ha^{-1}) yields. The use of ZnCU enhanced rice productivity by approximately 25.4 per cent compared to conventional urea. This treatment also led to the greatest accumulation of zinc (35.93 mg kg^{-1} in grain and 81.64 mg kg^{-1} in straw) and nitrogen (1.19 per cent in grain and 0.45 per cent in straw). Additionally, ZnCU applied at 4.0 per cent demonstrated superior nitrogen use efficiency relative to soil-applied zinc alone. Zinc fertilization notably influenced grain quality traits, significantly improving the elongation ratio (1.90) and protein content (7.44 per cent). These findings suggest that ZnCU application represents a cost-effective and efficient approach to enhance rice yield, nutrient use efficiency, grain quality, and dietary zinc biofortification, while addressing zinc deficiency challenges in human nutrition.

Ramaiyan *et al.* (2023) evaluated zinc (Zn) application methods (soil-applied ZnSO_4 vs. ZnO nano particle seed priming \pm foliar spray) and fortified organic manures (farmyard manure/rice residue compost) across three rice systems: transplanted (TPR), direct-seeded (DSR), and aerobic (AR). ZnO nano particles + fortified rice residue compost maximized productivity by increasing the productive tillers m^{-2} (437), filled grains per panicle (186), grain weight (6.27 Mg ha^{-1}) and Zn fortification in grains (33.41 mg kg^{-1}). Furthermore, it improved the Zn fractions (plant-available soil Zn pools) in all the production systems.

Laik (2025) examined the interactive effects of zinc fertilization and long-term crop residue incorporation on soil biological properties within a rice-wheat cropping system. A split-plot experimental design was implemented, incorporating four levels of

crop residue addition (0, 25, 50 and 100 per cent) alongside four zinc application rates (0, 2.5, 5, and 10 kg ha⁻¹) on zinc-deficient calcareous soil. Crop residues were applied annually, while zinc was initially applied in 1994 and subsequently reapplied in 2018. The results revealed significant improvements in soil physical and biological quality, evidenced by reduced bulk density and enhanced soil organic carbon content and carbon stock. Application of zinc at 10 kg ha⁻¹ elevated soil active carbon and soil respiration by 35 per cent and 53 per cent, respectively, as estimated by a linear-plateau regression, with optimal residue levels of 73.73 per cent and 90.28 per cent. Furthermore, zinc application at 5 kg ha⁻¹ led to a 9.6 per cent increase in acid phosphatase enzyme (ACE) protein at an optimal residue level of 91.06 per cent. The combination of full (100 per cent) crop residue incorporation and zinc application at 10 kg ha⁻¹ produced the highest concentrations of available soil nutrients and rice grain yield. These findings underscore that integrating 10 kg ha⁻¹ of zinc with complete crop residue return substantially enhances soil biological activity, organic carbon accumulation, and nutrient availability in calcareous soils under a rice-wheat cropping sequence.

2.7 RESIDUAL EFFECT OF ZINC FERTILIZER IN RICE BASED CROPPING SYSTEMS

Kumari *et al.* (2017) reported the benefits of incorporating crop residues and applying zinc in improving soil health and crop productivity. By incorporating 100 per cent crop residues and applying 10 kg of zinc per hectare, the study achieved maximum yields for both rice and wheat from the 18 years of rice-wheat rotation in eastern Indo-Gangetic plains. Maximum rice and wheat yields were possible by incorporation of 100 per cent crop residue along with the application of 10 kg Zn ha⁻¹. The incorporation of crop residues significantly enhanced the availability of macro and micronutrients, by 60 per cent while zinc application increased its uptake by 57 per cent. However, zinc application also reduced the availability of other micronutrients like iron, copper, and manganese in calcareous soils.

Nadeem and Farooq (2019) conducted a field study within a rice-wheat rotation system to evaluate the residual effects of various zinc fertilizers namely zinc sulfate ($\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$), EDTA-chelated zinc, and zinc oxide (ZnO) on the subsequent wheat crop. Their findings demonstrated that EDTA-chelated zinc exhibited the most pronounced residual impact, as reflected in higher grain zinc concentration as well as increased grain and straw yields. This superior performance was attributed to the lower soil fixation of EDTA-chelated zinc, which facilitated enhanced zinc mobility and availability for root uptake in the following crop cycle.

Saxena and Singh (2019) conducted a field experiment in Modipuram, Meerut (U.P.) effectively demonstrated the positive impact of zinc (Zn) and farmyard manure (FYM) applications, both individually and in combination, on rice and subsequent wheat crop yields, as well as their micronutrient content. The combined application of 2.5 kg Zn and 5 t ha^{-1} significantly enhanced grain and straw yields by up to 39.3 per cent for rice and 29.5 per cent for wheat compared to the control. While the treatment schedule (application after two crop cycles or once in three years) did not significantly affect crop yields, applying treatments after two crop cycles improved Zn concentration in rice grains. Additionally, the interaction of treatments and schedules influenced Cu, Fe, and Mn concentrations in crops. Based on the findings, the combined application of Zn and FYM is recommended for rice-wheat rotations on Zn-deficient Ustochrept soils in western Uttar Pradesh to optimize productivity and micronutrient uptake.

Veni *et al.* (2019) studied the impact of residual zinc on wheat crops grown in soils previously used for rice cultivation. The results showed that while wheat yield was not significantly affected by residual zinc, the zinc concentration in wheat grains increased by 11.5 per cent compared to controls. The combination of basal zinc 5 mg Zn kg^{-1} (basal) plus FYM (5 mg Zn kg^{-1}) yielded the highest zinc content (33 mg kg^{-1}) in wheat grains compared to control. The study highlighted the potential of residual zinc to enhance micronutrient levels in crops, which is crucial for addressing micronutrient deficiencies in regions like India.

Amanullah *et al.* (2020) carried out an experiment during the summer season on clay loam soils to examine the influence of varying phosphorus (P) and zinc (Zn) application rates on a rice-wheat cropping system. The study demonstrated that wheat yield was significantly enhanced in plots where the preceding rice crop had been supplied with higher levels of phosphorus and zinc, indicating a positive residual effect of these nutrients on the subsequent wheat crop.

Nadeem *et al.* (2020) studied the effects of zinc (Zn) application to wheat on the subsequent rice crop under different tillage systems (residual effect). The results showed that zinc application significantly enhanced soil fertility and crop performance in wheat-rice cropping system. Direct-seeded aerobic rice (DSAR) outperforms puddled transplanted rice (PuTR) in terms of soil health and grain yield. Notably, zinc applied to wheat as soil application (SA) boosts the grain zinc concentration in rice by up to 15 per cent as residual effect. The combination of DSAR with no-till wheat (NTW) and zinc application (SA) offers the highest economic returns and best grain quality. Overall, this approach is beneficial for improving soil health and crop productivity in rice-wheat rotations.

Roy *et al.* (2025) revealed the potential of relay-cropped lentil in rice fallows using foliar nutrition strategies. They found that co-application of ZnSO₄ with NPK (19-19-19) or Diammonium Phosphate (DAP) at intervals of 25, 45 and 65 days after sowing significantly enhances nutrient uptake (N, P, K, Zn) and improves plant growth metrics such as biomass, leaf area index, chlorophyll content, nodulation traits, and yield attributes. These treatments resulted in higher grain yields (1117-1225 kg ha⁻¹) compared to other foliar strategies. Economically, the co-application of ZnSO₄ with NPK or DAP proved more profitable than other methods.

2.8 INTERACTION OF ZINC WITH OTHER ELEMENTS IN RICE BASED CROPPING SYSTEM

Aref (2010) reported that high levels of zinc (Zn) and boron (B) in the soil synergistically increase the grain B content and uptake in maize, when both nutrients are present in sufficient amounts; they enhance each other's effects on plant growth. Zn application increases B uptake by the maize grains, particularly at high Zn levels (16 and 24 kg ha⁻¹). This indicates that Zn plays a role in facilitating B absorption in plant. This B content in grains was positively correlated with grain N, P, Mn, and yield, as well as grain protein content. But it was negatively correlated with leaf N, Mn, and Cu contents. Whereas, Zn uptake is positively related to leaf P and Zn contents but negatively related to leaf B content.

Dash *et al.* (2015) conducted a field study in Inceptisol of coastal Odisha assessed the integrated effects of major (N, P, K), secondary (S), and micronutrients (B, Zn) on rice yield and nutrient uptake in rice based cropping systems. The results emphasized the significance of balanced fertilization, with the highest grain yield (76.70 q ha⁻¹) recorded under the combined application of all nutrients. The omission of Zn or K led to substantial reductions in yield and nutrient uptake. Notably, Zn deficiency affected K uptake, while K omission decreased Zn utilization, indicating their interdependence in rice nutrition. The highest grain yield response (37.23 kg grain per kg of fertilizer) was observed with integrated NPK + Zn + S + B application.

A study assessing various combinations of Zn and K applications revealed that foliar Zn application (2 kg ha⁻¹ at 30 and 60 days) combined with soil-applied K (33.2 kg ha⁻¹) significantly improved rice grain yield. This combination also increased Zn concentration in the flag leaves, grain, and straw of rice, while K concentration in rice leaves was also significantly elevated. Notably, K application enhanced Zn uptake in rice grain and straw, and Zn application improved the efficiency of soil K utilization. These synergistic effects indicate that integrated Zn and K management can substantially boost

rice nutrient uptake, biomass production, and overall productivity (Srivastava *et al.*, 2016).

Rinthas (2021) investigated the effects of phosphorus (P) and zinc (Zn) nutrition on nutrient uptake in lowland rice through an experiment comprising 16 treatment combinations. These included four phosphorus levels (0, 25, 50, and 100 mg kg⁻¹) applied as KH₂PO₄ and four zinc levels (0, 5, 10, and 15 mg kg⁻¹) applied as ZnSO₄.7H₂O. Phosphorus application significantly increased P concentrations in both grain and straw, whereas zinc application exhibited an antagonistic interaction. The treatment combination of 100 mg kg⁻¹ P without Zn (P100Zn0) recorded the highest phosphorus concentrations in grain (0.26 per cent) and straw (0.214 per cent). Conversely, zinc concentrations in both grain and straw rose significantly with Zn application; however, elevated phosphorus levels suppressed Zn uptake. The highest zinc concentrations in grain (61.28 mg kg⁻¹) and straw (44.19 mg kg⁻¹) were observed under the treatment without phosphorus and with the highest zinc level (P0Zn15).

A multi-locational field study conducted in West Bengal investigated the role of integrated nutrient management, including nitrogen (N), phosphorus (P), potassium (K), sulfur (S), and zinc (Zn), in enhancing rice productivity in a rice-rice-pulse (black gram) cropping system (Shankar *et al.*, 2021b). Results showed that the combined application of 100 per cent NPK along with S and Zn significantly improved growth parameters, biomass, yield attributes, and grain yield compared to nutrient omission treatments. Moreover, this comprehensive nutrient approach enhanced nutrient use efficiency (NUE) and nutrient response (NR). The study emphasized that site-specific and balanced application of macro and micronutrients, especially Zn and S, based on crop requirements and soil conditions, is vital for optimizing yield potential in rice-based cropping systems on red and lateritic soils.

Ji *et al.* (2023) reported that the integrated application of zinc (Zn) and nitrogen (N) markedly improved rice productivity and nutrient partitioning. Zinc supplementation

enhanced nitrogen translocation from roots to shoots by 12-70 per cent and increased nitrogen allocation to leaves by 19-49 per cent and to brown rice by 6-9 per cent. This synergistic interaction between Zn and N resulted in a 14-35 per cent increase in total biomass and a 13-63 per cent rise in grain yield relative to the application of either nutrient alone.

A study conducted by Tuiwong *et al.* (2024) investigated the impact of foliar applications of nitrogen (N) and zinc (Zn) at various growth stages on rice grain yield and nutrient uptake. The study revealed that applying N+Zn during the tillering stage resulted in a substantial 62.01 per cent increase in grain yield compared to the control, primarily attributed to the enhanced number of tillers and panicles. Additionally, this combined nutrient treatment increased zinc accumulation in brown rice by 34.20 per cent when applied at the panicle initiation stage, highlighting the synergistic effect of nitrogen and zinc.

Kumar *et al.* (2024) investigated the effects of zinc (Zn) and iron (Fe) application on nutrient content and uptake in transplanted rice. Treatments combined 100 per cent recommended fertilizer dose (RDF) with foliar sprays of ZnSO₄ (0.5 or 1 per cent) and FeSO₄ (0.3 or 0.5 per cent). The highest Zn and Fe content in grains or straw occurred with 100 per cent RDF + 1 per cent ZnSO₄ + 0.5 per cent FeSO₄, though it was statistically comparable to 100 per cent RDF + 0.5 per cent ZnSO₄ + 0.3 per cent FeSO₄ and 100 per cent RDF + 1 per cent ZnSO₄ for Zn, and to 100 per cent RDF + 0.5 per cent FeSO₄ for Fe. Total Zn and Fe uptake followed similar trends, indicating that combined moderate Zn-Fe sprays (100 per cent RDF + Spray of 0.5 per cent ZnSO₄ + 0.3 per cent FeSO₄) achieved near-optimal results with lower concentrations.

A greenhouse study by Moreira *et al.* (2025) to evaluate soybean growth across three soil types (Alfisol, Oxisol, and Entisol) with the two levels of liming (equivalent to 0 and 5.0 Mg ha⁻¹) and four concentrations zinc (0, 5, 10, and 20 mg kg⁻¹) (Zn), demonstrated that dolomitic limestone application (5.0 Mg ha⁻¹) significantly increased

soil pH and base cations while reducing Zn availability, particularly in Alfisols. This led to decreased Zn concentrations in soybean leaves and grains across all soils. The yield was improved with the liming, and further increment of yield was observed with the enhanced levels of Zn concentrations. Besides, the photosynthetic rates and stomatal conductance were improved with the higher concentrations of Zn. While liming enhances soil health and crop yields, complementary Zn application is essential to counteract induced deficiencies.

Zhang *et al.* (2025b) conducted a 20-year study to understand the interaction between phosphorus (P) and zinc (Zn) fertilization in paddy rice under varying soil textures. Their findings revealed that prolonged P application significantly increased soil total P, Olsen-P, and inorganic P fractions, particularly in clay soils. While P fertilization enhanced available Zn and its availability index, total Zn content declined across all soil types. Notably, Zn uptake in rice grain decreased in loam soils as Olsen-P increased, indicating an antagonistic P-Zn interaction. Redundancy analysis identified soil available Zn, Ca₂-P, and water-soluble P as key drivers of grain Zn and P uptake.

The two-year study demonstrated that combining soil (SA) and foliar (FA) applications of zinc (Zn) and boron (B) significantly improved maize growth, yield, and grain quality. The highest grain yields (5.39-5.84 t ha⁻¹) were achieved with Zn @ 5 kg ha⁻¹ SA + 1 kg ha⁻¹ FA (T₅), while the Zn content (25.90-25.95 mg kg⁻¹) and B content (24.95-25.08 mg kg⁻¹) peaked with T₅ and B @ 0.5 kg ha⁻¹ SA + 0.1 kg ha⁻¹ FA (T₉), respectively. Protein content (10.21-10.27 per cent) and yield (0.55-0.60 t ha⁻¹) were maximized under Zn @ 5 kg ha⁻¹ (SA) + B 0.5 kg ha⁻¹ (SA), respectively. These results highlight the synergistic benefits of combining soil and foliar micronutrient strategies for optimizing maize productivity and nutritional quality (Singh *et al.*, 2025).

2.9 EFFECT OF ZINC NUTRITION ON SYSTEM YIELD, SYSTEM PRODUCTIVITY AND SYSTEM ENERGETICS

Agriculture in India plays a pivotal role in sustaining the nation's economy and population. It not only provides food security but also serves as the backbone of employment, engaging 70 per cent of the population and contributing 40 per cent to the national income and consumes about 10 per cent of commercial energy. The sector's reliance on both animate energy (human and animal power) and inanimate energy (tractors, tillers, *etc.*) highlights its diverse operational framework. Nutrient supply through farmyard manure and chemical fertilizers, along with the use of pesticides for pest control, ensures crop health and productivity. Irrigation methods range from traditional manual systems to modern diesel or electric pumpsets, showcasing a blend of old and new techniques. However, the dependence on fossil fuels, a non-renewable resource, is a pressing concern due to their rapid depletion. This necessitates the urgent need for a sustainable agricultural system to meet the growing food demands of India's expanding population while safeguarding environmental resources. (Devasenapathy *et al.*, 2009).

Dey *et al.* (2024) evaluated the performance of cowpea in terms of pod yield, energy output, and carbon sequestration. The results showed that cowpea achieved a high pod yield of 14,440.74 kg ha⁻¹, with significant energy output, demonstrating a 15.6 per cent higher energy production compared to other crops. The crop also exhibited strong net energy production (2,075,562.75 MJ ha⁻¹) and energy use efficiency (EUE) of 45.01. In terms of energy productivity, cowpea recorded 3.06 t ha⁻¹. Additionally, it displayed the highest carbon sequestration index (CSI) and carbon emission levels, reflecting its effective carbon output.

Aktar *et al.* (2024) investigated the impact of nano zinc oxide on the energetics of summer maize under micro-irrigation conditions during the summer seasons utilizing a split-plot design with three replications, irrigation treatments were assigned to main plots

and zinc oxide treatments to subplots. They observed that surface flooding irrigation resulted in higher energy input among irrigation methods, while soil application of ZnSO₄ recorded the highest energy input among zinc treatments. Conversely, drip irrigation once in 2 days exhibited the highest energy output in grain yield, stover yield, total output energy, net energy, energy efficiency ratio and energy productivity. Among zinc treatments, seed coating with nano ZnO (40 ppm) achieved the highest values for these parameters and was comparable to seed priming with nano ZnO in grain yield energy output, energy efficiency ratio, and energy productivity.

Baheliya *et al.* (2025) evaluated ten rice-based crop sequences for energy dynamics, efficiency, productivity, and sustainability. Among the sequences, rice-potato-cowpea (vegetable) had the highest energy input at 53.58×10^3 MJ ha⁻¹. However, fodder-based systems recorded the maximum energy output, with values of 341.02×10^3 MJ ha⁻¹ in the first year and 331.84×10^3 MJ ha⁻¹ in the second year. Notably, rice-oat-maize+cowpea and rice-berseem-sudanchari sequences demonstrated superior energy use efficiency across both years. The rice-oat-maize+cowpea sequence stood out as the most effective system, achieving the highest energy output efficiency (1033), energy net return (299×10^3 MJ ha⁻¹), and energy intensity (3.89 MJ ₹⁻¹).

2.10 ECONOMICS OF RICE BASED CROPPING SYSTEMS

Ray *et al.* (2017) assessed the response of a rice-green gram cropping sequence to balanced nutrient management across 24 farmer fields, aiming to optimize yield, profitability, and soil fertility. The most effective nutrient management approach involved applying 80 kg ha⁻¹ N, 40 kg ha⁻¹ P, 40 kg ha⁻¹ K, and 25 kg ha⁻¹ ZnSO₄ to rice, followed by NPK application to green gram. This treatment led to a significant increase in yields for both rice (grain: 4.51 t ha⁻¹; straw: 6.48 t ha⁻¹) and green gram (seed: 0.92 t ha⁻¹). Additionally, it achieved the highest system rice equivalent yield (8.81 t ha⁻¹) and productivity (24 kg ha⁻¹ day⁻¹). Economic analysis showed that this approach also resulted in the highest gross return (₹ 190,699 ha⁻¹), net return (₹ 46,994 ha⁻¹), and

benefit-cost ratio (1.76). Moreover, the treatment improved the sustainable yield index (0.83) and contributed to enhanced soil fertility.

A four-year study by Pasha *et al.* (2018) found that applying the recommended doses of NPK (120-60-40 kg ha⁻¹) along with ZnSO₄ (50 kg ha⁻¹) significantly improved both grain and straw yields in rice-rice cropping systems during both *kharif* and *rabi* seasons. The average grain yields were 5.10 t ha⁻¹ in the *kharif* season and 5.84 t ha⁻¹ in the *rabi* season, while straw yields were 6.46 t ha⁻¹ and 7.49 t ha⁻¹, respectively. This combination resulted in the highest system rice grain equivalent yields at 12.19 t ha⁻¹, leading to considerable economic benefits. The gross returns amounted to ₹ 1,64,590 ha⁻¹, with net returns reaching ₹ 90,260 ha⁻¹. Additionally, the system productivity was notably higher at 33.40 kg ha⁻¹ day⁻¹.

Patra *et al.* (2019) studied the impact of balanced nutrient application on the rice-groundnut cropping system in Odisha. The study involved 48 farmers over two years demonstrated that applying recommended doses of nitrogen, phosphorus, potassium (NPK @ 80, 17.5 and 33 kg ha⁻¹), along with zinc sulfate (25 kg ZnSO₄ ha⁻¹) for rice and N, P K (40, 17.5 and 33 kg ha⁻¹) + 4 250 kg CaSO₄ ha⁻¹ to groundnut, resulted in the highest system rice-equivalent yield (REY) of 10.78 t ha⁻¹. This approach overtook treatments with NPK alone (10.36 t ha⁻¹), showing a substantial increase in REY by 73 per cent over the control and 25 per cent over farmers practices (8.63 t ha⁻¹). The balanced nutrient application also led to higher system net returns (₹ 63,123 ha⁻¹), surpassing treatments with NPK alone (₹ 60,509 ha⁻¹). The combined application of phosphorus at 80 kg ha⁻¹ and zinc at 10 kg ha⁻¹ in rice-based cropping systems significantly enhanced the profitability of rice, resulting in net returns of 26,774 PKR ha⁻¹ (Amanullah, 2020).

Application of balanced fertilization with NPK+ZnSO₄ (NPK at 80-60-50 kg ha⁻¹ for rice and 200-80-80 kg ha⁻¹ for maize, along with ZnSO₄ applied at 50 kg ha⁻¹) in a rice-maize cropping system resulted in significantly higher mean grain yields (5287 kg

ha⁻¹ for rice and 7172 kg ha⁻¹ for maize) and straw yields (7389 kg ha⁻¹ for rice and 9284 kg ha⁻¹ for maize) during both the *kharif* and *rabi* seasons. This fertilization strategy also led to the highest system rice grain equivalent yield of 8676 kg ha⁻¹, with gross returns of ₹ 2,16,611 ha⁻¹ and net returns of ₹ 1,36,579 ha⁻¹. Additionally, it improved soil fertility, resulted in a higher sustainable yield index (1.07), and enhanced per day system productivity (54.76 kg ha⁻¹ day⁻¹) (Rao *et al.*, 2022).

Ahmed *et al.* (2025) conducted an experiment in south-west Bangladesh on critical insights into sustainable intensification and diversification of rice-based cropping systems. The research evaluated five rice-based cropping systems, including rice-fallow-rice (R-F-R), rice-mustard-rice (R-M-R), rice-lentil-mung bean (R-L-M), rice-wheat-mung bean (R-W-M), and rice-relay mustard-rice (R-RM-R), across 60 farmers' fields over two years. They reported that, the rice-mustard-rice (R-M-R) system achieved the highest system rice equivalent yield (REY) of 14.1-14.4 t ha⁻¹, outperforming the traditional R-F-R system by 20-25 per cent. They also recorded that the highest net return (\$1610-1879 USD ha⁻¹) and sustainable yield index (SYI) of 0.84-0.85, showcasing its superior profitability and stability. While the R-L-M system demonstrated the highest benefit-cost ratio due to lower production costs, the R-RM-R system excelled in land-use efficiency. It emphasizes the importance of integrating high-value and climate-smart crops to enhance profitability and sustainability.

Jacob *et al.* (2025) found that the application of balanced fertilization with NPK + ZnSO₄ (NPK at 90:45:45 kg ha⁻¹ + ZnSO₄ at 20 kg ha⁻¹ during *kharif* and NPK at 90:45:45 kg ha⁻¹ in *rabi*) significantly enhanced system rice equivalent yield (5.25 t ha⁻¹ in *kharif* and 5.20 t ha⁻¹ in *rabi*). The highest system rice equivalent yield (10.46 t ha⁻¹), gross returns (₹ 2.92 lakh ha⁻¹), net returns (₹ 0.89 lakh ha⁻¹), and benefit-cost ratio (1.44) were observed with NPK + ZnSO₄. The farmer participatory study concluded that balanced fertilization with NPK + ZnSO₄ is crucial for improving rice yield, system productivity, and economic profitability in the rice-rice-fallow system.

The review highlights the importance of zinc nutrition in rice-based cropping systems, particularly under high phosphorus soils where zinc uptake is adversely affected due to P-Zn interactions. Although the role of micronutrients in enhancing productivity and nutrient use efficiency is well recognized, limited studies have evaluated the impact of nano zinc on rice in high P conditions. Further, the residual effects of nano zinc on succeeding crops and its influence on overall system energetics and profitability remain largely unexplored. In this context, the present study is undertaken to evaluate the response of rice to nano zinc in high phosphorus soils, study its residual effects on succeeding crops, understand P-Zn interactions, and identify promising crop sequences in terms of system productivity and profitability.

MATERIALS AND METHODS

3. MATERIALS AND METHODS

The study entitled “Nano zinc nutrition in rice based cropping systems in high phosphorus soils” was conducted during the period from April 2022 to May 2023. The study focused on evaluation of the response of rice to nano zinc in high P soils, study the residual effect of nano zinc nutrition on growth and yield of succeeding crops, study the P - Zn interactions and identification of the promising crop sequence in terms of system productivity and profitability. This chapter documents the material used and methodology followed in assessing the study.

3.1. EXPERIMENTAL SITE

The experiment was conducted in the lowlands of Integrated Farming System Research Station (IFSRS), Karamana, Thiruvananthapuram. The experimental field is located at 8°28'26"N latitude and 76°57'38"E longitude at an altitude of 10 m above mean sea level.

3.1.1. Soil

Before conducting the experiment, a composite soil sample was collected from a depth of 0-15 cm and characterized for its mechanical composition (Table 1.) and chemical properties (Table 2.).

The soil of the experimental site was sandy clay loam, moderately acidic in reaction, medium in organic carbon and available nitrogen, high in available phosphorus, and low in available potassium. It was deficient in available calcium and zinc but sufficient in available iron and boron.

Table 1. Mechanical composition of initial soil sample of the experimental site

Sl. No.	Fractions	Content in soil (%)	Method adopted
1.	Course sand	48.42	Bouyoucos hydrometer method (Bouyoucos, 1962)
2.	Fine sand	8.91	
3.	Silt	9.32	
4.	Clay	32.74	
Soil texture – Sandy clay loam			

Table 2. Chemical properties of initial soil sample of the experimental field

Sl. No.	Parameter	Content	Rating	Method used
1.	Soil reaction (pH)	5.15	Moderately acid	1:2.5 soil solution ratio using pH meter with glass electrode (Jackson, 1973)
2.	Electrical conductivity (dS m ⁻¹)	0.78	Normal	Digital conductivity meter (1:2.5 soil water ration) (Jackson, 1973)
3.	Organic carbon (%)	1.64	High	Walkley and Black rapid titration method (Jackson, 1973)
4.	Available N (kg ha ⁻¹)	365.79	Medium	Alkaline permanganate method (Subbiah and Asija, 1956)
5.	Available P (kg ha ⁻¹)	27.2	High	Brays colorimetric method (Jackson, 1973)
6.	Available K (kg ha ⁻¹)	56	Low	Ammonium acetate method (Jackson, 1973)
7.	Available Ca (mg kg ⁻¹)	210	Deficient	EDTA titration method (Tucker and Kurtz, 1960)
8.	Available Zn (mg kg ⁻¹)	0.96	Deficient	Extraction using 0.5 N HCl and atomic absorption spectroscopy (Sims and Johnson, 1991)
9.	Available Fe (mg kg ⁻¹)	212	Sufficient	Extraction using 0.5 N HCl and atomic absorption spectroscopy (Sims and Johnson, 1991)
10.	Available B (mg kg ⁻¹)	1.89	Sufficient	Hot water extraction- spectrophotometer (Gupta, 1967)
11.	Dehydrogenase activity - 34.34 g ⁻¹ soil 24h ⁻¹			
12.	Phosphatase activity - 18.53 g ⁻¹ soil h ⁻¹			

3.1.2. Climate and Cropping Season

The study was conducted over three seasons. The experimental site is situated in a warm humid tropical climate. The data on various weather parameters such as maximum temperature, minimum temperature, relative humidity and rainfall were collected from the Agrometereological observatory, IFSRS, Karamana. The data were tabulated based on the standard meteorological weeks and presented in Appendix Ia, Ib and Ic.

In *virippu* season, rice was cultivated during the period from 3 April to 22 August 2022. The maximum temperature during the growing period varied from 32.8°C to 28.02°C and minimum temperature varied from 26.79°C to 23.61°C. The mean relative humidity ranged from 86.63 per cent to 77.13 per cent. The total rainfall received during the season was 897.14 mm. The weather data during the period was graphically represented in Fig. 1a, 1b and 1c.

In *mundakan* season, rice was cultivated during the period from 12 September 2022 to 14 January 2023. The maximum temperature during the growing period varied from 31.53°C to 29.36°C and minimum temperature varied from 25.18°C to 21.77°C. The mean relative humidity ranged from 83.86 per cent to 74.83 per cent. The total rainfall received during the season was 489.95 mm. The weather data during the period was graphically represented in Fig. 2a, 2b and 2c.

In *puncha* season, bhindi and grain cowpea were raised during the period from 15 February to 4 May 2023. The maximum temperature during the growing period varied from 33.09°C to 30.10°C and minimum temperature varied from 26.97°C to 21.87°C. The mean relative humidity ranged from 83.86 per cent to 74.83 per cent. The total rainfall received during the season was 164.34 mm. The weather conditions over the cropping period are depicted in Fig. 3a, 3b and 3c.

3.1.3. Cropping History of the Field

The experimental site was lying fallow after *mundakan* crop, before execution of the experiment. The experiment was carried out in the lowlands of IFSRS, Karamana where the cropping sequence followed regularly was rice-rice-fallow.

3.2. MATERIALS

3.2.1. Crop and Variety

3.2.1.1. Rice

The rice variety selected for the execution of the *virippu* and *mundakan* was Uma (Mo 16) released from the M.S Swaminathan Rice Research Station (MSSRRS), Moncompu, Alappuzha, Kerala. It is a medium duration (120-125 days), semi tall, high tillering, non-lodging, red long bold grain type variety which is resistant to blast, bacterial blight and brown plant hopper. The seeds of Uma were procured from IFSRS, Karamana, Thiruvananthapuram, Kerala.

3.2.1.2. Grain Cowpea

The grain cowpea variety used was Kanakamony (PTB 1). It is a semi-trailing, dual purpose variety with an average duration of 75-80 days, producing green pods with bold seeds, released from the Regional Agricultural Research Station, Pattambi, Palakkad, Kerala.

3.2.1.3. Bhindi

The bhindi variety used was Anjitha. It is a yellow vein mosaic resistant variety with an average duration of 120 days, released from the Department of Genetics and Plant breeding, College of Agriculture, Vellayani.

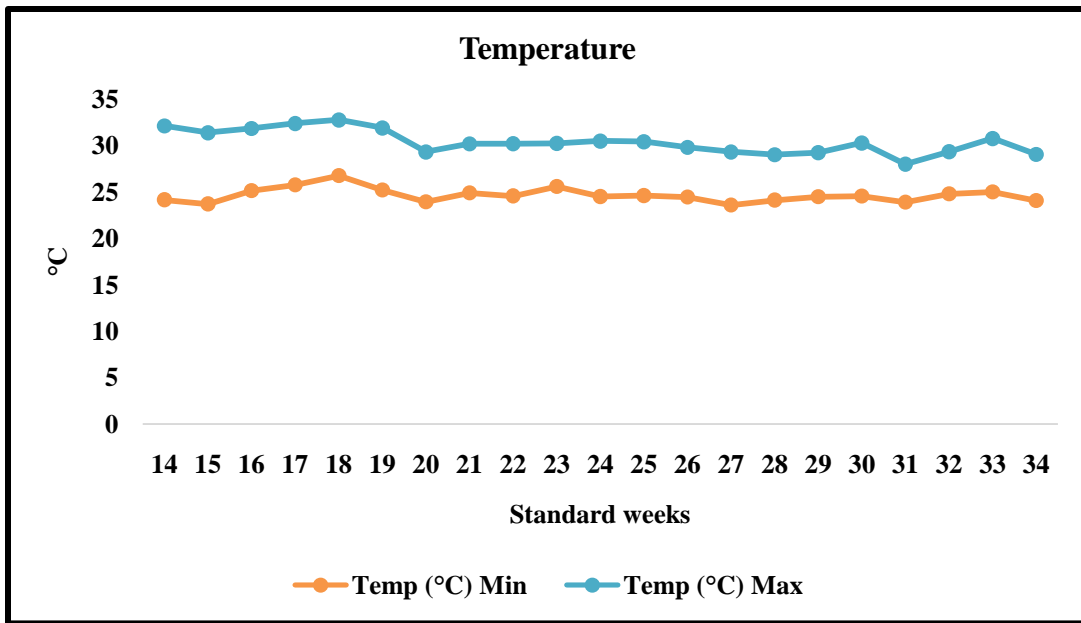


Fig. 1a. Standard week wise temperature during *virippu* (2022-2023)

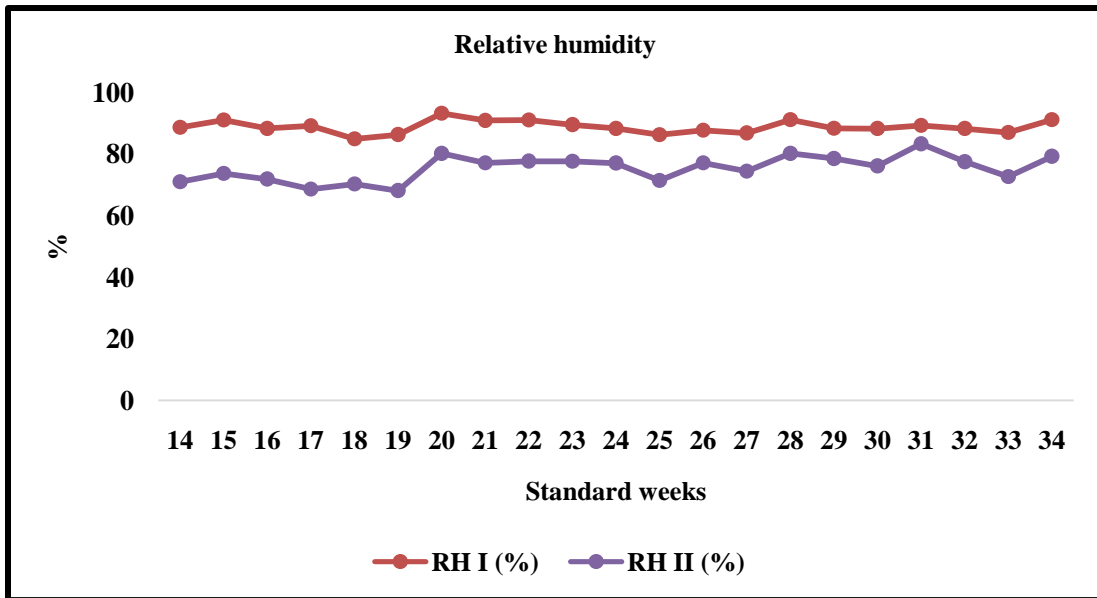


Fig. 1b. Standard week wise relative humidity during *virippu* (2022-2023)

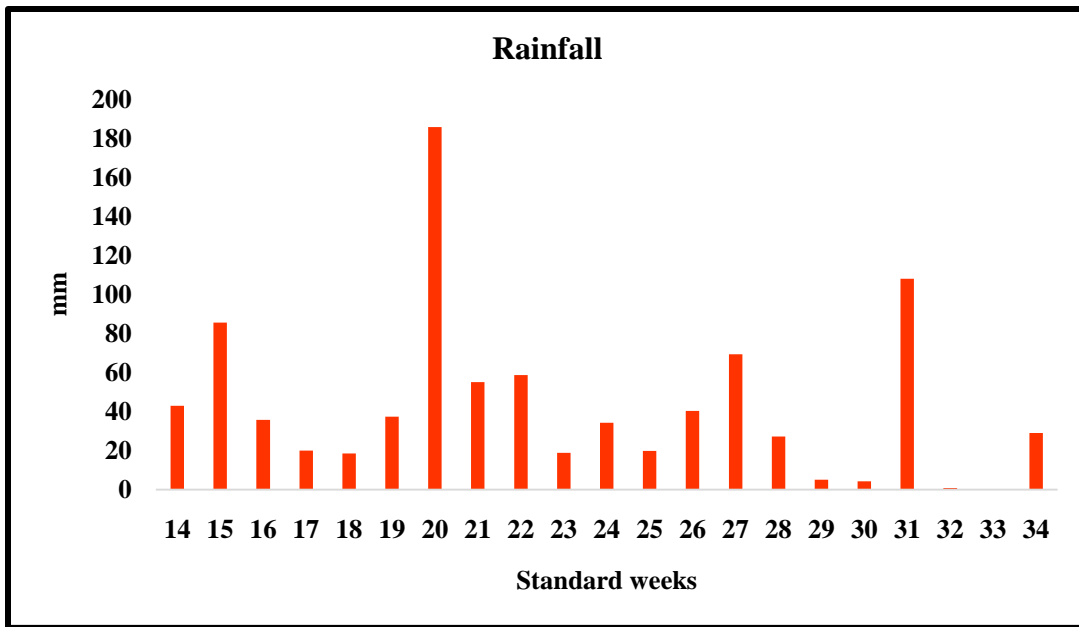


Fig. 1c. Standard week wise rainfall during *virippu* (2022-2023)

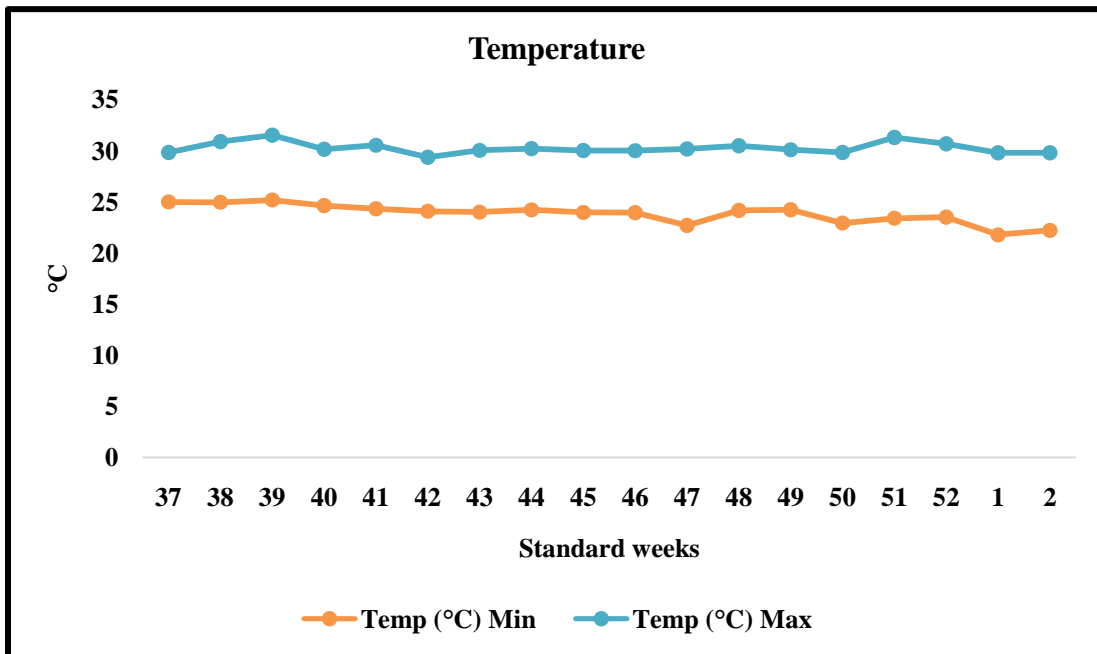


Fig. 2a. Standard week wise temperature during *mundakan* (2022-2023)

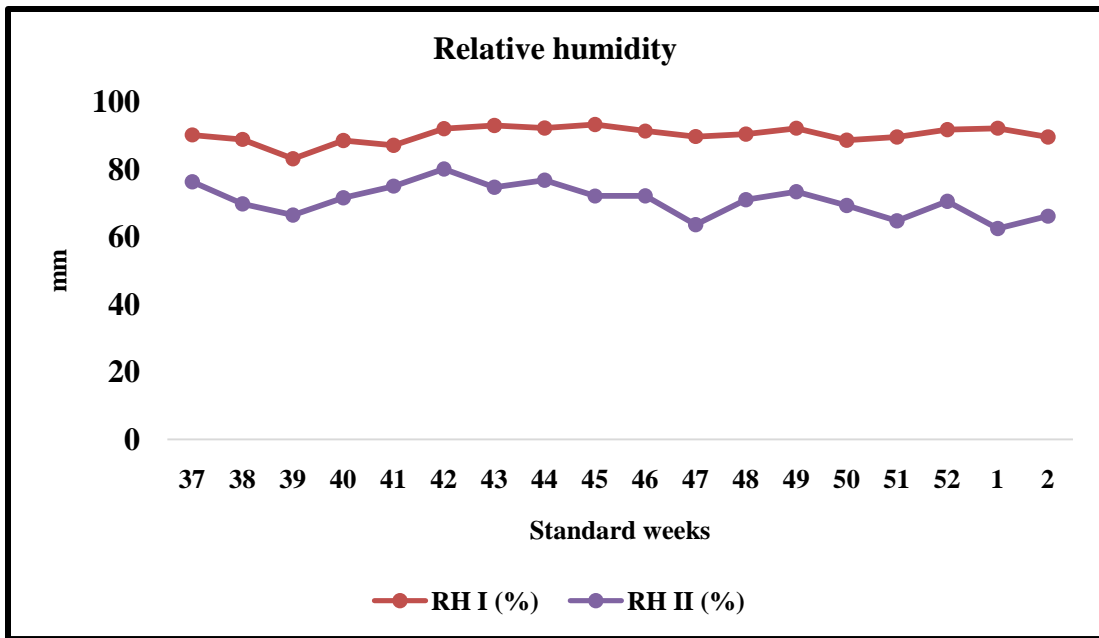


Fig. 2b. Standard week wise relative humidity during *mundakan* (2022-2023)

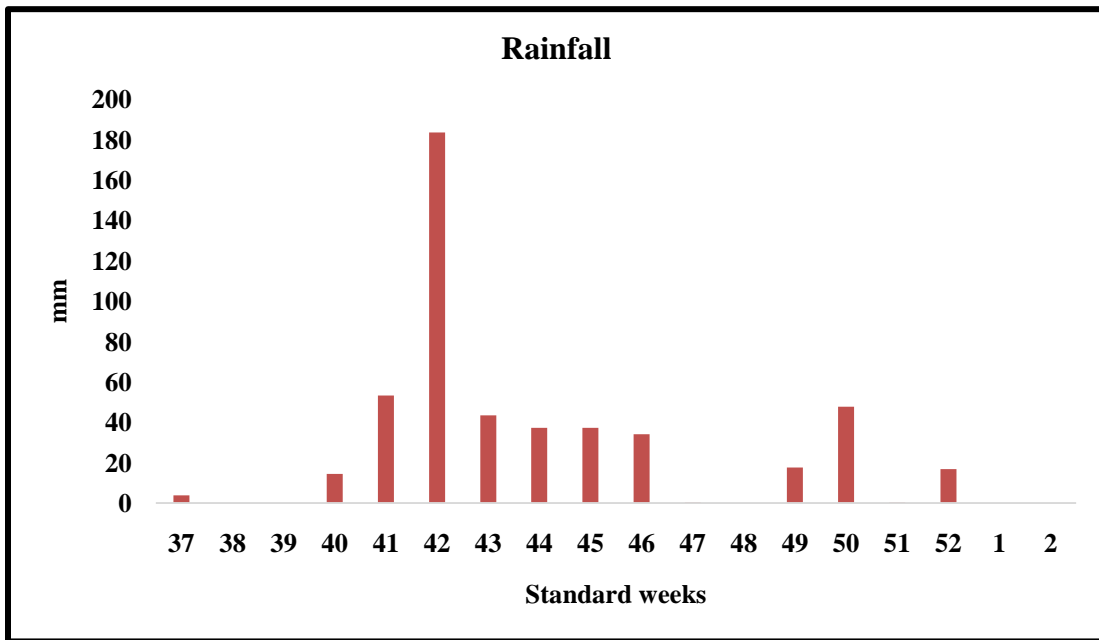


Fig. 2c. Standard week wise rainfall during *mundakan* (2022-2023)

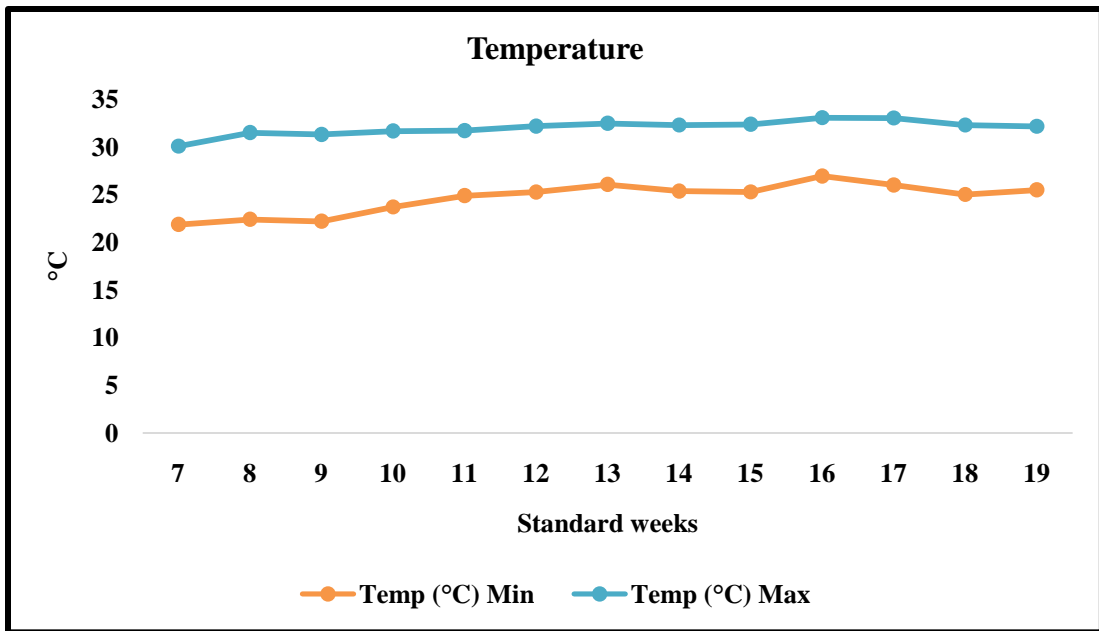


Fig. 3a. Standard week wise temperature during *puncha* (2022-2023)

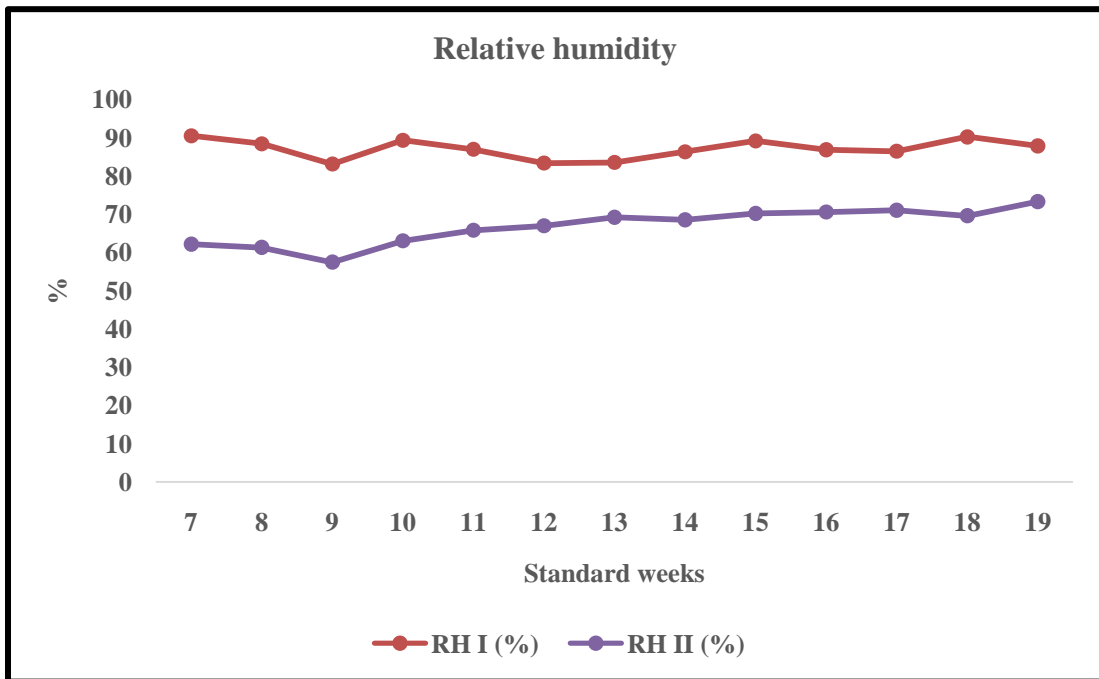


Fig. 3b. Standard week wise relative humidity during *puncha* (2022-2023)

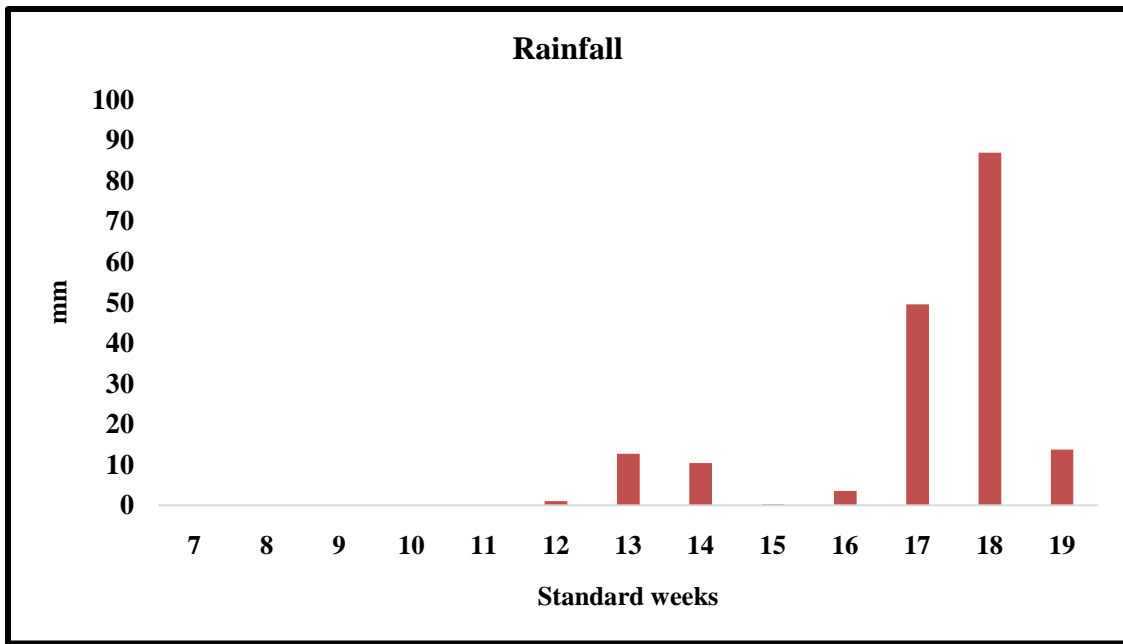


Fig. 3c. Standard week wise rainfall during *puncha* (2022-2023)

3.2.2. Manures and Fertilizers

Well decomposed farmyard manure (FYM) containing 0.48% N, 0.21% P₂O₅ and 0.42% K₂O was used as the source of organic manure and calcium carbonate was used as liming material. Urea (46% N), rock phosphate (20% P₂O₅) and muriate of potash (60% K₂O) were used as inorganic sources of N, P and K respectively. As a source of zinc, ZnSO₄.7H₂O (21% Zn) and Nano zinc developed by Indian Farmers Fertilizer Co-operative Ltd. (IFFCO) (ZnO-10000 ppm) were used as chemical fertilizers.

3.2.3. Plant Protection Chemicals

Dimethoate 30% EC (Roger) and hexaconazole 5% SC (Contaf) were used to manage pests and diseases, respectively. Weeds were managed with pendimethalin 30% EC.

3.3 METHODS

3.3.1. Design and Layout

The experiment “Nano zinc nutrition in rice based cropping systems in high phosphorus soils” was conducted in three parts. The effect of nano zinc nutrition on growth, yield, nutrient use efficiency and profitability of the rice based cropping system was evaluated. The field experiment was laid out in randomized block design (RBD) with 8 treatments and replicated thrice for the part I and II of the experiment. For part III of the experiment field was laid out in strip plot design with 8 main plot treatments and 3 sub plot treatments. The layout of the experiment is given in Fig. 4a and 4b. Plates 1, 2, 3 are the representation of the general view of the experiment.

Part I and II

Design	: RCBD
Replication	: 3
Treatments	: 8
Plot size	: 6 m x 4.5 m

Spacing	: <i>Virippu</i> - 20 cm × 15 cm <i>Mundakan</i> - 20 cm × 10 cm
Method of establishment	: Transplanting
Variety	: Uma
Season	: <i>Virippu</i> and <i>Mundakan</i> ,2022-23
Location	: IFSRS, Karamana

3.3.1.1. Treatment Details

- T₁- SA of ZnSO₄ at 20 kg ha⁻¹ (applied only in *virippu* season)
T₂- NP with Nano Zn at 0.05%
T₃- NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage
T₄- NP with ZnSO₄ at 0.5%
T₅- NP with ZnSO₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage
T₆- FS with Nano Zn at 0.05% at MT and PI stages
T₇- FS with ZnSO₄ at 0.5% at MT and PI stages
T₈- Control (RDN without application of P and Zn)

Part III

Design	: Strip plot
Treatment	: 8 x 3
Replication	: 3
Season	: <i>Puncha</i> , 2022-23
Location	: IFSRS, Karamana

3.3.1.2. Treatment Details

Nutrient levels - 8 (Residual)

N ₁ -	Residual nutrient status of the soil of	T ₁ -	SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)
N ₂ -	Residual nutrient status of the soil of	T ₂ -	NP with Nano Zn at 0.05%
N ₃ -	Residual nutrient status of the soil of	T ₃ -	NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage

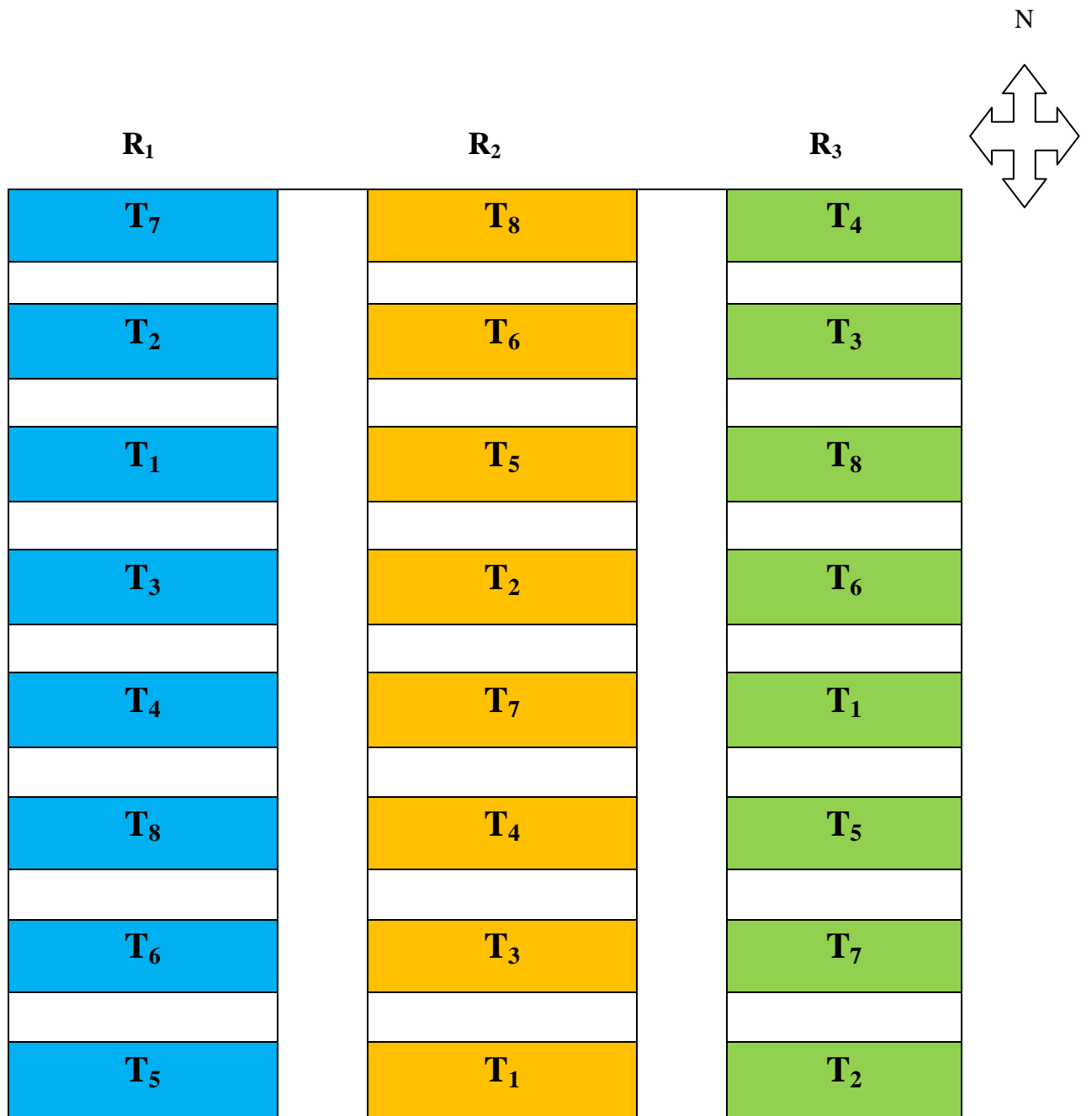
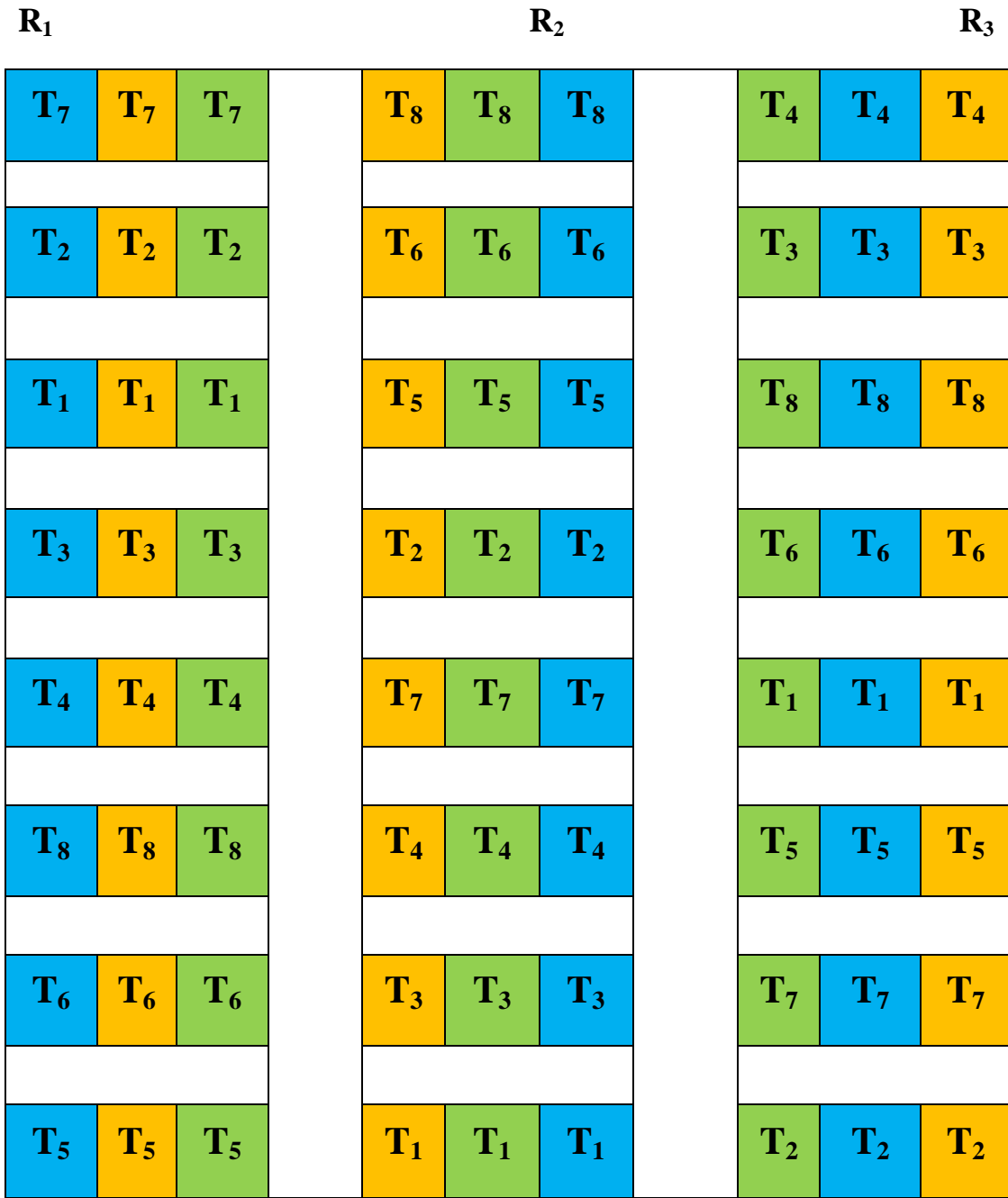


Fig.4a. Layout plan of experiment during *virippu* and *mundakan*



Cowpea
 Bhindi
 Fallow

Fig. 4b. Layout plan of experiment during *puncha*

N ₄ -	Residual nutrient status of the soil of	T ₄ -	NP with ZnSO ₄ at 0.5%
N ₅ -	Residual nutrient status of the soil of	T ₅ -	NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage
N ₆ -	Residual nutrient status of the soil of	T ₆ -	FS with Nano Zn at 0.05% at MT and PI stages
N ₇ -	Residual nutrient status of the soil of	T ₇ -	FS with ZnSO ₄ at 0.5% at MT and PI stages
N ₈ -	Residual nutrient status of the soil of	T ₈ -	Control (RDN without application of P and Zn)

Crop sequences - 3

C₁ - Rice - Rice - Grain cowpea

C₂ - Rice - Rice – Bhindi

C₃ - Rice - Rice – Fallow

Treatment combinations 24 (8 × 3)

n₁C₁, n₁C₂, n₁C₃, n₂C₁, n₂C₂, n₂C₃, n₃C₁, n₃C₂, n₃C₃, n₄C₁, n₄C₂, n₄C₃, n₅C₁, n₅C₂, n₅C₃, n₆C₁, n₆C₂, n₆C₃, n₇C₁, n₇C₂, n₇C₃, n₈C₁, n₈C₂, n₈C₃.

Note: Individual plots were sub divided into three for accommodating the third crop components of the cropping system.

3.3.2. Crop Management

3.3.2.1. Part I and II (*virippu* and *mundakan* rice)

3.3.2.1.1. Nursery

Wet nursery method was adopted. The nursery area was ploughed, leveled, weeds and stubbles were removed and beds of 10 m length, 1m width and 15 cm height were prepared with drainage channels between the beds. FYM was incorporated at the rate of 1 kg m⁻². Pre- germinated seeds of paddy (*Uma*) were sown at the rate of 65 kg ha⁻¹ in *virippu* and 75 kg ha⁻¹ in *mundakan*. Twenty three day old seedlings were pulled out from the nursery beds and transplanted in the main field.

3.3.2.1.2. Main Field

The experimental area was ploughed twice, puddled and levelled without disturbing the external bunds. The experimental area was divided into three blocks of eight plots each. Irrigation and drainage channels were provided between the blocks and plots with a width of 30 cm

3.3.2.1.3. Application of Lime

Lime was applied to the field at the rate of 600 kg ha⁻¹ in two split doses of 350 kg ha⁻¹ and 250 kg ha⁻¹ the earlier was applied after ploughing and the later was applied before tillering stage.

3.3.2.1.4. Manures and Fertilizers

During land preparation, well decomposed farmyard manure (5 t ha⁻¹) was applied uniformly to all the plots. Major nutrients N, P and K were supplied as urea, rock phosphate and MOP on soil test basis (KAU, 2016). The RDN were 90:45:45 modified to 64:22:53 based on soil test. Zinc was supplied in the form of ZnSO₄ and Nano zinc (ZnO) according to the mentioned concentrations in treatments. Half the dose of nitrogen, potassium and entire dose of phosphorus were applied basally, while remaining dose of nitrogen and potassium was applied at maximum tillering stage. In case of zinc application, ZnSO₄ was applied basally as soil application in T₁, 0.5 per cent of ZnSO₄ and 0.05 per cent of ZnO were sprayed as foliar application according to the treatments at specified stages. In nutri priming treatments 0.5 per cent of ZnSO₄ and 0.05 per cent of ZnO solutions were prepared and the seeds were allowed to soak in the solution for 14 hours.



Plate 1. General view of the experiment during *virippu*



Plate 2. General view of the experiment during *mundakan*



Plate 3. General view of the experiment during *puncha*

3.3.2.1.5. Transplanting

Twenty three days old seedling were pulled out of the nursery and transplanted at the rate of 2-3 seedlings per hill at a spacing of 20 cm × 15 cm in *virippu* and 20 cm × 10 cm in *mundakan*. Gap filling was done one week after the transplanting to maintain uniform plant population.

3.3.2.1.6. Water Management

The water level was maintained at about 1.5 cm during transplanting and gradually increased and maintained at 5 cm throughout the growth period. However, the field was occasionally drained to ensure soil aeration. Water was drained 10 days before harvest to facilitate uniform maturity of the grains.

3.3.2.1.7. Weed Management

The field was maintained weed free upto 45 DAT with two hand weedings at 20 DAT and 40 DAT.

3.3.2.1.8. Plant Protection

Dimethoate 30% EC (Roger) was sprayed to manage stem borer and rice bug infestation in the field, concentration used was 2 ml L⁻¹. Hexaconazole 5% SC (Contaf) at the rate of 2 ml L⁻¹ was sprayed to manage leaf spot and leaf blight disease infestation in the field.

3.3.2.1.9. Harvest

The rice crop was harvested after the grains attained maturity, from the net plot area leaving two rows on all sides. The net plot area was harvested, threshed, winnowed and sun dried. The weight of grain and straw were recorded separately from the individual plots. The weight of the grain and straw were expressed in kg ha⁻¹.

3.3.2.2. Part III (puncha)

3.3.2.2.1. Land Preparation and Layout

After the harvest of *mundakan* crop, crop residues were incorporated in the field. Each experimental plot was subdivided into three sub plots by making the raised beds with the width of 1.5 m and 30 cm height and was levelled. A distance of 20 cm was maintained between the bunds, which was used as irrigation channels as well.

3.3.2.2.2. Application of Manures and Fertilizers

The crop was raised under the residual nutrient contents of the previous season. Manures and fertilizers were not applied during the growth period of the crops to evaluate the growth and yield of the crops in residual nutrient contents.

3.3.2.2.3. Planting

For grain cowpea, seeds were sown in lines at a spacing of 25 cm × 15 cm at the rate of 40 kg ha⁻¹. In case of bhindi, seeds were sown in lines at a spacing of 60 cm × 30 cm at the rate of 8 kg ha⁻¹.

3.3.2.2.4. Weeding

Pre emergence application of Pendimethalin 30% EC was applied to the field one day after sowing at the rate of 1 L ha⁻¹.

3.3.2.2.5. Harvest

Cowpea was harvested once the pods attained maturity, sundried, threshed and winnowed. The grain weight of the cowpea is expressed in kg ha⁻¹ whereas, in bhindi, the fruits were harvested while they were tender and immature for culinary purposes. Harvesting begins around 45 days after sowing, with regular picking at weekly intervals to ensure consistent harvesting.



Nursery



Maximum tillering



Panicle initiation



Flowering



Harvest

Plate 4. Different growth stages of the *virippu* rice



Nursery



Tillering



Panicle initiation



Flowering



Harvest

Plate 5. Different growth stages of the *mundakan* rice

3.4. OBSERVATIONS

3.4.1 Part I and II (*virippu and mundakan rice*)

3.4.1.1 *Growth and Growth Attributes*

Two rows of plants were left in the borders on all sides and observations on parameters associated with growth and yield of rice were taken from the net plot. Six hills were selected randomly from the net plot area of each plot and tagged them as sample plants for recording observations. The following observations were recorded from the sample plants and the mean values were worked out.

3.4.1.1.1. *Plant Height*

Plant height was recorded at maximum tillering, panicle initiation, flowering and at harvest stages using the method described by Gomez (1972). The height was measured from the base of the plant to the tip of the longest leaf or tip of the longest ear head, whichever was longer and the mean is expressed in centimeter.

3.4.1.1.2. *Tillers per Square Meter*

Tiller count was taken from the tagged sample hills at maximum tillering, panicle initiation, flowering and at harvest stages. The mean value was computed and expressed as number of tillers per square meter.

3.4.1.1.3. *Leaf Area per Hill*

Leaf area per hill was observed at maximum tillering, panicle initiation, flowering and at harvest stages using the method suggested by Yoshida *et al.* (1976). The maximum length 'l' and width 'w' of all the leaves of the middle tiller of the six sample hills were recorded from all the plots and the mean leaf area was calculated and expressed in cm² hill⁻¹.

Leaf area of a single leaf = l x w x k

k- Adjustment factor

(0.75 at active tillering, panicle initiation and flowering stages; 0.67 at harvest stage)

3.4.1.1.4. Leaf Area Index at Panicle Initiation

Leaf area index (LAI) was calculated as the ratio between total leaf area and land area occupied (spacing) at panicle initiation stage.

$$\text{LAI} = \frac{\text{Sum of leaf area / hill of six sample hills (cm}^2\text{)}}{\text{Area of land covered by the six sample hills (cm}^2\text{)}}$$

3.1.1.1.5. Dry Matter Production at Harvest

Dry matter production was computed at harvest. Six sample hills were randomly selected and uprooted from the area demarcated for destructive sampling outside the net plot area leaving the border rows. The plant samples were cleaned free of debris, air dried for two days and oven dried at $(65\pm 5)^{\circ}\text{C}$ until constant weights were attained. The mean weight was expressed as g per hill.

3.4.1.2 Yield Attributes and Yield

3.4.1.2.1. Days to 50 per cent Flowering

Number of days taken by 50 per cent of the hills to flower was recorded.

3.4.1.2.2. Productive Tillers per Hill

At harvest, the number of productive tillers were recorded from six randomly selected sample hills in the net plot area and was expressed as number of productive tillers per hill.

3.4.1.2.3. Number of Grains per Panicle

The number of spikelets per panicle was recorded by counting the spikelets separated from ten randomly selected panicles.

3.4.1.2.4. Sterility Percentage

The sterility percentage was worked out using the following formula

$$\text{Sterility percentage} = \frac{\text{Number of unfilled grains per panicle}}{\text{Number of total grains per panicle}} \times 100$$

3.4.1.2.5. Grain Weight per Panicle

The grains from ten randomly selected panicles were removed, dried separately, weighed and expressed as g per panicle.

3.4.1.2.6. Thousand Grain Weight

One thousand grains were counted from the cleaned and dried produce from the net plot area of each plot and the weight of the grains was recorded in grams.

3.4.1.2.7. Grain Yield

The net plot area was harvested individually, threshed, cleaned, dried and weighed to express the grain yield in kg ha⁻¹ at 14 per cent moisture.

3.4.1.2.8. Straw Yield

The straw harvested from net plot area was dried to constant weight under sun and then weighed to express the straw yield in kg ha⁻¹.

3.4.1.2.9. Harvest Index

The harvest index (HI) was worked out using the formula suggested by Donald and Hamblin (1976).

$$\text{HI} = \frac{\text{Economic yield}}{\text{Biological yield}}$$

3.4.2 Part III (*puncha*)

3.4.2.1 *Cowpea*

3.4.2.1.1 *Growth and Growth Attributes*

For the purpose of recording the observations on growth and growth attributes, five plants were randomly selected and tagged from the net plot area of each treatment plot.

3.4.2.1.1.1. *Plant Height*

Plant height was measured from the ground level to the tip of the plant from the tagged plants at 30 DAS, 45 DAS and at harvest. The average was worked out and expressed in cm.

3.4.2.1.1.2. *Number of Branches per Plant*

Number of branches were counted from the tagged five plants at 30 DAS, 45 DAS and at harvest and the average was worked out.

3.4.2.1.1.3. *Dry Matter Production at Harvest*

Three sample plants were taken from each treatment plot at the time of harvest. The plant samples were sun dried for two days and then oven dried at 65°C until constant weight was attained. The average was worked out and expressed as g per plant.

3.4.2.1.2 *Yield and Yield Attributes*

3.4.2.1.2.1. *Days to 50 per cent flowering*

Number of days taken by the plants in each treatment for 50 per cent flowering was recorded and expressed in days.

3.4.2.1.2.2. *Number of pods per Plant*

Number of pods harvested from the observation plants in each treatment was recorded and average was worked out and expressed as number of pods per plant.

3.4.2.1.2.3.100 Seed Weight

Hundred fully filled bold grains were drawn randomly, dried, weighed and expressed in g.

3.4.2.1.2.4. Seed Yield per Plant

At the time of harvest, from five sample plants the pods were collected separately, dried, threshed, winnowed and the weight of the seed from each plant was recorded and the average was worked out and expressed in g per plant.

3.4.2.1.2.5. Seed Yield per Hectare

After harvesting pods from net plot, seeds were dried, threshed, winnowed. Seed yield obtained from the net plot area of each treatment was recorded and expressed in kg ha⁻¹.

3.4.2.1.2.6. Haulm Yield per Plant

At the time of harvesting, five sample plants were uprooted from each treatment, dried under sun and the weight was recorded separately for each plant and expressed in g per plant.

3.4.2.1.2.7. Haulm Yield per Hectare

Plants from the net plot area of each treatment were uprooted at the time of harvest, dried under sun and haulm was weighed treatment wise. Total haulm yield per hectare was worked out from the net plot haulm yield and expressed in kg ha⁻¹.

3.4.2.2 Bhindi

3.4.2.2.1 Growth and Growth Attributes

For the purpose of recording the observations on growth and growth attributes, five plants were randomly selected and tagged from the net plot area of each treatment plot.

3.4.2.2.1.1. Plant Height

Plant height was measured from the ground level to the tip of the plant from the tagged plants at 30 DAS, 45 DAS and at harvest. The average was worked out and was expressed in cm.

3.4.2.2.1.2. Number of Branches per Plant

Number of branches was counted from the tagged five plants at 30 DAS, 45 DAS and at harvest and the average was worked out.

3.4.2.2.1.3. Dry Matter Production at Harvest

Three sample plants were taken from each treatment plot at the time of harvest. The plant samples were sun dried for two days and then oven dried at 65°C until constant weight was attained. The average was worked out and expressed as g per plant.

3.4.2.2.2 Yield and Yield Attributes

3.4.2.2.2.1. Days to 50 per cent flowering

Number of days taken by the plants in each treatment for 50 per cent flowering was recorded and expressed in days.

3.4.2.2.2.2. Number of Fruits per Plant

Number of fruits harvested from the observation plants in each treatment was recorded and average was worked out and expressed as number of fruits per plant.

3.4.2.2.2.3. Fruit Weight

Ten bhindi fruits harvested from the each treatment plots were weighed separately and average was worked out and expressed in g.

3.4.2.2.2.4. Fruit Yield per Plant

Fruit yield from the tagged plants were noted in each picking, summed and average was worked out and expressed in kg per plant.

3.4.2.2.2.5. Fruit Yield per Hectare

Fruit yield harvested in each picking from the net plot area was noted, summed and average was worked out and expressed in kg ha⁻¹.

3.4.2.2.2.6. Haulm Yield per Plant

At the time of harvesting, five sample plants were uprooted from each treatment, dried under sun and the weight was recorded separately for each plant and expressed in g per plant.

3.4.2.2.2.7. Haulm Yield per Hectare

Plants from the net plot area of each treatment were uprooted at the time of harvest, dried under sun and haulm was weighed treatment wise. Total haulm yield per hectare was worked out from the net plot haulm yield and expressed in kg ha⁻¹.

3.5. CHEMICAL ANALYSIS

3.5.1. Soil Analysis

Soil samples were collected from the experimental field before the experiment, randomly from different sites in the field, air dried, 2 mm sieved and was analyzed for physical, chemical and biological properties of the soil and the values are presented in the Table 2. After each part of the experiment, soil samples were collected from each treatment plots, air dried, powdered and passed through 2 mm sieve and analysed for physical, chemical and biological properties using the standard procedures given in Table 3.

Table 3. Basic procedure for the analysis of soil samples

Parameter	Method	Reference
Soil reaction (pH)	1:2.5 soil solution ratio using pH meter with glass electrode	Jackson (1973)
Electrical conductivity (dS m ⁻¹)	Digital conductivity meter (1:2.5 soil water ration)	Jackson (1973)
Organic carbon (%)	Walkley and Black rapid titration method	Jackson (1973)
Available N	Alkaline potassium permanganate method	Subbiah and Asija (1956)
Available P	Bray No. 1 extraction - spectrophotometer	Jackson (1973)
Available K	Neutral normal ammonium acetate extraction – flame photometer	Jackson (1973)
Available Ca	EDTA titration method	Tucker and Kurtz (1960)
Available Zn and Fe	Extraction using 0.5 N HCl and atomic absorption spectroscopy	Sims and Johnson (1991)
Available B	Hot water extraction- spectrophotometer	Gupta(1967)
Dehydrogenase	Incubation – TPF released - spectrophotometer	Thalman (1966)
Acid Phosphatase	Incubation – p- nitrophenol released- spectrophotometer	Tabatabai and Bremner (1969)

3.5.2 Plant Analysis

The plant samples were collected at panicle initiation stage and at harvest, the samples were air dried for 2 days and then dried in an electric hot air oven at (65 ± 5)°C to constant weight, ground for analysis. The required quantity of the sample was weighed accurately in an electronic balance, subjected to acid extraction and analyzed for the nutrients. At panicle initiation stage, nutrient uptake was analyzed for root and shoot

separately, at harvest stage, nutrient uptake was analyzed for root, shoot and grain separately. The standard analytical procedures adopted for the plant analysis was depicted in the Table 4.

Table 4. Standard analytical procedure adopted for the plant analysis

Nutrient	Method adopted
Nitrogen (N)	Micro kjeldhal distillation after digestion using concentrated sulphuric acid (Jackson, 1973)
Phosphorus (P)	Nitric-perchloric (9:4) acid digestion and spectrophotometry using vanado- molybdo yellow colour method (Jackson, 1973)
Potassium (K)	Nitric-perchloric (9:4) acid digestion and flame photometry (Jackson, 1973)
Calcium (Ca)	Nitric-perchloric (9:4) acid digestion and atomic absorption spectrophotometry (Piper, 1966)
Zinc (Zn) and Iron (Fe)	Nitric-perchloric (9:4) acid digestion and atomic absorption spectrophotometry (Lindsay and Norval, 1978)
Boron (B)	Hot water extraction and estimation using Azomethane – H spectrophotometer (Gupta 1967)

3.5.3 Nutrient Use Efficiency

The nutrient use efficiency was computed in terms of agronomic efficiency, physiological efficiency and apparent recovery efficiency.

3.5.3.1. Agronomic Efficiency

Agronomic efficiency (AE) was calculated by using the formula given below (Fageria and Baligar, 2005) and expressed as kg yield per kg nutrient applied.

$$AE = (Y_f - Y_0) / F$$

Y_f – Crop yield in fertilized plot

Y_0 – Crop yield in control plot

F – Fertilizer rate

3.5.3.2. Physiological Efficiency

Physiological efficiency (PE) was calculated by using the formula given below (Fageria and Baligar, 2005), and expressed as kg yield increase per kg nutrient uptake.

$$PE = (Y_f - Y_0) / (N_f - N_0)$$

Y_f – Crop yield in fertilized plot

Y_0 – Crop yield in control plot

N_f – Nutrient uptake in fertilized plot

N_0 – Nutrient uptake in control plot

3.5.3.3. Apparent Recovery Efficiency

Apparent recovery efficiency (ARE) was computed using the formula given below (Fageria and Baligar, 2005), and expressed as kg increase in nutrient uptake per kg nutrient applied.

$$ARE = (N_f - N_0) / F$$

N_f – Nutrient uptake in fertilized plot

N_0 – Nutrient uptake in control plot

F – Fertilizer rate

3.6. SYSTEM ANALYSIS

3.6.1. System Yield

System yield refers to yield per unit area and expressed in kg ha⁻¹. The yield here is the equivalent yield in terms of a single commodity. The equivalent yield was calculated in terms of rice using the following formula

$$REY = \frac{\sum Y_i \times P_i}{P_r}$$

Where,

REY – Rice equivalent yield

Y_i – Yield of different crops

P_i – Price of respective crops

P_r – Price of rice

3.6.2. System Productivity

System productivity refers to yield per unit area per unit time. The yield here is the equivalent yield in terms of rice. The time here is agricultural year (365 days). The equivalent yield was calculated and then divided by 365 and expressed in kg ha⁻¹ day⁻¹.

3.7. SYSTEM ENERGETICS

The direct energy input and output were calculated in terms of Mega joules per hectare (MJ ha⁻¹) based on energy equivalent values for the various inputs and outputs. The details regarding the energy equivalents of inputs and outputs are presented in Appendix III and the fixed and variable energies of the three seasons are presented in the Appendices IVa, IVb, Va, Vb, VI and VII . The system energetic was calculated using the formulas given by (Soltani *et al.*, 2013).

3.7.1. Energy Efficiency (EE)

The energy utilized through inputs and energy produced as products were calculated. Energy efficiency was worked out taking into account the input and output energy for each treatment.

$$EE = \frac{\text{Energy output (MJ ha}^{-1}\text{)}}{\text{Energy input (MJ ha}^{-1}\text{)}}$$

3.7.2. Specific Energy (SE)

Specific energy of the treatment was calculated in terms of energy required to produce unit quantity of main product and expressed in MJ kg⁻¹.

$$SE = \frac{\text{Energy input (MJ ha}^{-1}\text{)}}{\text{Total crop yield (kg ha}^{-1}\text{)}}$$

3.7.3. Energy Productivity (EP)

Energy productivity describes the quantity of physical output obtained for every unit of input and expressed in kg MJ⁻¹.

$$EP = \frac{\text{Output (Total crop yield + by product) (kg ha}^{-1}\text{)}}{\text{Energy input (MJ ha}^{-1}\text{)}}$$

3.7.4. Energy Intensity (EI)

Energy intensity (economic terms) is the ratio between energy output and cultivation expenses and expressed in MJ ₹⁻¹

$$EI = \frac{\text{Energy output (MJ ha}^{-1}\text{)}}{\text{Cost of cultivation (₹ ha}^{-1}\text{)}}$$

3.8. NUTRIENT BALANCE OF THE SYSTEM

Nutrient balance sheets were worked out for available N, P, K, Ca, Zn, Fe and B in post-harvest soil on the basis of the following parameters, adopting the procedure outlined by Sadanandan and Mahaptra (1973).

1. Initial status of nutrient in soil (A)
2. Total amount of nutrient added through manures and fertilizers (B)
3. Amount of nutrient removed by the crop or uptake (C)
4. Expected nutrient balance (D) = (A+B) -C
5. Available nutrient of soil after the experiment (E)
6. Net gain (+) or loss (-) = (E - D) kg ha⁻¹

3.9. ECONOMIC ANALYSIS

The economics of cultivation was expressed in terms of net income and benefit cost ratio based on cost of cultivation and prevailing price of the produce. The average input cost and market price of the produce are presented in Appendix II.

3.9.1. Net Income

Net income was computed using the formula

$$\text{Net income (₹ ha}^{-1}\text{)} = \text{Gross income} - \text{Cost of cultivation}$$

3.9.2. Benefit Cost Ratio

Benefit cost ratio (BCR) was computed as follows

$$\text{Benefit cost ratio (BCR)} = \frac{\text{Gross income}}{\text{Cost of cultivation}}$$

3.10. STATISTICAL ANALYSIS

The data generated from the experiment was statistically analyzed using Analysis of Variance (ANOVA) technique as applied to Randomized Complete Block Design (Panse and Sukhatme, 1985) and the significance was tested using F test (Snedecor and Cochran, 1967). Wherever the F values were found significant, critical difference was worked out at five per cent and one per cent probability levels. The entire statistical analysis was done using the General R based Analysis Platform Empowered by Statistics (GRAPES 1.0.0) software developed by Gopinath *et al.* (2021).

RESULTS

4. RESULTS

An experiment entitled “Nano zinc nutrition in rice based cropping systems in high phosphorus soils” was undertaken to evaluate the response of rice to nano zinc in high P soils and its residual effect on growth and yield of succeeding crops. The study also aims to study the P - Zn interactions and to identify the promising cropping sequence in terms of system productivity and profitability. The experiment was conducted during the period April 2022 to March 2023 at the IFSRS, Karamana. The experimental data collected were statistically analyzed and the results are presented below.

4.1. GROWTH PARAMETERS OF RICE

The data on growth attributes of rice as influenced by zinc nutrition during the *virippu* and *mundakan* season are presented below. The growth attributes were recorded at maximum tillering, panicle initiation, flowering and at harvest.

4.1.1. Plant Height

The mean plant height observed at various growth stages during the *virippu* and *mundakan* seasons are given in Tables 5a and 5b.

Persual of data revealed that the treatments significantly influenced the plant height during both the seasons. During the *virippu* season, at maximum tillering stage, taller plants were observed in T₃ (60.17 cm), which was found on par with T₂ (58.27 cm) and T₁ (53.87 cm) respectively. Shorter plants were recorded in T₅ (41.30 cm) which was on par with T₄ (41.53 cm), T₆ (49.40 cm), T₈ (49.17 cm) and T₇ (50.10 cm) respectively. At panicle initiation stage, taller plants were observed in T₃ (73.82 cm) which was on par with T₂ (70.36 cm), T₆ (65.65 cm), T₅ (61.09 cm). Shorter plants were observed in T₈ (52.03 cm), which were on par with T₄ (54.77 cm), T₁ (56.81 cm) and T₇ (60.05 cm). At flowering stage also, taller plants (112.45 cm) were observed in T₃ which were on par with T₂ (108.33 cm) and T₆ (106.39 cm) respectively. Shorter plants was observed in T₈ (63.37 cm), which were on par with T₁ (75.50 cm) and T₄ (79.10 cm) respectively. At harvest stage, taller plants were recorded in T₃ (124.87 cm), which were on par with T₂ (116.53 cm) and T₆ (113.15 cm) respectively. Shorter plants were found in T₈ (72.81 cm), which were on par with T₁ (81.90 cm) and T₄ (86.90 cm) respectively.

Table 5a. Effect of nano zinc nutrition on plant height at different stages of *virippu* rice, cm

Treatments		Maximum tillering	Panicle initiation	Flowering	At harvest
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	53.87 ± 8.30 ^{ab}	56.81 ± 6.00 ^{cd}	75.50 ± 4.68 ^{cd}	81.90 ± 7.59 ^{cd}
T ₂	– NP with Nano Zn at 0.05%	58.27 ± 5.66 ^{ab}	70.36 ± 1.96 ^{ab}	108.33 ± 10.92 ^{ab}	116.53 ± 11.06 ^{ab}
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	60.17 ± 3.98 ^a	73.82 ± 5.06 ^a	112.45 ± 26.40 ^a	124.87 ± 20.35 ^a
T ₄	– NP with ZnSO ₄ at 0.5%	41.53 ± 2.05 ^c	54.77 ± 13.83 ^{cd}	79.10 ± 4.98 ^{cd}	86.90 ± 8.64 ^{cd}
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	41.30 ± 2.52 ^c	61.09 ± 2.70 ^{abcd}	89.94 ± 7.01 ^{bc}	100.84 ± 8.35 ^{bc}
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	49.40 ± 7.71 ^{bc}	65.65 ± 2.29 ^{abc}	106.39 ± 9.68 ^{ab}	113.15 ± 13.44 ^{ab}
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	50.10 ± 8.25 ^{bc}	60.05 ± 6.43 ^{bcd}	88.56 ± 2.13 ^{bc}	98.63 ± 10.74 ^{bc}
T ₈	– Control (RDN without application of P and Zn)	49.17 ± 12.46 ^{bc}	52.03 ± 13.82 ^d	63.37 ± 7.04 ^d	72.81 ± 7.85 ^d
SEm (±)		3.29	4.37	6.57	7.2
CD (0.05)		9.981	13.249	19.939	21.839

Table 5b. Effect of nano zinc nutrition on plant height at different stages of *mundakan* rice, cm

Treatments		Maximum tillering	Panicle initiation	Flowering	At harvest
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	38.93 ± 3.22 ^{bc}	46.33 ± 3.21 ^{de}	62.70 ± 2.36 ^d	78.70 ± 2.87 ^{de}
T ₂	– NP with Nano Zn at 0.05%	52.23 ± 9.78 ^{ab}	70.57 ± 8.26 ^{abc}	80.33 ± 4.70 ^c	96.37 ± 1.82 ^{bc}
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	58.60 ± 3.83 ^a	74.70 ± 8.32 ^a	97.70 ± 2.05 ^a	118.20 ± 6.30 ^a
T ₄	– NP with ZnSO ₄ at 0.5%	43.60 ± 6.73 ^{bc}	62.27 ± 5.10 ^c	71.53 ± 14.51 ^{cd}	87.00 ± 5.72 ^{cd}
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	47.43 ± 7.68 ^{abc}	63.40 ± 7.56 ^{bc}	82.43 ± 7.49 ^{bc}	100.83 ± 17.86 ^{bc}
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	49.67 ± 9.81 ^{abc}	72.53 ± 4.84 ^{ab}	94.53 ± 3.65 ^{ab}	110.23 ± 20.96 ^{ab}
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	39.50 ± 16.13 ^{bc}	52.10 ± 7.37 ^d	77.77 ± 9.65 ^c	91.77 ± 7.85 ^{cd}
T ₈	– Control (RDN without application of P and Zn)	38.13 ± 7.07 ^c	41.80 ± 1.51 ^e	60.07 ± 9.37 ^d	68.60 ± 1.80 ^e
SEm (±)		4.40	3.32	4.62	5.70
CD (0.05)		13.340	10.082	14.001	17.287

During the *mundakan* season, at maximum tillering stage, the taller plants were observed in T₃ (58.60 cm), which were on par with T₂ (52.23 cm), T₅ (47.43 cm), and T₆ (49.67 cm). Shorter plants were recorded in T₈ (38.13 cm), which was on par with T₁ (38.93 cm), T₇ (39.50 cm), T₄ (43.60 cm), T₅ (47.43 cm) and T₆ (49.67 cm). At panicle initiation stage, comparatively taller plants were observed in T₃ (74.70 cm), which were on par with T₆ (72.53 cm), and T₂ (70.57 cm). Plants were shorter in T₈ (41.80 cm), which was on par with T₁ (46.33 cm). At flowering stage, taller plants were observed in T₃ (97.70 cm), which were on par with T₆ (94.53 cm). Shorter plants were observed in T₈ (60.07 cm), which was on par with T₁ (62.70 cm) and T₄ (71.53 cm). At harvest stage, the taller plants were again observed in T₃ (118.20 cm), which was on par with T₆ (110.23 cm). Shorter plants were recorded in T₈ (68.60 cm), which was on par with T₁ (78.70 cm).

4.1.2. Tiller m⁻²

The effect of nano zinc nutrition on tillers per m² at different growth stages during *virippu* and *mundakan* seasons were significant and are presented in Tables 6a and 6b.

During the *virippu* season, at the maximum tillering stage, the highest number of tillers per m² was observed in T₂ (486) and T₃ (468) which was comparable to T₁ (459), T₆ (440) and T₇ (432). Lower number of tillers was recorded in T₅ (296), which were on par with T₄ (314). At the panicle initiation stage, a significantly higher number of tillers were recorded in T₃ (654), which were on par with T₂ (628) and T₆ (590). Lower tiller number was observed in T₄ (423) and T₈ (429), which were on par with T₁ (485). At flowering stage, the maximum number of tillers was observed in T₃ (677), which were on par with T₆ (650) and T₂ (623). The lower tiller count was recorded in T₈ (411), which were on par with T₁ (476) and T₄ (455). At the harvest stage, the highest number of tillers was again observed in T₃ (658), which were on par with T₂ (573) and T₆ (571). The lowest number of tillers was recorded in T₈ (357), which were on par with T₁ (389) and T₄ (413).

Table 6a. Effect of nano zinc nutrition on tillers m⁻² at different stages of *virippu* rice

Treatments		Maximum tillering	Panicle initiation	Flowering	At harvest
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	459 ± 48 ^{ab}	485 ± 71 ^{cd}	476 ± 96 ^{cd}	389 ± 17 ^{cd}
T ₂	– NP with Nano Zn at 0.05%	486 ± 32 ^a	628 ± 60 ^{ab}	623 ± 115 ^{ab}	573 ± 96 ^{ab}
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	468 ± 23 ^a	654 ± 118 ^a	677 ± 45 ^a	658 ± 61 ^a
T ₄	– NP with ZnSO ₄ at 0.5%	314 ± 15 ^{cd}	423 ± 75 ^d	455 ± 82 ^{cd}	413 ± 54 ^{cd}
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	296 ± 57 ^d	527 ± 74 ^{bcd}	534 ± 85 ^{bc}	509 ± 82 ^{bc}
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	440 ± 37 ^{ab}	590 ± 40 ^{abc}	650 ± 28 ^{ab}	571 ± 114 ^{ab}
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	432 ± 75 ^{ab}	515 ± 41 ^{bcd}	545 ± 71 ^{bc}	495 ± 65 ^{bcd}
T ₈	– Control (RDN without application of P and Zn)	387 ± 35 ^{bc}	429 ± 47 ^d	411 ± 84 ^d	357 ± 112 ^d
SEm (±)		26	40	39	48
CD (0.05)		79	123	119	148

Table 6b. Effect of nano zinc nutrition on tillers per m⁻² at different stages of *mundakan* rice

Treatments		Maximum tillering	Panicle initiation	Flowering	At harvest
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	503 ± 86 ^{abc}	532 ± 90 ^{de}	511 ± 149 ^{ef}	440 ± 19 ^e
T ₂	– NP with Nano Zn at 0.05%	701 ± 31 ^a	779 ± 17 ^{ab}	694 ± 71 ^{cd}	561 ± 36 ^{bcd}
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	689 ± 26 ^{ab}	828 ± 52 ^a	868 ± 125 ^a	711 ± 62 ^a
T ₄	– NP with ZnSO ₄ at 0.5%	609 ± 156 ^{abc}	663 ± 42 ^{bc}	592 ± 122 ^{de}	473 ± 117 ^{de}
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	644 ± 112 ^{ab}	698 ± 80 ^b	761 ± 201 ^{bc}	594 ± 49 ^{bc}
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	516 ± 153 ^{abc}	745 ± 32 ^{ab}	811 ± 115 ^{ab}	663 ± 80 ^{ab}
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	478 ± 118 ^{bc}	569 ± 17 ^{cd}	617 ± 98 ^d	507 ± 58 ^{cde}
T ₈	– Control (RDN without application of P and Zn)	427 ± 171 ^c	440 ± 131 ^e	432 ± 29 ^f	325 ± 27 ^f
SEm (±)		71.12	41.44	33.82	37.12
CD (0.05)		216.000	125.704	102.569	112.599

NS- Non significant

During the *mundakan* season, at the maximum tillering stage, the highest number of tillers per m² was recorded in T₂ (701), which was on par with T₃ (689), T₅ (644), T₄ (609), T₆ (516), and T₁ (503). The lower number of tillers was observed in T₈ (427), which was on par with T₇ (478), T₁ (503), T₆, T₄. At the panicle initiation stage, the highest number of tillers was observed in T₃ (828), which were on par with T₂ (779) and T₆ (745). The lowest tiller count was recorded in T₈ (440), which was on par with T₁ (532). At the flowering stage, the highest number of tillers was observed in T₃ (868), which was on par with T₆ (811). The lower number of tillers was observed in T₈ (432), which was on par with T₁ (511). At the harvest stage, the highest number of tillers was recorded in T₃ (711), which were on par with T₆ (663). The lowest tiller count was observed in T₈ (325).

4.1.3. Leaf area per hill

The leaf area per hill was significantly affected by the treatments imposed both during *virippu* and *mundakan* seasons at all the growth stages and the same is presented in Tables 7a and 7b.

During the *virippu* season, the highest leaf area per hill was recorded in T₂ (776.53 cm²) and T₃ (774.52 cm²) which were on par with T₁ (691.85 cm²) at maximum tillering stage and the lowest leaf area was recorded in T₅ (497.45 cm²), which was on par with T₄ (541.40 cm²) and T₈ (582.37 cm²). At panicle initiation stage, the highest leaf area per hill was observed in T₃ (1101.41 cm²), which was on par with T₂ (991.28 cm²) and T₆ (943.93 cm²). The lowest value was recorded in T₄, T₁, T₈ (672.50, 704.56, 691.81 cm², respectively). At flowering stage, the leaf area significantly differed, the maximum leaf area per hill was recorded in T₃ (1379.20 cm²), which is on par with T₂ (1266.75 cm²) and T₆ (1222.06 cm²). The minimum leaf area per hill was recorded in T₈ (855.75 cm²), which was found on par with T₄ (910.78 cm²) and T₁ (944.76 cm²).

Table 7a. Effect of nano zinc nutrition on leaf area per hill at different stages of *virippu* rice and leaf area index (LAI) at panicle initiation stage

Treatments	Leaf area per hill (cm ²)				LAI
	Maximum tillering	Panicle initiation	Flowering	At harvest	Panicle initiation
T ₁ – SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	691.85 ± 80.69 ^{ab}	704.56 ± 33.37 ^d	944.76 ± 84.71 ^{de}	662.28 ± 54.52 ^{ef}	2.35 ± 0.11 ^d
T ₂ – NP with Nano Zn at 0.05%	776.53 ± 49.72 ^a	991.28 ± 134.71 ^{ab}	1266.75 ± 151.89 ^{ab}	1013.49 ± 61.36 ^{bc}	3.31 ± 0.45 ^{ab}
T ₃ – NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	774.52 ± 45.61 ^a	1101.41 ± 187.72 ^a	1379.20 ± 127.28 ^a	1187.25 ± 94.19 ^a	3.67 ± 0.63 ^a
T ₄ – NP with ZnSO ₄ at 0.5%	541.40 ± 50.31 ^{cd}	672.50 ± 51.51 ^d	910.78 ± 99.90 ^{de}	721.35 ± 91.00 ^{ef}	2.24 ± 0.17 ^d
T ₅ – NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	497.45 ± 51.77 ^d	899.17 ± 58.22 ^{bc}	1146.74 ± 124.67 ^{bc}	907.28 ± 130.07 ^{cd}	3.00 ± 0.20 ^{bc}
T ₆ – FS with Nano Zn at 0.05% at MT and PI stages	640.36 ± 35.96 ^{bc}	943.93 ± 121.16 ^{abc}	1222.06 ± 60.44 ^{abc}	1096.11 ± 127.87 ^{ab}	3.15 ± 0.41 ^{abc}
T ₇ – FS with ZnSO ₄ at 0.5% at MT and PI stages	657.53 ± 26.24 ^b	799.08 ± 66.57 ^{cd}	1051.53 ± 60.19 ^{cd}	822.10 ± 131.70 ^{de}	2.66 ± 0.23 ^{cd}
T ₈ – Control (RDN without application of P and Zn)	582.37 ± 107.39 ^{bcd}	691.81 ± 75.96 ^d	855.75 ± 36.66 ^e	622.03 ± 123.27 ^f	2.31 ± 0.25 ^d
SEm (±)	37.37	62.78	56.55	56.06	0.21
CD (0.05)	113.348	190.438	171.523	170.057	0.636

Table 7b. Effect of nano zinc nutrition on leaf area per hill at different stages of *mundakan* rice and leaf area index (LAI) at panicle initiation stage

Treatments	Leaf area per hill (cm ²)				LAI
	Maximum tillering	Panicle initiation	Flowering	At harvest	Panicle initiation
T ₁ – SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	556.69 ± 30.32 ^{cde}	569.99 ± 65.07 ^{cd}	672.50 ± 89.46 ^e	569.50 ± 31.23 ^e	2.85 ± 0.32 ^{cd}
T ₂ – NP with Nano Zn at 0.05%	675.00 ± 17.50 ^{ab}	875.23 ± 107.49 ^{ab}	880.15 ± 39.77 ^{bcd}	702.60 ± 26.50 ^{cd}	4.38 ± 0.54 ^{ab}
T ₃ – NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	706.65 ± 48.48 ^a	981.49 ± 152.30 ^a	1112.11 ± 87.37 ^a	935.70 ± 56.18 ^a	4.91 ± 0.76 ^a
T ₄ – NP with ZnSO ₄ at 0.5%	581.64 ± 26.66 ^{bcd}	632.15 ± 33.08 ^{cd}	739.58 ± 82.45 ^{de}	594.58 ± 118.24 ^{de}	3.16 ± 0.16 ^{cd}
T ₅ – NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	623.69 ± 82.82 ^{abc}	792.50 ± 57.42 ^b	954.56 ± 169.31 ^{bc}	801.86 ± 55.19 ^{bc}	3.96 ± 0.29 ^b
T ₆ – FS with Nano Zn at 0.05% at MT and PI stages	512.56 ± 101.68 ^{def}	834.32 ± 76.13 ^b	1011.88 ± 67.05 ^{ab}	854.67 ± 97.87 ^{ab}	4.17 ± 0.38 ^b
T ₇ – FS with ZnSO ₄ at 0.5% at MT and PI stages	474.34 ± 45.38 ^{ef}	640.38 ± 31.59 ^c	826.48 ± 7.13 ^{cd}	621.55 ± 24.67 ^{de}	3.20 ± 0.16 ^c
T ₈ – Control (RDN without application of P and Zn)	433.70 ± 48.33 ^f	496.05 ± 20.99 ^d	661.48 ± 12.44 ^e	429.25 ± 96.38 ^f	2.48 ± 0.10 ^d
SEm (±)	34.88	47.23	50.49	43.42	0.24
CD (0.05)	105.796	143.26	153.133	131.708	0.716

At the harvest stage, the highest leaf area per hill was recorded in T₃ (1187.25 cm²), which was on par with T₆ (1096.11 cm²). The lowest value was recorded in T₈ (622.03 cm²), which was on par with T₁ (662.28 cm²) and T₄ (721.35 cm²).

During the *mundakan* season, at the maximum tillering stage, the highest leaf area per hill was recorded in T₃ (706.65 cm²), which was on par with T₂ (675.00 cm²) and T₅ (623.69 cm²). The lowest leaf area per hill was recorded in T₈ (433.70 cm²), which was on par with T₇ (474.34 cm²) and T₆ (512.56 cm²). Highest leaf area per hill was observed in T₃ (981.49 cm²), which was on par with T₂ (875.23 cm²) at panicle initiation stage. The lowest leaf area per hill was recorded in T₈ (496.05 cm²), which was on par with T₁ (569.99 cm²) and T₄ (632.15 cm²). At flowering stage, the highest leaf area per hill was recorded in T₃ (1112.11 cm²), which was on par with T₆ (1011.88 cm²). The lowest leaf area per hill was observed in T₈ (661.48 cm²), which was on par with T₁ (672.50 cm²) and T₄ (739.58 cm²). At harvest stage, the highest leaf area per hill was recorded in T₃ (935.70 cm²), which was on par with T₆ (854.67 cm²). The lowest leaf area per hill was recorded in T₈ (429.25 cm²).

4.1.4. Leaf Area Index (LAI)

Leaf Area Index (LAI) as influenced by nano zinc nutrition at panicle initiation stage varied significantly during *virippu* at panicle initiation stage (Table 7a) and *mundakan* (Table 7b.)

During *virippu*, at panicle initiation stage the highest LAI was recorded in T₃ (3.67), which was on par with T₂ (3.31) and T₆ (3.15). The lowest LAI was observed in T₄ (2.24), T₈ (2.31) and T₁ (2.35) which were comparable to T₇ (2.66).

During the *mundakan* season, for LAI at the panicle initiation stage, the highest value was observed in T₃ (4.91), which was on par with T₂ (4.38). The lowest LAI was recorded in T₈ (2.48), which was on par with T₄ (3.16) and T₁ (2.85).

4.1.5. Dry Matter Production at Harvest

Nano zinc nutrition was found to affect the dry matter production at harvest significantly during *virippu* and *mundakan*. The recorded values are tabulated in Table 8a and 8b

In *virippu* season, the highest dry matter production at harvest was recorded with nutria priming with T₃- nano zinc at 0.05% followed by foliar spray with nano zinc at 0.05% at maximum tillering stage (37.38 g per hill), which was found on par with T₆ (35.36 g per hill). The lowest dry matter production was observed in T₈- control (20.13 g per hill), which was on par with T₁ (23.41 g per hill).

In *mundakan* season, the highest dry matter production at harvest was recorded in T₃ (34.27 g per hill), which was on par with T₆ (31.00 g per hill). The lowest dry matter production was observed in T₈ (15.99 g per hill).

4.2. YIELD AND YIELD ATTRIBUTES OF RICE

4.2.1. Days to 50 per cent Flowering

Days to 50 per cent flowering was recorded during both *virippu* and *mundakan* and are presented in the Tables 8a and 8b respectively.

The result of effect of nano zinc nutrition on days to 50 per cent flowering was not significant during both the seasons.

4.2.2. Sterility Percentage

Sterility percentage of rice as influenced by nano zinc nutrition in rice was significantly varying during *virippu* and *mundakan*, presented in Tables 8a and 8b.

In *virippu*, significantly least sterility percentage was noticed in T₃- nutri priming with nano zinc at 0.05% followed by foliar spray with nano zinc at 0.05% at maximum

tillering stage (6.51%), which was on par with T₆ (7.00%). The highest percentage of sterility (16.59%) was observed in the control treatment (T₈).

Sterility percentage during *mundakan* varied significantly among treatments the least sterility percentage was recorded with nutri priming with nano zinc at 0.05% followed by foliar spray with nano zinc at 0.05% at maximum tillering (4.83%), which was statistically on par with T₆- foliar spray of nano zinc at 0.05% at maximum tillering and panicle initiation stages (6.17%). The highest percentage of sterility was noticed in T₈- control (19.63%).

4.2.3. Productive Tillers per Hill

Effect of nano zinc nutrition on productive tillers per hill in *virippu* and *mundakan* was presented in the Tables 9a and 9b respectively.

Productive tillers per hill during *virippu* was significantly affected due to the nano zinc nutrition in rice. The highest number of productive tillers were observed in T₃- nutri priming with nano zinc at 0.05% followed by foliar spray with nano zinc at 0.05% at maximum tillering stage (19), which was on par with T₆ (17) and T₂ (17). The lowest number of productive tillers were noticed in T₈- control (9), which was found on par with T₁ (11).

During *mundakan*, significantly higher number of productive tillers were observed in T₃ (18), which was on par with T₆ (16), where as lower number of productive tillers (7) were observed in control treatment (T₈).

Table 8a. Effect of nano zinc nutrition on dry matter production at harvest, days to 50% flowering, sterility % of *virippu* rice

Treatments		Dry matter production at harvest (g per hill)	Days to 50% flowering	Sterility %
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	23.41 ± 1.32 ^{ef}	74	15.20 ± 1.07 ^{ab}
T ₂	– NP with Nano Zn at 0.05%	31.80 ± 4.17 ^{bc}	75	9.08 ± 0.60 ^{cd}
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	37.38 ± 3.97 ^a	75	6.51 ± 0.84 ^e
T ₄	– NP with ZnSO ₄ at 0.5%	25.81 ± 4.48 ^{de}	73	13.81 ± 0.93 ^b
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	31.50 ± 5.94 ^{bc}	74	9.85 ± 1.53 ^c
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	35.36 ± 2.36 ^{ab}	75	7.00 ± 0.87 ^{de}
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	29.72 ± 3.71 ^{cd}	74	10.81 ± 1.37 ^c
T ₈	– Control (RDN without application of P and Zn)	20.13 ± 3.52 ^f	74	16.59 ± 2.31 ^a
SEm (±)		1.79	0.5	0.69
CD (0.05)		5.441	NS	2.088

NS- Non significant

Table 8b. Effect of nano zinc nutrition on dry matter production at harvest, days to 50% flowering, sterility % of *mundakan* rice

Treatments		Dry matter production at harvest (g per hill)	Days to 50% flowering	Sterility %
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	21.00 ± 0.61 ^e	69.00 ± 1.00	12.96 ± 0.97 ^b
T ₂	– NP with Nano Zn at 0.05%	26.20 ± 0.62 ^{cd}	70.00 ± 1.73	9.17 ± 1.53 ^c
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	34.27 ± 2.07 ^a	70.00 ± 1.73	4.83 ± 1.04 ^e
T ₄	– NP with ZnSO ₄ at 0.5%	22.57 ± 2.74 ^{de}	68.67 ± 1.53	12.28 ± 2.12 ^b
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	28.43 ± 5.44 ^{bc}	69.33 ± 2.08	7.87 ± 0.13 ^{cd}
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	31.00 ± 1.41 ^{ab}	69.67 ± 1.53	6.17 ± 1.03 ^{de}
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	24.73 ± 3.95 ^{cde}	68.67 ± 1.53	10.24 ± 1.69 ^{bc}
T ₈	– Control (RDN without application of P and Zn)	15.99 ± 0.81 ^f	69.00 ± 1.73	19.63 ± 2.13 ^a
SEm (±)		1.54	0.36	0.90
CD (0.05)		4.683	NS	2.732

NS- Non significant

4.2.4. No. of Grains per Panicle

The result on number of grains per panicle during *virippu* and *mundakan* are depicted in the Tables 9a and 9b respectively.

During *virippu* and *mundakan*, significantly highest number of grains per panicle was observed in treatment containing nutri priming with nano zinc at 0.05% followed by foliar spray with nano zinc at 0.05% at maximum tillering stage (217) and (204) respectively, which was on par with T₆ (210,197) and T₂ (190,171) in *virippu* and *mundakan* respectively.

The lowest number of grains per panicle was recorded in T₈ (136), which was comparable to T₁ and on par with T₄ (149) during *virippu*, whereas in *mundakan* the lowest number of grains per panicle was recorded in T₈ (control).

4.2.5. Grain Weight per Panicle

Grain weight per panicle as affected by nano zinc nutrition in rice during *virippu* and *mundakan* are presented in Tables 9a and 9b respectively.

Grain weight per panicle was observed to differ significantly to zinc nutrition during *virippu*. Highest grain weight per panicle (6.15 g) was recorded in nutri priming with nano zinc at 0.05% followed by foliar spray with nano zinc at 0.05% at maximum tillering stage (T₃) and T₆- foliar spray of nano zinc at 0.05% at maximum tillering and panicle initiation stages (5.96 g) which were comparable to T₂- nutri priming with nano zinc at 0.05% (4.95 g). The lowest grain weight per panicle was recorded in T₈ (2.60 g), which was comparable to T₄- Nutri priming with ZnSO₄ at 0.5% (2.77 g) and on par with T₁ (2.94 g) and T₇ (3.40 g).

In *mundakan*, greater grain weight per panicle was observed in T₃ (5.62 g), which was on par with T₆ (5.49 g). The lesser grain weight per panicle was observed in control T₈ (1.44g).

Table 9a. Effect of nano zinc nutrition on productive tillers per hill, no. of grains per panicle, grain weight per panicle, thousand grain weight of *virippu* rice

Treatments		Productive tillers per hill	No. grains per panicle	Grain weight per panicle (g)	Thousand grain weight (g)
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	11 ± 1 ^{cd}	138 ± 15 ^d	2.94 ± 0.54 ^{cd}	23.48 ± 2.69
T ₂	– NP with Nano Zn at 0.05%	17 ± 1 ^{ab}	190 ± 10 ^{ab}	4.95 ± 0.93 ^{ab}	25.18 ± 1.95
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	19 ± 4 ^a	217 ± 16 ^a	6.15 ± 0.50 ^a	26.33 ± 1.61
T ₄	– NP with ZnSO ₄ at 0.5%	12 ± 1 ^{cd}	149 ± 8 ^{cd}	2.77 ± 0.77 ^d	24.58 ± 1.94
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	16 ± 1 ^b	183 ± 35 ^b	4.16 ± 0.54 ^{bc}	26.20 ± 1.86
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	17 ± 4 ^{ab}	210 ± 40 ^{ab}	5.96 ± 1.38 ^a	26.65 ± 1.53
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	14 ± 2 ^{bc}	179 ± 9 ^{bc}	3.40 ± 0.43 ^{cd}	24.49 ± 3.77
T ₈	– Control (RDN without application of P and Zn)	9 ± 1 ^d	136 ± 4 ^d	2.60 ± 1.10 ^d	23.87 ± 2.58
SEm (±)		1	10	0.41	1.22
CD (0.05)		3	32	1.236	NS

NS- Non significant

Table 9b. Effect of nano zinc nutrition on productive tillers per hill, no. of grains per panicle, grain weight per panicle, thousand grain weight of *mundakan* rice

Treatments		Productive tillers per hill	No. grains per panicle	Grain weight per panicle (g)	Thousand grain weight (g)
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	10 ± 1 ^e	135 ± 9 ^d	2.53 ± 0.25 ^e	22.34 ± 2.12
T ₂	– NP with Nano Zn at 0.05%	13 ± 1 ^{cd}	171 ± 33 ^{abc}	3.72 ± 0.58 ^{cd}	24.51 ± 1.45
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	18 ± 2 ^a	204 ± 14 ^a	5.62 ± 0.78 ^a	24.19 ± 3.63
T ₄	– NP with ZnSO ₄ at 0.5%	11 ± 1 ^{de}	137 ± 8 ^{cd}	2.54 ± 0.30 ^e	20.35 ± 3.55
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	14 ± 3 ^{bc}	168 ± 15 ^{bcd}	4.43 ± 0.71 ^{bc}	25.87 ± 1.90
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	16 ± 2 ^{ab}	197 ± 37 ^{ab}	5.49 ± 1.34 ^{ab}	25.62 ± 0.97
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	12 ± 3 ^{cde}	167 ± 7 ^{bcd}	2.97 ± 0.49 ^{de}	22.82 ± 1.54
T ₈	– Control (RDN without application of P and Zn)	7 ± 1 ^f	99 ± 1 ^e	1.44 ± 0.09 ^f	20.32 ± 3.63
SEm (±)		0.97	11.24	0.354	1.56
CD (0.05)		2.932	34.080	1.073	NS

NS- Non significant

4.2.6. Thousand Grain Weight

Tables 9a and 9b contains the data pertaining to thousand grain weight of rice grains as affected to the zinc nutrition during *virippu* and *mundakan*.

The data revealed that thousand grain weight of rice grains did not differ significantly to the zinc nutrition both during *virippu* and *mundakan*.

4.2.7. Grain Yield ha⁻¹

The results on grain yield ha⁻¹ of rice as affected by nano zinc nutrition during *virippu* and *mundakan* are presented in the Tables 10a and 10b. The data on pooled mean of the grain yield over two seasons is shown in Table 10c.

Nutri priming with nano zinc at 0.05% followed by foliar spray with nano zinc at 0.05% at maximum tillering stage (T₃) produced significantly higher grain yield during both *virippu* (5025 kg ha⁻¹) and *mundakan* (5297 kg ha⁻¹). During *virippu* T₃ was on par with T₆ (4753 kg ha⁻¹) and T₂ (4494 kg ha⁻¹), whereas in *mundakan* T₃ was on par with T₆ (5023 kg ha⁻¹). The lowest grain yield per hectare was recorded in the control treatment in *virippu* and *mundakan*, which was treated with recommended dose of nutrients without application of phosphorus and zinc -T₈ (*virippu*-2988 kg ha⁻¹, *mundakan*-2807 kg ha⁻¹), in *virippu* it was on par with T₁ (3222 kg ha⁻¹) and T₄ (3272 kg ha⁻¹).

The pooled mean of the grain yield over two seasons was observed to be highest in the treatment T₃ (5161 kg ha⁻¹) which was on par with T₆ (4888 kg ha⁻¹) and the lowest grain yield was observed in T₈ (2897 kg ha⁻¹) which was on par with T₁ (3378 kg ha⁻¹).

Table 10a. Effect of nano zinc nutrition on grain yield, straw yield and harvest index of *virippu* rice

Treatments		Grain yield (kg ha ⁻¹)	Straw yield (kg ha ⁻¹)	HI
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	3222 ± 74 ^{ef}	3889 ± 490 ^{de}	0.45 ± 0.04
T ₂	– NP with Nano Zn at 0.05%	4494 ± 406 ^{abc}	5383 ± 299 ^{ab}	0.45 ± 0.04
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	5025 ± 817 ^a	5864 ± 315 ^a	0.46 ± 0.05
T ₄	– NP with ZnSO ₄ at 0.5%	3272 ± 107 ^{def}	4074 ± 926 ^{cde}	0.45 ± 0.06
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	4049 ± 223 ^{bcd}	5000 ± 556 ^{abc}	0.45 ± 0.04
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	4753 ± 822 ^{ab}	5432 ± 214 ^{ab}	0.46 ± 0.03
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	3802 ± 344 ^{cde}	4506 ± 466 ^{bcd}	0.46 ± 0.05
T ₈	– Control (RDN without application of P and Zn)	2988 ± 43 ^f	3519 ± 490 ^e	0.46 ± 0.03
SEm (±)		257	312	0.03
CD (0.05)		781	947	NS

NS- Non significant

Table 10b. Effect of nano zinc nutrition on grain yield, straw yield and harvest index of *mundakan* rice

Treatments		Grain yield (kg ha ⁻¹)	Straw yield (kg ha ⁻¹)	HI
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	3534 ± 585 ^d	4198 ± 566 ^d	0.46 ± 0.08
T ₂	– NP with Nano Zn at 0.05%	4396 ± 121 ^{bc}	5222 ± 427 ^c	0.46 ± 0.02
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	5297 ± 214 ^a	6432 ± 299 ^a	0.45 ± 0.02
T ₄	– NP with ZnSO ₄ at 0.5%	4051 ± 52 ^{cd}	4815 ± 490 ^{cd}	0.46 ± 0.02
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	4568 ± 652 ^{bc}	5432 ± 650 ^{bc}	0.46 ± 0.05
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	5023 ± 305 ^{ab}	6185 ± 882 ^{ab}	0.45 ± 0.05
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	4263 ± 104 ^c	5173 ± 150 ^c	0.45 ± 0.00
T ₈	– Control (RDN without application of P and Zn)	2807 ± 525 ^e	3271 ± 386 ^e	0.46 ± 0.02
SEm (±)		239	305	0.02
CD (0.05)		725	924	NS

NS- Non significant

4.2.8. Straw Yield ha⁻¹

Data pertaining to straw yield ha⁻¹ as affected by different methods and concentrations of zinc nutrition was presented in Tables 10a and 10b for *virippu* and *mundakan* respectively. The data on pooled mean of the straw yield over two seasons is shown in Table 10c.

Straw yield during *virippu* was observed to be significantly affected by the treatments imposed, highest straw yield ha⁻¹ was recorded in T₃- Nutri priming with nano zinc at 0.05% followed by foliar spray with nano zinc at 0.05% at maximum tillering stage (5864 kg ha⁻¹), which was statistically on par with T₆ (5432 kg ha⁻¹) and T₂ (5383 kg ha⁻¹). The lowest straw yield ha⁻¹ was recorded in control treatment T₈ (3519 kg ha⁻¹) which was statistically on par with T₁ (3889 kg ha⁻¹) and T₄ (4074 kg ha⁻¹).

Similarly, in *mundakan*, straw yield ha⁻¹ was recorded highest in T₃ (6432 kg ha⁻¹), which was on par with T₆- foliar spraying of nano zinc at 0.05% at maximum tillering and panicle initiation stages (6185 kg ha⁻¹). The lowest straw yield ha⁻¹ of 3271 kg ha⁻¹ was recorded in T₈.

The pooled mean of the straw yield over two seasons was observed to be highest in the treatment T₃ (6148 kg ha⁻¹) which was on par with T₆ (5809 kg ha⁻¹) and the lowest grain yield was observed in T₈ (3395 kg ha⁻¹), which was on par with T₁ (4043 kg ha⁻¹).

4.2.9. Harvest index

Harvest index calculated during *virippu* and *mundakan* seasons are presented in the Tables 10a and table 10b.

The results revealed that effect of nano zinc nutrition on rice during both *virippu* and *mundakan* did not affect the harvest index and was not significant.

Table 10c . Effect of nano zinc nutrition on pooled mean of grain yield and straw yield of rice, kg ha⁻¹

Treatments		Grain yield (kg ha ⁻¹)	Straw yield (kg ha ⁻¹)
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	3378 ^{ef}	4043 ^{ef}
T ₂	– NP with Nano Zn at 0.05%	4445 ^{bc}	5303 ^{bc}
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	5161 ^a	6148 ^a
T ₄	– NP with ZnSO ₄ at 0.5%	3661 ^{de}	4445 ^{de}
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	4309 ^c	5216 ^{bc}
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	4888 ^{ab}	5809 ^{ab}
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	4033 ^{cd}	4840 ^{cd}
T ₈	– Control (RDN without application of P and Zn)	2897 ^f	3395 ^f
SEm (±)			
CD (0.05)		526	657

4.3. PLANT ANALYSIS OF RICE

4.3.1. Nutrient Uptake

4.3.1.1 Nitrogen Uptake

4.3.1.1.1 Panicle Initiation

The effect of nano-zinc nutrition on nitrogen uptake by different parts of rice plant at the panicle initiation stage in *virippu* and *mundakan* are presented in Tables 11a and 11b, respectively.

The nitrogen (N) uptake by different parts of the rice plant during *virippu* differed significantly, higher uptake of N by root was observed in T₃- Nutri priming with nano zinc at 0.05% followed by foliar spray with nano zinc at 0.05% at maximum tillering stage (6.21 kg ha⁻¹), which was on par with T₂ (5.77 kg ha⁻¹) and T₆ (5.89 kg ha⁻¹). The N uptake of 3.06 kg ha⁻¹ by root was lower in T₈, which was on par with T₁ (3.35 kg ha⁻¹), T₄ (3.45 kg ha⁻¹) and T₇ (4.23 kg ha⁻¹). The higher uptake of N by shoot was observed in T₃ (91.52 kg ha⁻¹) which was on par with T₂ (81.43 kg ha⁻¹) and T₆ (80.31 kg ha⁻¹) whereas the lowest N uptake was recorded in T₈ (44.11 kg ha⁻¹), which was on par with T₁ (48.65 kg ha⁻¹) and T₄ (54.41 kg ha⁻¹). The total uptake of nitrogen at panicle initiation stage was higher in T₃ (97.73 kg ha⁻¹), which was on par with T₂ (87.21 kg ha⁻¹) and T₆ (86.20 kg ha⁻¹).

In *mundakan*, the higher root uptake of N was observed in T₃ (6.91 kg ha⁻¹), which was on par with T₂ (6.39 kg ha⁻¹) and T₆ (6.29 kg ha⁻¹). The N uptake was lower in T₈ (2.63 kg ha⁻¹), which was on par with T₁ (3.46 kg ha⁻¹). In case of shoot N uptake, the higher uptake were observed in T₃ (103.94 kg ha⁻¹) and T₂ (94.81 kg ha⁻¹). The lower uptake was observed in T₈ (44.38 kg ha⁻¹), which was on par with T₁ (51.35 kg ha⁻¹). Total nitrogen uptake at panicle initiation was higher in T₃ (110.86 kg ha⁻¹) and T₂ (101.2 kg ha⁻¹) and lower in T₈ (47.01 kg ha⁻¹), which was comparable to T₁ (54.81 kg ha⁻¹).

Table 11a. Effect of nano zinc nutrition on nitrogen uptake by different parts of rice plant at panicle initiation stage in *virippu*, kg ha⁻¹

Treatments		Root	Shoot	Total
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	3.35 ± 0.49 ^{cd}	48.65 ± 4.68 ^{cd}	52.00 ± 5.15 ^{cd}
T ₂	– NP with Nano Zn at 0.05%	5.77 ± 0.95 ^{ab}	81.43 ± 19.32 ^{ab}	87.21 ± 18.64 ^{ab}
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	6.21 ± 1.15 ^a	91.52 ± 11.45 ^a	97.73 ± 11.68 ^a
T ₄	– NP with ZnSO ₄ at 0.5%	3.45 ± 0.64 ^{cd}	54.41 ± 10.98 ^{cd}	57.86 ± 11.56 ^{cd}
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	4.60 ± 0.92 ^{bc}	64.94 ± 14.53 ^{bc}	69.54 ± 14.87 ^{bc}
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	5.89 ± 0.63 ^{ab}	80.31 ± 8.10 ^{ab}	86.20 ± 8.07 ^{ab}
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	4.23 ± 0.17 ^{cd}	60.25 ± 3.31 ^{cd}	64.48 ± 3.48 ^{cd}
T ₈	– Control (RDN without application of P and Zn)	3.06 ± 0.41 ^d	44.11 ± 6.62 ^d	47.17 ± 6.59 ^d
SEm (±)		0.44	6.51	6.57
CD (0.05)		1.32	19.76	19.929

Table 11b. Effect of nano zinc nutrition on nitrogen uptake by different parts of rice plant at panicle initiation stage in *mundakan*, kg ha⁻¹

Treatments		Root	Shoot	Total
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	3.46 ± 0.29 ^{cd}	51.35 ± 10.76 ^{cd}	54.81 ± 10.98 ^{de}
T ₂	– NP with Nano Zn at 0.05%	6.39 ± 0.43 ^{ab}	94.81 ± 7.57 ^a	101.20 ± 7.97 ^a
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	6.91 ± 0.54 ^a	103.94 ± 3.64 ^a	110.86 ± 4.05 ^a
T ₄	– NP with ZnSO ₄ at 0.5%	4.12 ± 0.74 ^c	72.17 ± 9.67 ^b	76.29 ± 10.28 ^c
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	5.42 ± 0.21 ^b	76.96 ± 2.51 ^b	82.39 ± 2.51 ^{bc}
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	6.29 ± 0.64 ^{ab}	82.53 ± 6.74 ^b	88.83 ± 7.33 ^b
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	3.93 ± 1.03 ^c	60.00 ± 5.50 ^c	63.93 ± 5.06 ^d
T ₈	– Control (RDN without application of P and Zn)	2.63 ± 0.80 ^d	44.38 ± 3.81 ^d	47.01 ± 4.59 ^e
SEm (±)		0.37	3.65	3.85
CD (0.05)		1.13	11.057	11.671

4.3.1.1.2 Harvest

Data pertaining to nitrogen uptake by different parts of the rice plant during *virippu* and *mundakan* at harvest are presented in the Tables 12a and 12b, respectively and was found significantly affected by the nano zinc nutrition.

In *virippu*, higher uptake of N by roots were observed in T₃ (4.95 kg ha⁻¹), T₆ (4.46 kg ha⁻¹) and T₂ (4.38 kg ha⁻¹) whereas, uptake of N by roots was lower in T₈ (2.03 kg ha⁻¹), T₁ (2.28 kg ha⁻¹) and T₄ (2.44 kg ha⁻¹), respectively. Shoot uptake of N was higher in T₃ (55.74 kg ha⁻¹) which was on par with T₆ (52.65 kg ha⁻¹) and T₂ (48.44 kg ha⁻¹). Lower uptake of N was recorded in T₈ (26.65 kg ha⁻¹) which was on par with T₁ (30.28 kg ha⁻¹) and T₄ (31.61 kg ha⁻¹), respectively. Grain uptake of N was higher in T₃ (61.26 kg ha⁻¹) which was on par with T₆ (54.98 kg ha⁻¹) and lower value was recorded in T₈ (28.68 kg ha⁻¹) and T₁ (33.16 kg ha⁻¹) which were on par with T₄ (34.39 kg ha⁻¹). The total N uptake was higher in T₃ (121.94 kg ha⁻¹) which was on par with T₆ (112.08 kg ha⁻¹), lowest uptake were observed in T₈ (57.36 kg ha⁻¹), T₁ (65.72 kg ha⁻¹) and T₄ (68.44 kg ha⁻¹), respectively.

During *mundakan*, higher uptake of N was observed in T₃- (Nutri priming with nano zinc at 0.05% followed by foliar spray with nano zinc at 0.05% at maximum tillering stage) by root (5.52 kg ha⁻¹), shoot (82.00 kg ha⁻¹), grain (67.45 kg ha⁻¹) and respectively total (154.97 kg ha⁻¹). The shoot, grain and total uptake were on par with T₆. The lowest uptake of N was reported in T₈ (control with recommended dose of nutrients without application of P and Zn) by root (1.65 kg ha⁻¹), shoot (31.26 kg ha⁻¹), grain (23.61 kg ha⁻¹) and total (56.52 kg ha⁻¹), respectively.

Table 12a. Effect of nano zinc nutrition on nitrogen uptake by different parts of rice plant at harvest stage in *virippu*, kg ha⁻¹

Treatments		Root	Shoot	Grain	Total
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	2.28 ± 0.21 ^c	30.28 ± 5.58 ^{de}	33.16 ± 0.77 ^e	65.72 ± 4.83 ^d
T ₂	– NP with Nano Zn at 0.05%	4.38 ± 0.44 ^a	48.44 ± 2.69 ^{ab}	51.68 ± 0.24 ^b	104.50 ± 2.26 ^b
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	4.95 ± 0.64 ^a	55.74 ± 4.56 ^a	61.26 ± 8.36 ^a	121.94 ± 4.46 ^a
T ₄	– NP with ZnSO ₄ at 0.5%	2.44 ± 0.21 ^c	31.61 ± 6.13 ^{de}	34.39 ± 1.38 ^{de}	68.44 ± 7.39 ^d
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	3.39 ± 0.73 ^b	42.64 ± 6.77 ^{bc}	43.91 ± 3.01 ^c	89.94 ± 5.62 ^c
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	4.46 ± 0.36 ^a	52.65 ± 6.95 ^a	54.98 ± 6.24 ^{ab}	112.08 ± 12.29 ^{ab}
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	3.33 ± 0.49 ^b	37.18 ± 3.85 ^{cd}	40.11 ± 2.62 ^{cd}	80.61 ± 2.75 ^c
T ₈	– Control (RDN without application of P and Zn)	2.03 ± 0.48 ^c	26.65 ± 3.68 ^e	28.68 ± 0.56 ^e	57.36 ± 4.02 ^d
SEm (±)		0.24	3.22	2.24	3.76
CD (0.05)		0.727	9.769	6.782	11.408

Table 12b. Effect of nano zinc nutrition on nitrogen uptake by different parts of rice plant at harvest stage in *mundakan*, kg ha⁻¹

Treatments		Root	Shoot	Grain	Total
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	2.77 ± 0.29 ^e	44.89 ± 3.67 ^c	35.27 ± 2.64 ^d	82.92 ± 5.57 ^d
T ₂	– NP with Nano Zn at 0.05%	4.01 ± 0.57 ^{bc}	60.09 ± 8.47 ^b	52.32 ± 3.62 ^b	116.43 ± 11.63 ^b
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	5.52 ± 0.19 ^a	82.00 ± 3.55 ^a	67.45 ± 3.99 ^a	154.97 ± 5.34 ^a
T ₄	– NP with ZnSO ₄ at 0.5%	3.14 ± 0.39 ^{de}	53.02 ± 4.49 ^{bc}	41.79 ± 1.54 ^{cd}	97.95 ± 4.03 ^{cd}
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	4.19 ± 0.03 ^{bc}	63.22 ± 11.86 ^b	50.89 ± 7.06 ^b	118.30 ± 14.89 ^b
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	4.55 ± 0.36 ^b	77.57 ± 11.15 ^a	63.55 ± 5.18 ^a	145.68 ± 10.07 ^a
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	3.73 ± 0.14 ^{cd}	58.06 ± 4.92 ^b	47.16 ± 6.90 ^{bc}	108.95 ± 5.94 ^{bc}
T ₈	– Control (RDN without application of P and Zn)	1.65 ± 0.59 ^f	31.26 ± 4.21 ^d	23.61 ± 4.40 ^e	56.52 ± 7.98 ^e
SEm (±)		0.22	4.32	2.92	5.38
CD (0.05)		0.674	13.096	8.852	16.327

4.3.1.2 Phosphorus Uptake

4.3.1.2.1 Panicle Initiation

The effect of nano zinc nutrition on phosphorus uptake by different parts of the rice plant was observed to be significantly varying and the data pertaining to it is shown in the Tables 13a and 13b during *virippu* and *mundakan*, respectively.

The phosphorus uptake by the root was significantly higher in T₃ (1.89, 1.84 kg ha⁻¹) and T₂ (1.62, 1.70 kg ha⁻¹) during *virippu* and *mundakan*, respectively. The lowest P uptake was recorded in T₈ (0.72 and 0.37 kg ha⁻¹ during *virippu* and *mundakan*, respectively) and during *virippu* T₈ was on par with T₁ and T₇. The shoot uptake of P was higher in T₃ (15.93 kg ha⁻¹ in *virippu*), which was on par with T₂ (14.72 kg ha⁻¹) and T₆ (14.64 kg ha⁻¹), the shoot uptake of P was higher in T₃ (15.90 kg ha⁻¹) and was on par with T₂ (15.60 kg ha⁻¹) in *mundakan*. The total uptake of P was higher in T₃ (17.82 kg ha⁻¹), which was on par with T₂ (16.33 kg ha⁻¹), whereas in *mundakan*, higher uptake was reported in T₃ (17.73 kg ha⁻¹) and T₂ (17.30 kg ha⁻¹), respectively. During *virippu*, lower uptake of P by roots were observed in T₈ (0.72 kg ha⁻¹), which was on par with T₁ (0.74 kg ha⁻¹), T₄ (0.82 kg ha⁻¹) and T₅ (1.10 kg ha⁻¹). In shoot and total uptake of P, the lower uptake was recorded in T₈ (7.55, 8.27 kg ha⁻¹, respectively), which were on par with T₁ and T₄. During *mundakan*, the lower uptake of P was reported in T₈ (6.61 kg ha⁻¹) which was on par with T₁ (8.36 kg ha⁻¹)

4.3.1.2.2 Harvest

Tables 14a and 14b represents the data pertaining to phosphorus uptake in rice by different parts of the rice plant during *virippu* and *mundakan*, and the data revealed that the P uptake has been significantly differed due to the treatments.

Table 13a. Effect of nano zinc nutrition on phosphorus uptake by different parts of rice plant at panicle initiation stage in *virippu*, kg ha⁻¹

Treatments		Root	Shoot	Total
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	0.74 ± 0.16 ^c	8.56 ± 1.30 ^{cd}	9.30 ± 1.42 ^{de}
T ₂	– NP with Nano Zn at 0.05%	1.62 ± 0.20 ^a	14.72 ± 1.68 ^{ab}	16.33 ± 1.51 ^{ab}
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	1.89 ± 0.58 ^a	15.93 ± 2.61 ^a	17.82 ± 3.15 ^a
T ₄	– NP with ZnSO ₄ at 0.5%	0.82 ± 0.23 ^c	9.74 ± 1.53 ^{cd}	10.56 ± 1.69 ^{de}
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	1.10 ± 0.13 ^{bc}	11.91 ± 4.13 ^{bc}	13.01 ± 4.23 ^{bcd}
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	1.57 ± 0.22 ^{ab}	14.64 ± 2.58 ^{ab}	16.22 ± 2.66 ^{abc}
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	1.04 ± 0.24 ^c	11.01 ± 1.08 ^{bcd}	12.06 ± 1.13 ^{cde}
T ₈	– Control (RDN without application of P and Zn)	0.72 ± 0.04 ^c	7.55 ± 0.90 ^d	8.27 ± 0.92 ^e
SEm (±)		0.16	1.31	1.39
CD (0.05)		0.485	3.973	4.201

Table 13b. Effect of nano zinc nutrition on phosphorus uptake by different parts of rice plant at panicle initiation stage in *mundakan*, kg ha⁻¹

Treatments		Root	Shoot	Total
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	0.65 ± 0.19 ^d	7.71 ± 1.65 ^{cd}	8.36 ± 1.83 ^{de}
T ₂	– NP with Nano Zn at 0.05%	1.70 ± 0.07 ^a	15.60 ± 1.01 ^a	17.30 ± 1.08 ^a
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	1.84 ± 0.29 ^a	15.90 ± 1.10 ^a	17.73 ± 1.13 ^a
T ₄	– NP with ZnSO ₄ at 0.5%	0.91 ± 0.11 ^c	11.07 ± 2.20 ^b	11.98 ± 2.21 ^c
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	1.28 ± 0.12 ^b	12.11 ± 0.63 ^b	13.39 ± 0.74 ^{bc}
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	1.61 ± 0.17 ^a	12.55 ± 1.78 ^b	14.16 ± 1.91 ^b
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	0.80 ± 0.25 ^{cd}	8.69 ± 0.28 ^c	9.49 ± 0.48 ^d
T ₈	– Control (RDN without application of P and Zn)	0.37 ± 0.01 ^e	6.23 ± 0.15 ^d	6.61 ± 0.15 ^e
SEm (±)		0.08	0.64	0.65
CD (0.05)		0.248	1.956	1.985

During both *virippu* and *mundakan*, the root uptake of P was higher in T₃ (1.50, 1.40 kg ha⁻¹, respectively) and was on par with T₆ (1.31 kg ha⁻¹ in *virippu*), whereas the lower uptake was recorded in T₈, T₁ and T₄ (0.55, 0.61 and 0.70 kg ha⁻¹ in *virippu*, respectively) and lower uptake was recorded in T₈ (0.29 kg ha⁻¹) in *mundakan*.

Shoot uptake of phosphorus in *virippu* was higher in T₃ (12.42 kg ha⁻¹), which was on par with T₆ (11.16 kg ha⁻¹) and the lower uptake was recorded in T₈ (5.36 kg ha⁻¹), which was on par with T₁ and T₄. Grain uptake of P was higher in T₃ (13.49 kg ha⁻¹), T₆ (13.28 kg ha⁻¹) and T₂ (13.13 kg ha⁻¹). The total uptake of P was higher in T₃ (27.41 kg ha⁻¹). Lower P uptake was recorded in T₈ (5.36, 6.77 kg ha⁻¹, respectively in shoot and grain) and was on par with T₁ (6.10, 7.43 kg ha⁻¹) and T₄ (6.65, 7.80 kg ha⁻¹) in shoot and grain, respectively. Total P uptake was lower in T₈, T₁ and T₄.

In *mundakan*, the P uptake was higher in T₃ (12.89, 13.60, 27.90 kg ha⁻¹ in shoot, grain and total, respectively) and was on par with T₆ (9.38, 20.92 kg ha⁻¹ in shoot and total) and with T₆ (12.65 kg ha⁻¹) in grain uptake. The P uptake in shoot, grain and total were lower in T₈ (4.21, 4.21 and 8.71 kg ha⁻¹, respectively).

4.3.1.3 Potassium Uptake

4.3.1.3.1 Panicle Initiation

The results on uptake of potassium by different parts of the rice plant at panicle initiation stage during *virippu* and *mundakan* are tabulated in the Tables 15a and 15b.

In *virippu*, the uptake of K by different parts of rice plant differed significantly for the nano zinc nutrition. The uptake of K by roots was higher in T₃ (4.65 kg ha⁻¹), T₆ (4.48 kg ha⁻¹) and T₂ (4.37 kg ha⁻¹), respectively. The shoot and total uptake were higher in T₃ (79.23, 83.88 kg ha⁻¹), which was comparable to T₂ (75.13, 79.50 kg ha⁻¹) and T₆ (72.91, 77.40 kg ha⁻¹), respectively. The uptake of K by root, shoot and total was lower in

Table 14a. Effect of nano zinc nutrition on phosphorus uptake by different parts of rice plant at harvest stage in *virippu*, kg ha⁻¹

Treatments		Root	Shoot	Grain	Total
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	0.61 ± 0.06 ^d	6.10 ± 1.13 ^{de}	7.43 ± 0.48 ^{cd}	14.14 ± 1.01 ^e
T ₂	– NP with Nano Zn at 0.05%	1.27 ± 0.02 ^b	9.73 ± 0.86 ^b	13.13 ± 1.30 ^a	24.13 ± 0.49 ^b
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	1.50 ± 0.34 ^a	12.42 ± 0.63 ^a	13.49 ± 1.96 ^a	27.41 ± 2.20 ^a
T ₄	– NP with ZnSO ₄ at 0.5%	0.70 ± 0.07 ^d	6.65 ± 1.53 ^{de}	7.80 ± 0.60 ^{cd}	15.14 ± 1.05 ^e
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	0.98 ± 0.10 ^c	9.55 ± 1.09 ^{bc}	10.42 ± 0.65 ^b	20.96 ± 0.88 ^c
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	1.31 ± 0.09 ^{ab}	11.16 ± 1.35 ^{ab}	13.28 ± 2.00 ^a	25.74 ± 3.14 ^{ab}
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	0.99 ± 0.11 ^c	7.64 ± 0.70 ^{cd}	9.32 ± 0.34 ^{bc}	17.95 ± 0.83 ^d
T ₈	– Control (RDN without application of P and Zn)	0.55 ± 0.13 ^d	5.36 ± 0.53 ^e	6.77 ± 0.26 ^d	12.68 ± 0.77 ^e
SEm (±)		0.07	0.63	0.66	0.90
CD (0.05)		0.214	1.92	2.001	2.732

Table 14b. Effect of nano zinc nutrition on phosphorus uptake by different parts of rice plant at harvest stage in *mundakan*, kg ha⁻¹

Treatments		Root	Shoot	Grain	Total
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	0.62 ± 0.23 ^e	6.80 ± 1.62 ^d	6.74 ± 1.06 ^d	14.15 ± 0.77 ^e
T ₂	– NP with Nano Zn at 0.05%	0.96 ± 0.12 ^{bcd}	8.58 ± 0.09 ^{bc}	9.82 ± 0.31 ^c	19.35 ± 0.14 ^{bc}
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	1.40 ± 0.05 ^a	12.89 ± 1.66 ^a	13.60 ± 0.69 ^a	27.90 ± 1.06 ^a
T ₄	– NP with ZnSO ₄ at 0.5%	0.77 ± 0.11 ^{de}	7.21 ± 1.20 ^{cd}	8.40 ± 0.23 ^{cd}	16.39 ± 1.13 ^{de}
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	1.02 ± 0.13 ^{bc}	9.38 ± 1.22 ^b	10.51 ± 3.14 ^{bc}	20.92 ± 1.92 ^b
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	1.16 ± 0.08 ^b	11.70 ± 1.82 ^a	12.65 ± 1.23 ^{ab}	25.51 ± 2.27 ^a
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	0.87 ± 0.08 ^{cd}	8.16 ± 0.64 ^{bcd}	9.32 ± 0.63 ^c	18.36 ± 1.23 ^{cd}
T ₈	– Control (RDN without application of P and Zn)	0.29 ± 0.08 ^f	4.21 ± 1.19 ^e	4.21 ± 0.95 ^e	8.71 ± 1.98 ^f
SEm (±)		0.07	0.57	0.80	0.80
CD (0.05)		0.223	1.739	2.413	2.428

T₈ (2.61, 45.84, 48.45 kg ha⁻¹), T₁ (2.80, 50.03, 52.83 kg ha⁻¹) and T₄ (2.76, 55.27, 58.03 kg ha⁻¹), respectively.

In *mundakan*, higher uptake of K by root and shoot were recorded in T₃ (4.85, 81.89 kg ha⁻¹) which was on par with T₂ (4.53, 79.64 kg ha⁻¹) and T₆ (4.41, 71.34 kg ha⁻¹). The data revealed that total uptake was higher in T₃ (86.74 kg ha⁻¹) and T₂ (84.18 kg ha⁻¹) and was on par with T₆ (75.74 kg ha⁻¹). The K uptake was lower in T₈ (2.13 kg ha⁻¹) by roots, which was on par with the treatments T₁ and T₇, whereas in shoot uptake, the lower values were recorded in T₈ and T₁ which were on par with T₇, lower total K uptake was recorded in T₈ (41.70 kg ha⁻¹), which was on par with T₁ (49.76 kg ha⁻¹).

4.3.1.3.2 Harvest

The effect of nano zinc nutrition on potassium uptake by different parts of rice plant at harvest was found to be significantly varied with the treatments imposed and the data is shown in Tables 16a and 16b.

The results revealed that, during *virippu*, the uptake of K by roots was higher in T₃ (2.44 kg ha⁻¹), T₆ (2.28 kg ha⁻¹) and T₂ (2.22 kg ha⁻¹) whereas, lower uptake was recorded in T₈ (1.22 kg ha⁻¹), T₁ (1.29 kg ha⁻¹) and T₄ (1.32 kg ha⁻¹). Shoot uptake of K was higher in T₃ and T₆, which were on par with T₂, whereas lower uptake was recorded in T₈ (32.21 kg ha⁻¹), which was on par with T₁ (35.68 kg ha⁻¹) and T₄ (37.47 kg ha⁻¹). The grain uptake was higher in T₃ (16.62 kg ha⁻¹), which was on par with T₆ (14.95 kg ha⁻¹) whereas, lower uptake was recorded in T₈ (7.44 kg ha⁻¹) and T₁ (8.03 kg ha⁻¹) which was on par with T₄ (9.09 kg ha⁻¹). The total uptake of K was higher in T₃ (74.50 kg ha⁻¹) and T₆ (69.35 kg ha⁻¹), which were on par with T₂ (66.39 kg ha⁻¹) whereas, lower uptake was recorded in T₈ (40.87 kg ha⁻¹) and T₁ (45.00 kg ha⁻¹) which were on par with T₄ (47.88 kg ha⁻¹).

Table 15a. Effect of nano zinc nutrition on potassium uptake by different parts of rice plant at panicle initiation stage in *virippu*, kg ha⁻¹

Treatments		Root	Shoot	Total
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	2.80 ± 0.52 ^c	50.03 ± 6.13 ^c	52.83 ± 6.60 ^c
T ₂	– NP with Nano Zn at 0.05%	4.37 ± 0.85 ^a	75.13 ± 8.98 ^{ab}	79.50 ± 8.14 ^{ab}
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	4.65 ± 0.31 ^a	79.23 ± 8.74 ^a	83.88 ± 8.80 ^a
T ₄	– NP with ZnSO ₄ at 0.5%	2.76 ± 0.55 ^c	55.27 ± 7.07 ^c	58.03 ± 7.61 ^c
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	3.57 ± 0.66 ^b	61.51 ± 12.83 ^{bc}	65.08 ± 13.25 ^{bc}
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	4.48 ± 0.75 ^a	72.91 ± 13.65 ^{ab}	77.40 ± 14.03 ^{ab}
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	3.23 ± 0.51 ^{bc}	59.59 ± 4.26 ^{bc}	62.82 ± 3.77 ^{bc}
T ₈	– Control (RDN without application of P and Zn)	2.61 ± 0.16 ^c	45.84 ± 6.54 ^c	48.45 ± 6.70 ^c
SEm (±)		0.25	5.44	5.54
CD (0.05)		0.764	16.512	16.799

Table 15b. Effect of nano zinc nutrition on potassium uptake by different parts of rice plant at panicle initiation stage in *mundakan*, kg ha⁻¹

Treatments		Root	Shoot	Total
T ₁	SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	2.53 ± 0.02 ^{cd}	47.23 ± 6.60 ^e	49.76 ± 6.59 ^{de}
T ₂	NP with Nano Zn at 0.05%	4.53 ± 0.45 ^{ab}	79.64 ± 3.07 ^{ab}	84.18 ± 3.45 ^a
T ₃	NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	4.85 ± 0.10 ^a	81.89 ± 2.57 ^a	86.74 ± 2.58 ^a
T ₄	NP with ZnSO ₄ at 0.5%	3.03 ± 0.89 ^c	64.28 ± 16.65 ^{cd}	67.31 ± 17.50 ^{bc}
T ₅	NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	3.92 ± 0.21 ^b	67.03 ± 8.82 ^{bc}	70.94 ± 8.99 ^b
T ₆	FS with Nano Zn at 0.05% at MT and PI stages	4.41 ± 0.25 ^{ab}	71.34 ± 14.49 ^{abc}	75.74 ± 14.38 ^{ab}
T ₇	FS with ZnSO ₄ at 0.5% at MT and PI stages	2.82 ± 0.52 ^{cd}	52.25 ± 5.23 ^{de}	55.07 ± 4.81 ^{cd}
T ₈	Control (RDN without application of P and Zn)	2.13 ± 0.11 ^d	39.58 ± 5.75 ^e	41.70 ± 5.73 ^e
SEm (±)		0.24	4.22	4.33
CD (0.05)		0.721	12.803	13.138

Table 16a. Effect of nano zinc nutrition on potassium uptake by different parts of rice plant at harvest stage in *virippu*, kg ha⁻¹

Treatments		Root	Shoot	Grain	Total
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	1.29 ± 0.12 ^c	35.68 ± 4.46 ^{cd}	8.03 ± 0.97 ^e	45.00 ± 4.10 ^e
T ₂	– NP with Nano Zn at 0.05%	2.22 ± 0.12 ^a	50.65 ± 2.81 ^{ab}	13.52 ± 1.15 ^{bc}	66.39 ± 1.68 ^{ab}
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	2.44 ± 0.23 ^a	55.44 ± 2.75 ^a	16.62 ± 1.83 ^a	74.50 ± 2.00 ^a
T ₄	– NP with ZnSO ₄ at 0.5%	1.32 ± 0.18 ^c	37.47 ± 8.85 ^{cd}	9.09 ± 0.24 ^{de}	47.88 ± 8.72 ^{de}
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	1.73 ± 0.16 ^b	46.63 ± 4.95 ^{ab}	11.71 ± 0.53 ^{cd}	60.08 ± 4.54 ^{bc}
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	2.28 ± 0.06 ^a	52.12 ± 2.65 ^a	14.95 ± 2.99 ^{ab}	69.35 ± 5.00 ^a
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	1.76 ± 0.09 ^b	41.84 ± 4.35 ^{bc}	10.88 ± 1.93 ^{cd}	54.48 ± 2.46 ^{cd}
T ₈	– Control (RDN without application of P and Zn)	1.22 ± 0.39 ^c	32.21 ± 4.48 ^d	7.44 ± 0.51 ^e	40.87 ± 3.94 ^e
SEm (±)		0.10	2.93	0.90	2.81
CD (0.05)		0.29	8.894	2.718	8.533

Table 16b. Effect of nano zinc nutrition on potassium uptake by different parts of rice plant at harvest stage in *mundakan*, kg ha⁻¹

Treatments		Root	Shoot	Grain	Total
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	1.40 ± 0.16 ^e	37.20 ± 3.28 ^c	10.56 ± 0.90 ^{ef}	49.16 ± 2.96 ^d
T ₂	– NP with Nano Zn at 0.05%	2.19 ± 0.20 ^{bc}	51.59 ± 4.58 ^b	13.49 ± 2.18 ^{cd}	67.27 ± 2.65 ^{bc}
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	3.26 ± 0.26 ^a	70.42 ± 3.02 ^a	18.62 ± 0.91 ^a	92.30 ± 2.67 ^a
T ₄	– NP with ZnSO ₄ at 0.5%	1.67 ± 0.26 ^{de}	47.14 ± 6.65 ^b	11.99 ± 0.44 ^{de}	60.81 ± 6.46 ^c
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	2.32 ± 0.14 ^{bc}	53.59 ± 8.25 ^b	15.56 ± 1.98 ^{bc}	71.46 ± 8.13 ^b
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	2.54 ± 0.35 ^b	64.93 ± 6.81 ^a	17.69 ± 2.43 ^{ab}	85.17 ± 4.73 ^a
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	1.98 ± 0.07 ^{cd}	50.70 ± 1.69 ^b	13.20 ± 0.52 ^{cd}	65.89 ± 2.02 ^{bc}
T ₈	– Control (RDN without application of P and Zn)	0.89 ± 0.30 ^f	26.24 ± 2.97 ^d	8.44 ± 1.40 ^f	35.56 ± 4.08 ^e
SEm (±)		0.13	3.16	0.85	2.87
CD (0.05)		0.407	9.584	2.57	8.701

During *mundakan*, the uptake of potassium was significantly higher in T₃ (3.26, 70.42, 18.62 and 92.30 kg ha⁻¹ by root, shoot, grain and total, respectively) and was on par with T₆ in shoot uptake (64.93 kg ha⁻¹) and total K uptake (85.17 kg ha⁻¹) and grain K uptake (17.69 kg ha⁻¹). The K uptake was lower in T₈ (0.89, 26.24, 8.44, 35.56 kg ha⁻¹ by root, shoot, grain and total, respectively), which was on par with T₁ in grain uptake (10.56 kg ha⁻¹).

4.3.1.4 Calcium Uptake

4.3.1.4.1 Panicle Initiation

Calcium uptake by different parts of plant as affected by the nano zinc nutrition in rice is presented in the Tables 17a and 17b, respectively in *virippu* and *mundakan*.

The results revealed that during *virippu*, the uptake of Ca by different parts of the rice plant was significantly affected by treatments and higher uptake by roots was observed in T₃ (2.63 kg ha⁻¹) and T₂ (2.50 kg ha⁻¹), which were on par with T₆ (2.32 kg ha⁻¹), whereas T₈ (1.23 kg ha⁻¹), T₁ (1.25 kg ha⁻¹) and T₄ (1.32 kg ha⁻¹) and T₇ (1.67 kg ha⁻¹) had lower uptake. The shoot uptake of Ca was higher in T₃ (29.39 kg ha⁻¹) and T₆ (27.72 kg ha⁻¹), which were on par with T₂ (25.66 kg ha⁻¹); whereas, the lowest uptake was observed in T₈ (12.66 kg ha⁻¹), which was on par with T₁ (16.30 kg ha⁻¹) and T₄ (16.84 kg ha⁻¹), respectively. Total Ca uptake was higher in T₃ (32.02 kg ha⁻¹), T₆ (30.04 kg ha⁻¹) and T₂ (28.17 kg ha⁻¹), whereas the lower uptake was recorded in T₈ (13.89 kg ha⁻¹), which was on par with T₁ (17.55 kg ha⁻¹) and T₄ (18.16 kg ha⁻¹).

During *mundakan*, the Ca uptake by root was higher and on par in T₃ (3.06 kg ha⁻¹), T₆ (2.93 kg ha⁻¹) and T₂ (2.85 kg ha⁻¹) whereas, lower uptake was recorded in T₈ (1.24 kg ha⁻¹), T₁ (1.50 kg ha⁻¹) and T₄ (1.74 kg ha⁻¹). The shoot and total uptake was significantly higher in T₃ (31.30, 34.36 kg ha⁻¹, respectively) and T₂ (29.77, 32.63 kg ha⁻¹, respectively); whereas, lower shoot uptake of Ca was recorded in T₈ (12.03, 13.27 kg ha⁻¹, respectively), which was on par with T₁ (15.26 kg ha⁻¹ in shoot uptake). Significantly lowest uptake was observed in T₈ (13.27 kg ha⁻¹).

Table 17a. Effect of nano zinc nutrition on calcium uptake by different parts of rice plant at panicle initiation stage in *virippu*, kg ha⁻¹

Treatments		Root	Shoot	Total
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	1.25 ± 0.29 ^c	16.30 ± 1.63 ^{cd}	17.55 ± 1.81 ^{bc}
T ₂	– NP with Nano Zn at 0.05%	2.50 ± 0.48 ^a	25.66 ± 1.77 ^{ab}	28.17 ± 1.69 ^a
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	2.63 ± 0.63 ^a	29.39 ± 2.85 ^a	32.02 ± 3.28 ^a
T ₄	– NP with ZnSO ₄ at 0.5%	1.32 ± 0.23 ^c	16.84 ± 4.71 ^{cd}	18.16 ± 4.89 ^{bc}
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	1.80 ± 0.20 ^{bc}	19.99 ± 4.33 ^{bc}	21.78 ± 4.42 ^b
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	2.32 ± 0.14 ^{ab}	27.72 ± 5.14 ^a	30.04 ± 5.20 ^a
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	1.67 ± 0.14 ^c	19.52 ± 1.96 ^c	21.19 ± 1.97 ^b
T ₈	– Control (RDN without application of P and Zn)	1.23 ± 0.14 ^c	12.66 ± 1.03 ^d	13.89 ± 1.03 ^c
SEm (±)		0.20	1.98	2.04
CD (0.05)		0.603	5.995	6.199

Table 17b. Effect of nano zinc nutrition on calcium uptake by different parts of rice plant at panicle initiation stage in *mundakan*, kg ha⁻¹

Treatments		Root	Shoot	Total
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	1.50 ± 0.03 ^c	15.26 ± 4.19 ^{cd}	16.76 ± 4.21 ^d
T ₂	– NP with Nano Zn at 0.05%	2.85 ± 0.14 ^a	29.77 ± 1.34 ^a	32.63 ± 1.48 ^a
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	3.06 ± 1.02 ^a	31.30 ± 2.23 ^a	34.36 ± 2.26 ^a
T ₄	– NP with ZnSO ₄ at 0.5%	1.74 ± 0.53 ^c	22.03 ± 2.66 ^b	23.77 ± 2.88 ^c
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	2.49 ± 0.18 ^{ab}	23.75 ± 0.50 ^b	26.23 ± 0.52 ^{bc}
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	2.93 ± 0.37 ^a	25.38 ± 1.98 ^b	28.30 ± 2.35 ^b
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	1.77 ± 0.42 ^{bc}	17.16 ± 0.91 ^c	18.93 ± 1.16 ^d
T ₈	– Control (RDN without application of P and Zn)	1.24 ± 0.21 ^c	12.03 ± 2.49 ^d	13.27 ± 2.46 ^e
SEm (±)		0.24	1.12	1.13
CD (0.05)		0.728	3.387	3.414

4.3.1.4.2 Harvest

Calcium uptake by different parts of the rice plant at harvest is shown in Tables 18a and 18b, respectively in *virippu* and *mundakan*. A perusal of the data revealed that there is a significant difference among treatments with nano zinc nutrition.

During *virippu*, the root Ca uptake was higher in T₃ (2.17 kg ha⁻¹), which was on par with T₆ (1.92 kg ha⁻¹) whereas, the lower uptake was recorded in T₈ (0.94 kg ha⁻¹), T₁ (1.09 kg ha⁻¹) and T₄ (1.18 kg ha⁻¹), respectively. The shoot Ca uptake was higher in T₃ (21.78 kg ha⁻¹), which was on par with T₆ (19.34 kg ha⁻¹) and T₂ (8.95 kg ha⁻¹) whereas, the lower uptake was recorded in T₈ (9.19 kg ha⁻¹), which was on par with T₁ (11.06 kg ha⁻¹) and T₄ (13.38 kg ha⁻¹). The grain uptake of Ca was higher in T₃ (2.40 kg ha⁻¹), which was on par with T₆ (2.23 kg ha⁻¹) and T₂ (2.01 kg ha⁻¹); whereas, lower uptake was recorded in T₈ (1.04 kg ha⁻¹), T₁ (1.20 kg ha⁻¹) and T₄ (1.03 kg ha⁻¹). The total uptake of Ca was higher in T₃ (26.35 kg ha⁻¹), which was on par with T₆ (23.49 kg ha⁻¹) and T₂ (22.70 kg ha⁻¹); whereas, the lower uptake was recorded in T₈ (11.17 kg ha⁻¹), which was on par with T₁ (13.34 kg ha⁻¹) and T₄ (15.59 kg ha⁻¹).

In *mundakan*, the higher Ca uptake by root, shoot, grain and total plant was observed in T₃ (2.12, 21.87, 2.63, 26.21 kg ha⁻¹), respectively, which was on par with T₆ (1.73, 20.54, 2.47, 24.77 kg ha⁻¹ in root, shoot and total, respectively). The lowest uptake of Ca was in T₈ (0.68, 8.52, 0.98, 10.18 kg ha⁻¹ in root, shoot, grain and total, respectively), which was on par with T₁ (1.28 kg ha⁻¹) in grain uptake.

Table 18a. Effect of nano zinc nutrition on calcium uptake by different parts of rice plant at harvest stage in *virippu*, kg ha⁻¹

Treatments		Root	Shoot	Grain	Total
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	1.09 ± 0.15 ^d	11.06 ± 1.36 ^{de}	1.20 ± 0.11 ^d	13.34 ± 1.27 ^{de}
T ₂	– NP with Nano Zn at 0.05%	1.75 ± 0.18 ^{bc}	18.95 ± 1.03 ^{ab}	2.01 ± 0.40 ^{ab}	22.70 ± 1.37 ^{ab}
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	2.17 ± 0.22 ^a	21.78 ± 3.83 ^a	2.40 ± 0.49 ^a	26.35 ± 3.74 ^a
T ₄	– NP with ZnSO ₄ at 0.5%	1.18 ± 0.19 ^d	13.38 ± 3.91 ^{cde}	1.03 ± 0.11 ^d	15.59 ± 3.93 ^{cde}
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	1.58 ± 0.23 ^c	16.22 ± 1.83 ^{bc}	1.78 ± 0.31 ^{bc}	19.58 ± 1.80 ^{bc}
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	1.92 ± 0.11 ^{ab}	19.34 ± 3.17 ^{ab}	2.23 ± 0.49 ^{ab}	23.49 ± 3.28 ^{ab}
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	1.58 ± 0.12 ^c	14.89 ± 2.06 ^{bcd}	1.41 ± 0.16 ^{cd}	17.88 ± 1.89 ^{cd}
T ₈	– Control (RDN without application of P and Zn)	0.94 ± 0.31 ^d	9.19 ± 1.73 ^e	1.04 ± 0.07 ^d	11.17 ± 1.64 ^e
SEm (±)		0.10	1.59	0.18	1.59
CD (0.05)		0.315	4.815	0.556	4.818

Table 18b. Effect of nano zinc nutrition on calcium uptake by different parts of rice plant at harvest stage in *mundakan*, kg ha⁻¹

Treatments		Root	Shoot	Grain	Total
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	1.02 ± 0.08 ^e	12.73 ± 0.10 ^e	1.28 ± 0.29 ^{cd}	15.02 ± 0.37 ^e
T ₂	– NP with Nano Zn at 0.05%	1.50 ± 0.23 ^{bc}	16.07 ± 1.58 ^{cd}	2.18 ± 0.31 ^{ab}	19.75 ± 1.42 ^{cd}
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	2.12 ± 0.09 ^a	21.87 ± 1.11 ^a	2.63 ± 0.35 ^a	26.61 ± 0.72 ^a
T ₄	– NP with ZnSO ₄ at 0.5%	1.13 ± 0.16 ^{de}	14.49 ± 2.14 ^{de}	1.91 ± 0.18 ^{bc}	17.52 ± 2.18 ^{de}
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	1.64 ± 0.07 ^b	18.16 ± 2.62 ^{bc}	2.42 ± 0.58 ^{ab}	22.22 ± 2.84 ^{bc}
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	1.73 ± 0.12 ^b	20.54 ± 2.38 ^{ab}	2.51 ± 0.49 ^{ab}	24.77 ± 2.91 ^{ab}
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	1.34 ± 0.05 ^{cd}	15.91 ± 0.61 ^{cd}	1.89 ± 0.25 ^{bc}	19.14 ± 0.59 ^{cd}
T ₈	– Control (RDN without application of P and Zn)	0.68 ± 0.25 ^f	8.52 ± 0.86 ^f	0.98 ± 0.31 ^d	10.18 ± 0.96 ^f
SEm (±)		0.09	1.02	0.22	1.09
CD (0.05)		0.275	3.092	0.675	3.32

4.3.1.5 Zinc Uptake

4.3.1.5.1 Panicle Initiation

The results on zinc uptake by the different parts of the rice plant at panicle initiation stage during *virippu* and *mundakan* are depicted in Tables 19a and 19a, respectively. A perusal of the data revealed that there is a significant effect of nano zinc nutrition on the uptake of Zn by the rice plants by different parts during both the seasons.

The results revealed that during *virippu*, the root uptake of Zn was higher in T₃ (0.03 kg ha⁻¹) and T₆ (0.03 kg ha⁻¹), which were on par with T₂ (0.03 kg ha⁻¹), whereas lower uptake was recorded in T₈ (0.01 kg ha⁻¹), which was on par with T₁ (0.02 kg ha⁻¹). The shoot uptake of Zn was higher in T₃ (0.27 kg ha⁻¹), which was on par with T₆ (0.24 kg ha⁻¹) and T₂ (0.24 kg ha⁻¹) whereas, lower uptake was recorded in T₈ (0.12 kg ha⁻¹), which was on par with T₁ (0.14 kg ha⁻¹), T₄ (0.16 kg ha⁻¹) and T₇ (0.17 kg ha⁻¹). The total Zn uptake was higher in T₃ (0.30 kg ha⁻¹), which was on par with T₆ (0.27 kg ha⁻¹) and T₂ (0.27 kg ha⁻¹); whereas, lower uptake was recorded in T₈ (0.14 kg ha⁻¹), which was on par with T₁ (0.15 kg ha⁻¹), T₄ (0.18 kg ha⁻¹) and T₇ (0.20 kg ha⁻¹), respectively.

During *mundakan*, higher Zn uptake by the plant was observed in T₃ (0.03, 0.27, 0.30 kg ha⁻¹ by root, shoot and total, respectively), which was comparable to T₂ (0.03, 0.26, 0.29 kg ha⁻¹ by root, shoot and total, respectively) and T₆ (0.03 kg ha⁻¹ in root). The uptake of Zn was lower in T₈ (0.01, 0.10, 0.11 kg ha⁻¹ by root, shoot and total, respectively), which was on par with T₁, T₄ and T₇ in root uptake whereas, it was on par with T₁ (0.13 kg ha⁻¹) in shoot uptake.

4.3.1.5.2 Harvest

The zinc uptake by the rice plants as affected by the nano zinc nutrition was significantly different during *virippu* and *mundakan* and the same is shown in the Tables 20a and 20b, respectively.

Table 19a. Effect of nano zinc nutrition on zinc uptake by different parts of rice plant at panicle initiation stage in *virippu*, kg ha⁻¹

Treatments		Root	Shoot	Total
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	0.02 ± 0.01 ^{de}	0.14 ± 0.02 ^{cd}	0.15 ± 0.03 ^{cd}
T ₂	– NP with Nano Zn at 0.05%	0.03 ± 0.00 ^{ab}	0.24 ± 0.03 ^{ab}	0.27 ± 0.03 ^{ab}
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	0.03 ± 0.01 ^a	0.27 ± 0.04 ^a	0.30 ± 0.04 ^a
T ₄	– NP with ZnSO ₄ at 0.5%	0.02 ± 0.00 ^{cd}	0.16 ± 0.02 ^{cd}	0.18 ± 0.02 ^{cd}
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	0.03 ± 0.01 ^{abc}	0.19 ± 0.06 ^{bc}	0.21 ± 0.06 ^{bc}
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	0.03 ± 0.01 ^a	0.24 ± 0.05 ^{ab}	0.27 ± 0.05 ^{ab}
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	0.02 ± 0.01 ^{bcd}	0.17 ± 0.01 ^{cd}	0.20 ± 0.01 ^{cd}
T ₈	– Control (RDN without application of P and Zn)	0.01 ± 0.00 ^e	0.12 ± 0.02 ^d	0.14 ± 0.02 ^d
SEm (±)		0.00	0.02	0.02
CD (0.05)		0.008	0.061	0.063

Table 19b. Effect of nano zinc nutrition on zinc uptake by different parts of rice plant at panicle initiation stage in *mundakan*, kg ha⁻¹

Treatments		Root	Shoot	Total
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	0.02 ± 0.01 ^{cd}	0.13 ± 0.03 ^{de}	0.15 ± 0.03 ^f
T ₂	– NP with Nano Zn at 0.05%	0.03 ± 0.00 ^{ab}	0.26 ± 0.02 ^{ab}	0.29 ± 0.02 ^{ab}
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	0.03 ± 0.01 ^a	0.27 ± 0.03 ^a	0.30 ± 0.03 ^a
T ₄	– NP with ZnSO ₄ at 0.5%	0.02 ± 0.01 ^{bcd}	0.19 ± 0.03 ^c	0.21 ± 0.03 ^{de}
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	0.03 ± 0.01 ^{abc}	0.21 ± 0.02 ^c	0.23 ± 0.02 ^{cd}
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	0.03 ± 0.00 ^{ab}	0.22 ± 0.04 ^{bc}	0.25 ± 0.03 ^{bc}
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	0.02 ± 0.01 ^{bcd}	0.15 ± 0.01 ^d	0.17 ± 0.00 ^{ef}
T ₈	– Control (RDN without application of P and Zn)	0.01 ± 0.00 ^d	0.10 ± 0.02 ^e	0.11 ± 0.01 ^g
SEm (±)		0.00	0.01	0.01
CD (0.05)		0.01	0.039	0.04

In *virippu*, the uptake of Zn by roots was higher in T₃, T₆ and T₂ (0.03 kg ha⁻¹) whereas, the lower uptake was recorded in T₈, T₁ and T₄ (0.01 kg ha⁻¹). The shoot Zn uptake was higher in T₃ (0.19 kg ha⁻¹), which was on par with T₆ (0.18 kg ha⁻¹) and T₂ (0.17 kg ha⁻¹) whereas, lower uptake was recorded in T₈ (0.10 kg ha⁻¹), which was on par with T₁ (0.12 kg ha⁻¹) and T₄ (0.12 kg ha⁻¹). The grain uptake of Zn was higher in T₃ (0.17 kg ha⁻¹) and T₆ (0.16 kg ha⁻¹), which were on par with T₂ (0.14 kg ha⁻¹); whereas lower uptake was recorded in T₈ (0.07 kg ha⁻¹), which was on par with T₁ (0.08 kg ha⁻¹) and T₄ (0.08 kg ha⁻¹), respectively. The total uptake of Zn was higher in T₃ (0.39 kg ha⁻¹), which was on par with T₆ (0.36 kg ha⁻¹) whereas, lower uptake was observed in T₈ (0.18 kg ha⁻¹), which was on par with T₁ (0.21 kg ha⁻¹).

In *mundakan*, root uptake of Zn was the highest in T₃ (0.03 kg ha⁻¹) and lower uptake was recorded in T₈ (0.01 kg ha⁻¹), which was on par with T₁ (0.01 kg ha⁻¹) and T₄ (0.02 kg ha⁻¹), respectively. The shoot uptake of Zn was higher in T₃ and T₆ (0.19 kg ha⁻¹) and lower uptake was recorded in T₈ (0.08 kg ha⁻¹). The grain uptake of Zn was higher in T₃ (0.18 kg ha⁻¹) and T₆ (0.16 kg ha⁻¹), where as the lower uptake was recorded in T₈ (0.06 kg ha⁻¹). The total uptake of Zn was significantly higher in T₃ (0.40 kg ha⁻¹) and lower uptake was recorded in T₈ (0.15 kg ha⁻¹).

Table 20a. Effect of nano zinc nutrition on zinc uptake by different parts of rice plant at harvest stage in *virippu*, kg ha⁻¹

Treatments		Root	Shoot	Grain	Total
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	0.01 ± 0.00 ^c	0.12 ± 0.01 ^{de}	0.08 ± 0.01 ^{cd}	0.21 ± 0.01 ^{ef}
T ₂	– NP with Nano Zn at 0.05%	0.03 ± 0.00 ^a	0.17 ± 0.01 ^{ab}	0.14 ± 0.02 ^{ab}	0.34 ± 0.01 ^{bc}
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	0.03 ± 0.00 ^a	0.19 ± 0.00 ^a	0.17 ± 0.04 ^a	0.39 ± 0.04 ^a
T ₄	– NP with ZnSO ₄ at 0.5%	0.01 ± 0.01 ^c	0.12 ± 0.03 ^{de}	0.08 ± 0.01 ^{cd}	0.23 ± 0.03 ^e
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	0.02 ± 0.00 ^b	0.16 ± 0.01 ^{bc}	0.12 ± 0.01 ^b	0.30 ± 0.00 ^{cd}
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	0.03 ± 0.00 ^a	0.18 ± 0.02 ^{ab}	0.16 ± 0.03 ^a	0.36 ± 0.04 ^{ab}
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	0.02 ± 0.00 ^b	0.14 ± 0.02 ^{cd}	0.11 ± 0.01 ^{bc}	0.27 ± 0.01 ^d
T ₈	– Control (RDN without application of P and Zn)	0.01 ± 0.01 ^c	0.10 ± 0.02 ^e	0.07 ± 0.01 ^d	0.18 ± 0.01 ^f
SEm (±)		0.00	0.01	0.01	0.01
CD (0.05)		0.01	0.03	0.03	0.04

Table 20b. Effect of nano zinc nutrition on zinc uptake by different parts of rice plant at harvest stage in *mundakan*, kg ha⁻¹

Treatments		Root	Shoot	Grain	Total
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	0.01 ± 0.01 ^{cd}	0.11 ± 0.01 ^c	0.09 ± 0.02 ^d	0.21 ± 0.02 ^f
T ₂	– NP with Nano Zn at 0.05%	0.02 ± 0.01 ^b	0.15 ± 0.03 ^b	0.12 ± 0.01 ^{bc}	0.29 ± 0.01 ^{cd}
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	0.03 ± 0.01 ^a	0.19 ± 0.02 ^a	0.18 ± 0.01 ^a	0.40 ± 0.00 ^a
T ₄	– NP with ZnSO ₄ at 0.5%	0.02 ± 0.01 ^{bcd}	0.13 ± 0.01 ^{bc}	0.11 ± 0.01 ^{cd}	0.25 ± 0.01 ^e
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	0.02 ± 0.00 ^{bc}	0.15 ± 0.01 ^b	0.14 ± 0.02 ^b	0.32 ± 0.01 ^c
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	0.02 ± 0.01 ^b	0.19 ± 0.02 ^a	0.16 ± 0.01 ^a	0.37 ± 0.03 ^b
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	0.02 ± 0.00 ^{bc}	0.14 ± 0.01 ^b	0.12 ± 0.01 ^c	0.28 ± 0.01 ^{de}
T ₈	– Control (RDN without application of P and Zn)	0.01 ± 0.00 ^d	0.08 ± 0.02 ^d	0.06 ± 0.02 ^e	0.15 ± 0.03 ^g
SEm (±)		0.00	0.01	0.01	0.01
CD (0.05)		0.008	0.028	0.022	0.033

4.3.2. Nutrient Use Efficiency

4.3.2.1 Agronomic Efficiency

4.3.2.1.1 Phosphorus (AE_P)

The results on the effect of nano zinc nutrition on agronomic efficiency of phosphorus during both *virippu* and *mundakan* are presented in the Tables 21a and 21b, respectively.

During both *virippu* and *mundakan* seasons, the highest agronomic efficiency of phosphorus (94.29 and 58.87 kg kg⁻¹, respectively) was recorded in T₃; T₁ resulted in lowest agronomic efficiency of phosphorus (10.84 and 19.46 kg kg⁻¹, respectively).

4.3.2.1.1 Zinc (AE_{Zn})

The agronomic efficiency of zinc as affected by the nano zinc nutrition during both *virippu* and *mundakan* seasons are presented in the Table 21a and 21b, respectively.

During both *virippu* and *mundakan* seasons, the highest agronomic efficiency of phosphorus was recorded in T₂ (30116.45 and 31780 kg kg⁻¹, respectively). Agronomic efficiency of phosphorus was lower in T₁ during *virippu* (55.77 kg ka⁻¹) and in T₇ during *mundakan* (291.20 kg ka⁻¹).

4.3.2.1 Physiological Efficiency

4.3.2.1.1 Phosphorus (PE_P)

Physiological efficiency of phosphorus as influenced by nano zinc nutrition during both *virippu* and *mundakan* are presented in the Tables 21a and 21b, respectively.

During *virippu* season, T₁ showed the highest physiological efficiency of phosphorus (160.78 kg kg⁻¹) and T₄ had the lowest physiological efficiency of phosphorus (115.20 kg kg⁻¹). Further, during *mundakan*, higher physiological efficiency of phosphorus was recorded in T₄ (162.08 kg kg⁻¹) and T₃ showed lower physiological efficiency of phosphorus (129.77 kg kg⁻¹).

Table 21a. Effect of nano zinc nutrition on agronomic efficiency, physiological efficiency and apparent recovery efficiency in *virippu*, kg kg⁻¹

Treatments		Agronomic Efficiency		Physiological efficiency		Apparent recovery Efficiency	
		AE _P	AE _{Zn}	PE _P	PE _{Zn}	ARE _P	ARE _{Zn}
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	10.84	55.77	160.48	7936.25	0.07	0.01
T ₂	– NP with Nano Zn at 0.05%	69.71	30116.45	131.46	9413.83	0.61	3.20
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	94.29	6788.95	138.28	9660.01	0.63	0.70
T ₄	– NP with ZnSO ₄ at 0.5%	13.13	567.20	115.20	6554.20	0.11	0.09
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	49.14	1929.78	128.26	8930.05	0.36	0.22
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	81.72	3530.16	135.12	9591.34	0.60	0.37
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	37.71	162.89	154.63	9014.13	0.24	0.02
T ₈	– Control (RDN without application of P and Zn)	-	-	-	-	-	-

Table 21b. Effect of nano zinc nutrition on agronomic efficiency, physiological efficiency and apparent recovery efficiency in *mundakan*, kg kg⁻¹

Treatments		Agronomic Efficiency		Physiological efficiency		Apparent recovery Efficiency	
		AE _P	AE _{Zn}	PE _P	PE _{Zn}	ARE _P	ARE _{Zn}
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	19.46	-	133.56	12038.98	0.15	-
T ₂	– NP with Nano Zn at 0.05%	37.57	31780.00	149.28	11304.66	0.25	2.81
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	58.87	8300.00	129.77	9829.61	0.45	0.84
T ₄	– NP with ZnSO ₄ at 0.5%	33.31	2488.00	162.08	12001.24	0.21	0.21
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	41.63	3201.82	144.27	10663.85	0.29	0.30
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	52.39	4432.00	131.90	10097.05	0.40	0.44
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	38.98	291.20	150.96	11330.08	0.26	0.03
T ₈	– Control (RDN without application of P and Zn)	-	-	-	-	-	-

4.3.2.1.1 Zinc (PE_{Zn})

The effect of nano zinc nutrition on physiological efficiency of zinc during both *virippu* and *mundakan* seasons are presented in the Tables 21a and 21b, respectively.

During *virippu*, higher physiological efficiency of zinc was observed in T₃ (9660.01 kg kg⁻¹) and T₄ showed lower physiological efficiency of zinc (6554.20 kg kg⁻¹). However, during *mundakan* season, T₁ resulted higher physiological efficiency of zinc (12038.98 kg kg⁻¹) and T₃ had lower physiological efficiency of zinc (9829.61 kg kg⁻¹).

4.3.2.2 Apparent Recovery Efficiency

4.3.2.2.1 Phosphorus (ARE_P)

The data pertaining to apparent recovery efficiency of phosphorus as affected by nano zinc nutrition during both *virippu* and *mundakan* seasons are presented in Tables 21a and 21b, respectively.

During both *virippu* and *mundakan* seasons, T₃ resulted in higher apparent recovery efficiency of phosphorus (0.63 and 0.45 kg kg⁻¹, respectively) and T₁ showed lower physiological efficiency of phosphorus (0.07 and 0.15 kg kg⁻¹, respectively).

4.3.2.2.2 Zinc (ARE_{Zn})

Tables 21a and 21b represents the data pertaining to apparent recovery efficiency of zinc as affected by nano zinc nutrition during both *virippu* and *mundakan* seasons, respectively.

During both *virippu* and *mundakan* seasons, T₂ resulted in highest apparent recovery efficiency of zinc (3.20 and 2.81 kg kg⁻¹) and T₁ (0.01 kg kg⁻¹) showed lower

apparent recovery efficiency of zinc during *virippu* while T₇ recorded the lowest apparent recovery efficiency of zinc (0.03 kg kg⁻¹) during *mundakan* season.

4.4 SOIL ANALYSIS

4.4.1 Chemical Properties

4.4.1.1 pH

The effect of nano zinc nutrition on pH during both *virippu* and *mundakan* seasons are presented in the Tables 22a and 22b, respectively. It was observed that the nano zinc nutrition showed no significant variation on the pH during both seasons.

4.4.1.2 Electrical Conductivity (EC)

The data pertaining to EC as influenced by nano zinc nutrition during both *virippu* and *mundakan* are presented in the Tables 22a and 22b, respectively. The results showed no significant variation in EC due to nano zinc nutrition among the treatments during both seasons.

4.4.1.3 Organic Carbon (OC)

The result on the effect of nano zinc nutrition on organic carbon is presented in Tables 22a and 22b for both *virippu* and *mundakan* seasons, respectively. It was noted that nano zinc nutrition showed no significant variation in organic carbon during both seasons.

Table 22a. Effect of nano zinc nutrition on soil reaction (pH), electrical conductivity (EC) and organic carbon (OC) content of the soil after *virippu* rice experiment.

Treatments		pH	EC (dS m ⁻¹)	OC (%)
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	5.48 ± 0.39	0.73 ± 0.21	1.70 ± 0.18
T ₂	– NP with Nano Zn at 0.05%	5.05 ± 0.19	0.83 ± 0.15	1.85 ± 0.48
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	5.02 ± 0.13	0.67 ± 0.14	1.96 ± 0.12
T ₄	– NP with ZnSO ₄ at 0.5%	5.19 ± 0.27	0.50 ± 0.10	1.80 ± 0.40
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	5.00 ± 0.18	0.65 ± 0.17	1.91 ± 0.28
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	5.10 ± 0.02	0.76 ± 0.08	1.96 ± 0.81
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	5.00 ± 0.04	0.77 ± 0.06	1.86 ± 0.10
T ₈	– Control (RDN without application of P and Zn)	5.08 ± 0.29	0.83 ± 0.15	1.68 ± 0.11
SEm (±)		0.12	0.08	0.20
CD (0.05)		NS	NS	NS

NS- Non Significant

Table 22b. Effect of nano zinc nutrition on soil reaction (pH), electrical conductivity (EC) and organic carbon (OC) content of the soil after *mundakan* rice experiment

Treatments		pH	EC (dS m ⁻¹)	OC (%)
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	5.50 ± 0.11	0.63 ± 0.15	1.29 ± 1.21
T ₂	– NP with Nano Zn at 0.05%	5.25 ± 0.13	0.70 ± 0.10	1.60 ± 0.12
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	5.35 ± 0.17	0.47 ± 0.15	1.77 ± 0.16
T ₄	– NP with ZnSO ₄ at 0.5%	5.36 ± 0.27	0.66 ± 0.13	1.62 ± 0.42
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	5.21 ± 0.25	0.55 ± 0.10	1.56 ± 0.50
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	5.21 ± 0.10	0.70 ± 0.08	1.70 ± 0.66
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	5.18 ± 0.18	0.67 ± 0.06	1.66 ± 0.45
T ₈	– Control (RDN without application of P and Zn)	5.42 ± 0.31	0.77 ± 0.15	1.29 ± 1.21
SEm (±)		0.09	0.06	0.30
CD (0.05)		NS	NS	NS

NS- Non Significant

4.4.1.4 Available Nitrogen

Nano zinc nutrition showed significant differences in available nitrogen and the results are presented in Tables 23a and 23b during *virippu* and *mundakan* seasons, respectively.

During *virippu*, T₆ and T₃ showed higher and similar available nitrogen (373.37, 356.14 kg ha⁻¹) and were comparable to T₅, T₇ and T₂ (347.05, 339.97 and 331.05 kg ha⁻¹, respectively). In contrast, T₈, T₁, T₄ had lower available nitrogen (303.33, 309.24, 305.24 kg ha⁻¹, respectively), which were comparable to T₂, T₇ and T₅.

During *mundakan* season, higher available nitrogen was recorded in T₃ (353.33 kg ha⁻¹) and T₆ (347.93 kg ha⁻¹) which were comparable to T₇ (345.33 kg ha⁻¹) and T₂ (324.83 kg ha⁻¹). Lower available nitrogen was noted in T₈ (290.67 kg ha⁻¹), T₄ (304.90 kg ha⁻¹) and T₁ (306.00 kg ha⁻¹) and were comparable to T₅ and T₂.

4.4.1.5 Available Phosphorus

The results on the effect of nano zinc nutrition on available phosphorus are presented in Tables 23a and 23b. There was a significant difference observed in available phosphorus due to nano zinc nutrition for both *virippu* and *mundakan* seasons.

During *virippu*, T₃, T₇, T₆, T₅ resulted in higher and similar available phosphorus (18.12, 17.51, 17.37, 17.28 kg ha⁻¹, respectively); whereas, T₈, T₁ and T₄ showed lower available phosphorus (13.25, 13.51 and 13.51 kg ha⁻¹, respectively).

During *mundakan*, T₃ showed the highest available phosphorus (19.87 kg ha⁻¹) and was comparable to T₂, T₅, T₄ and T₆ (18.97, 18.73, 18.17 and 18.07 kg ha⁻¹, respectively). A lower available phosphorus was noted in T₈ (15.67 kg ha⁻¹) and was comparable to T₁ and T₇ (17.32 and 17.37 kg ha⁻¹).

Table 23a. Effect of nano zinc nutrition on available nitrogen, phosphorus and potassium in soil after *virippu* rice experiment, kg ha⁻¹

Treatments		Available N	Available P	Available K
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	309.24 ± 7.24 ^b	13.51 ± 0.98 ^b	62.50 ± 1.47 ^c
T ₂	– NP with Nano Zn at 0.05%	331.05 ± 33.19 ^{ab}	14.38 ± 0.21 ^b	72.50 ± 1.47 ^{abc}
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	356.14 ± 12.55 ^a	18.12 ± 3.54 ^a	76.86 ± 7.85 ^{ab}
T ₄	– NP with ZnSO ₄ at 0.5%	305.24 ± 26.11 ^b	13.51 ± 0.98 ^b	66.74 ± 14.83 ^{bc}
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	347.05 ± 50.70 ^{ab}	17.28 ± 0.47 ^a	69.80 ± 2.74 ^{abc}
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	373.37 ± 8.50 ^a	17.37 ± 0.16 ^a	79.54 ± 1.14 ^a
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	339.97 ± 19.16 ^{ab}	17.51 ± 0.18 ^a	74.60 ± 7.85 ^{ab}
T ₈	– Control (RDN without application of P and Zn)	303.33 ± 30.55 ^b	13.25 ± 0.67 ^b	62.27 ± 1.51 ^c
SEm (±)		15.28	0.84	3.68
CD (0.05)		46.35	2.55	11.166

Table 23b. Effect of nano zinc nutrition on available nitrogen, phosphorus and potassium in soil after *mundakan* rice experiment, kg ha⁻¹

Treatments		Available N	Available P	Available K
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	306.00 ± 31.43 ^{bc}	17.32 ± 2.28 ^{bc}	60.23 ± 1.57 ^d
T ₂	– NP with Nano Zn at 0.05%	324.83 ± 28.33 ^{abc}	18.97 ± 1.27 ^{ab}	67.40 ± 1.45 ^{abcd}
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	353.33 ± 22.12 ^a	19.87 ± 0.47 ^a	72.57 ± 0.75 ^{ab}
T ₄	– NP with ZnSO ₄ at 0.5%	304.90 ± 8.69 ^c	18.17 ± 0.29 ^{ab}	62.33 ± 0.35 ^{cd}
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	317.00 ± 46.87 ^{abc}	18.73 ± 0.71 ^{ab}	75.81 ± 2.47 ^a
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	347.93 ± 24.26 ^a	18.07 ± 1.00 ^{ab}	71.30 ± 8.55 ^{abc}
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	345.33 ± 21.03 ^{ab}	17.37 ± 0.76 ^{bc}	63.57 ± 0.78 ^{bcd}
T ₈	– Control (RDN without application of P and Zn)	290.67 ± 8.08 ^c	15.67 ± 1.53 ^c	60.13 ± 11.10 ^d
SEm (±)		13.11	0.73	3.02
CD (0.05)		39.767	2.221	9.158

4.4.1.6 Available Potassium

Nano zinc nutrition showed significant differences in available potassium and the results are given in Tables 23a and 23b for both *virippu* and *mundakan* seasons, respectively.

The analyzed data revealed that during *virippu*, higher available K was recorded in T₆ (79.54 kg ha⁻¹), which was on par with T₃ (76.86 kg ha⁻¹), T₂ (72.50 kg ha⁻¹) and T₅ (69.80 kg ha⁻¹); whereas, lower available K was reported in T₈ (62.27 kg ha⁻¹) and T₁ (62.50 kg ha⁻¹), which were on par with T₄, T₅ and T₂, respectively.

During *mundakan*, higher available K was observed in T₅ (75.81 kg ha⁻¹), which was on par with T₃ (72.57 kg ha⁻¹), T₆ (71.30 kg ha⁻¹) and T₂ (67.40 kg ha⁻¹) and lower available K was recorded in T₈ and T₁, which were comparable to T₄ (62.33 kg ha⁻¹), T₇ (63.57 kg ha⁻¹) and T₂ (67.40 kg ha⁻¹).

4.4.1.7 Available Calcium

Tables 24a and 24b contains the data pertaining available calcium during both *virippu* and *mundakan* seasons as affected by effect of nano zinc nutrition, respectively.

The data revealed that the available calcium did not differ significantly due to nano zinc nutrition both during *virippu* and *mundakan* seasons.

4.4.1.8 Available Zinc

The results of the impact of nano zinc nutrition on available zinc are presented in Tables 24a and 24b. The data on available zinc exhibited significant variation during both *virippu* and *mundakan* seasons.

During *virippu*, the higher available zinc was recorded in T₃ (1.47 mg kg⁻¹), T₂ (1.40 mg kg⁻¹), which were on par with T₅ (1.26 mg kg⁻¹), T₆ (1.33 mg kg⁻¹) and

Table 24a. Effect of nano zinc nutrition on available calcium and zinc in soil after *virippu* rice experiment, mg kg⁻¹

Treatments		Available Ca	Available Zn
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	209.40 ± 12.67	1.09 ± 0.09 ^c
T ₂	– NP with Nano Zn at 0.05%	221.13 ± 27.83	1.40 ± 0.05 ^a
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	255.81 ± 26.41	1.47 ± 0.06 ^a
T ₄	– NP with ZnSO ₄ at 0.5%	218.30 ± 22.46	1.17 ± 0.15 ^{bc}
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	233.00 ± 29.23	1.26 ± 0.05 ^{abc}
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	220.33 ± 14.58	1.33 ± 0.06 ^{ab}
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	211.90 ± 14.58	1.26 ± 0.14 ^{abc}
T ₈	– Control (RDN without application of P and Zn)	207.36 ± 5.53	1.07 ± 0.21 ^c
SEm (±)		10.95	0.07
CD (0.05)		NS	0.210

NS- Non significant

Table 24b. Effect of nano zinc nutrition on available calcium and zinc in soil after *mundakan* rice experiment, mg kg⁻¹

Treatments		Available Ca	Available Zn
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	210.00 ± 39.69	1.23 ± 0.09 ^c
T ₂	– NP with Nano Zn at 0.05%	237.93 ± 11.57	1.67 ± 0.32 ^{ab}
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	215.00 ± 4.36	1.76 ± 0.10 ^a
T ₄	– NP with ZnSO ₄ at 0.5%	229.14 ± 22.04	1.27 ± 0.06 ^{bc}
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	233.33 ± 17.01	1.68 ± 0.13 ^a
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	219.30 ± 11.00	1.74 ± 0.07 ^a
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	237.00 ± 6.08	1.23 ± 0.40 ^c
T ₈	– Control (RDN without application of P and Zn)	210.00 ± 0.00	1.20 ± 0.26 ^c
SEm (±)		10.29	0.13
CD (0.05)		NS	0.402

NS- Non significant

T₇ (1.26 mg kg⁻¹) whereas, lower available Zn was recorded in T₈ (1.07 mg kg⁻¹) and T₁ (1.09 mg kg⁻¹), which were on par with T₄, T₅ and T₇.

During *mundakan*, higher available zinc was recorded in T₃ (1.76 mg kg⁻¹), T₆ (1.74 mg kg⁻¹) and T₅ (1.68 mg kg⁻¹) which were on par with T₂ (1.67 mg kg⁻¹) whereas, lower available Zn was observed in T₈ (1.20 mg kg⁻¹), T₁ (1.23 mg kg⁻¹) and T₇ (1.23 mg kg⁻¹) which were on par with T₄ (1.27 mg kg⁻¹).

4.4.2 Soil Enzyme Activity

4.4.2.1 Dehydrogenase

The data on the effect of nano zinc nutrition on dehydrogenase activity revealed that there was significant variation in enzyme activity and the results are presented in Tables 25a and 25b for both *virippu* and *mundakan* seasons, respectively.

During both *virippu* and *mundakan* seasons, T₃ resulted in higher dehydrogenase activity (54.80 and 54.13 g⁻¹soil 24h⁻¹, respectively) and was comparable to T₆ (50.23 and 51.57 g⁻¹soil 24h⁻¹, respectively). During both seasons, lower dehydrogenase activity was noted in T₈ (34.20 and 32.80 g⁻¹soil 24h⁻¹, respectively) and it was on par with T₁ (37.57 g⁻¹soil 24h⁻¹) during *virippu* season.

4.4.2.2 Phosphatase

The results on the phosphatase activity as influenced by nano zinc nutrition are presented in Tables 25a and 25b. The data indicated that phosphatase enzyme activity varied significantly due to nano zinc nutrition during both *virippu* and *mundakan* seasons, respectively.

During both *virippu* and *mundakan* seasons, higher phosphatase activity was noted in T₈ (29.80 and 25.97 g⁻¹soil h⁻¹, respectively), which was on par with T₄ (27.53 and 23.37 g⁻¹soil h⁻¹, respectively). During both seasons, T₃ showed lower phosphatase activity (20.80 and 15.30 g⁻¹soil h⁻¹, respectively) and it was comparable to T₆ (21.27 g⁻¹soil h⁻¹) during *virippu* season.

Table 25a. Effect of nano zinc nutrition on dehydrogenase enzyme activity and phosphatase enzyme activity in soil of *virippu* rice

Treatments		Dehydrogenase activity $\text{g}^{-1}\text{soil } 24\text{h}^{-1}$	Phosphatase activity $\text{g}^{-1}\text{soil h}^{-1}$
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	37.57 ± 4.60 ^{ef}	26.37 ± 1.36 ^{bc}
T ₂	– NP with Nano Zn at 0.05%	48.07 ± 1.80 ^{bc}	23.43 ± 0.87 ^{de}
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	54.80 ± 4.33 ^a	20.80 ± 0.53 ^f
T ₄	– NP with ZnSO ₄ at 0.5%	39.43 ± 0.91 ^{de}	27.53 ± 2.78 ^{ab}
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	44.97 ± 3.85 ^c	26.07 ± 1.18 ^{bc}
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	50.23 ± 4.86 ^{ab}	21.27 ± 0.95 ^{ef}
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	43.77 ± 3.65 ^{cd}	24.67 ± 0.80 ^{cd}
T ₈	– Control (RDN without application of P and Zn)	34.20 ± 5.41 ^f	29.80 ± 0.40 ^a
SEm (±)		1.67	0.80
CD (0.05)		5.075	2.424

Table 25b. Effect of nano zinc nutrition on dehydrogenase enzyme activity and phosphatase enzyme activity in soil of *mundakan* rice

Treatments		Dehydrogenase Activity $\text{g}^{-1}\text{soil } 24\text{h}^{-1}$	Phosphatase activity $\text{g}^{-1}\text{soil h}^{-1}$
T ₁	SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	39.27 ± 4.11 ^d	22.73 ± 0.06 ^{bc}
T ₂	NP with Nano Zn at 0.05%	46.60 ± 0.53 ^{bc}	21.07 ± 0.61 ^{bcd}
T ₃	NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	54.13 ± 6.12 ^a	15.30 ± 0.26 ^f
T ₄	NP with ZnSO ₄ at 0.5%	40.57 ± 2.72 ^d	23.37 ± 3.84 ^{ab}
T ₅	NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	48.07 ± 2.77 ^{bc}	20.50 ± 0.95 ^{cde}
T ₆	FS with Nano Zn at 0.05% at MT and PI stages	51.57 ± 5.11 ^{ab}	18.10 ± 0.95 ^e
T ₇	FS with ZnSO ₄ at 0.5% at MT and PI stages	42.97 ± 4.88 ^{cd}	19.43 ± 0.74 ^{de}
T ₈	Control (RDN without application of P and Zn)	32.80 ± 4.36 ^e	25.97 ± 1.63 ^a
SEm (±)		1.93	0.89
CD (0.05)		5.850	2.694

4.5 ECONOMIC ANALYSIS

4.5.1 Net Returns

The effect of nano-zinc nutrition on net returns during both *virippu* and *mundakan* seasons are presented in the Table 26. The results indicated that net returns varied significantly due to nano zinc nutrition during both the seasons.

During both *virippu* and *mundakan* seasons, T₃ resulted in the highest net returns (₹ 76622 ha⁻¹ and ₹ 86368 ha⁻¹). During both seasons, the lowest net returns was noted in T₈ (₹ 6989 ha⁻¹ and 1436 ha⁻¹, respectively).

4.5.2 Benefit Cost Ratio (B:C Ratio)

The results on the B:C ratio as influenced by nano zinc nutrition are presented in Table 26 for both *virippu* and *mundakan* seasons.

During both *virippu* and *mundakan* seasons, T₃ resulted in higher B:C ratio (1.74 and 1.82, respectively) and lower B:C ratio was noticed in T₈ (1.07 and 1.01, respectively).

4.6 GROWTH PARAMETERS OF GRAIN COWPEA

4.6.1 Plant Height

The plant height of the grain cowpea at different stages as affected by the residual nutrient status of the soil is shown in the Table 27.

The data revealed that taller plants of grain cowpea at 30 DAS (45.23 cm), 45 DAS (68.77 cm) and at harvest (81.03 cm) respectively were observed in the treatment N₁ (residual nutrient status of the soil of the treatment T₁). The shorter plants at 30 DAS (32.83 cm), 45 DAS (40.13 cm) and at harvest (46.80 cm) were observed in N₈ (residual nutrient status of the soil of the treatment T₈).

Table 26. Effect of nano zinc nutrition on economics of rice

Treatments		Net returns (₹ ha ⁻¹)	B:C	Net returns (₹ ha ⁻¹)	B:C
		<i>Virippu</i>		<i>Mundakan</i>	
T ₁	– SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in <i>virippu</i> season)	12324	1.12	24760	1.24
T ₂	– NP with Nano Zn at 0.05%	60681	1.60	55673	1.55
T ₃	– NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage	76622	1.74	86368	1.82
T ₄	– NP with ZnSO ₄ at 0.5%	17462	1.18	43286	1.42
T ₅	– NP with ZnSO ₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage	43032	1.41	59480	1.57
T ₆	– FS with Nano Zn at 0.05% at MT and PI stages	64476	1.61	74581	1.70
T ₇	– FS with ZnSO ₄ at 0.5% at MT and PI stages	30734	1.29	46612	1.44
T ₈	– Control (RDN without application of P and Zn)	6989	1.07	1436	1.01

4.6.2 Number of Branches per Plant

Number of branches per plant of grain cowpea as affected by the residual nutrient status of the soil are presented in the Table 28.

The highest number of branches in cowpea at 30 DAS (3.17), 45 DAS (4.83) and at harvest (9.33) were observed in N₁ (residual nutrient status of the soil of the treatment T₁) whereas, the lowest number of branches at 30 DAS (2.00), 45 DAS (2.00) and at harvest (5.67) were observed in the treatment N₈ (residual nutrient status of the soil of the treatment T₈).

4.6.3 Dry Matter Production at Harvest

The data on effect of residual nutrient status of soil on dry matter production of grain cowpea at harvest are given in Table 29.

The highest dry matter per plant at harvest (38.90 g per plant) was observed in N₁ and the lowest dry matter per plant was reported in the treatment N₈ (21.33 g per plant).

4.7 YIELD AND YIELD ATTRIBUTES OF GRAIN COWPEA

4.7.1 Days to 50 per cent Flowering

Days to 50 per cent flowering of grain cowpea as affected by the residual nutrient status of the soil is shown in the Table 29.

Grain cowpea took on an average 43 to 46 days for 50 per cent flowering in the residual nutrient status of the soil after conduct of the previous experiment.

4.7.2 Number of Pods per Plant

The effect of residual nutrient status on no of pods per plant of grain cowpea was presented in the Table 29.

The data revealed that number of pods per plant of cowpea varied between 7 in N₈ to 12 in N₁.

Table 27. Effect of residual nutrient status of soil on plant height of grain cowpea, cm

Treatments (Residual nutrients)	30 DAS	45 DAS	At harvest
N ₁	45.23	68.77	81.03
N ₂	39.60	54.20	64.53
N ₃	35.60	47.67	55.33
N ₄	42.07	60.40	71.40
N ₅	38.10	50.60	61.00
N ₆	36.17	48.80	56.73
N ₇	41.07	58.33	69.00
N ₈	32.83	40.13	46.80

Table 28. Effect of residual nutrient status of soil on number of branches per plant of grain cowpea

Treatments (Residual nutrients)	30 DAS	45 DAS	At harvest
N ₁	3.17	4.83	9.33
N ₂	2.33	3.47	7.67
N ₃	2.27	3.13	7.17
N ₄	3.00	3.67	8.00
N ₅	2.00	3.40	7.67
N ₆	2.03	3.33	7.33
N ₇	2.80	3.53	8.00
N ₈	2.00	2.00	5.67

Table 29. Effect of residual nutrient status of soil on dry matter production at harvest, days to 50 per cent flowering, number of pods per plant, 100 seed weight of grain cowpea

Treatments (Residual nutrients)	Dry matter production at harvest (g per plant)	Days to 50 per cent flowering	Number of pods per plant	100 seed weight (g)
N ₁	38.90	45	12	12.57
N ₂	29.20	45	10	12.37
N ₃	26.63	45	9	12.23
N ₄	32.07	46	10	12.00
N ₅	28.00	45	10	12.53
N ₆	27.03	44	9	12.00
N ₇	31.73	45	10	11.67
N ₈	21.33	43	7	11.17

Table 30. Effect of residual nutrient status of soil on seed yield per plant, seed yield ha⁻¹, haulm yield per plant, haulm yield ha⁻¹ of grain cowpea

Treatments (Residual nutrients)	Seed yield per plant (g)	Seed yield ha ⁻¹ (kg ha ⁻¹)	Haulm yield per plant (g)	Haulm yield ha ⁻¹ (kg ha ⁻¹)	Harvest index
N ₁	32.27	855	43.63	2030	0.30
N ₂	26.03	732	36.27	1667	0.31
N ₃	25.00	667	33.97	1499	0.31
N ₄	27.50	751	36.90	1784	0.30
N ₅	25.67	696	35.33	1642	0.30
N ₆	25.17	668	34.67	1557	0.30
N ₇	26.70	741	36.40	1737	0.30
N ₈	20.33	562	27.00	1253	0.31

4.7.3 100 Seed Weight

The data on 100 seed weight of grain cowpea as affected by the residual nutrient status of the soil are shown in the Table 29.

The 100 seed weight of the grain cowpea varied between 11.17 g (N₈) to 12.57 g (N₁).

4.7.4 Seed Yield per Plant

The effect of residual nutrient status of the soil on seed yield per plant of grain cowpea is presented in the Table 30.

The highest seed yield per plant was observed in N₁ (32.27 g) which is the residual nutrient status of the soil T₁. The lowest seed yield per plant was observed in N₈ (20.33 g) which is the residual nutrient status of the soil T₈.

4.7.5 Seed Yield ha⁻¹

The data pertaining to the seed yield of grain cowpea as affected by the residual nutrient status of the soil is presented in the Table 30 and its rice equivalent yield is depicted in Table 35.

The data revealed that in grain cowpea, the highest seed yield was observed in N₁ (855 kg ha⁻¹) and the lowest seed yield was recorded in N₈ (562 kg ha⁻¹). The rice equivalent yield of cowpea was the highest in N₁ (2280 kg ha⁻¹) and the lowest was observed in N₈ (1500 kg ha⁻¹).

4.7.6 Haulm Yield per Plant

The haulm yield per plant of grain cowpea as affected by the residual nutrient status of the soil is presented in the Table 30.

The highest haulm yield per plant was observed in the treatment N₁ (43.63 g) and the lowest haulm yield per plant was recorded in N₈ (27 g).

4.7.7 Haulm Yield ha⁻¹

The effect of residual nutrient status of the soil on haulm yield per hectare of grain cowpea is presented in the Table 30.

The highest haulm yield of 2030 kg ha⁻¹ was observed in N₁ and the lowest haulm yield of 1253 kg ha⁻¹ was observed in N₈.

4.7.8 Harvest Index

The harvest index of the grain cowpea as affected by the residual nutrient status of the soil is presented in the Table 30.

The harvest index of the grain cowpea ranged from 0.30 to 0.31 among the treatments.

4.8 GROWTH PARAMETERS OF BHINDI

4.8.1 Plant height

The data on plant height of bhindi as affected by the residual nutrient status of the soil are given in the Table 31.

The taller plants were observed in the treatment N₁ (34.63, 63.00 and 96.30 cm at 30 DAS, 45 DAS and at harvest, respectively) and the shorter plants were observed in N₈ (28.23, 37.07 and 64.00 cm at 30 DAS, 45 DAS and at harvest, respectively).

4.8.2 Number of Branches per Plant

The data pertaining to the number of branches per plant as affected by the residual nutrient status of the soil are presented in the Table 32.

The number of branches was higher in the treatment N₁ (1.07, 2.67 and 3.67 at 30 DAS, 45 DAS and at harvest, respectively) and the lower number of branches were observed in N₈ (0.80, 1.00 and 3.67 at 30 DAS, 45 DAS and at harvest, respectively).

Table 31. Effect of residual nutrient status of soil on plant height of bhindi, cm

Treatments (Residual nutrients)	30 DAS	45 DAS	At harvest
N ₁	34.63	63.00	96.30
N ₂	32.07	50.53	81.37
N ₃	31.07	44.77	78.43
N ₄	31.70	55.13	83.73
N ₅	32.73	49.23	80.13
N ₆	31.67	47.70	79.70
N ₇	30.50	51.23	82.00
N ₈	28.23	37.07	64.00

Table 32. Effect of residual nutrient status of soil on number of branches per plant of bhindi

Treatments (Residual nutrients)	30 DAS	45 DAS	At harvest
N ₁	1.07	2.67	3.67
N ₂	0.77	2.00	3.00
N ₃	0.83	1.56	2.67
N ₄	0.87	2.22	3.11
N ₅	0.80	1.78	2.78
N ₆	0.77	1.67	2.67
N ₇	0.70	2.11	3.11
N ₈	0.80	1.00	3.67

Table 33. Effect of residual nutrient status of soil on dry matter production at harvest, days to 50 per cent flowering, number of fruits per plant, fruit weight of bhindi

Treatments (Residual nutrients)	Dry matter production at harvest (g per plant)	Days to 50 per cent flowering	Number of fruits per plant	Fruit weight (g)
N ₁	95.13	40	25	16.70
N ₂	85.87	40	17	13.53
N ₃	78.47	40	14	11.70
N ₄	89.00	41	21	15.67
N ₅	82.40	40	15	12.80
N ₆	81.03	40	14	12.67
N ₇	87.32	40	18	13.33
N ₈	72.77	42	10	10.17

Table 34. Effect of residual nutrient status of soil on fruit yield per plant, fruit yield ha⁻¹, haulm yield per plant, haulm yield ha⁻¹ of bhindi

Treatments (Residual nutrients)	Fruit yield per plant (g)	Fruit yield ha⁻¹ (kg ha⁻¹)	Haulm yield per plant (g)	Haulm yield ha⁻¹ (kg ha⁻¹)	Harvest index
N ₁	299.37	1945	51.17	1897	0.51
N ₂	246.03	1612	40.27	1493	0.52
N ₃	227.50	1326	35.30	1235	0.52
N ₄	251.03	1606	44.23	1617	0.50
N ₅	240.90	1509	39.20	1375	0.52
N ₆	236.87	1451	37.67	1290	0.53
N ₇	248.30	1621	42.10	1598	0.50
N ₈	183.53	932	27.67	939	0.50

Table 35. Rice equivalent yield of cowpea and bhindi, kg ha⁻¹

Treatments (Residual nutrients)	Cowpea	Bhindi
N ₁	2280	2594
N ₂	1952	2149
N ₃	1778	1768
N ₄	2002	2141
N ₅	1855	2011
N ₆	1782	1935
N ₇	1976	2162
N ₈	1500	1243

4.8.3 Dry Matter Production at Harvest

The data on effect of residual nutrient status of soil on dry matter production of bhindi at harvest are presented in Table 33.

The highest dry matter production at harvest was observed in N₁ (95.13 g per plant) and the lowest dry matter production was observed in N₈ (72.77 g per plant).

4.9 YIELD AND YIELD ATTRIBUTES OF BHINDI

4.9.1 Days to 50 per cent Flowering

The effect of residual nutrient status of the soil on days to 50 per cent flowering of bhindi is presented in the Table 33.

Bhindi took 41 to 42 days for 50 per cent flowering in the residual nutrient status of the soil after conduct of the previous experiment.

4.9.2 Number of Fruits per Plant

The data on effect of residual nutrient status of soil on number of fruits per plant of bhindi at harvest are given in Table 33.

The highest number of fruits per plant were observed in N₁ (25) and the lowest number of fruits were observed in N₈ (10).

4.9.3 Fruit Weight

The data pertaining to the fruit weight of bhindi as affected by the residual nutrient status of the soil is given in the Table 33.

The highest fruit weight of 16.70 g was observed in N₁ and the lowest fruit weight was recorded in N₈ (10.17 g).

4.9.4 Fruit Yield per Plant

The effect of residual nutrient status of the soil on fruit yield per plant of bhindi is presented in the Table 34.

The fruit yield per plant was the highest in the treatment N₁ (299.37 g) and the lowest fruit yield per plant was observed in N₈ (183.53 g).

4.9.5 Fruit Yield ha⁻¹

Fruit yield per hectare as affected by the residual nutrient status of the soil is presented in Table 34 and its rice equivalent yield is depicted in Table 35.

The fruit yield was the highest in N₁ (1945 kg ha⁻¹) and the lowest fruit yield was reported in N₈ (932 kg ha⁻¹). The rice equivalent yield of bhindi was the highest in the N₁ (2594 kg ha⁻¹) and the lowest in N₈ (1243 kg ha⁻¹).

4.9.6 Haulm Yield per Plant

The data pertaining to the haulm yield per plant of bhindi as affected by the residual nutrient status of the soil is given in the Table 34.

The highest haulm yield per plant was recorded in N₁ (51.17 g) and the lowest haulm yield per plant was recorded in N₈ (27.67 g).

4.9.7 Haulm Yield ha⁻¹

The data pertaining to the haulm yield of bhindi as affected by the residual nutrient status of the soil is given in the Table 34.

The haulm yield was the highest in N₁ (1897 kg ha⁻¹) and the lowest haulm yield in treatment N₈ (939 kg ha⁻¹).

4.9.8 Harvest Index

The harvest index of bhindi as affected by the residual nutrient status of the soil is shown in the Table 34.

The harvest index of the bhindi ranged from 0.50 to 0.51 among the treatments.

4.10 SOIL ANALYSIS

4.10.1 Chemical Properties

4.10.1.1 pH

Data pertaining to the effect of residual nutrient status and crop sequence on pH of the soil after the experiment is presented in Table 36a and the interaction effect of residual nutrient status and crop sequence on pH is presented in Table 36b.

The data revealed that pH of the soil after the experiment did not vary significantly by the residual nutrient status, crop sequence and their interaction.

4.10.1.2 Electrical Conductivity (EC)

The EC of the soil after the experiment as affected by residual nutrient status and crop sequence is presented in the Table 36a and its interaction is shown in Table 36b.

The results revealed that EC of the soil after the experiment did not vary significantly by residual nutrients and crop sequences. The interaction effect of residual nutrients with crop sequences was also observed to be not significant.

4.10.1.3 Organic Carbon (OC)

The effect of residual nutrient status and crop sequence on soil organic carbon after the experiment is shown in the Tables 36a and 36b.

The data revealed that, OC of the soil after the experiment did not get affected by the residual nutrient status, crop sequence and their interaction.

Table 36a. Effect of residual nutrient status and crop sequence on chemical properties of soil after the experiment.

Treatments	pH	EC	OC
Residual nutrients			
N ₁	5.22 ± 0.28	0.60 ± 0.13	1.39 ± 0.34
N ₂	5.15 ± 0.07	0.71 ± 0.10	1.43 ± 0.24
N ₃	5.14 ± 0.18	0.61 ± 0.13	1.61 ± 0.28
N ₄	5.32 ± 0.31	0.67 ± 0.22	1.30 ± 0.19
N ₅	5.37 ± 0.29	0.65 ± 0.15	1.75 ± 0.30
N ₆	5.15 ± 0.19	0.72 ± 0.11	1.53 ± 0.45
N ₇	5.17 ± 0.19	0.63 ± 0.16	1.74 ± 0.15
N ₈	5.22 ± 0.23	0.64 ± 0.18	1.33 ± 0.30
SEm (±)	0.08	0.05	0.13
CD (0.05)	NS	NS	NS
Crop sequence			
C ₁ - Rice-rice- grain cowpea	5.12 ± 0.24	0.64 ± 0.15	1.48 ± 0.35
C ₂ - Rice-rice-bhindi	5.23 ± 0.22	0.64 ± 0.14	1.51 ± 0.29
C ₃ - Rice-rice-fallow	5.31 ± 0.20	0.69 ± 0.16	1.54 ± 0.35
SEm (±)	0.05	0.02	0.05
CD (0.05)	NS	NS	NS

NS- Non significant

Table 36b . Interaction effects of residual nutrient status and crop sequence on chemical properties of soil after the experiment.

Treatments	pH	EC	OC
n ₁ C ₁	5.00 ± 0.18	0.70 ± 0.10	1.21 ± 0.28
n ₁ C ₂	5.33 ± 0.29	0.55 ± 0.10	1.66 ± 0.13
n ₁ C ₃	5.33 ± 0.29	0.57 ± 0.16	1.30 ± 0.43
n ₂ C ₁	5.10 ± 0.02	0.73 ± 0.15	1.41 ± 0.33
n ₂ C ₂	5.17 ± 0.08	0.70 ± 0.08	1.43 ± 0.11
n ₂ C ₃	5.17 ± 0.08	0.71 ± 0.10	1.46 ± 0.34
n ₃ C ₁	5.00 ± 0.04	0.49 ± 0.17	1.55 ± 0.36
n ₃ C ₂	5.20 ± 0.22	0.67 ± 0.06	1.66 ± 0.06
n ₃ C ₃	5.20 ± 0.22	0.68 ± 0.03	1.62 ± 0.42
n ₄ C ₁	5.08 ± 0.29	0.56 ± 0.25	1.24 ± 0.10
n ₄ C ₂	5.44 ± 0.30	0.77 ± 0.15	1.35 ± 0.35
n ₄ C ₃	5.44 ± 0.30	0.70 ± 0.26	1.32 ± 0.10
n ₅ C ₁	5.48 ± 0.39	0.62 ± 0.15	1.81 ± 0.36
n ₅ C ₂	5.26 ± 0.30	0.63 ± 0.15	1.56 ± 0.29
n ₅ C ₃	5.37 ± 0.23	0.71 ± 0.18	1.88 ± 0.25
n ₆ C ₁	5.05 ± 0.19	0.65 ± 0.08	1.45 ± 0.58
n ₆ C ₂	5.10 ± 0.23	0.70 ± 0.10	1.43 ± 0.59
n ₆ C ₃	5.29 ± 0.10	0.82 ± 0.10	1.71 ± 0.26
n ₇ C ₁	5.02 ± 0.13	0.70 ± 0.00	1.75 ± 0.16
n ₇ C ₂	5.17 ± 0.18	0.47 ± 0.15	1.66 ± 0.10
n ₇ C ₃	5.32 ± 0.16	0.73 ± 0.14	1.81 ± 0.18
n ₈ C ₁	5.19 ± 0.27	0.70 ± 0.17	1.43 ± 0.29
n ₈ C ₂	5.12 ± 0.16	0.66 ± 0.13	1.30 ± 0.40
n ₈ C ₃	5.34 ± 0.27	0.57 ± 0.25	1.25 ± 0.30
SEm (±)	0.11	0.09	0.16
CD (0.05)	NS	NS	NS

NS- Non significant

4.10.1.4 Available Nitrogen (N)

The effect of residual nutrients, crop sequences and their interaction effect on available nitrogen status of the soil after the experiment are shown in the Tables 37a and 37b, respectively.

The analyzed data revealed that available N was significantly influenced by the residual nutrients and crop sequences whereas, their interactions were found non significant. Among the residual nutrients, available N was higher in N₆ (339.25 kg ha⁻¹) and N₅ (338.43 kg ha⁻¹) which were comparable to N₃, N₂ and N₄, respectively. The lower available N was observed in N₈ (274.96 kg ha⁻¹). Among the crop sequences, higher available N was observed in rice-rice-grain cowpea and rice-rice-bhindi whereas, the lowest values were recorded in rice-rice-fallow sequence.

4.10.1.5 Available Phosphorus (P)

Available P in the soil after the experiment as affected by the residual nutrients, crop sequences and their interactions varied significantly and the data pertaining to it were presented in the Tables 37a and 37b, respectively.

The analyzed data revealed that available P was the highest in N₃ (18.33 kg ha⁻¹) and lower values were observed in N₁ (13.58 kg ha⁻¹) and N₈ (14.44 kg ha⁻¹), which were on par with N₄ (14.87 kg ha⁻¹). Among the crop sequences, the highest available P of 17.40 kg ha⁻¹ was observed in the rice-rice-grain cowpea sequence which was on par with the C₂ (16.01 kg ha⁻¹) and the lowest available P was observed in the rice-rice fallow sequence (C₃-14.15 kg ha⁻¹). Among the interactions, the highest available P was observed in n₆c₁ (21.56 kg ha⁻¹), which was comparable to n₃c₁ (20.59 kg ha⁻¹) and n₃c₂ (19.69 kg ha⁻¹), respectively. The lowest available P was reported in n₁c₃ (12.67 kg ha⁻¹), which was on par with n₁c₁, n₁c₂, n₂c₃, n₄c₁, n₅c₃, n₆c₃, n₇c₃, n₈c₁ and n₈c₃, respectively.

Table.37a. Effect of residual nutrients and crop sequences on available nutrient status of N, P, K and Ca in the soil after the experiment

Treatments	Available N (kg ha ⁻¹)	Available P (kg ha ⁻¹)	Available K (kg ha ⁻¹)	Available Ca (mg kg ⁻¹)
Residual nutrients				
N ₁	313.17 ± 37.12 ^b	13.58 ± 1.39 ^d	61.21 ± 5.94 ^c	214.56 ± 10.41
N ₂	323.52 ± 37.39 ^{ab}	15.85 ± 2.26 ^{bc}	69.15 ± 9.39 ^b	216.07 ± 11.18
N ₃	331.29 ± 41.81 ^{ab}	18.83 ± 3.28 ^a	79.18 ± 10.02 ^a	220.64 ± 15.64
N ₄	322.69 ± 52.95 ^{ab}	14.87 ± 1.48 ^{cd}	66.66 ± 8.73 ^b	220.37 ± 13.89
N ₅	338.43 ± 42.65 ^a	15.87 ± 1.76 ^{bc}	70.96 ± 7.92 ^b	218.02 ± 12.37
N ₆	339.25 ± 49.59 ^a	16.98 ± 3.72 ^b	78.61 ± 6.71 ^a	216.83 ± 18.92
N ₇	316.66 ± 37.10 ^b	16.40 ± 2.06 ^b	70.69 ± 9.16 ^b	216.57 ± 18.91
N ₈	274.96 ± 39.54 ^c	14.44 ± 1.99 ^d	59.42 ± 4.73 ^c	220.97 ± 18.45
SEm (±)	7.16	0.45	1.62	6.34
CD (0.05)	21.733	1.374	4.924	NS
Crop sequence				
C ₁ - Rice-rice-grain cowpea	346.70 ± 28.31 ^a	17.40 ± 3.36 ^a	76.21 ± 10.16 ^a	212.60 ± 14.16
C ₂ - Rice-rice-bhindi	340.03 ± 26.92 ^a	16.01 ± 1.99 ^{ab}	69.03 ± 7.93 ^b	222.80 ± 14.38
C ₃ - Rice-rice-fallow	273.26 ± 35.26 ^b	14.15 ± 1.49 ^b	63.22 ± 8.04 ^c	218.60 ± 14.40
SEm (±)	8.74	0.52	0.40	2.26
CD (0.05)	34.315	2.041	1.555	NS

NS-Non significant

Table 37b. Interaction effect of residual nutrients and crop sequences on available nutrient status of N, P, K and Ca in the soil after the experiment

Treatments	Available N (kg ha ⁻¹)	Available P (kg ha ⁻¹)	Available K (kg ha ⁻¹)	Available Ca (mg kg ⁻¹)
n ₁ C ₁	324.47 ± 7.52	14.08 ± 2.12 ^{ghij}	62.09 ± 5.89	224.10 ± 10.23 ^{abcde}
n ₁ C ₂	343.38 ± 22.78	14.00 ± 1.00 ^{ghij}	63.88 ± 7.04	210.13 ± 10.00 ^{cdefgh}
n ₁ C ₃	271.66 ± 28.11	12.67 ± 0.58 ^l	57.67 ± 5.13	209.45 ± 4.85 ^{defgh}
n ₂ C ₁	342.15 ± 11.91	18.26 ± 1.21 ^{bcd}	79.64 ± 5.39	213.08 ± 10.51 ^{bcdefgh}
n ₂ C ₂	351.29 ± 5.05	15.53 ± 1.35 ^{efghi}	65.43 ± 7.18	221.93 ± 12.07 ^{abcdef}
n ₂ C ₃	277.11 ± 22.76	13.75 ± 1.30 ^{ghij}	62.39 ± 4.19	213.22 ± 12.92 ^{bcdefgh}
n ₃ C ₁	336.15 ± 20.77	20.59 ± 4.93 ^{ab}	87.39 ± 3.57	201.65 ± 6.52 ^{gh}
n ₃ C ₂	363.19 ± 14.96	19.69 ± 0.59 ^{abc}	79.52 ± 3.19	230.71 ± 5.59 ^{ab}
n ₃ C ₃	294.52 ± 52.40	16.20 ± 1.54 ^{defg}	70.63 ± 12.95	229.54 ± 9.66 ^{ab}
n ₄ C ₁	347.05 ± 30.89	14.08 ± 2.12 ^{ghij}	76.78 ± 5.52	218.38 ± 11.22 ^{abcdefg}
n ₄ C ₂	353.33 ± 45.09	15.18 ± 1.28 ^{efghi}	64.15 ± 1.66	215.04 ± 9.66 ^{bcdefgh}
n ₄ C ₃	267.69 ± 37.32	15.37 ± 1.10 ^{efghi}	59.05 ± 4.64	227.67 ± 20.60 ^{abc}
n ₅ C ₁	371.67 ± 2.08	17.50 ± 1.36 ^{cde}	80.29 ± 3.42	206.36 ± 9.79 ^{efgh}
n ₅ C ₂	359.95 ± 11.22	15.63 ± 1.89 ^{efgh}	68.18 ± 2.81	224.33 ± 10.07 ^{abcde}
n ₅ C ₃	283.67 ± 17.21	14.49 ± 0.21 ^{fghij}	64.39 ± 4.95	223.38 ± 10.39 ^{abcde}
n ₆ C ₁	363.75 ± 36.33	21.56 ± 1.27 ^a	85.28 ± 4.97	198.17 ± 9.38 ^h
n ₆ C ₂	362.63 ± 25.23	16.10 ± 0.66 ^{defg}	75.98 ± 3.99	226.41 ± 22.08 ^{abcd}
n ₆ C ₃	291.39 ± 52.18	13.27 ± 0.31 ^{hij}	74.56 ± 6.13	225.90 ± 8.53 ^{abcd}
n ₇ C ₁	333.49 ± 1.16	18.27 ± 0.81 ^{bcd}	77.47 ± 2.78	216.00 ± 20.71 ^{bcdefgh}
n ₇ C ₂	344.84 ± 7.77	16.61 ± 1.95 ^{def}	73.61 ± 9.82	219.12 ± 25.31 ^{abcdefg}
n ₇ C ₃	271.66 ± 28.11	14.33 ± 0.90 ^{fghij}	61.00 ± 3.00	214.57 ± 18.58 ^{bcdefgh}
n ₈ C ₁	301.53 ± 17.96	14.83 ± 2.04 ^{fghij}	60.76 ± 4.70	223.09 ± 18.10 ^{abcdef}
n ₈ C ₂	294.97 ± 20.21	15.34 ± 1.90 ^{efghi}	61.47 ± 6.10	234.74 ± 9.85 ^a
n ₈ C ₃	228.38 ± 24.70	13.13 ± 2.01 ^{ij}	56.03 ± 2.05	205.08 ± 16.36 ^{fgh}
SEm (±)	12.00	0.85	3.70	6.28
CD (0.05)	NS	2.462	NS	18.185

NS-Non significant

4.10.1.6 Available Potassium (K)

The data pertaining to the available K in the soil after the experiment as affected by the residual nutrients, crop sequences and their interactions were presented in the Tables 37a and 37b, respectively. The available K varied significantly to residual nutrients and crop sequences but the interactions were not significant.

Among the residual nutrients, higher available K was observed in N₃ (79.18 kg ha⁻¹) and N₆ (78.61 kg ha⁻¹) whereas, the lower available K was observed in N₈ (59.42 kg ha⁻¹) and N₁ (61.21 kg ha⁻¹). Among the crop sequences, C₁ (76.21 kg ha⁻¹) had the highest available K and the lowest was recorded in C₃.

4.10.1.7 Available Calcium (Ca)

The effect of residual nutrients, crop sequences and their interaction effects on available calcium status of the soil after the experiment are shown in the Tables 37a and 37b, respectively.

A perusal of data revealed that available Ca was not affected by the residual nutrients and crop sequences whereas, it varied significantly for their interactions. Among the interactions, the highest available Ca was observed in n₈c₂ (234.74 mg kg⁻¹) which was on par with n₃c₂, n₃c₃, n₄c₃, n₁c₁, n₅c₂, n₅c₃, n₆c₂, n₆c₃, n₇c₂ and n₈c₁, respectively whereas, the lowest available Ca was observed in n₆c₁ (198.17 mg kg⁻¹) which was on par with n₃c₁, n₈c₃, n₅c₁, n₁c₃, n₁c₂, n₂c₁, n₂c₃, n₄c₂, n₇c₁ and n₇c₃.

4.10.1.8 Available Zinc (Zn)

Available Zn in the soil after the experiment as affected by the residual nutrients, crop sequences and their interactions varied significantly among treatments and the data pertaining to it were presented in the Tables 38a and 38b, respectively.

Among the residual nutrients, the highest available Zn was observed in N₆ (1.67 mg ha⁻¹), which was on par with the N₃ (1.66 mg kg⁻¹), N₅ (1.62 mg kg⁻¹) N₈ (1.58 mg kg⁻¹) N₄ (1.50 mg kg⁻¹) and N₇ (1.46 mg kg⁻¹); whereas, the lowest available Zn was observed in N₁ (1.14 mg kg⁻¹). Among the crop sequences, the highest available Zn was observed in C₁ (1.70 mg kg⁻¹) and lower available zinc was observed in C₂ and C₃. Among the interactions, n₃c₁ had the highest available Zn (1.87 mg kg⁻¹) and the lowest was observed in n₁c₃.

4.10.1.9 Available Iron (Fe)

The effect of residual nutrients, crop sequences and their interactions on available iron status of the soil after the experiment is presented in the Tables 38a and 38b, respectively.

A perusal of the data revealed that crop sequences affected the available Fe after the experiment significantly. The analyzed data revealed that higher available Fe was in C₂ (232.53 mg kg⁻¹) and C₁ (226.22 mg kg⁻¹) and the lowest available Fe was observed in C₃ (209.12 mg kg⁻¹). Available Fe did not vary significantly by residual nutrients and the interactions.

4.10.1.10 Available Boron (B)

The data pertaining to available B in the soil after the experiment as affected by the residual nutrients, crop sequences and their interactions and the results were presented in the Tables 38a and 38b, respectively.

The mean data revealed that crop sequences affected the available B after the experiment significantly and higher available B was found in C₁ (1.85 mg kg⁻¹) and C₂ (1.78 mg kg⁻¹) and the lowest available B was observed in C₃ (1.65 mg kg⁻¹). Available B did not vary significantly by residual nutrients and the interactions.

Table 38a. Effect of residual nutrients and crop sequences on available nutrient status of Zn, Fe and B in the soil after the experiment, mg kg⁻¹

Treatments	Available Zn	Available Fe	Available B
Residual nutrients			
N ₁	1.14 ± 0.20 ^c	225.73 ± 16.60	1.75 ± 0.21 ^b
N ₂	1.43 ± 0.29 ^b	223.03 ± 10.78	1.74 ± 0.11 ^{bc}
N ₃	1.66 ± 0.25 ^{ab}	231.81 ± 18.48	1.91 ± 0.29 ^a
N ₄	1.50 ± 0.25 ^{ab}	218.85 ± 20.68	1.75 ± 0.14 ^b
N ₅	1.62 ± 0.23 ^{ab}	222.21 ± 22.20	1.76 ± 0.10 ^b
N ₆	1.67 ± 0.17 ^a	227.44 ± 19.56	1.82 ± 0.08 ^{ab}
N ₇	1.46 ± 0.24 ^{ab}	220.47 ± 15.41	1.75 ± 0.14 ^b
N ₈	1.58 ± 0.31 ^{ab}	211.47 ± 24.59	1.63 ± 0.21 ^c
SEm (±)	0.08	5.86	0.04
CD (0.05)	0.236	NS	NS
Crop sequence			
C ₁ - Rice-rice-grain cowpea	1.70 ± 0.19 ^a	226.22 ± 14.94 ^a	1.85 ± 0.17 ^a
C ₂ - Rice-rice-bhindi	1.41 ± 0.28 ^b	232.53 ± 20.12 ^a	1.78 ± 0.18 ^a
C ₃ - Rice-rice-fallow	1.42 ± 0.28 ^b	209.12 ± 12.99 ^b	1.65 ± 0.15 ^b
SEm (±)	0.01	3.89	0.03
CD (0.05)	0.045	15.266	0.115

NS- Non significant

Table 38b. Interaction effect of residual nutrients and crop sequences on available nutrient status of Zn, Fe and B in the soil after the experiment, mg kg⁻¹

Treatments	Available Zn	Available Fe	Available B
n ₁ C ₁	1.34 ± 0.03 ^{fgh}	227.75 ± 3.25	1.93 ± 0.28
n ₁ C ₂	1.10 ± 0.10 ^{hi}	242.13 ± 11.14	1.70 ± 0.02
n ₁ C ₃	0.99 ± 0.23 ⁱ	207.30 ± 6.97	1.62 ± 0.16
n ₂ C ₁	1.76 ± 0.13 ^{abc}	226.64 ± 7.47	1.78 ± 0.11
n ₂ C ₂	1.20 ± 0.20 ^{ghi}	229.82 ± 4.46	1.79 ± 0.10
n ₂ C ₃	1.35 ± 0.17 ^{fgh}	212.62 ± 11.75	1.64 ± 0.10
n ₃ C ₁	1.87 ± 0.21 ^a	231.15 ± 3.28	2.01 ± 0.18
n ₃ C ₂	1.50 ± 0.30 ^{cdef}	247.08 ± 19.95	1.97 ± 0.47
n ₃ C ₃	1.60 ± 0.10 ^{abcdef}	217.19 ± 16.92	1.76 ± 0.12
n ₄ C ₁	1.65 ± 0.22 ^{abcde}	220.41 ± 20.24	1.84 ± 0.05
n ₄ C ₂	1.49 ± 0.21 ^{cdefg}	236.36 ± 16.98	1.84 ± 0.10
n ₄ C ₃	1.37 ± 0.31 ^{efgh}	199.78 ± 2.08	1.59 ± 0.11
n ₅ C ₁	1.74 ± 0.14 ^{abc}	227.04 ± 11.04	1.84 ± 0.10
n ₅ C ₂	1.69 ± 0.25 ^{abcd}	228.06 ± 39.11	1.77 ± 0.06
n ₅ C ₃	1.42 ± 0.20 ^{defg}	211.54 ± 7.88	1.67 ± 0.08
n ₆ C ₁	1.80 ± 0.00 ^{ab}	235.96 ± 35.51	1.86 ± 0.07
n ₆ C ₂	1.70 ± 0.12 ^{abcd}	224.70 ± 6.00	1.79 ± 0.11
n ₆ C ₃	1.51 ± 0.18 ^{bcdef}	221.67 ± 8.01	1.82 ± 0.09
n ₇ C ₁	1.67 ± 0.03 ^{abcd}	224.37 ± 9.96	1.87 ± 0.08
n ₇ C ₂	1.37 ± 0.28 ^{efgh}	230.23 ± 15.47	1.75 ± 0.05
n ₇ C ₃	1.35 ± 0.21 ^{fgh}	206.81 ± 12.87	1.62 ± 0.16
n ₈ C ₁	1.73 ± 0.12 ^{abc}	216.47 ± 14.73	1.71 ± 0.28
n ₈ C ₂	1.20 ± 0.20 ^{ghi}	221.89 ± 35.11	1.67 ± 0.06
n ₈ C ₃	1.80 ± 0.00 ^{ab}	196.03 ± 20.26	1.51 ± 0.26
SEm (±)	0.10	9.99	0.09
CD (0.05)	0.293	NS	NS

NS- Non significant

4.10.2 Soil Enzyme Activity

4.10.2.1 Dehydrogenase

Tables 39a and 39b represents the data pertaining to the effect of residual nutrient status, crop sequence and their interaction effect, respectively on dehydrogenase activity in the soil after the experiment.

A perusal of the data revealed that dehydrogenase activity in the soil after the experiment varied significantly in residual nutrients, crop sequences and their interaction. Among residual nutrients, N₃ (56.25 g⁻¹ soil 24h⁻¹) resulted in higher dehydrogenase activity, which was comparable to treatment N₆ (53.01 g⁻¹soil 24h⁻¹) whereas, the lowest dehydrogenase activity was observed in the treatment N₈ (35.16 g⁻¹ soil 24h⁻¹). Among the crop sequences, C₁ (50.16) was observed to have the highest dehydrogenase activity, followed by C₂ (44.50 g⁻¹ soil 24h⁻¹) and C₃ (44.13 g⁻¹ soil 24h⁻¹), respectively. The interaction effect of residual nutrient status with crop sequences on dehydrogenase activity was observed to be not significant.

4.10.2.2 Phosphatase

Phosphatase activity as affected by the residual nutrient status, crop sequence and their interaction are presented in the Tables 39a and 39b, respectively.

Phosphatase activity was significantly affected by the residual nutrient status and higher phosphatase activity was observed in N₁ (31.99 g⁻¹ soil h⁻¹), which was on par with N₄ (30.64 g⁻¹ soil h⁻¹) whereas, the lower phosphatase activity was observed in the treatment N₆ which was comparable to N₃ (25.78 g⁻¹ soil h⁻¹), N₈ (26.02 g⁻¹ soil h⁻¹) and N₂ (27.52 g⁻¹ soil h⁻¹), respectively. Crop sequences did not affect the phosphatase activity. The interaction effect of residual nutrient status and crop sequence was significant, the treatment n₁c₁ (34.97 g⁻¹ soil h⁻¹) was observed with higher phosphatase activity, which was comparable to n₈c₃ (32.47 g⁻¹ soil h⁻¹) and n₄c₁ (32.37 g⁻¹ soil h⁻¹).

Table 39a. Effect of residual nutrients and crop sequences on soil enzyme activity after the experiment

Treatments	Dehydrogenase activity g⁻¹ soil 24h⁻¹	Phosphatase activity g⁻¹ soil h⁻¹
Residual nutrients		
N ₁	40.59 ± 5.52 ^d	31.99 ± 2.83 ^a
N ₂	48.98 ± 2.86 ^{bc}	27.52 ± 3.01 ^{cde}
N ₃	56.25 ± 5.94 ^a	25.78 ± 3.16 ^{de}
N ₄	42.08 ± 3.78 ^d	30.64 ± 3.05 ^{ab}
N ₅	48.92 ± 5.17 ^{bc}	28.24 ± 1.92 ^{bcd}
N ₆	53.01 ± 6.04 ^{ab}	25.16 ± 2.76 ^e
N ₇	45.12 ± 5.37 ^{cd}	28.82 ± 3.29 ^{bc}
N ₈	35.16 ± 5.37 ^e	26.02 ± 5.32 ^{de}
SEm (±)	1.60	0.86
CD (0.05)	4.838	2.607
Crop sequence		
C ₁ - Rice-rice-grain cowpea	50.16 ± 8.30 ^a	29.81 ± 3.59
C ₂ - Rice-rice-bhindi	44.50 ± 7.53 ^b	26.81 ± 3.84
C ₃ - Rice-rice-fallow	44.13 ± 7.35 ^b	27.45 ± 3.65
SEm (±)	1.14	0.80
CD (0.05)	4.47	NS

NS- Non significant

Table 39b. Interaction effect of residual nutrients and crop sequences on soil enzyme activity after the experiment

Treatments	Dehydrogenase Activity g ⁻¹ soil 24h ⁻¹	Acid phosphatase activity g ⁻¹ soil h ⁻¹
n ₁ C ₁	44.93 ± 6.27	34.97 ± 0.49 ^a
n ₁ C ₂	39.27 ± 4.11	31.97 ± 1.07 ^{bc}
n ₁ C ₃	37.57 ± 4.60	29.03 ± 2.06 ^{defg}
n ₂ C ₁	52.27 ± 1.79	30.07 ± 2.27 ^{bcd}
n ₂ C ₂	46.60 ± 0.53	27.07 ± 3.06 ^{fghij}
n ₂ C ₃	48.07 ± 1.80	25.43 ± 2.25 ^{ijkl}
n ₃ C ₁	59.80 ± 7.49	28.43 ± 2.27 ^{efgh}
n ₃ C ₂	54.13 ± 6.12	25.43 ± 3.09 ^{ijkl}
n ₃ C ₃	54.80 ± 4.33	23.47 ± 2.57 ^{lm}
n ₄ C ₁	46.23 ± 3.00	32.37 ± 1.94 ^{ab}
n ₄ C ₂	40.57 ± 2.72	29.37 ± 2.11 ^{cdef}
n ₄ C ₃	39.43 ± 0.91	30.20 ± 4.66 ^{bcd}
n ₅ C ₁	53.73 ± 5.03	29.50 ± 1.65 ^{cdef}
n ₅ C ₂	48.07 ± 2.77	26.50 ± 1.95 ^{ghijk}
n ₅ C ₃	44.97 ± 3.85	28.73 ± 0.95 ^{efgh}
n ₆ C ₁	57.23 ± 7.41	27.10 ± 2.95 ^{fghi}
n ₆ C ₂	51.57 ± 5.11	24.10 ± 3.54 ^{klm}
n ₆ C ₃	50.23 ± 4.86	24.27 ± 0.83 ^{ijkl}
n ₇ C ₁	48.63 ± 7.06	31.73 ± 2.00 ^{bcd}
n ₇ C ₂	42.97 ± 4.88	28.73 ± 2.67 ^{efgh}
n ₇ C ₃	43.77 ± 3.65	26.00 ± 2.72 ^{hijkl}
n ₈ C ₁	38.47 ± 6.41	24.30 ± 1.81 ^{ijkl}
n ₈ C ₂	32.80 ± 4.36	21.30 ± 2.52 ^m
n ₈ C ₃	34.20 ± 5.41	32.47 ± 1.81 ^{ab}
SEm (±)	1.96	0.97
CD (0.05)	NS	2.821

NS- Non significant

4.11 SYSTEM ANALYSIS

4.11.1 System Yield

The data pertaining to the effect of residual nutrients and crop sequences on system yield is presented in the Table 40a and the interaction effect of residual nutrients and crop sequences is shown in the Table 40b.

The system yield was significantly influenced by residual nutrients, crop sequences and their interactions. The highest system yield among the residual nutrients was observed in N₃ (11504 kg ha⁻¹), which was comparable to N₆ (11015 kg ha⁻¹); whereas, the lower system yield was observed in the N₁ (8381 kg ha⁻¹) and N₈ (8529 kg ha⁻¹), which were on par with N₇ (9444 kg ha⁻¹). Among the crop sequences, the highest system yield was recorded in the rice-rice-bhindi (10592 kg ha⁻¹), in contrast rice-rice-fallow had the lowest system yield. Among the interactions, n₃c₁ (12100 kg ha⁻¹) and n₃c₂ (12090 kg ha⁻¹) had higher system yield, which were on par with n₆c₂ (11711 kg ha⁻¹); whereas, the lowest system yield was recorded in the n₁c₃ (6756 kg ha⁻¹).

4.11.2 System Productivity

The data pertaining to the effect of residual nutrient status, crop sequence and their interaction effect, respectively on system productivity are given in Tables 40a and 40b.

Among the residual nutrients, higher system productivity of 32 kg ha⁻¹ day⁻¹ was recorded in N₃, which was on par with N₆ (30 kg ha⁻¹ day⁻¹) whereas, the lowest system productivity was recorded in N₈. Among the crop sequences, higher system productivity was reported in C₂ (rice-rice-bhindi) and C₁ (rice-rice-grain cowpea). Among the interactions, n₃c₂ and n₃c₁ produced the highest system productivity of 33 kg ha⁻¹ day⁻¹, whereas the lowest system productivity was recorded in n₈c₃ (16 kg ha⁻¹ day⁻¹).

Table 40a. Effect of residual nutrients and crop sequences on system yield and system productivity

Treatments	System yield (kg ha⁻¹)	System productivity (kg ha⁻¹ day⁻¹)
Residual nutrients		
N ₁	8381 ± 1386 ^d	23 ± 4 ^d
N ₂	10257 ± 1129 ^{bc}	28 ± 3 ^{bc}
N ₃	11504 ± 1087 ^a	32 ± 3 ^a
N ₄	8704 ± 1043 ^d	24 ± 3 ^d
N ₅	9906 ± 1168 ^c	27 ± 3 ^{bc}
N ₆	11015 ± 1348 ^{ab}	30 ± 4 ^{ab}
N ₇	9444 ± 1095 ^{cd}	26 ± 3 ^{cd}
N ₈	8529 ± 1378 ^d	18 ± 2 ^e
SEm (±)	359.17	1.06
CD (0.05)	1089.444	3.202
Crop sequence		
C ₁ - Rice-rice-grain cowpea	10084 ± 1562 ^b	28 ± 4 ^a
C ₂ - Rice-rice-bhindi	10592 ± 1129 ^a	28 ± 5 ^a
C ₃ - Rice-rice-fallow	8477 ± 1243 ^c	22 ± 4 ^b
SEm (±)	45.48	0.10
CD (0.05)	178.573	0.39

Table 40b. Interaction effect of residual nutrients and crop sequences on system yield and system productivity

Treatments	System yield (kg ha ⁻¹)	System productivity (kg ha ⁻¹ day ⁻¹)
n ₁ C ₁	9036 ± 850 ^{kl}	25 ± 2 ^k
n ₁ C ₂	9350 ± 723 ^{jk}	26 ± 2 ^j
n ₁ C ₃	6756 ± 657 ^p	19 ± 2 ^p
n ₂ C ₁	10842 ± 611 ^{cd}	30 ± 2 ^{cd}
n ₂ C ₂	11038 ± 545 ^c	30 ± 1 ^c
n ₂ C ₃	8890 ± 439 ^{lm}	24 ± 1 ^k
n ₃ C ₁	12100 ± 687 ^a	33 ± 2 ^a
n ₃ C ₂	12090 ± 856 ^a	33 ± 2 ^a
n ₃ C ₃	10322 ± 616 ^{efg}	28 ± 2 ^{fg}
n ₄ C ₁	9325 ± 138 ^{jk}	26 ± 0 ^j
n ₄ C ₂	9464 ± 114 ^{ij}	26 ± 0 ^j
n ₄ C ₃	7322 ± 104 ^o	20 ± 0 ⁿ
n ₅ C ₁	10472 ± 749 ^{def}	29 ± 2 ^{ef}
n ₅ C ₂	10628 ± 805 ^{de}	29 ± 2 ^{de}
n ₅ C ₃	8617 ± 703 ^m	24 ± 2 ^l
n ₆ C ₁	11558 ± 977 ^b	32 ± 3 ^b
n ₆ C ₂	11711 ± 1273 ^{ab}	32 ± 3 ^b
n ₆ C ₃	9776 ± 1108 ^{hi}	27 ± 3 ⁱ
n ₇ C ₁	10042 ± 291 ^{gh}	28 ± 1 ^h
n ₇ C ₂	10226 ± 572 ^{fg}	28 ± 2 ^{gh}
n ₇ C ₃	8065 ± 286 ⁿ	22 ± 1 ^m
n ₈ C ₁	7294 ± 504 ^o	20 ± 1 ⁿ
n ₈ C ₂	10226 ± 572 ^{fg}	19 ± 1 ^o
n ₈ C ₃	8065 ± 286 ⁿ	16 ± 1 ^q
SEm (±)	136.46	0.23
CD (0.05)	395.299	0.656

4.12 SYSTEM ENERGETICS

4.12.1 Energy Efficiency

Energy efficiency as affected by the residual nutrient status, crop sequence and their combinations are presented in the Tables 41a and 41b, respectively.

The highest energy efficiency was found in N_3 (9.12) which was the residual nutrient status of the treatment T_3 , it was followed by N_6 (8.65) whereas, the lowest energy efficiency was observed in the N_8 (5.75). Among the crop sequences rice-rice-cowpea (7.42) had the highest energy efficiency and the lowest was recorded in rice-rice-bhindi sequence (7.30). Among the treatment combinations n_3c_3 (9.17) resulted in the highest energy efficiency and the lowest was recorded in n_8c_3 (5.75).

4.12.2 Specific Energy

Specific energy as affected by the residual nutrients, crop sequences and their combinations are presented in the Tables 41a and 41b, respectively.

The lowest specific energy among the residual nutrients was recorded in N_3 (3.10 MJ kg⁻¹) and the highest specific energy was recorded in N_8 (4.83 MJ kg⁻¹). Among the crop sequences, the lowest specific energy was recorded in rice-rice-bhindi sequence and the highest was recorded in rice-rice-fallow sequence. Among the treatment combinations, n_3c_2 (2.93 MJ kg⁻¹) was observed to have the least specific energy and the highest specific energy was observed in n_8c_3 (5.12 MJ kg⁻¹).

Table 41a. Effect of residual nutrients and crop sequences on energy efficiency and specific energy

Treatment	Energy efficiency	Specific energy (MJ kg⁻¹)
Residual nutrients		
N ₁	6.01	4.52
N ₂	7.92	3.52
N ₃	9.12	3.10
N ₄	6.60	4.20
N ₅	7.70	3.66
N ₆	8.65	3.28
N ₇	7.15	3.88
N ₈	5.75	4.83
Crop sequence		
C ₁ - Rice-rice-grain cowpea	7.42	3.93
C ₂ - Rice-rice-bhindi	7.30	3.55
C ₃ - Rice-rice-fallow	7.37	4.14

Table 41b. Interaction effect of residual nutrients and crop sequences on energy efficiency and specific intensity

Treatments	Energy efficiency	Specific energy (MJ kg ⁻¹)
n ₁ C ₁	6.13	4.60
n ₁ C ₂	5.95	3.96
n ₁ C ₃	5.96	5.01
n ₂ C ₁	7.97	3.58
n ₂ C ₂	7.85	3.23
n ₂ C ₃	7.93	3.74
n ₃ C ₁	9.15	3.14
n ₃ C ₂	9.05	2.93
n ₃ C ₃	9.17	3.23
n ₄ C ₁	6.69	4.26
n ₄ C ₂	6.54	3.80
n ₄ C ₃	6.59	4.53
n ₅ C ₁	7.75	3.71
n ₅ C ₂	7.64	3.37
n ₅ C ₃	7.72	3.88
n ₆ C ₁	8.68	3.33
n ₆ C ₂	8.58	3.06
n ₆ C ₃	8.68	3.45
n ₇ C ₁	7.22	3.94
n ₇ C ₂	7.09	3.54
n ₇ C ₃	7.15	4.16
n ₈ C ₁	5.81	4.85
n ₈ C ₂	5.68	4.51
n ₈ C ₃	5.75	5.12

4.12.3 Energy Productivity

The effect of residual nutrients and crop sequences on energy productivity was presented in Table 42a and their combinations are presented in the Table 42b.

Among the residual nutrients, N_3 (0.71 kg MJ^{-1}) resulted in the highest energy productivity and the lowest was recorded in the N_8 (0.46 kg MJ^{-1}). Rice-rice-bhindi had the highest energy productivity of 0.62. Among treatment combinations, n_3c_2 (0.74 kg MJ^{-1}) recorded the highest energy productivity and the lowest was recorded in n_8c_3 (0.43 kg MJ^{-1}).

4.12.4 Energy Intensity

Tables 42a and 42b represents the data pertaining to the effect of residual nutrient status, crop sequence and their combination effect on energy intensity.

The highest energy intensity was observed in the treatment N_3 ($1.34 \text{ MJ } \text{₹}^{-1}$) and the lowest energy intensity was recorded in N_8 ($0.78 \text{ MJ } \text{₹}^{-1}$). Among the crop sequences, C_3 had the highest energy intensity ($1.17 \text{ MJ } \text{₹}^{-1}$). Among the treatment combinations, n_3c_3 ($1.47 \text{ MJ } \text{₹}^{-1}$) had the highest energy intensity and the lowest energy intensity of $0.74 \text{ MJ } \text{₹}^{-1}$ was recorded in the n_8c_1 .

Table 42a. Effect of residual nutrients and crop sequences on energy productivity and energy intensity

Treatment	Energy productivity (kg MJ⁻¹)	Energy Intensity (MJ ₹⁻¹)
Residual nutrients		
N ₁	0.50	0.90
N ₂	0.63	1.18
N ₃	0.71	1.34
N ₄	0.54	0.98
N ₅	0.61	1.13
N ₆	0.68	1.25
N ₇	0.57	1.03
N ₈	0.46	0.78
Crop sequence		
C ₁ - Rice-rice-grain cowpea	0.60	1.02
C ₂ - Rice-rice-bhindi	0.62	1.02
C ₃ - Rice-rice-fallow	0.55	1.17

Table 42b. Interaction effect of residual nutrients and crop sequences on energy productivity and energy intensity

Treatments	Energy productivity (kg MJ⁻¹)	Energy Intensity (MJ ₹⁻¹)
n ₁ C ₁	0.51	0.87
n ₁ C ₂	0.55	0.85
n ₁ C ₃	0.44	0.97
n ₂ C ₁	0.64	1.12
n ₂ C ₂	0.67	1.12
n ₂ C ₃	0.59	1.30
n ₃ C ₁	0.72	1.27
n ₃ C ₂	0.74	1.27
n ₃ C ₃	0.68	1.47
n ₄ C ₁	0.54	0.94
n ₄ C ₂	0.57	0.93
n ₄ C ₃	0.49	1.08
n ₅ C ₁	0.62	1.08
n ₅ C ₂	0.65	1.07
n ₅ C ₃	0.57	1.24
n ₆ C ₁	0.68	1.19
n ₆ C ₂	0.71	1.19
n ₆ C ₃	0.64	1.37
n ₇ C ₁	0.58	0.99
n ₇ C ₂	0.61	0.98
n ₇ C ₃	0.53	1.13
n ₈ C ₁	0.47	0.74
n ₈ C ₂	0.48	0.74
n ₈ C ₃	0.43	0.85

4.13 NUTRIENT BALANCE OF THE SYSTEM

4.13.1 Nitrogen Balance in the System

The effect of nano zinc nutrition on N balance of the system is represented in the Tables 43a, 43b and 43c, respectively in rice-rice-grain cowpea, rice-rice-bhindi and rice-rice-fallow sequences.

The nitrogen balance was net gain in all the treatments in rice- rice-grain cowpea system, except in N₈, which was negatively affected by a net loss of 94.12 kg ha⁻¹. Among all the treatments, N₆ (132.79 kg ha⁻¹) had the highest net gain and the lowest net gain was recorded in N₁ (4.28 kg ha⁻¹).

In rice-rice-bhindi sequence, net gain was observed in all the treatments, except in N₈, which was observed to have net loss of 113.28 kg ha⁻¹ nitrogen in the system. The higher net gain of (139.51 kg ha⁻¹) was reported in N₃ and the lowest net gain was recorded in N₁ (23.51 kg ha⁻¹).

The highest net gain of nitrogen was reported in N₃ (37.04 kg ha⁻¹) in rice-rice-fallow sequence and the lowest net gain was reported in N₇ (14.76 kg ha⁻¹), except for N₃ and N₇, all others had a net loss of nitrogen in the sequence. The highest net loss in the system was recorded in N₈.

4.13.2 Phosphorus Balance in the System

Tables 44a, 44b and 44c represent the effect of nano zinc nutrition on phosphorus balance in the rice-rice-grain cowpea, rice-rice-bhindi, and rice-rice-fallow cropping sequences, respectively.

A perusal of the data revealed that there was a net loss of phosphorus in all the treatments except N₈. Among the three sequences N₈ showed a net gain of 13.76, 14.08 and 7.32 kg ha⁻¹, respectively in rice-rice-grain cowpea, rice-rice-bhindi and rice-rice-fallow sequences.

Table 43a. Effect of nano zinc nutrition on N balance sheet of rice-rice- grain cowpea system, kg ha⁻¹

Treatments	Initial N (A) (kg ha ⁻¹)	Added N (B) (kg ha ⁻¹)			Total N Input (A+B) (kg ha ⁻¹)	Crop N uptake (kg ha ⁻¹)			Total N uptake (C) (kg ha ⁻¹)	Balance		
		I Crop	II Crop	III Crop		I Crop	II Crop	III Crop		Computed balance D=(A)+(B)-C	Actual balance (E)	Net gain/loss (E-D)
N ₁	365.79	87.9	87.9	-	541.59	65.71	82.92	72.76	221.40	320.19	324.47	4.28
N ₂	365.79	87.9	80.7	-	534.39	104.50	116.43	51.31	272.24	262.15	342.15	80.00
N ₃	365.79	87.9	80.7	-	534.39	121.94	154.96	43.41	320.32	214.07	336.15	122.08
N ₄	365.79	87.9	87.9	-	541.59	68.43	97.94	57.23	223.62	317.97	347.047	29.07
N ₅	365.79	87.9	80.7	-	534.39	89.93	118.29	49.92	258.15	276.24	371.667	95.42
N ₆	365.79	87.9	80.7	-	534.39	112.08	145.68	45.67	303.43	230.96	363.75	132.79
N ₇	365.79	87.9	80.7	-	534.39	80.61	108.94	54.76	244.33	290.06	333.487	43.42
N ₈	365.79	87.9	87.9	-	541.59	57.35	56.52	32.06	145.94	395.65	301.53	-94.12

*SA- Soil application, NP- Nutri priming, FS- Foliar spray, RDN- Recommended dose of nutrients

(N₁, N₂, N₃, N₄, N₅, N₆, N₇ and N₈ are the residual nutrient treatments of T₁, T₂, T₃, T₄, T₅, T₆, T₇ and T₈, respectively)

T₁- SA of ZnSO₄ at 20 kg ha⁻¹ (applied only in *virippu* season)

T₂- NP with Nano Zn at 0.05%

T₃- NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage

T₄- NP with ZnSO₄ at 0.5%

T₅- NP with ZnSO₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage

T₆- FS with Nano Zn at 0.05% at MT and PI stages

T₇- FS with ZnSO₄ at 0.5% at MT and PI stages

T₈- Control (RDN without application of P and Zn)

Table 43b. Effect of nano zinc nutrition on N balance sheet of rice-rice-bhindi system, kg ha⁻¹

Treatments	Initial N (A) (kg ha ⁻¹)	Added N (B) (kg ha ⁻¹)			Total N Input (A+B) (kg ha ⁻¹)	Crop N uptake (kg ha ⁻¹)			Total N uptake (C) (kg ha ⁻¹)	Balance		
		I Crop	II Crop	III Crop		I Crop	II Crop	III Crop		Computed balance D=(A)+(B)-C	Actual balance (E)	Net gain/loss (E-D)
N ₁	365.79	87.9	87.9	-	541.59	65.71	82.92	73.07	221.71	319.88	343.38	23.51
N ₂	365.79	87.9	80.7	-	534.39	104.50	116.43	45.70	266.64	267.75	351.29	83.53
N ₃	365.79	87.9	80.7	-	534.39	121.94	154.96	33.80	310.71	223.68	363.19	139.51
N ₄	365.79	87.9	87.9	-	541.59	68.43	97.94	51.18	217.57	324.02	353.33	29.31
N ₅	365.79	87.9	80.7	-	534.39	89.93	118.29	37.12	245.35	289.04	359.95	70.90
N ₆	365.79	87.9	80.7	-	534.39	112.08	145.68	30.86	288.62	245.77	362.63	116.86
N ₇	365.79	87.9	80.7	-	534.39	80.61	108.94	51.46	241.02	293.37	344.84	51.47
N ₈	365.79	87.9	87.9	-	541.59	57.35	56.52	19.46	133.34	408.25	294.97	-113.28

*SA- Soil application, NP- Nutri priming, FS- Foliar spray, RDN- Recommended dose of nutrients

(N₁, N₂, N₃, N₄, N₅, N₆, N₇ and N₈ are the residual nutrient treatments of T₁, T₂, T₃, T₄, T₅, T₆, T₇ and T₈, respectively)

T₁- SA of ZnSO₄ at 20 kg ha⁻¹ (applied only in *virippu* season)

T₂- NP with Nano Zn at 0.05%

T₃- NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage

T₄- NP with ZnSO₄ at 0.5%

T₅- NP with ZnSO₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage

T₆- FS with Nano Zn at 0.05% at MT and PI stages

T₇- FS with ZnSO₄ at 0.5% at MT and PI stages

T₈- Control (RDN without application of P and Zn)

Table 43c. Effect of nano zinc nutrition on N balance sheet of rice-rice-fallow system, kg ha⁻¹

Treatments	Initial N (A) (kg ha ⁻¹)	Added N (B) (kg ha ⁻¹)			Total N Input (A+B) (kg ha ⁻¹)	Crop N uptake (kg ha ⁻¹)			Total N uptake (C) (kg ha ⁻¹)	Balance		
		I Crop	II Crop	III Crop		I Crop	II Crop	III Crop		Computed balance D=(A)+(B)-C	Actual balance (E)	Net gain/loss (E-D)
N ₁	365.79	87.9	87.9	-	541.59	65.72	82.92	-	148.64	392.95	271.66	-121.29
N ₂	365.79	87.9	80.7	-	534.39	104.50	116.43	-	220.93	313.46	277.11	-36.35
N ₃	365.79	87.9	80.7	-	534.39	121.94	154.96	-	276.91	257.48	294.52	37.04
N ₄	365.79	87.9	87.9	-	541.59	68.44	97.94	-	166.39	375.20	267.69	-107.51
N ₅	365.79	87.9	80.7	-	534.39	89.93	118.29	-	208.23	326.16	283.67	-42.49
N ₆	365.79	87.9	80.7	-	534.39	112.08	145.68	-	257.76	276.63	291.39	14.76
N ₇	365.79	87.9	80.7	-	534.39	80.61	108.94	-	189.56	344.83	271.66	-73.17
N ₈	365.79	87.9	87.9	-	541.59	57.36	56.52	-	113.88	427.71	228.38	-199.33

*SA- Soil application, NP- Nutri priming, FS- Foliar spray, RDN- Recommended dose of nutrients

(N₁, N₂, N₃, N₄, N₅, N₆, N₇ and N₈ are the residual nutrient treatments of T₁, T₂, T₃, T₄, T₅, T₆, T₇ and T₈, respectively)

T₁- SA of ZnSO₄ at 20 kg ha⁻¹ (applied only in *virippu* season)

T₂- NP with Nano Zn at 0.05%

T₃- NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage

T₄- NP with ZnSO₄ at 0.5%

T₅- NP with ZnSO₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage

T₆- FS with Nano Zn at 0.05% at MT and PI stages

T₇- FS with ZnSO₄ at 0.5% at MT and PI stages

T₈- Control (RDN without application of P and Zn)

Table 44a. Effect of nano zinc nutrition on P balance sheet of rice-rice- grain cowpea system, kg ha⁻¹

Treatments	Initial P (A) (kg ha ⁻¹)	Added P (B) (kg ha ⁻¹)			Total P Input (A+B) (kg ha ⁻¹)	Crop P uptake (kg ha ⁻¹)			Total P uptake (C) (kg ha ⁻¹)	Balance		
		I Crop	II Crop	III Crop		I Crop	II Crop	III Crop		Computed balance D = (A)+(B)-C	Actual balance (E)	Net gain/loss (E-D)
N ₁	27.2	32.1	52.8	-	112.1	14.13	14.15	11.69	39.98	72.12	14.08	-58.04
N ₂	27.2	32.1	47.85	-	107.15	25.79	19.35	8.23	53.38	53.77	18.26	-35.51
N ₃	27.2	32.1	42.45	-	101.75	26.18	27.89	6.47	60.55	41.20	20.59	-20.61
N ₄	27.2	32.1	52.8	-	112.1	15.14	16.38	9.30	40.83	71.27	14.08	-57.20
N ₅	27.2	32.1	42.45	-	101.75	20.45	20.91	7.62	48.99	52.76	17.50	-35.26
N ₆	27.2	32.1	42.45	-	101.75	25.74	25.51	7.20	58.45	43.30	21.56	-21.74
N ₇	27.2	32.1	42.45	-	101.75	17.94	18.35	8.85	45.15	56.60	18.27	-38.33
N ₈	27.2	0	0	-	27.2	12.68	8.707	4.74	26.13	1.07	14.83	13.76

*SA- Soil application, NP- Nutri priming, FS- Foliar spray, RDN- Recommended dose of nutrients

(N₁, N₂, N₃, N₄, N₅, N₆, N₇ and N₈ are the residual nutrient treatments of T₁, T₂, T₃, T₄, T₅, T₆, T₇ and T₈, respectively)

T₁- SA of ZnSO₄ at 20 kg ha⁻¹ (applied only in *virippu* season)

T₂- NP with Nano Zn at 0.05%

T₃- NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage

T₄- NP with ZnSO₄ at 0.5%

T₅- NP with ZnSO₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage

T₆- FS with Nano Zn at 0.05% at MT and PI stages

T₇- FS with ZnSO₄ at 0.5% at MT and PI stages

T₈- Control (RDN without application of P and Zn)

Table 44b. Effect of nano zinc nutrition on P balance sheet of rice-rice-bhindi system, kg ha⁻¹

Treatments	Initial P (A) (kg ha ⁻¹)	Added P (B) (kg ha ⁻¹)			Total P Input (A+B) (kg ha ⁻¹)	Crop P uptake (kg ha ⁻¹)			Total P uptake (C) (kg ha ⁻¹)	Balance		
		I Crop	II Crop	III Crop		I Crop	II Crop	III Crop		Computed balance D=(A)+(B)-C	Actual balance (E)	Net gain/loss (E-D)
N ₁	27.20	32.10	52.80	-	112.10	14.14	14.15	14.72	43.01	69.09	14.00	-55.09
N ₂	27.20	32.10	47.85	-	107.15	25.80	19.35	9.84	54.99	52.16	15.53	-36.63
N ₃	27.20	32.10	42.45	-	101.75	26.19	27.90	7.07	61.15	40.60	19.69	-20.91
N ₄	27.20	32.10	52.80	-	112.10	15.14	16.39	11.33	42.86	69.24	15.18	-54.06
N ₅	27.20	32.10	42.45	-	101.75	20.45	20.92	8.69	50.06	51.69	15.63	-36.05
N ₆	27.20	32.10	42.45	-	101.75	25.74	25.51	8.28	59.54	42.21	16.10	-26.11
N ₇	27.20	32.10	42.45	-	101.75	17.95	18.36	10.76	47.07	54.68	16.61	-38.07
N ₈	27.20	0.00	0.00	-	27.20	12.68	8.71	4.55	25.94	1.26	15.34	14.08

*SA- Soil application, NP- Nutri priming, FS- Foliar spray, RDN- Recommended dose of nutrients

(N₁, N₂, N₃, N₄, N₅, N₆, N₇ and N₈ are the residual nutrient treatments of T₁, T₂, T₃, T₄, T₅, T₆, T₇ and T₈, respectively)

T₁- SA of ZnSO₄ at 20 kg ha⁻¹ (applied only in *virippu* season)

T₂- NP with Nano Zn at 0.05%

T₃- NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage

T₄- NP with ZnSO₄ at 0.5%

T₅- NP with ZnSO₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage

T₆- FS with Nano Zn at 0.05% at MT and PI stages

T₇- FS with ZnSO₄ at 0.5% at MT and PI stages

T₈- Control (RDN without application of P and Zn)

Table 44c. Effect of nano zinc nutrition on P balance sheet of rice-rice-fallow system, kg ha⁻¹

Treatments	Initial P (A) (kg ha ⁻¹)	Added P (B) (kg ha ⁻¹)			Total P Input (A+B) (kg ha ⁻¹)	Crop P uptake (kg ha ⁻¹)			Total P uptake (C) (kg ha ⁻¹)	Balance		
		I Crop	II Crop	III Crop		I Crop	II Crop	III Crop		Computed balance D=(A)+(B)-C	Actual balance (E)	Net gain/loss (E-D)
N ₁	27.2	32.1	52.8	-	112.1	14.13	14.15	-	28.29	83.81	12.67	-71.14
N ₂	27.2	32.1	47.85	-	107.15	25.79	19.35	-	45.15	62.00	13.75	-48.25
N ₃	27.2	32.1	42.45	-	101.75	26.18	27.89	-	54.08	47.67	16.20	-31.47
N ₄	27.2	32.1	52.8	-	112.1	15.14	16.38	-	31.53	80.57	15.37	-65.21
N ₅	27.2	32.1	42.45	-	101.75	20.45	20.91	-	41.37	60.38	14.49	-45.89
N ₆	27.2	32.1	42.45	-	101.75	25.74	25.51	-	51.25	50.50	13.27	-37.23
N ₇	27.2	32.1	42.45	-	101.75	17.94	18.35	-	36.30	65.45	14.33	-51.11
N ₈	27.2	0	0	-	27.2	12.68	8.707	-	21.39	5.81	13.13	7.32

*SA- Soil application, NP- Nutri priming, FS- Foliar spray, RDN- Recommended dose of nutrients

(N₁, N₂, N₃, N₄, N₅, N₆, N₇ and N₈ are the residual nutrient treatments of T₁, T₂, T₃, T₄, T₅, T₆, T₇ and T₈, respectively)

T₁- SA of ZnSO₄ at 20 kg ha⁻¹ (applied only in *virippu* season)

T₂- NP with Nano Zn at 0.05%

T₃- NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage

T₄- NP with ZnSO₄ at 0.5%

T₅- NP with ZnSO₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage

T₆- FS with Nano Zn at 0.05% at MT and PI stages

T₇- FS with ZnSO₄ at 0.5% at MT and PI stages

T₈- Control (RDN without application of P and Zn)

4.13.3 Potassium Balance in the System

Potassium balance in the system as affected by the nano zinc nutrition is shown in the Tables 45a, 45b and 45c, respectively in rice-rice-grain cowpea, rice-rice-bhindi and rice-rice-fallow sequences.

A critical analysis of the balance sheet of the potassium revealed that there was a positive balance of potassium in rice-rice-grain cowpea in all the treatments, except N₈ which had a net loss of 32.64 kg ha⁻¹. The highest net gain was recorded in N₃ (88.17 kg ha⁻¹) and the lowest net gain was recorded in N₁ (15.38 kg ha⁻¹). Similarly, a net loss of 37.38 kg ha⁻¹ K in N₈, the highest net gain of 79.00 kg ha⁻¹ in N₃ and lowest net gain of 18.67 kg ha⁻¹ in N₄ were observed in rice-rice-bhindi sequence.

In rice-rice-fallow sequence, there was a net gain of K in N₃ (39.08 kg ha⁻¹) and N₆ (30.72 kg ha⁻¹) treatments, whereas, all the other treatments showed a net loss in potassium.

4.13.4 Calcium Balance in the System

The calcium balance in the system as affected by nano zinc nutrition is presented in the Tables 46a, 46b and 46c, respectively for rice-rice-grain cowpea, rice-rice-bhindi and rice-rice-fallow sequences.

A perusal of the data pertaining to the calcium balance among the rice-rice-grain cowpea, rice-rice-bhindi and rice-rice-fallow sequences revealed that there was a net loss of calcium in all crop sequences.

4.13.5 Zinc Balance in the System

The effect of nano zinc nutrition on zinc balance of the system is presented in the Tables 47a, 47b and 47c, respectively in rice-rice-grain cowpea, rice-rice-bhindi and rice-rice-fallow sequences.

Zinc balance of the system in rice-rice-grain cowpea sequence has showed a positive balance, except in N₁ and N₇ which were on negative balance with a net loss of 2.89 and 2.82 mg kg⁻¹, respectively and the highest net gain was recorded in N₃ (2.57 mg kg⁻¹). Rice-rice-bhindi sequence observed a net loss of Zn in N₁ (3.05 mg kg⁻¹) and N₇ (3.22 mg kg⁻¹), whereas the highest net gain of Zn was observed in N₆ (2.15 mg kg⁻¹). Similar results were observed in the rice- rice-fallow sequence, where N₁ and N₇ had a net loss of 3.71 and 3.57 mg ha⁻¹ and the highest net gain of zinc was observed in the treatment N₃ (1.93 mg kg⁻¹).

4.13.6 Iron Balance in the System

Effect of nano zinc nutrition on iron balance in the rice-rice-grain cowpea, rice-rice-bhindi, and rice-rice-fallow cropping sequences, respectively are given in Tables 48a, 48b and 48c.

Iron balance in the rice-rice-grain cowpea sequence was positive with the highest net gain in N₆ (55.24 mg kg⁻¹) and the lowest net gain was reported in N₈ (10.71 mg kg⁻¹). In rice-rice-bhindi sequence, there was a net gain in iron in all the treatments; N₃ had the highest net gain of 80.60 kg ha⁻¹ and the lowest net gain was observed in N₈ (23.06 mg kg⁻¹). In case of rice-rice-fallow sequence, there was a net loss of iron in treatments N₈ (35.20 mg kg⁻¹), N₄ (26.54 mg kg⁻¹), N₇ (10.58 kg ha⁻¹) and N₁ (9.80 mg kg⁻¹) whereas, there was a net gain in Fe in N₆ (23.07 mg kg⁻¹), N₃ (13.18 mg kg⁻¹), N₂ (2.59 mg kg⁻¹) and N₅ (0.17 mg kg⁻¹), respectively.

4.13.7 Boron Balance in the System

The boron balance in the system as affected by nano zinc nutrition is presented in the Tables 49a, 49b and 49c, respectively for rice-rice-grain cowpea, rice-rice-bhindi and rice-rice-fallow sequences.

Boron balance in the rice-rice-grain cowpea sequence was observed to be positive with a net gain of the boron in all the treatments, except N₈ and N₂, which were with a net

loss of 0.29 and 0.01 mg kg⁻¹, respectively. In rice-rice-bhindi sequence, there was a net gain in boron in N₃ (0.49 mg kg⁻¹), N₄ (0.08 mg kg⁻¹), N₆ (0.08 mg kg⁻¹) and N₂ (0.03 mg kg⁻¹). In rice-rice-fallow sequence there was a negative balance in all the treatments, except in N₆ and N₃ with a net gain of 0.12 and 0.01 mg kg⁻¹ of boron.

Table 45a. Effect of nano zinc nutrition on K balance sheet of rice-rice-grain cowpea system, kg ha⁻¹

Treatments	Initial K (A) (kg ha ⁻¹)	Added K (B) (kg ha ⁻¹)			Total K Input (A+B) (kg ha ⁻¹)	Crop K uptake (kg ha ⁻¹)			Total K uptake (C) (kg ha ⁻¹)	Balance		
		I Crop	II Crop	III Crop		I Crop	II Crop	III Crop		Computed balance D=(A)+(B)-C	Actual balance (E)	Net gain/loss (E-D)
N ₁	56	73.65	73.65	-	198.35	44.99	49.16	57.48	151.64	46.71	62.09	15.38
N ₂	56	73.65	73.65	-	203.3	66.39	67.26	42.19	175.85	27.45	79.64	52.19
N ₃	56	73.65	68.7	-	203.3	74.49	92.30	37.28	204.08	-0.78	87.39	88.17
N ₄	56	73.65	73.65	-	203.3	47.87	60.80	46.28	154.96	48.34	76.78	28.44
N ₅	56	73.65	73.65	-	203.3	60.08	71.46	40.39	171.93	31.37	80.29	48.92
N ₆	56	73.65	68.7	-	203.3	69.34	85.16	38.17	192.69	10.61	85.28	74.67
N ₇	56	73.65	73.65	-	203.3	54.47	65.88	44.37	164.73	38.57	77.47	38.90
N ₈	56	73.65	73.65	-	198.35	40.86	35.56	28.53	104.96	93.39	60.76	-32.64

*SA- Soil application, NP- Nutri priming, FS- Foliar spray, RDN- Recommended dose of nutrients

(N₁, N₂, N₃, N₄, N₅, N₆, N₇ and N₈ are the residual nutrient treatments of T₁, T₂, T₃, T₄, T₅, T₆, T₇ and T₈, respectively)

T₁- SA of ZnSO₄ at 20 kg ha⁻¹ (applied only in *virippu* season)

T₂- NP with Nano Zn at 0.05%

T₃- NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage

T₄- NP with ZnSO₄ at 0.5%

T₅- NP with ZnSO₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage

T₆- FS with Nano Zn at 0.05% at MT and PI stages

T₇- FS with ZnSO₄ at 0.5% at MT and PI stages

T₈- Control (RDN without application of P and Zn)

Table 45b. Effect of nano zinc nutrition on K balance sheet of rice-rice-bhindi system, kg ha⁻¹

Treatments	Initial K (A) (kg ha ⁻¹)	Added K (B) (kg ha ⁻¹)			Total K Input (A+B) (kg ha ⁻¹)	Crop K uptake (kg ha ⁻¹)			Total K uptake (C) (kg ha ⁻¹)	Balance		
		I Crop	II Crop	III Crop		I Crop	II Crop	III Crop		Computed balance D=(A)+(B)-C	Actual balance (E)	Net gain/loss (E-D)
N ₁	56	73.65	73.65	-	198.35	44.99	49.16	64.52	158.68	39.67	63.88	24.21
N ₂	56	73.65	73.65	-	203.3	66.39	67.26	46.53	180.19	23.11	65.43	42.32
N ₃	56	73.65	68.7	-	203.3	74.49	92.30	35.98	202.78	0.52	79.52	79.00
N ₄	56	73.65	73.65	-	203.3	47.87	60.80	49.15	157.83	45.47	64.15	18.67
N ₅	56	73.65	73.65	-	203.3	60.08	71.46	42.38	173.92	29.38	68.18	38.81
N ₆	56	73.65	68.7	-	203.3	69.34	85.16	39.77	194.28	9.02	75.98	66.96
N ₇	56	73.65	73.65	-	203.3	54.47	65.88	47.97	168.34	34.96	73.61	38.65
N ₈	56	73.65	73.65	-	198.35	40.86	35.56	23.07	99.50	98.85	61.47	-37.38

*SA- Soil application, NP- Nutri priming, FS- Foliar spray, RDN- Recommended dose of nutrients

(N₁, N₂, N₃, N₄, N₅, N₆, N₇ and N₈ are the residual nutrient treatments of T₁, T₂, T₃, T₄, T₅, T₆, T₇ and T₈, respectively)

T₁- SA of ZnSO₄ at 20 kg ha⁻¹ (applied only in *virippu* season)

T₂- NP with Nano Zn at 0.05%

T₃- NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage

T₄- NP with ZnSO₄ at 0.5%

T₅- NP with ZnSO₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage

T₆- FS with Nano Zn at 0.05% at MT and PI stages

T₇- FS with ZnSO₄ at 0.5% at MT and PI stages

T₈- Control (RDN without application of P and Zn)

Table 45c. Effect of nano zinc nutrition on K balance sheet of rice-rice-fallow system, kg ha⁻¹

Treatments	Initial K (A) (kg ha ⁻¹)	Added K (B) (kg ha ⁻¹)			Total K Input (A+B) (kg ha ⁻¹)	Crop K uptake (kg ha ⁻¹)			Total K uptake (C) (kg ha ⁻¹)	Balance		
		I Crop	II Crop	III Crop		I Crop	II Crop	III Crop		Computed balance D=(A)+(B)-C	Actual balance (E)	Net gain/loss (E-D)
N ₁	56	73.65	73.65	-	203.30	44.99	49.16	-	94.16	109.14	57.67	-51.47
N ₂	56	73.65	73.65	-	203.30	66.39	67.26	-	133.66	69.64	62.39	-7.24
N ₃	56	73.65	68.7	-	198.35	74.49	92.30	-	166.80	31.55	70.63	39.08
N ₄	56	73.65	73.65	-	203.30	47.87	60.80	-	108.68	94.62	59.05	-35.57
N ₅	56	73.65	73.65	-	203.30	60.08	71.46	-	131.54	71.76	64.39	-7.36
N ₆	56	73.65	68.7	-	198.35	69.34	85.16	-	154.51	43.84	74.56	30.72
N ₇	56	73.65	73.65	-	203.30	54.47	65.88	-	120.37	82.93	61.00	-21.93
N ₈	56	73.65	73.65	-	203.30	40.86	35.56	-	76.43	126.87	56.03	-70.84

*SA- Soil application, NP- Nutri priming, FS- Foliar spray, RDN- Recommended dose of nutrients
(N₁, N₂, N₃, N₄, N₅, N₆, N₇ and N₈ are the residual nutrient treatments of T₁, T₂, T₃, T₄, T₅, T₆, T₇ and T₈, respectively)

T₁- SA of ZnSO₄ at 20 kg ha⁻¹ (applied only in *virippu* season)

T₂- NP with Nano Zn at 0.05%

T₃- NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage

T₄- NP with ZnSO₄ at 0.5%

T₅- NP with ZnSO₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage

T₆- FS with Nano Zn at 0.05% at MT and PI stages

T₇- FS with ZnSO₄ at 0.5% at MT and PI stages

T₈- Control (RDN without application of P and Zn)

Table 46a. Effect of nano zinc nutrition on Ca balance sheet of rice-rice-grain cowpea system, kg ha⁻¹

Treatments	Initial Ca (A) (kg ha ⁻¹)	Added Ca (B) (kg ha ⁻¹)			Total Ca Input (A+B) (kg ha ⁻¹)	Crop Ca uptake (kg ha ⁻¹)			Total Ca uptake (C) (kg ha ⁻¹)	Balance		
		I Crop	II Crop	III Crop		I Crop	II Crop	III Crop		Computed balance D=(A)+(B)-C	Actual balance (E)	Net gain/loss (E-D)
N ₁	470.4	240	240	-	950.4	13.33	15.02	0.06	28.43	921.97	501.98	-419.99
N ₂	470.4	240	240	-	950.4	22.70	19.75	0.05	42.49	907.91	477.30	-430.61
N ₃	470.4	240	240	-	950.4	26.28	26.61	0.04	52.93	897.47	451.70	-445.76
N ₄	470.4	240	240	-	950.4	15.58	17.52	0.05	33.16	917.24	489.18	-428.06
N ₅	470.4	240	240	-	950.4	19.58	22.22	0.04	41.84	908.56	462.25	-446.31
N ₆	470.4	240	240	-	950.4	23.55	24.77	0.04	48.36	902.04	443.89	-458.14
N ₇	470.4	240	240	-	950.4	17.88	19.14	0.05	37.07	913.33	483.85	-429.48
N ₈	470.4	240	240	-	950.4	11.16	10.18	0.03	21.38	929.02	499.71	-429.30

*SA- Soil application, NP- Nutri priming, FS- Foliar spray, RDN- Recommended dose of nutrients

(N₁, N₂, N₃, N₄, N₅, N₆, N₇ and N₈ are the residual nutrient treatments of T₁, T₂, T₃, T₄, T₅, T₆, T₇ and T₈, respectively)

T₁- SA of ZnSO₄ at 20 kg ha⁻¹ (applied only in *virippu* season)

T₂- NP with Nano Zn at 0.05%

T₃- NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage

T₄- NP with ZnSO₄ at 0.5%

T₅- NP with ZnSO₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage

T₆- FS with Nano Zn at 0.05% at MT and PI stages

T₇- FS with ZnSO₄ at 0.5% at MT and PI stages

T₈- Control (RDN without application of P and Zn)

Table 46b. Effect of nano zinc nutrition on Ca balance sheet of rice-rice-bhindi system, kg ha⁻¹

Treatments	Initial Ca (A) (kg ha ⁻¹)	Added Ca (B) (kg ha ⁻¹)			Total Ca Input (A+B) (kg ha ⁻¹)	Crop Ca uptake (kg ha ⁻¹)			Total Ca uptake (C) (kg ha ⁻¹)	Balance		
		I Crop	II Crop	III Crop		I Crop	II Crop	III Crop		Computed balance D=(A)+(B)-C	Actual balance (E)	Net gain/loss (E-D)
N ₁	470.4	240	240	-	950.4	13.33	15.02	6.12	34.48	915.92	470.70	-445.22
N ₂	470.4	240	240	-	950.4	22.70	19.74	3.85	46.30	904.10	497.12	-406.98
N ₃	470.4	240	240	-	950.4	26.28	26.61	2.47	55.37	895.03	516.79	-378.24
N ₄	470.4	240	240	-	950.4	15.58	17.52	4.73	37.84	912.56	481.70	-430.87
N ₅	470.4	240	240	-	950.4	19.58	22.21	3.30	45.10	905.30	502.50	-402.80
N ₆	470.4	240	240	-	950.4	23.55	24.77	3.01	51.33	899.07	507.17	-391.90
N ₇	470.4	240	240	-	950.4	17.88	19.13	4.24	41.27	909.13	490.84	-418.30
N ₈	470.4	240	240	-	950.4	11.16	10.18	1.63	22.98	927.42	525.83	-401.60

*SA- Soil application, NP- Nutri priming, FS- Foliar spray, RDN- Recommended dose of nutrients

(N₁, N₂, N₃, N₄, N₅, N₆, N₇ and N₈ are the residual nutrient treatments of T₁, T₂, T₃, T₄, T₅, T₆, T₇ and T₈, respectively)

T₁- SA of ZnSO₄ at 20 kg ha⁻¹ (applied only in *virippu* season)

T₂- NP with Nano Zn at 0.05%

T₃- NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage

T₄- NP with ZnSO₄ at 0.5%

T₅- NP with ZnSO₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage

T₆- FS with Nano Zn at 0.05% at MT and PI stages

T₇- FS with ZnSO₄ at 0.5% at MT and PI stages

T₈- Control (RDN without application of P and Zn)

Table 46c. Effect of nano zinc nutrition on Ca balance sheet of rice-rice-fallow system, kg ha⁻¹

Treatments	Initial Ca (A) (kg ha ⁻¹)	Added Ca (B) (kg ha ⁻¹)			Total Ca Input (A+B) (kg ha ⁻¹)	Crop Ca uptake (kg ha ⁻¹)			Total Ca uptake (C) (kg ha ⁻¹)	Balance		
		I Crop	II Crop	III Crop		I Crop	II Crop	III Crop		Computed balance D=(A)+(B)-C	Actual balance (E)	Net gain/loss (E-D)
N ₁	470.4	240	240	-	950.4	13.33	15.02	-	28.3632	922.037	469.16	-452.88
N ₂	470.4	240	240	-	950.4	22.70	19.74	-	42.4489	907.951	477.61	-430.35
N ₃	470.4	240	240	-	950.4	26.28	26.61	-	52.8949	897.505	514.18	-383.33
N ₄	470.4	240	240	-	950.4	15.58	17.52	-	33.1097	917.29	509.98	-407.31
N ₅	470.4	240	240	-	950.4	19.58	22.21	-	41.7982	908.602	500.37	-408.23
N ₆	470.4	240	240	-	950.4	23.55	24.77	-	48.3239	902.076	506.01	-396.07
N ₇	470.4	240	240	-	950.4	17.88	19.13	-	37.0206	913.379	480.64	-432.74
N ₈	470.4	240	240	-	950.4	11.16	10.18	-	21.3547	929.045	459.39	-469.66

*SA- Soil application, NP- Nutri priming, FS- Foliar spray, RDN- Recommended dose of nutrients
(N₁, N₂, N₃, N₄, N₅, N₆, N₇ and N₈ are the residual nutrient treatments of T₁, T₂, T₃, T₄, T₅, T₆, T₇ and T₈, respectively)

T₁- SA of ZnSO₄ at 20 kg ha⁻¹ (applied only in *virippu* season)

T₂- NP with Nano Zn at 0.05%

T₃- NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage

T₄- NP with ZnSO₄ at 0.5%

T₅- NP with ZnSO₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage

T₆- FS with Nano Zn at 0.05% at MT and PI stages

T₇- FS with ZnSO₄ at 0.5% at MT and PI stages

T₈- Control (RDN without application of P and Zn)

Table 47a. Effect of nano zinc nutrition on Zn balance sheet of rice-rice-grain cowpea system, kg ha⁻¹

Treatments	Initial Zn (A) (kg ha ⁻¹)	Added Zn (B) (kg ha ⁻¹)			Total Zn Input (A+B) (kg ha ⁻¹)	Crop Zn uptake (kg ha ⁻¹)			Total Zn uptake (C) (kg ha ⁻¹)	Balance		
		I Crop	II Crop	III Crop		I Crop	II Crop	III Crop		Computed balance D=(A)+(B)-C	Actual balance (E)	Net gain/loss (E-D)
N ₁	2.15	4.20	0.00	-	6.35	0.21	0.21	0.05	0.47	5.88	2.99	-2.89
N ₂	2.15	0.05	0.05	-	2.20	0.34	0.29	0.03	0.67	1.53	3.93	2.40
N ₃	2.15	0.30	0.30	-	2.45	0.39	0.40	0.03	0.82	1.63	4.20	2.57
N ₄	2.15	0.50	0.50	-	2.65	0.22	0.25	0.04	0.51	2.14	3.69	1.55
N ₅	2.15	0.55	0.55	-	2.70	0.30	0.32	0.03	0.65	2.05	3.90	1.84
N ₆	2.15	0.50	0.50	-	2.65	0.36	0.37	0.03	0.76	1.89	4.03	2.15
N ₇	2.15	5.00	5.00	-	7.15	0.27	0.28	0.04	0.58	6.57	3.75	-2.82
N ₈	2.15	0.00	0.00	-	2.15	0.18	0.15	0.02	0.35	1.80	3.88	2.09

*SA- Soil application, NP- Nutri priming, FS- Foliar spray, RDN- Recommended dose of nutrients

(N₁, N₂, N₃, N₄, N₅, N₆, N₇ and N₈ are the residual nutrient treatments of T₁, T₂, T₃, T₄, T₅, T₆, T₇ and T₈, respectively)

T₁- SA of ZnSO₄ at 20 kg ha⁻¹ (applied only in *virippu* season)

T₂- NP with Nano Zn at 0.05%

T₃- NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage

T₄- NP with ZnSO₄ at 0.5%

T₅- NP with ZnSO₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage

T₆- FS with Nano Zn at 0.05% at MT and PI stages

T₇- FS with ZnSO₄ at 0.5% at MT and PI stages

T₈- Control (RDN without application of P and Zn)

Table 47b. Effect of nano zinc nutrition on Zn balance sheet of rice-rice-bhindi system, kg ha⁻¹

Treatments	Initial Zn (A) (kg ha ⁻¹)	Added Zn (B) (kg ha ⁻¹)			Total Zn Input (A+B) (kg ha ⁻¹)	Crop Zn uptake (kg ha ⁻¹)			Total Zn uptake (C) (kg ha ⁻¹)	Balance		
		I Crop	II Crop	III Crop		I Crop	II Crop	III Crop		Computed balance D=(A)+(B)-C	Actual balance (E)	Net gain/loss (E-D)
N ₁	2.15	4.20	0.00	-	6.35	0.21	0.21	0.41	0.83	5.52	2.46	-3.05
N ₂	2.15	0.05	0.05	-	2.20	0.34	0.29	0.30	0.93	1.27	2.69	1.42
N ₃	2.15	0.30	0.30	-	2.45	0.39	0.40	0.24	1.03	1.42	3.37	1.95
N ₄	2.15	0.50	0.50	-	2.65	0.22	0.25	0.32	0.80	1.85	3.33	1.48
N ₅	2.15	0.55	0.55	-	2.70	0.30	0.32	0.27	0.89	1.81	3.79	1.97
N ₆	2.15	0.50	0.50	-	2.65	0.36	0.37	0.25	0.99	1.66	3.82	2.15
N ₇	2.15	5.00	5.00	-	7.15	0.27	0.28	0.31	0.86	6.29	3.06	-3.22
N ₈	2.15	0.00	0.00	-	2.15	0.18	0.15	0.16	0.49	1.66	2.69	1.03

*SA- Soil application, NP- Nutri priming, FS- Foliar spray, RDN- Recommended dose of nutrients (N₁, N₂, N₃, N₄, N₅, N₆, N₇ and N₈ are the residual nutrient treatments of T₁, T₂, T₃, T₄, T₅, T₆, T₇ and T₈, respectively)

T₁- SA of ZnSO₄ at 20 kg ha⁻¹ (applied only in *virippu* season)

T₂- NP with Nano Zn at 0.05%

T₃- NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage

T₄- NP with ZnSO₄ at 0.5%

T₅- NP with ZnSO₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage

T₆- FS with Nano Zn at 0.05% at MT and PI stages

T₇- FS with ZnSO₄ at 0.5% at MT and PI stages

T₈- Control (RDN without application of P and Zn)

Table 47c. Effect of nano zinc nutrition on Zn balance sheet of rice-rice-fallow system, kg ha⁻¹

Treatments	Initial Zn (A) (kg ha ⁻¹)	Added Zn (B) (kg ha ⁻¹)			Total Zn Input (A+B) (kg ha ⁻¹)	Crop Zn uptake (kg ha ⁻¹)			Total Zn uptake (C) (kg ha ⁻¹)	Balance		
		I Crop	II Crop	III Crop		I Crop	II Crop	III Crop		Computed balance D=(A)+(B)-C	Actual balance (E)	Net gain/loss (E-D)
N ₁	2.15	4.20	0.00	-	6.35	0.21	0.21	-	0.42	5.93	2.22	-3.71
N ₂	2.15	0.05	0.05	-	2.20	0.34	0.29	-	0.63	1.57	3.02	1.45
N ₃	2.15	0.30	0.30	-	2.45	0.39	0.40	-	0.79	1.66	3.58	1.93
N ₄	2.15	0.50	0.50	-	2.65	0.22	0.25	-	0.48	2.17	3.06	0.89
N ₅	2.15	0.55	0.55	-	2.70	0.30	0.32	-	0.61	2.09	3.17	1.09
N ₆	2.15	0.50	0.50	-	2.65	0.36	0.37	-	0.73	1.92	3.39	1.47
N ₇	2.15	5.00	5.00	-	7.15	0.27	0.28	-	0.55	6.60	3.03	-3.57
N ₈	2.15	0.00	0.00	-	2.15	0.18	0.15	-	0.33	1.82	4.03	2.22

*SA- Soil application, NP- Nutri priming, FS- Foliar spray, RDN- Recommended dose of nutrients

(N₁, N₂, N₃, N₄, N₅, N₆, N₇ and N₈ are the residual nutrient treatments of T₁, T₂, T₃, T₄, T₅, T₆, T₇ and T₈, respectively)

T₁- SA of ZnSO₄ at 20 kg ha⁻¹ (applied only in *virippu* season)

T₂- NP with Nano Zn at 0.05%

T₃- NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage

T₄- NP with ZnSO₄ at 0.5%

T₅- NP with ZnSO₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage

T₆- FS with Nano Zn at 0.05% at MT and PI stages

T₇- FS with ZnSO₄ at 0.5% at MT and PI stages

T₈- Control (RDN without application of P and Zn)

Table 48a. Effect of nano zinc nutrition on Fe balance sheet of rice-rice-grain cowpea system, kg ha⁻¹

Treatments	Initial Fe (A) (kg ha ⁻¹)	Added Fe (B) (kg ha ⁻¹)			Total Fe Input (A+B) (kg ha ⁻¹)	Crop Fe uptake (kg ha ⁻¹)			Total Fe uptake (C) (kg ha ⁻¹)	Balance		
		I Crop	II Crop	III Crop		I Crop	II Crop	III Crop		Computed balance D=(A)+(B)-C	Actual balance (E)	Net gain/loss (E-D)
N ₁	474.88	-	-	-	474.88	0.33	0.39	0.22	0.95	473.93	510.15	36.22
N ₂	474.88	-	-	-	474.88	0.64	0.56	0.17	1.37	473.51	507.68	34.17
N ₃	474.88	-	-	-	474.88	0.73	0.83	0.15	1.70	473.18	517.78	44.60
N ₄	474.88	-	-	-	474.88	0.35	0.48	0.18	1.02	473.86	493.71	19.85
N ₅	474.88	-	-	-	474.88	0.56	0.65	0.16	1.37	473.51	508.58	35.07
N ₆	474.88	-	-	-	474.88	0.67	0.75	0.15	1.57	473.31	528.54	55.24
N ₇	474.88	-	-	-	474.88	0.50	0.54	0.17	1.21	473.67	502.59	28.92
N ₈	474.88	-	-	-	474.88	0.31	0.26	0.12	0.69	474.19	484.90	10.71

*SA- Soil application, NP- Nutri priming, FS- Foliar spray, RDN- Recommended dose of nutrients (N₁, N₂, N₃, N₄, N₅, N₆, N₇ and N₈ are the residual nutrient treatments of T₁, T₂, T₃, T₄, T₅, T₆, T₇ and T₈, respectively)

T₁- SA of ZnSO₄ at 20 kg ha⁻¹ (applied only in *virippu* season)

T₂- NP with Nano Zn at 0.05%

T₃- NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage

T₄- NP with ZnSO₄ at 0.5%

T₅- NP with ZnSO₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage

T₆- FS with Nano Zn at 0.05% at MT and PI stages

T₇- FS with ZnSO₄ at 0.5% at MT and PI stages

T₈- Control (RDN without application of P and Zn)

Table 48b. Effect of nano zinc nutrition on Fe balance sheet of rice-rice-bhindi system, kg ha⁻¹

Treatments	Initial Fe (A) (kg ha ⁻¹)	Added Fe (B) (kg ha ⁻¹)			Total Fe Input (A+B) (kg ha ⁻¹)	Crop Fe uptake (kg ha ⁻¹)			Total Fe uptake (C) (kg ha ⁻¹)	Balance		
		I Crop	II Crop	III Crop		I Crop	II Crop	III Crop		Computed balance D=(A)+(B)-C	Actual balance (E)	Net gain/loss (E-D)
N ₁	474.88	-	-	-	474.88	0.33	0.39	0.78	1.51	473.37	542.38	69.01
N ₂	474.88	-	-	-	474.88	0.64	0.56	0.60	1.80	473.08	514.80	41.72
N ₃	474.88	-	-	-	474.88	0.73	0.83	0.48	2.03	472.85	553.45	80.60
N ₄	474.88	-	-	-	474.88	0.35	0.48	0.64	1.47	473.41	529.44	56.03
N ₅	474.88	-	-	-	474.88	0.56	0.65	0.56	1.77	473.11	510.86	37.75
N ₆	474.88	-	-	-	474.88	0.67	0.75	0.52	1.94	472.94	503.32	30.38
N ₇	474.88	-	-	-	474.88	0.50	0.54	0.63	1.67	473.21	515.71	42.50
N ₈	474.88	-	-	-	474.88	0.31	0.26	0.33	0.90	473.98	497.04	23.06

*SA- Soil application, NP- Nutri priming, FS- Foliar spray, RDN- Recommended dose of nutrients

(N₁, N₂, N₃, N₄, N₅, N₆, N₇ and N₈ are the residual nutrient treatments of T₁, T₂, T₃, T₄, T₅, T₆, T₇ and T₈, respectively)

T₁- SA of ZnSO₄ at 20 kg ha⁻¹ (applied only in *virippu* season)

T₂- NP with Nano Zn at 0.05%

T₃- NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage

T₄- NP with ZnSO₄ at 0.5%

T₅- NP with ZnSO₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage

T₆- FS with Nano Zn at 0.05% at MT and PI stages

T₇- FS with ZnSO₄ at 0.5% at MT and PI stages

T₈- Control (RDN without application of P and Zn)

Table 48c. Effect of nano zinc nutrition on Fe balance sheet of rice-rice- fallow system, kg ha⁻¹

Treatments	Initial Fe (A) (kg ha ⁻¹)	Added Fe (B) (kg ha ⁻¹)			Total Fe Input (A+B) (kg ha ⁻¹)	Crop Fe uptake (kg ha ⁻¹)			Total Fe uptake (C) (kg ha ⁻¹)	Balance		
		I Crop	II Crop	III Crop		I Crop	II Crop	III Crop		Computed balance D=(A)+(B)-C	Actual balance (E)	Net gain/loss (E-D)
N ₁	474.88	-	-	-	474.88	0.33	0.39	-	0.73	474.15	464.35	-9.80
N ₂	474.88	-	-	-	474.88	0.64	0.56	-	1.20	473.68	476.28	2.59
N ₃	474.88	-	-	-	474.88	0.73	0.83	-	1.55	473.33	486.51	13.18
N ₄	474.88	-	-	-	474.88	0.35	0.48	-	0.84	474.04	447.50	-26.54
N ₅	474.88	-	-	-	474.88	0.56	0.65	-	1.21	473.67	473.84	0.17
N ₆	474.88	-	-	-	474.88	0.67	0.75	-	1.42	473.46	496.53	23.07
N ₇	474.88	-	-	-	474.88	0.50	0.54	-	1.04	473.84	463.26	-10.58
N ₈	474.88	-	-	-	474.88	0.31	0.26	-	0.57	474.31	439.11	-35.20

*SA- Soil application, NP- Nutri priming, FS- Foliar spray, RDN- Recommended dose of nutrients (N₁, N₂, N₃, N₄, N₅, N₆, N₇ and N₈ are the residual nutrient treatments of T₁, T₂, T₃, T₄, T₅, T₆, T₇ and T₈, respectively)

T₁- SA of ZnSO₄ at 20 kg ha⁻¹ (applied only in *virippu* season)

T₂- NP with Nano Zn at 0.05%

T₃- NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage

T₄- NP with ZnSO₄ at 0.5%

T₅- NP with ZnSO₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage

T₆- FS with Nano Zn at 0.05% at MT and PI stages

T₇- FS with ZnSO₄ at 0.5% at MT and PI stages

T₈- Control (RDN without application of P and Zn)

Table 49a. Effect of nano zinc nutrition on B balance sheet of rice-rice-grain cowpea system, kg ha⁻¹

Treatments	Initial B (A) (kg ha ⁻¹)	Added B (B) (kg ha ⁻¹)			Total B Input (A+B) (kg ha ⁻¹)	Crop B uptake (kg ha ⁻¹)			Total B uptake (C) (kg ha ⁻¹)	Balance		
		I Crop	II Crop	III Crop		I Crop	II Crop	III Crop		Computed balance D=(A)+(B)-C	Actual balance (E)	Net gain/loss (E-D)
N ₁	4.23	-	-	-	4.23	0.07	0.07	0.01	0.16	4.07	4.33	0.26
N ₂	4.23	-	-	-	4.23	0.12	0.11	0.01	0.24	3.99	3.98	-0.01
N ₃	4.23	-	-	-	4.23	0.14	0.15	0.01	0.30	3.93	4.51	0.58
N ₄	4.23	-	-	-	4.23	0.08	0.09	0.01	0.18	4.05	4.11	0.06
N ₅	4.23	-	-	-	4.23	0.10	0.12	0.01	0.23	4.00	4.12	0.12
N ₆	4.23	-	-	-	4.23	0.13	0.14	0.01	0.28	3.95	4.17	0.22
N ₇	4.23	-	-	-	4.23	0.09	0.10	0.01	0.20	4.03	4.20	0.17
N ₈	4.23	-	-	-	4.23	0.06	0.05	0.01	0.12	4.11	3.82	-0.29

*SA- Soil application, NP- Nutri priming, FS- Foliar spray, RDN- Recommended dose of nutrients (N₁, N₂, N₃, N₄, N₅, N₆, N₇ and N₈ are the residual nutrient treatments of T₁, T₂, T₃, T₄, T₅, T₆, T₇ and T₈, respectively)

T₁- SA of ZnSO₄ at 20 kg ha⁻¹ (applied only in *virippu* season)

T₂- NP with Nano Zn at 0.05%

T₃- NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage

T₄- NP with ZnSO₄ at 0.5%

T₅- NP with ZnSO₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage

T₆- FS with Nano Zn at 0.05% at MT and PI stages

T₇- FS with ZnSO₄ at 0.5% at MT and PI stages

T₈- Control (RDN without application of P and Zn)

Table 49b. Effect of nano zinc nutrition on B balance sheet of rice-rice-bhindi system, kg ha⁻¹

Treatments	Initial B (A) (kg ha ⁻¹)	Added B (B) (kg ha ⁻¹)			Total B Input (A+B) (kg ha ⁻¹)	Crop B uptake (kg ha ⁻¹)			Total B uptake (C) (kg ha ⁻¹)	Balance		
		I Crop	II Crop	III Crop		I Crop	II Crop	III Crop		Computed balance D=(A)+(B)-C	Actual balance (E)	Net gain/loss (E-D)
N ₁	4.23	-	-	-	4.23	0.07	0.07	0.04	0.19	4.04	3.81	-0.24
N ₂	4.23	-	-	-	4.23	0.12	0.11	0.03	0.26	3.97	4.00	0.03
N ₃	4.23	-	-	-	4.23	0.14	0.15	0.02	0.32	3.91	4.41	0.49
N ₄	4.23	-	-	-	4.23	0.08	0.09	0.03	0.20	4.03	4.11	0.08
N ₅	4.23	-	-	-	4.23	0.10	0.12	0.02	0.25	3.98	3.96	-0.02
N ₆	4.23	-	-	-	4.23	0.13	0.14	0.02	0.30	3.93	4.01	0.08
N ₇	4.23	-	-	-	4.23	0.09	0.10	0.03	0.22	4.01	3.91	-0.10
N ₈	4.23	-	-	-	4.23	0.06	0.05	0.01	0.13	4.10	3.73	-0.37

*SA- Soil application, NP- Nutri priming, FS- Foliar spray, RDN- Recommended dose of nutrients

(N₁, N₂, N₃, N₄, N₅, N₆, N₇ and N₈ are the residual nutrient treatments of T₁, T₂, T₃, T₄, T₅, T₆, T₇ and T₈, respectively)

T₁- SA of ZnSO₄ at 20 kg ha⁻¹ (applied only in *virippu* season)

T₂- NP with Nano Zn at 0.05%

T₃- NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage

T₄- NP with ZnSO₄ at 0.5%

T₅- NP with ZnSO₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage

T₆- FS with Nano Zn at 0.05% at MT and PI stages

T₇- FS with ZnSO₄ at 0.5% at MT and PI stages

T₈- Control (RDN without application of P and Zn)

Table 49c. Effect of nano zinc nutrition on B balance sheet of rice-rice-fallow system, kg ha⁻¹

Treatments	Initial B (A) (kg ha ⁻¹)	Added B (B) (kg ha ⁻¹)			Total B Input (A+B) (kg ha ⁻¹)	Crop B uptake (kg ha ⁻¹)			Total B uptake (C) (kg ha ⁻¹)	Balance		
		I Crop	II Crop	III Crop		I Crop	II Crop	III Crop		Computed balance D=(A)+(B)-C	Actual balance (E)	Net gain/loss (E-D)
N ₁	4.23	-	-	-	4.23	0.07	0.07	-	0.15	4.08	3.64	-0.45
N ₂	4.23	-	-	-	4.23	0.12	0.11	-	0.23	4.00	3.68	-0.31
N ₃	4.23	-	-	-	4.23	0.14	0.15	-	0.30	3.93	3.94	0.01
N ₄	4.23	-	-	-	4.23	0.08	0.09	-	0.17	4.06	3.56	-0.50
N ₅	4.23	-	-	-	4.23	0.10	0.12	-	0.22	4.01	3.73	-0.27
N ₆	4.23	-	-	-	4.23	0.13	0.14	-	0.27	3.96	4.08	0.12
N ₇	4.23	-	-	-	4.23	0.09	0.10	-	0.19	4.04	3.64	-0.40
N ₈	4.23	-	-	-	4.23	0.06	0.05	-	0.11	4.12	3.38	-0.74

*SA- Soil application, NP- Nutri priming, FS- Foliar spray, RDN- Recommended dose of nutrients

(N₁, N₂, N₃, N₄, N₅, N₆, N₇ and N₈ are the residual nutrient treatments of T₁, T₂, T₃, T₄, T₅, T₆, T₇ and T₈, respectively)

T₁- SA of ZnSO₄ at 20 kg ha⁻¹ (applied only in *virippu* season)

T₂- NP with Nano Zn at 0.05%

T₃- NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage

T₄- NP with ZnSO₄ at 0.5%

T₅- NP with ZnSO₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage

T₆- FS with Nano Zn at 0.05% at MT and PI stages

T₇- FS with ZnSO₄ at 0.5% at MT and PI stages

T₈- Control (RDN without application of P and Zn)

4.14 SYSTEM ECONOMICS

4.14.1 Net Returns

The effect of residual nutrients and crop sequences on net returns of rice based cropping system is presented in the Tables 50a and 50b.

The highest net returns of (₹ 173627 ha⁻¹) was observed in the treatment N₃ and the lowest net returns were observed in N₈ (₹ 11024 ha⁻¹). Among the crop sequences, the highest net returns were observed in C₂- rice-rice-bhindi sequence (₹114127 ha⁻¹) and the lowest net returns (₹ 88065 ha⁻¹) was observed in rice-rice-fallow sequence. Among the treatment combinations, n₃c₂ (₹ 182091 ha⁻¹) resulted in the highest net returns and the lowest net returns were observed in n₈c₃ (₹ 8425 ha⁻¹).

4.14.2 B:C

The B:C ratio as affected by residual nutrients and crop sequences on net returns of rice based cropping system are presented in the Tables 50a and 50b.

The treatment N₃ recorded the highest B:C ratio of 1.49 among the residual nutrients whereas, the lowest B:C of 0.91 was observed in the treatment N₈. Rice-rice-bhindi sequence resulted in the highest B:C ratio (1.47). Among the treatment combinations, the highest B:C ratio was observed in n₃c₃ (1.79) and the lowest B:C ratio was observed in n₈c₁ (0.64).

Table 50a. Effect of residual nutrients and crop sequences on economics of rice based cropping system

Treatments	Net returns (₹ ha⁻¹)	B:C
Residual nutrients		
N ₁	60991	1.09
N ₂	132539	1.37
N ₃	173627	1.49
N ₄	77355	1.14
N ₅	116348	1.28
N ₆	151394	1.40
N ₇	93897	1.19
N ₈	11024	0.91
Crop sequence		
C ₁ - Rice-rice-grain cowpea	104249	0.80
C ₂ - Rice-rice-bhindi	114127	1.47
C ₃ - Rice-rice-fallow	88065	1.42

Table 50b. Interaction effect of residual nutrients and crop sequences on economics of rice based cropping system

Treatments	Net returns (₹ ha⁻¹)	B:C
n ₁ C ₁	64948	0.75
n ₁ C ₂	80941	1.34
n ₁ C ₃	37084	1.18
n ₂ C ₁	134388	0.90
n ₂ C ₂	146876	1.62
n ₂ C ₃	116354	1.57
n ₃ C ₁	175798	0.94
n ₃ C ₂	182091	1.75
n ₃ C ₃	162990	1.79
n ₄ C ₁	80276	0.73
n ₄ C ₂	91041	1.38
n ₄ C ₃	60747	1.30
n ₅ C ₁	117627	0.81
n ₅ C ₂	128904	1.53
n ₅ C ₃	102513	1.49
n ₆ C ₁	151973	0.88
n ₆ C ₂	163153	1.66
n ₆ C ₃	139057	1.65
n ₇ C ₁	96105	0.77
n ₇ C ₂	108241	1.44
n ₇ C ₃	77346	1.36
n ₈ C ₁	12876	0.64
n ₈ C ₂	11772	1.05
n ₈ C ₃	8425	1.04

DISCUSSION

5. DISCUSSION

A field experiment titled “Nano zinc nutrition in rice based cropping systems in high phosphorus soils” was conducted at IFSRS, Karamana during 2022-2023 in the double cropped wet lands, in order to evaluate the response of rice to nano zinc in high P soils, study the residual effect of nano zinc nutrition on growth and yield of succeeding crops, study the P - Zn interactions and identification of the promising crop sequence in terms of system productivity and profitability. This chapter critically discusses the results obtained from the field experiment, supported by scientific evidences from similar studies.

5.1 EFFECT OF NANO ZINC NUTRITION ON GROWTH, YIELD ATTRIBUTES AND YIELD OF RICE

5.1.1. Growth Attributes

Application of nano zinc significantly influenced the growth parameters of rice in both *virippu* and *mundakan* seasons. Treatments involving nano zinc nutri priming at 0.05% combined with foliar application at 0.05% at maximum tillering stage (T₃) and foliar application of nano zinc at 0.05% at maximum tillering and panicle initiation stages (T₆) showed superior performance over the control and conventional soil application of zinc sulphate treatments.

Plant height is a reliable indicator of vegetative growth and overall crop vigor. In this study, the treatments involving nano zinc (T₃ and T₆) resulted in significantly taller plants throughout the crop growth stages. This could be attributed to the enhanced zinc bioavailability and uptake associated with nano zinc application. Zinc, as an essential component in tryptophan synthesis, promotes the production of Indole Acetic Acid (IAA), which directly influences cell elongation and shoot growth (Alloway, 2008a). These results align with Chandra (2020), who reported taller plants in upland rice with zinc sulphate, and with Rinthas (2021), who observed similar effects in low land rice

under adequate zinc and high phosphorus. Rameshraddy *et al.* (2017) also noted that nano zinc improved rice architecture through enhanced nutrient mobilization and uptake.

Tillering capacity is a crucial yield contributing trait in cereals. Treatments with nano zinc showed a significant increase in number of tillers m^{-2} compared to control and ZnSO_4 treatments. Nano zinc nutri priming combined with foliar application (T_3) resulted in the highest number of productive tillers, indicated improved early vigor and nutrient uptake (Plate 6 and 7). Hanif *et al.* (2024) confirmed the superior absorption of nano-sized particles into plant tissues, reinforcing the physiological advantages of nano zinc observed in the present study. The observed improvement can be attributed to zinc's role in cell division and hormonal regulation during tillering (Upadhaya *et al.*, 2022), with nano zinc offering added benefits due to its high surface area and reactivity, enabling better penetration through seed coats and root membranes and enhancing nutrient availability in early stages. This is supported by findings from Khanm (2015) in tomato and radish, and Adhikari *et al.* (2016) in maize, where nano zinc-primed seeds showed vigorous seedling growth and improved tillering.

Leaf area per hill is a critical physiological parameter that denotes canopy development and potential for photosynthetic assimilation. In this study, nano zinc nutri priming combined with foliar application (T_3) significantly enhanced leaf area values, especially during the reproductive phase. This indicated a prolonged photosynthetically active period and higher source capacity for grain filling. The increased LAI (Fig. 5.) under nano zinc treatments can be attributed to zinc's role in chlorophyll biosynthesis and membrane stability, which supports larger and healthier leaf development (Cakmak, 2008). Foliar application of nano zinc ensures rapid delivery to metabolically active mesophyll cells, which may explain the better performance of foliar treatments over soil-applied or seed-primed bulk ZnSO_4 . Similar trends were observed by Prasad *et al.* (2012) in peanut and Dasilva *et al.* (2006) in wheat, where nano zinc treatments resulted in improved leaf growth due to higher mobility and uptake. Wang *et al.* (2023) also reported

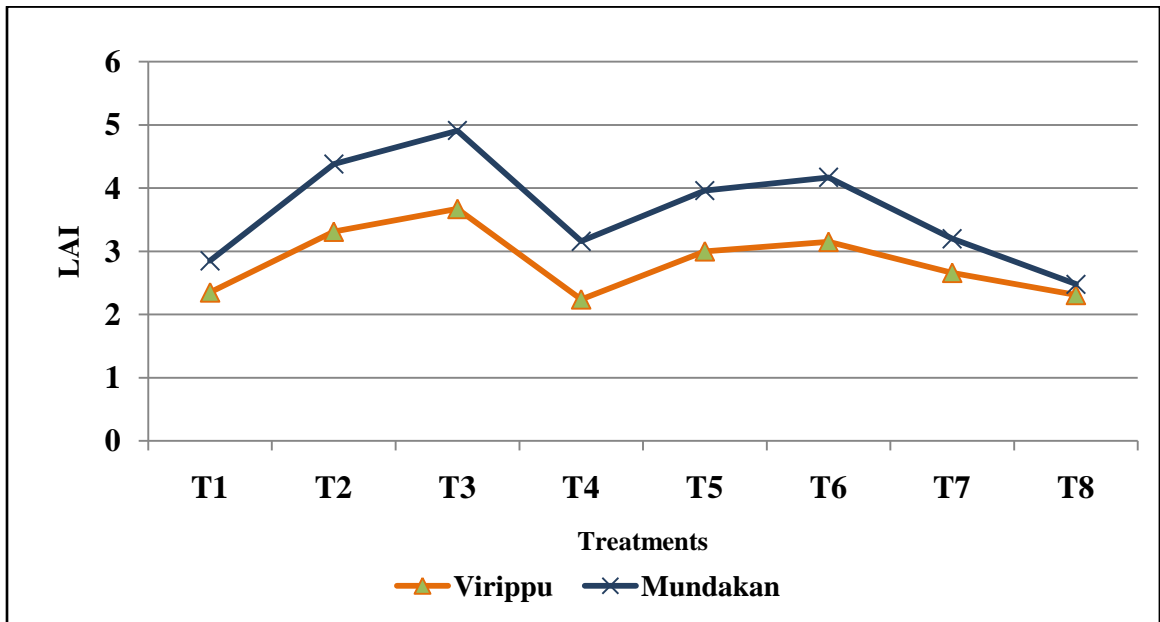


Fig. 5. Effect of nano zinc nutrition on leaf area index (LAI) at panicle initiation stage during *virippu* and *mundakan* rice

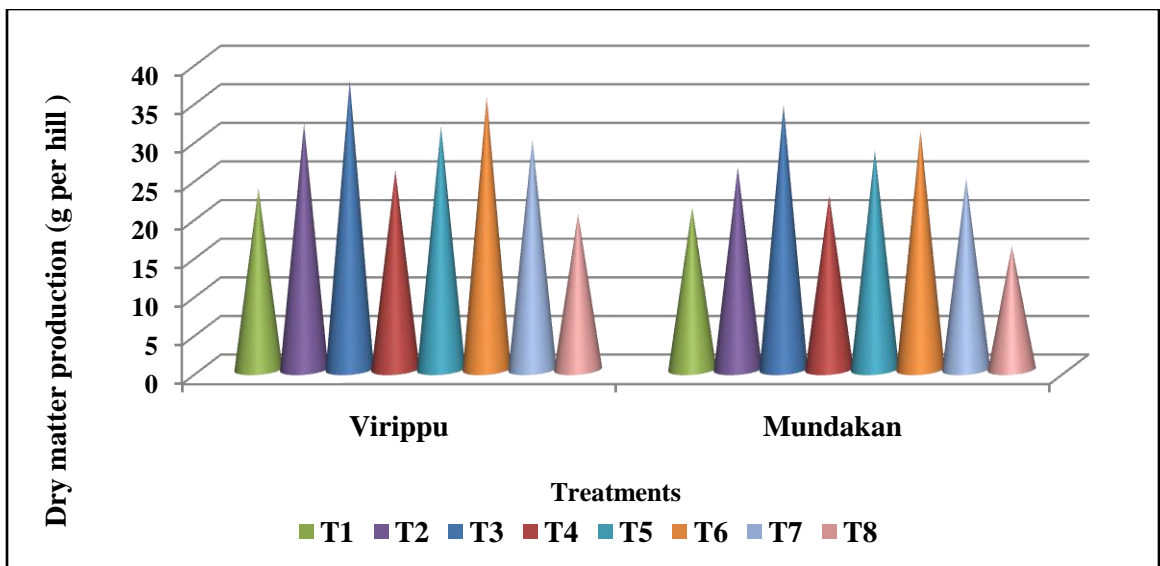


Fig. 6. Effect of nano zinc nutrition on dry matter production at harvest during *virippu* and *mundakan* rice



T₁

T₂

T₃

T₄

T₅

T₆

T₇

T₈

Plate 6. Comparison of treatments at maximum tillering stage during *virippu*



Plate 7. Comparison of treatments at maximum tillering stage during *mundakan*

that nano zinc oxide particles were primarily adsorbed onto cell surfaces and rapidly absorbed, leading to enhanced chlorophyll production and photosynthetic capacity.

The dry matter production (DMP) at harvest was significantly higher in nano zinc-treated plots across both seasons, with T₃ and T₆ showing higher values (Fig. 6.). Improved DMP can be linked to efficient nutrient uptake, particularly zinc, nitrogen and phosphorus, which are vital for cellular function and biomass production. Zinc facilitates protein synthesis and enzyme activation, which enhances photosynthate accumulation and dry matter translocation (Saleem *et al.*, 2022). This is in line with the observations of Boonchuay *et al.* (2013) and Islam (2015), who found that zinc application improved plant height and biomass in rice. Moreover, Rameshraddy *et al.* (2017) reported that nano zinc application improved the antioxidant system, metabolic activity and hormone production, resulting in higher vegetative biomass in rice and sorghum.

The enhanced growth parameters under nano zinc nutrition clearly indicated its superior efficacy over conventional zinc sources, especially in high phosphorus soils where zinc availability is often limited. The nano form, with its increased solubility, surface area, and reactivity, enables improved nutrient uptake, translocation, and physiological activity, leading to better vegetative growth and crop establishment. The present findings are well supported by earlier reports (Prasad *et al.*, 2012; Rameshraddy *et al.*, 2017; Rinthas, 2021), confirming the potential of nano zinc as a sustainable nutrient management strategy in rice-based cropping systems.

While both seasons responded positively to nano zinc application, the magnitude of response was more in *mundakan* (Plate 8 and 9). This may be attributed to lower leaching losses, reduced soil moisture variability, and more stable climatic conditions that enhance zinc retention and uptake. This observation aligns with Rinthas (2021), who reported seasonal differences in Zn transformation and availability under varying soil phosphorus levels.

5.1.2. Yield and Yield attributes

Yield formation in rice is the cumulative effects of various yield components such as productive tillers, number of grains per panicle, grain weight per panicle, sterility percentage and ultimately the grain and straw yields. In the present study, treatments involving nano zinc nutri priming at 0.05% combined with foliar application at 0.05% at maximum tillering stage (T₃) and foliar application of nano zinc at 0.05% at maximum tillering and panicle initiation stages (T₆) consistently outperformed both the control with recommended dose of nutrients without application of P and Zn (T₈) and conventional zinc sulphate treatments (Plates 10, 11, 12 and 13).

Productive tillers per hill are crucial as they directly determine the number of panicles and ultimately the grain yield in rice. Increased productive tillering is a result of improved early seedling vigor and overall plant health conferred by adequate zinc nutrition. Zinc plays a critical role in cell division and elongation, which promotes a more robust tillering pattern. This relationship has been reported in previous studies where better zinc nutrition resulted in a higher number of productive tillers (Upadhaya *et al.*, 2022).

The panicle, as the primary reproductive structure, is directly influenced by zinc levels. In the current study, nano zinc-treated plants exhibited a greater number of grains per panicle as well as increased grain weight per panicle. The increased grain number is likely due to improved inflorescence development and spikelet fertility, supported by zinc's role in auxin synthesis and enzyme function (Rajput *et al.*, 2021). The higher grain weight per panicle might be due to efficient translocation of assimilates, which is crucial for grain filling which is directly related to the lower sterility percentage. Zinc's involvement in regulating carbohydrate metabolism and storage emphasizes its role in ensuring proper grain filling. Enhanced enzyme activities related to starch synthesis under optimal zinc nutrition likely play an important role in maintaining grain weight (Suganya *et al.*, 2020).

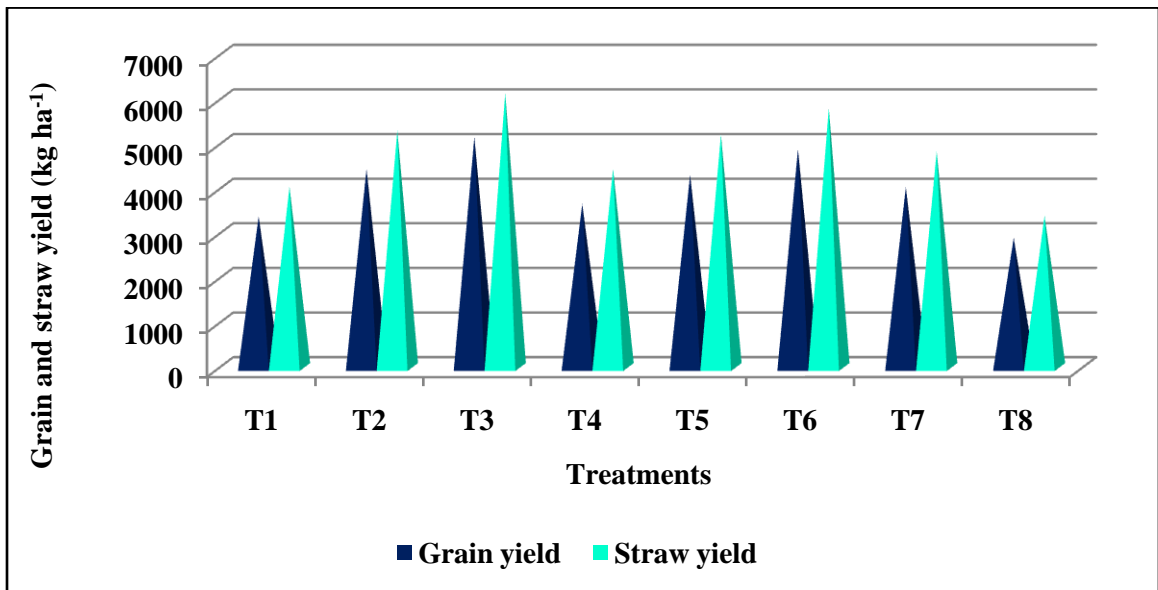


Fig. 7. Effect of nano zinc nutrition on pooled mean of grain and straw yield of rice, kg ha⁻¹



Plate 8. Comparison of treatments at panicle initiation stage during *virippu*



Plate 9. Comparison of treatments at panicle initiation stage during *mundakan*

Although the thousand grain weight did not show significant differences across treatments, the overall improvement in grain number and panicle weight under nano zinc applications contributes significantly to the final yield.

The grain yield in T₃ was improved by 78.14 per cent increase over control and that in T₆ by 68.72 per cent over control during both the seasons in pooled analysis. This can be attributed to higher nutrient use efficiency associated with the nano formulation (Fig. 7.). Nano zinc, due to its small particle size and increased reactivity, ensured better zinc availability in high phosphorus soils, where conventional ZnSO₄ would otherwise precipitate as insoluble compounds. This enhanced bioavailability supports the vital functions of zinc in protein synthesis, enzyme activation, and hormonal regulation (Cakmak, 2000; Hansch and Mendel, 2009). Continuous supply of zinc in nano formulations positively influenced yield formation as a result of enhanced translocation of carbohydrates from source organs (leaves) to the grain, thus increasing the sink strength and final grain filling Rameshraddy *et al.* (2017). Similar studies where enhanced Zn uptake translated into a significant improvement in grain yield of rice by 11 per cent over control were reported by Akmal *et al.* (2022). Zhang *et al.* (2025b) also reported the same in rice.

Straw yield also improved significantly under nano zinc treatments. Increased vegetative biomass, through enhanced plant height, tillering, and leaf development, naturally contributes to higher straw yield. The better developed root and shoot systems under nano zinc treatments increase the overall assimilate accumulation during the crop growth period. This accumulated biomass is crucial not only for yield formation but also for subsequent soil fertility, as crop residues often contribute to organic matter and residual nutrient levels Rout (2020). Enhanced grain and straw yield with the application of ZnO nano particles was also observed by Mi *et al.* (2023).

While both seasons performed well with nano zinc applications, the response in the *mundakan* season was comparatively high. This seasonal variation may be due to

differences in environmental conditions such as temperature, humidity, rainfall and soil moisture, which affect zinc mobility and uptake. In more stable growing conditions (as in *mundakan*), nano zinc remains available for longer periods, ensuring a continuous supply during critical yield formation periods.

5.2 INTERACTION EFFECT OF P AND Zn IN HIGH P SOIL WITH RESPECT TO NUTRIENT UPTAKE AND NUTRIENT USE EFFICIENCY OF RICE

5.2.1. Nutrient uptake

Nutrient uptake is vital for plant growth, development, and yield formation. Nutrient uptake by crops depends on both the nutrient content in dry matter and the total dry matter produced. Higher uptake results from either increased nutrient concentration or greater biomass. Nutrient content is influenced by factors like soil availability, root absorption efficiency, photosynthetic activity, nutrient mobility and translocation within the plant, and application method. In the present study the nutrient dynamics of N, P, K, Ca and Zn were studied with respect to the Zn application in high P soils at panicle initiation and at harvest in rice during *virippu* and *mundakan* seasons (Fig. 8, 9, 10 and 11). The superior performance of treatments T₃ (Nano zinc nutri priming at 0.05% combined with foliar application at 0.05% at maximum tillering stage), T₂ (Nutri priming nano zinc at 0.05 %) and T₆ (Foliar applications of nano zinc at 0.05% at maximum tillering and panicle initiation) at panicle initiation stage during both the seasons showed the importance of early stage nutrient acquisition and its direct influence on differentiation and development of the reproductive structures. Better performance of treatments T₃ and T₆ at harvest across both the seasons explained the role of nano-formulated fertilizers in improving nutrient use efficiency, increased accumulation and translocation of nutrients especially in high-P soils where nutrient interactions can be antagonistic.

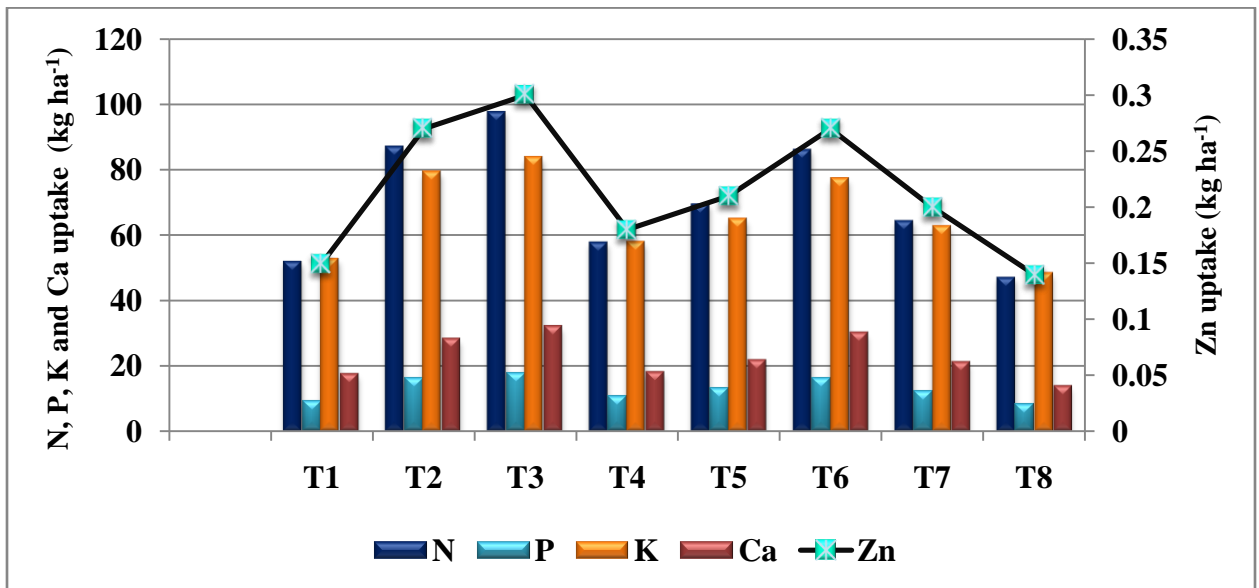


Fig 8. Effect of nano zinc nutrition on nutrient uptake in rice at panicle initiation stage during *virippu*, kg ha⁻¹

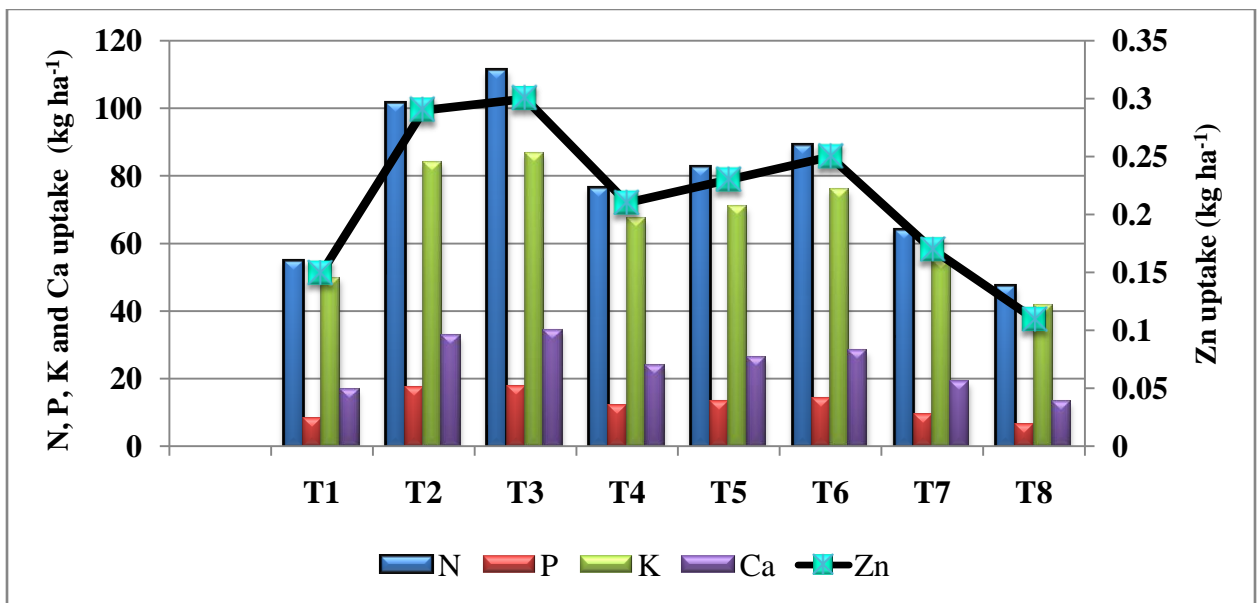


Fig. 9. Effect of nano zinc nutrition on nutrient uptake in rice at panicle initiation during *mundakan*, kg ha⁻¹

5.2.1.1. Nitrogen Uptake

Enhanced nitrogen uptake under nano zinc treatments (T₃, T₂ and T₆) at panicle initiation can be attributed to zinc's role in improving root system architecture and increasing nitrate reductase activity. Zinc activates enzymes associated with N metabolism and assimilation, such as glutamate dehydrogenase and asparaginase, which are essential for the formation of amino acids and proteins (Fageria *et al.*, 2002). The early availability of zinc through priming and foliar spray may have supported root proliferation and enhanced N uptake efficiency, which aligns with the findings of Chandra (2020) and Islam (2015) in rice. At harvest, T₆ surpassed T₂ in nutrient uptake. This might be due to the availability of nano Zn nutrients applied during the later stages through foliar application in T₆, which may have provided the plants with a continuous nutrient supply, indicating better translocation of nutrients from vegetative to reproductive tissues. Huang *et al.* (2022) also reported the similar results.

5.2.1.2. Phosphorus Uptake

Phosphorus (P) uptake in rice is often influenced by the availability and interaction of other nutrients, particularly zinc (Zn). In the present study, at the panicle initiation stage, treatments involving nano zinc particularly T₃, T₂ and T₆ reported better uptake compared to conventional zinc sulphate treated plots. This improvement can be attributed to the enhanced bioavailability of Zn in nano particle form, which may have positively influenced root morphology (increased root surface area through fine root proliferation), phosphatase activity, and microbial mobilization of P in the rhizosphere. Moreover, nano Zn's slow and sustained release may have allowed a more regulated nutrient environment at the root-soil interface, minimizing Zn-induced P precipitation or immobilization. At harvest, treatments T₃ and T₆ continued to outperform other treatments, including T₂. This shift underscores the importance of sustained Zn supply during the crop's reproductive stages. In T₂, no supply of zinc nutrition in later stages would have limited further improvements in P uptake.

Despite high P levels in the experimental soil, nano zinc applications enhanced P uptake, likely through spatial-temporal partitioning of Zn and P at the root interface, phosphorus is primarily taken up during early growth stages and tends to accumulate in upper soil layers, while zinc is needed more during later stages like panicle initiation and is often available in deeper or localized zones. Nano zinc application, especially through stage-specific foliar treatments like in T₃ and T₆, helps spatially and temporally separate Zn and P uptake, reducing antagonism and enhancing nutrient efficiency. The similar results were reported by Lahari *et al.* (2021), Haihan *et al.* (2024) and Chandana *et al.* (2021) in their experiments in rice.

5.2.1.3. Potassium Uptake

Potassium (K) is a vital macronutrient in rice cultivation, playing a crucial role in enzyme activation, osmoregulation, and photosynthesis. In high phosphorus (P) soils, nutrient imbalances can impede K uptake. In the present study, treatments involving application of nano zinc (T₃, T₂ and T₆) improved K uptake at the panicle initiation stage compared to conventional zinc sulphate treatments and control. This enhancement can be attributed to the role of Zn in maintaining membrane integrity and stimulating ATPase activity, which facilitates the active transport of K ions into plant cells. Foliar application of nano Zn ensures timely availability of Zn during critical growth stages, thereby supporting efficient K uptake. At the harvest stage, the prolonged supply of Zn through foliar applications in T₃ and T₆ likely contributed to continuous support for K transport mechanisms during the reproductive phase. These findings align with previous research indicating that foliar application of nano Zn enhances nutrient uptake in rice. Dharmvir *et al.* (2024) and Verma *et al.* (2024) also reported that foliar application of nano Zn, along with nano urea and nano potash, significantly increased available K in the soil, leading to improved nutrient uptake by rice plants. Similarly, Rout (2020) observed that foliar application of nano Zn at 14 and 28 days after transplanting resulted in higher grain and straw yields, suggesting improved nutrient assimilation, including K.

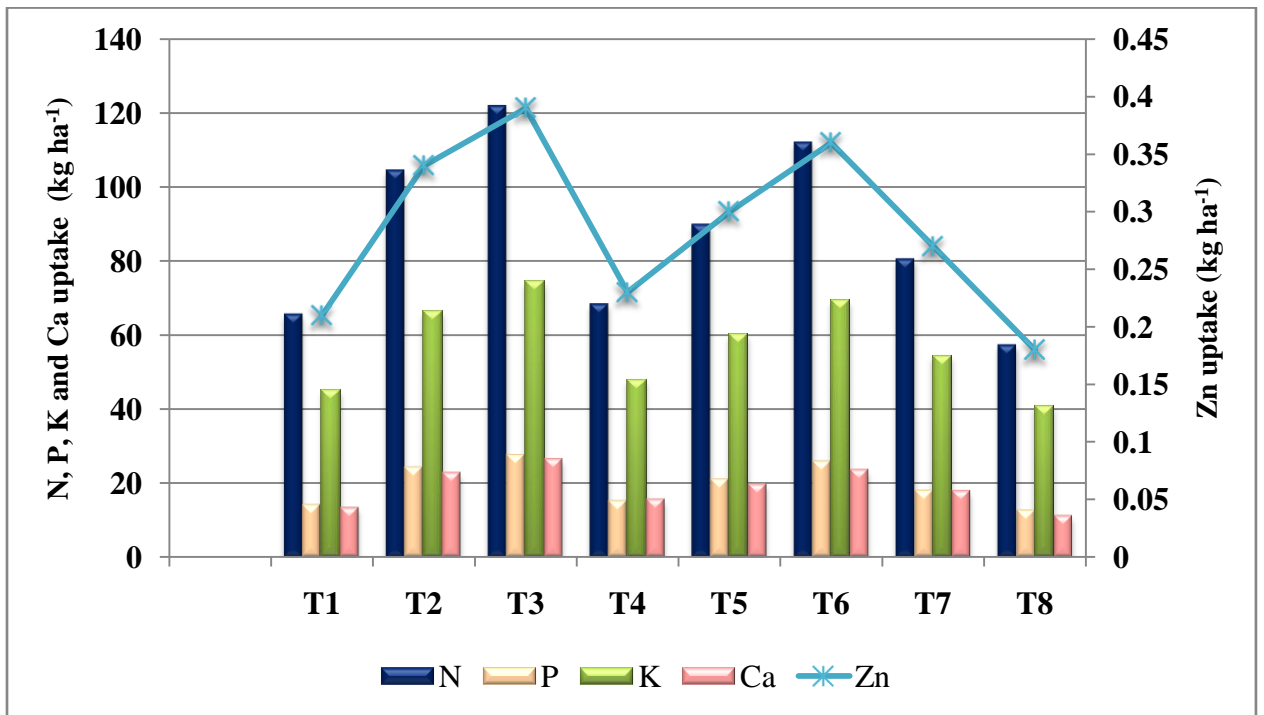


Fig. 10. Effect of nano zinc nutrition on nutrient uptake in rice at harvest stage during *virippu*, kg ha⁻¹

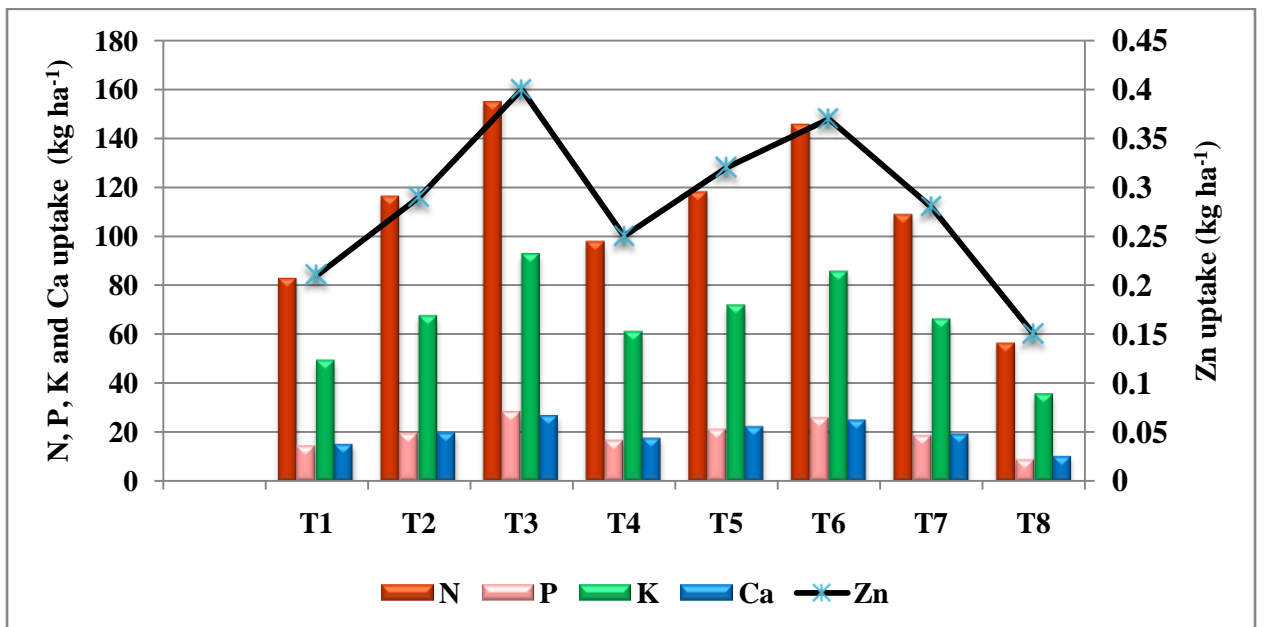


Fig. 11. Effect of nano zinc nutrition on nutrient uptake in rice at harvest stage during *mundakan*, kg ha⁻¹

5.2.1.4. Calcium uptake

Calcium (Ca) is an essential secondary nutrient required for various plant physiological functions, including cell wall structure, membrane stability, and signal transduction. In high phosphorus (P) soils, the availability of Ca can be limited due to nutrient imbalances and the formation of insoluble calcium-phosphate complexes, which restricts Ca absorption by plant roots. In this study, treatments involving application of nano zinc (T₃, T₂ and T₆) improved Ca uptake at the panicle initiation stage. Zn influences Ca uptake by maintaining membrane integrity and enhancing root cellular functions. It activates key enzymes like ATPases, which are involved in active ion transport across cell membranes. By promoting membrane stability, Zn helps to maintain efficient ion channels and transport systems, allowing better uptake of divalent cations such as calcium (Dang *et al.*, 2024). Moreover, zinc contributes to calcium-binding protein activity, which further supports the transport of Ca into plant cells. These proteins help in mobilizing calcium within the root system and transferring it to the shoot, where it is used for structural and signaling purposes. At harvest, treatments such as T₃ and T₆, which included later-stage foliar Zn applications, maintained higher Ca levels, likely due to prolonged Zn availability supporting Ca transport during the reproductive phase. From these results, it can be understood that nano Zn application not only mitigates the antagonistic effects of high phosphorus on calcium availability but also promotes spatial and temporal partitioning of Ca uptake, enhancing its translocation and contributing to improved calcium use efficiency and overall plant performance in high P soils. Similar results, where application of zinc improved the uptake of the calcium were reported by Haleema *et al.* (2024) in tomato.

5.2.1.5. Zinc Uptake

Zinc (Zn) is a vital micronutrient for rice, playing an important role in several physiological processes such as enzyme activation, protein synthesis, and hormone regulation. However, in soils with high phosphorus (P), zinc uptake is often reduced

because of the formation of insoluble zinc-phosphate complexes, which limit its availability to plant roots.

In this study, nano zinc treatments (T₃, T₂, and T₆) resulted in improved zinc uptake compared to conventional zinc sulfate (ZnSO₄) treatments. This improvement may be attributed to the reduced tendency of nano zinc to form insoluble Zn-P complexes, its enhanced solubility, improved root penetration and cellular uptake due to its nano scale size, better translocation to shoots and grains, and its positive influence on root physiology and rhizosphere activity, all of which collectively enhance zinc bioavailability and uptake efficiency. The early supply of Zn in T₃ and T₂ through seed priming helped in better zinc nutrition during the early stages of growth, which is crucial for root development and tillering. At the harvest stage, treatments like T₃ and T₆ maintained higher Zn uptake, likely because they provided a continued supply of zinc during the later stages of plant growth, especially during grain filling. Studies have shown that ZnO NPs can increase zinc content in milled rice by 20.46-41.09 per cent (Elshayb *et al.*, 2021) and in brown rice by 13.5-39.4 per cent (Yang *et al.*, 2021). They also help to move more zinc into the edible part of the grain by reducing its retention in the outer, non-edible hulls (by upto 45 per cent), due to its better transport through the xylem and more sustained release of zinc during grain formation (Mi *et al.*, 2023). Nano coated urea using ZnO NPs improved zinc assimilation by 30-40 per cent compared to regular urea (Dharmvir *et al.*, 2024).

5.2.2. Nutrient use efficiency

Agronomic efficiency, physiological efficiency, and apparent recovery efficiency are crucial indices that help understand how effectively applied nutrients contribute to crop productivity and nutrient use (Alloway, 2008a; Fageria *et al.*, 2010). In this study, phosphorus and zinc efficiencies were assessed separately to reflect their individual roles.



T₁

T₂

T₃

T₄

T₅

T₆

T₇

T₈

Plate 10. Comparison of treatments at flowering stage during *virippu*



Plate 11. Comparison of treatments at flowering stage during *mundakan*

Agronomic Efficiency

For phosphorus (AE_P), the highest agronomic efficiency was observed in T_3 (nutri priming with nano zinc + foliar spray at maximum tillering), recording 94.29 kg grain yield kg^{-1} P in *virippu* and 58.87 kg grain yield kg^{-1} P in *mundakan*. This superior response can be attributed to better root development and phosphorus uptake stimulated by improved zinc nutrition (Raliya *et al.*, 2016). In contrast, the lowest AE_P was recorded in T_1 (Soil application of $ZnSO_4$), possibly due to less synergistic interaction between soil-applied zinc and phosphorus uptake under field conditions.

For zinc (AE_{Zn}), T_2 (Nutripriming with nano zinc alone at 0.05%) recorded the highest efficiency (30116.45 kg grain yield kg^{-1} Zn in *virippu* and 31780.00 kg grain yield kg^{-1} Zn in *mundakan*), highlighting the rapid and efficient zinc assimilation through seed priming. Meanwhile, T_1 showed negligible AE_{Zn} values, indicating poor effectiveness of soil-applied $ZnSO_4$ (Alloway, 2008a).

Physiological Efficiency

In terms of physiological efficiency for phosphorus (PE_P), T_1 was observed with higher value of 160.48 kg grain yield kg^{-1} P uptake (*virippu*) and 162.08 kg grain yield kg^{-1} P (*mundakan*) was observed in T_4 . The lowest PE_P was observed in T_4 during *virippu* and in T_3 during *mundakan*. Although T_3 and T_6 were the most effective treatments in improving overall grain yield and nutrient uptake, the highest PE_P was observed in T_1 during *virippu* and in T_4 during *mundakan*. This could be attributed to moderate P uptake coupled with relatively high yield in these treatments, resulting in a higher grain yield per unit of phosphorus absorbed. In contrast, treatments such as T_3 and T_6 enhanced phosphorus uptake substantially, which, while contributing to higher yields, resulted in comparatively lower PE_P values due to a higher denominator in the efficiency calculation. Thus, a higher PE_P does not necessarily reflect higher yield but rather indicates greater efficiency in converting absorbed phosphorus into economic yield.

Regarding zinc (PE_{Zn}), T_1 treatment showed the highest PE_{Zn} in *virippu* and T_4 in *mundakan*, implying higher PE_{Zn} does not necessarily reflect higher yield but rather indicates greater internal efficiency in converting absorbed zinc into economic yield.

Apparent Recovery Efficiency

For phosphorus (ARE_P), the maximum recovery was seen in T_3 (0.63 kg increase in P uptake per kg P applied in *virippu* and 0.45 kg increase in P uptake per kg P applied in *mundakan*), demonstrating better phosphorus absorption facilitated by improved plant vigor through nano zinc treatments. T_1 exhibited minimal ARE_P values, further suggesting nutrient immobilization in soil (Fageria *et al.*, 2010).

For zinc (ARE_{Zn}), T_2 indicated the highest recovery (3.20 kg increase in Zn uptake per kg Zn applied in *virippu* and 2.81 kg increase in Zn uptake per kg Zn applied in *mundakan*), emphasizing the enhanced zinc availability and uptake from nano priming. T_1 had nearly zero ARE_{Zn} , underlining the inefficiency of soil $ZnSO_4$ application.

Nano zinc application enhanced phosphorus and zinc use efficiency in rice by stimulating root development and enzyme activity for better phosphorus metabolism, while its high surface area improved zinc absorption and translocation. Consequently, nano zinc treatments outperformed conventional $ZnSO_4$, leading to higher nutrient use efficiencies across seasons. Similar results were observed in the experiments conducted by Jalal *et al.* (2023) in wheat, in rice Shruthi *et al.* (2023) in maize and Dharmvir *et al.* (2024).

5.3 EFFECT OF RESIDUAL NUTRIENT STATUS ON GROWTH AND YIELD OF SUCCEEDING CROPS.

The residual nutrient status from previous rice crop significantly impacted the growth and yield of succeeding crops *viz.*, grain cowpea and bhindi. The residual nutrient



T₁

T₂

T₃

T₄

T₅

T₆

T₇

T₈

Plate 12. Comparison of treatments at harvest stage during *virippu*

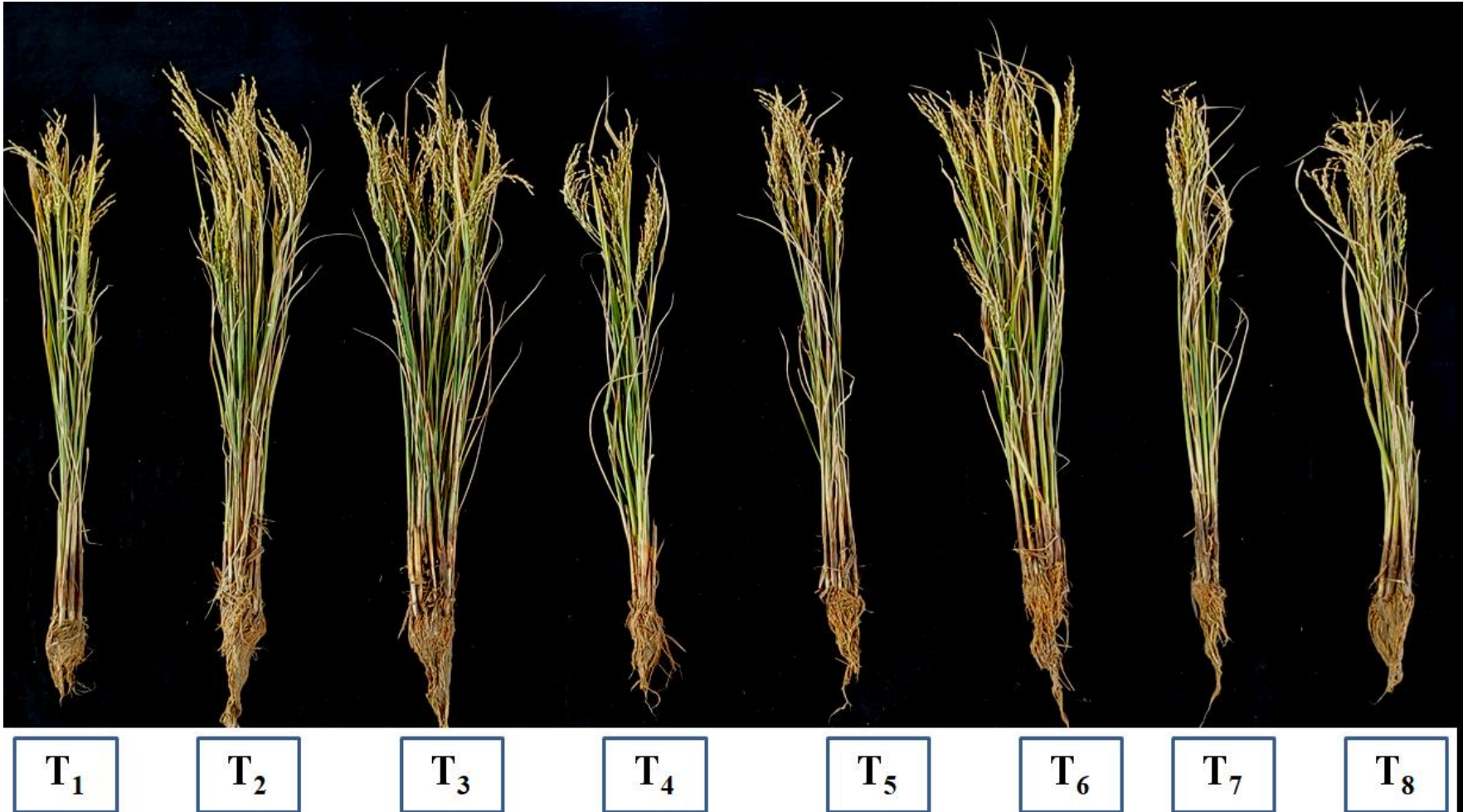


Plate 13. Comparison of treatments at harvest stage during *mundakan*

application of soil-applied zinc (N_1 treatment), which was only applied in the *virippu* season, showed the highest growth and yield attributes in grain cowpea and bhindi.

Grain cowpea, under N_1 , exhibited superior growth parameters, including plant height (81.03 cm), number of branches (3.67 per plant), dry matter production (38.90 g per plant), and seed yield (855 kg ha⁻¹), due to better zinc availability that was slowly released in the subsequent seasons. This sustained nutrient supply, despite the high phosphorus levels in the initial rice season, was sufficient to boost the growth of cowpea growth. In contrast, treatments with lower zinc availability, such as N_8 (control), showed the least growth and yield parameters. Cowpea under N_8 produced significantly lower seed yield (562 kg ha⁻¹), showing that residual zinc had a limited impact when phosphorus and other nutrients were insufficient. The reduced performance of N_8 might be attributed to the lack of available phosphorus and zinc as the treatment did not receive the P and Zn for earlier two seasons, residual zinc in soil would have been quickly immobilized by the high phosphorus, thereby limiting zinc uptake.

Bhindi followed a similar trend, benefiting from the residual nutrients left by the soil applied zinc treatments. N_1 treated soil showed a marked improvement in plant height (96.30 cm) and number of branches (3.67), contributing to a higher fruit yield per plant (299.37 g) and an overall fruit yield of 1945 kg ha⁻¹. This indicates that bhindi utilized the residual zinc and other nutrients effectively, aided by a decrease in phosphorus over the seasons, which reduced the antagonistic effect on zinc uptake. The harvest index for bhindi in N_1 was 0.51 and it indicated that a higher proportion of biomass was allocated to fruit production. In N_8 , bhindi showed less growth and yield parameters. Plant height (64.00 cm) and fruit yield (932 kg ha⁻¹) were significantly lower in comparison to N_1 , reflecting that the lack of sufficient residual zinc due to high phosphorus fixation limited bhindi's growth.

To conclude soil applied zinc did not benefit the preceding rice crops, but the residual effect in the succeeding season (third season) was evident in both cowpea and bhindi. The decreased phosphorus levels over time allowed the residual zinc to become

more available, thereby improving growth and yield. Conversely, the absence of sufficient zinc in the control treatment (N₈) showed the limitation of residual zinc when nutrients were not effectively replenished. This highlights the importance of considering long-term nutrient management strategies, including proper zinc application, to sustain productivity in multi-crop rotations. Similar results where the residual effect of Zn application to wheat benefitted the subsequent tomato and maize in yield and uptake of nutrients was observed by Shrestha *et al.* (2021). Benefits of the soil applied zinc on the maize planted two seasons after its application was observed by Botoman *et al.* (2023). The results were also in line with Kumari *et al.* (2017) in rice-wheat system; Veni *et al.* (2019) in wheat.

5.4 EFFECT OF RESIDUAL NUTRIENT STATUS AND CROP SEQUENCE ON SOIL ENZYME ACTIVITY, AVAILABLE NUTRIENTS AND NUTRIENT BALANCE OF THE SYSTEM

Soil nutrient status and biological activity in soil are the critical indicators of soil fertility and sustainability in cropping systems. Residual nutrient status, influenced by previous fertilization practices and crop uptake, plays a pivotal role in determining the availability of nutrients to succeeding crops. Additionally, crop sequence significantly impacts soil health through differential root activity, residue quality, and biological interactions, particularly in systems containing legumes and non-legumes like grain cowpea and bhindi.

In the present study, the residual effects of various zinc application treatments [T₁- SA of ZnSO₄ at 20 kg ha⁻¹ (applied only in *virippu* season), T₂- NP with Nano Zn at 0.05%, T₃- NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage, T₄- NP with ZnSO₄ at 0.5%, T₅- NP with ZnSO₄ at 0.5% + FS with Nano Zn at 0.05% at MT stage, T₆- FS with Nano Zn at 0.05% at MT and PI stages, T₇- FS with ZnSO₄ at 0.5% at MT and PI stages, T₈- Control (RDN without application of P and Zn)] applied over two consecutive rice growing seasons (*virippu* and *mundakan*) were assessed during the third season under different crops like grain cowpea and bhindi to understand their effect on crop sequence *i.e.*, rice-rice-grain cowpea, rice-rice-bhindi and rice-rice-fallow. The

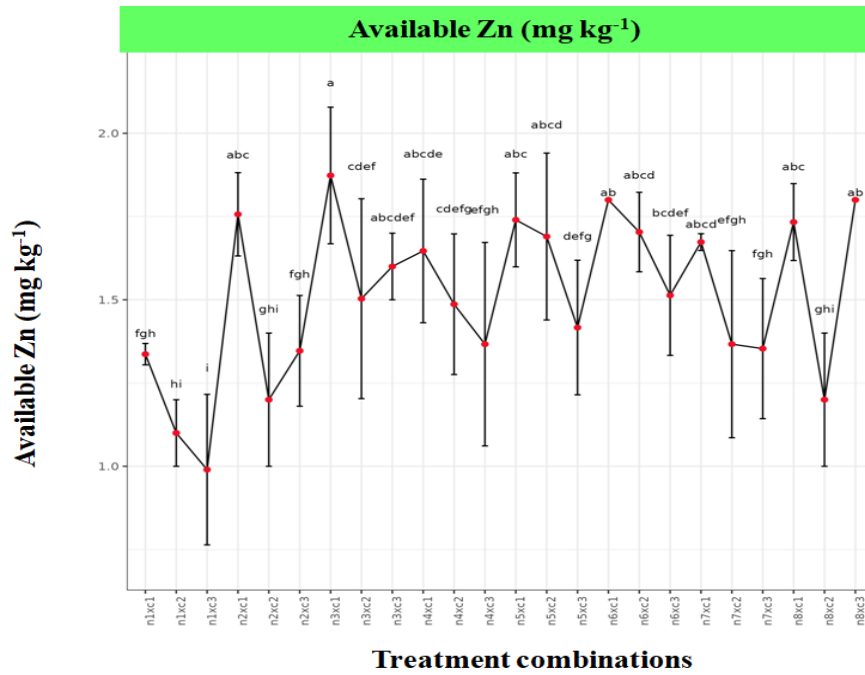


Fig. 12. Interaction effect of residual nutrients and crop sequences on available zinc status of the soil after the experiment

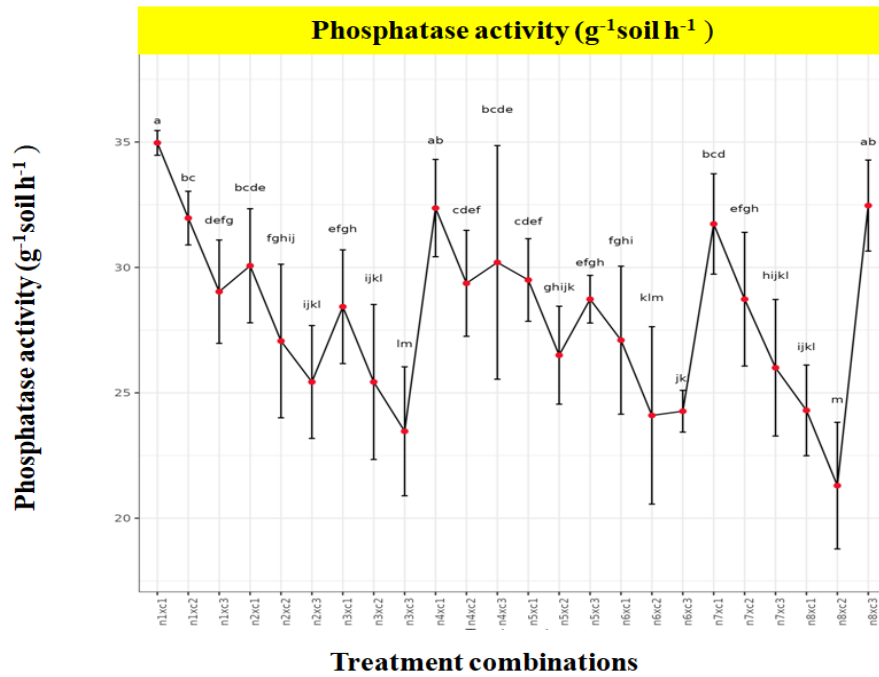


Fig. 13. Interaction effect of residual nutrients and crop sequences on phosphatase activity after the experiment

effect of residual nutrient status and crop sequence on soil enzyme activities, available macronutrients (N, P, K, Ca) and micronutrients (Zn, Fe, B), and overall nutrient balance of the system are discussed below.

5.4.1 Enzyme Activity

Soil biological activity, particularly enzyme activity, is a critical determinant of soil fertility and nutrient cycling, reflecting the metabolic potential of the microbial community. Among soil enzymes, dehydrogenase serves as a reliable indicator of total microbial activity due to its role in oxidative processes (Nannipieri *et al.*, 2003). In the present study, soils under residual nutrient treatments N₃ and N₆ exhibited the highest dehydrogenase activity (56.25 and 53.01 g⁻¹ soil 24 h⁻¹, respectively), highlighting the positive impact of nano zinc applications on microbial processes. Enhanced activity could be attributed to increased microbial proliferation through improved organic matter turnover and micronutrient availability, as also observed by Adhikari *et al.* (2016) and Rameshraddy *et al.* (2017).

Crop sequence further influenced dehydrogenase levels, with the rice-rice-grain cowpea (C₁) sequence showing the highest activity. This can be linked to the leguminous nature of cowpea, which enriches the soil through nitrogen fixation and organic inputs, thereby stimulating microbial growth and enzymatic functions (Aseri *et al.*, 2008; Wang *et al.*, 2017).

Soil phosphatase activity is essential for organic phosphorus mineralization and nutrient cycling (Richardson *et al.*, 2009a). In the present study, phosphatase activity was significantly influenced by residual nutrient status and its interaction with crop sequence (Fig. 14.), while crop sequence alone had no significant effect. Among the residual treatments, N₁ had the highest phosphatase activity (31.99 g⁻¹ soil h⁻¹), indicating that conventional soil application of ZnSO₄ (N₁) and nutri priming with ZnSO₄ (N₄) maintained higher microbial phosphorus mineralizing potential. In contrast, the lowest phosphatase activity was recorded under N₆ (25.12 g⁻¹ soil h⁻¹). Similar observations were reported by Tekam *et al.* (2024) in soybean-wheat cropping system. The highest

phosphatase activity was observed in the n_1c_1 combination ($34.97 \text{ g}^{-1} \text{ soil h}^{-1}$), which is the combination of residual nutrient status of soil applied ZnSO_4 with a legume-based crop sequence (grain cowpea) enhances soil biological functioning. Legume crops have been reported to stimulate microbial enzyme activities through increased root exudation and nitrogen enrichment (Sinsabaugh *et al.*, 2008; Deng and Tabatabai, 1997). Phosphatase activity in soils is closely linked to phosphorus availability, often exhibiting an inverse relationship. When inorganic phosphorus is abundant, plants and microorganisms reduce the synthesis and secretion of phosphatase enzymes, as the need to mineralize organic phosphorus diminishes. This phenomenon, known as inorganic phosphorus-repressible phosphatase activity (Manzoor *et al.*, 2022). Supporting this, Bassett *et al.* (2022) conducted a meta-analysis which found that monoesterase activity decreased by 23 per cent in soils with high inorganic P levels, indicating suppression of phosphatase activity under P-sufficient conditions.

5.4.2 Available Nutrients after the Experiment

Available nitrogen in soil was significantly influenced by residual nutrient treatments and crop sequences. Among the treatments, N_6 ($339.25 \text{ kg ha}^{-1}$) and N_5 ($338.43 \text{ kg ha}^{-1}$) resulted in the highest available nitrogen, attributed to the positive effects of nano zinc-based applications in enhancing nutrient use efficiency and stimulating microbial activity, thus improving nitrogen mineralization (Adhikari *et al.*, 2016; Dimkpa *et al.*, 2016; Raliya *et al.*, 2016). Similar results were reported by Beig *et al.* (2023) in wheat and Shruthi *et al.* (2023) in maize. Higher available nitrogen in rice-rice-grain cowpea sequence further highlighted the beneficial role of legumes in enriching soil nitrogen through biological nitrogen fixation and improved nutrient cycling (Kebede, 2021).

Residual phosphorus availability was significantly influenced by both the residual nutrient status and crop sequence in the present study (Fig. 12.) The treatment N_3 had the highest available phosphorus (18.33 kg ha^{-1}). Similarly, the rice-rice-grain cowpea sequence had superior P levels compared to the other crop sequences. This might be because nano zinc application improves phosphorus mobilization and availability in the

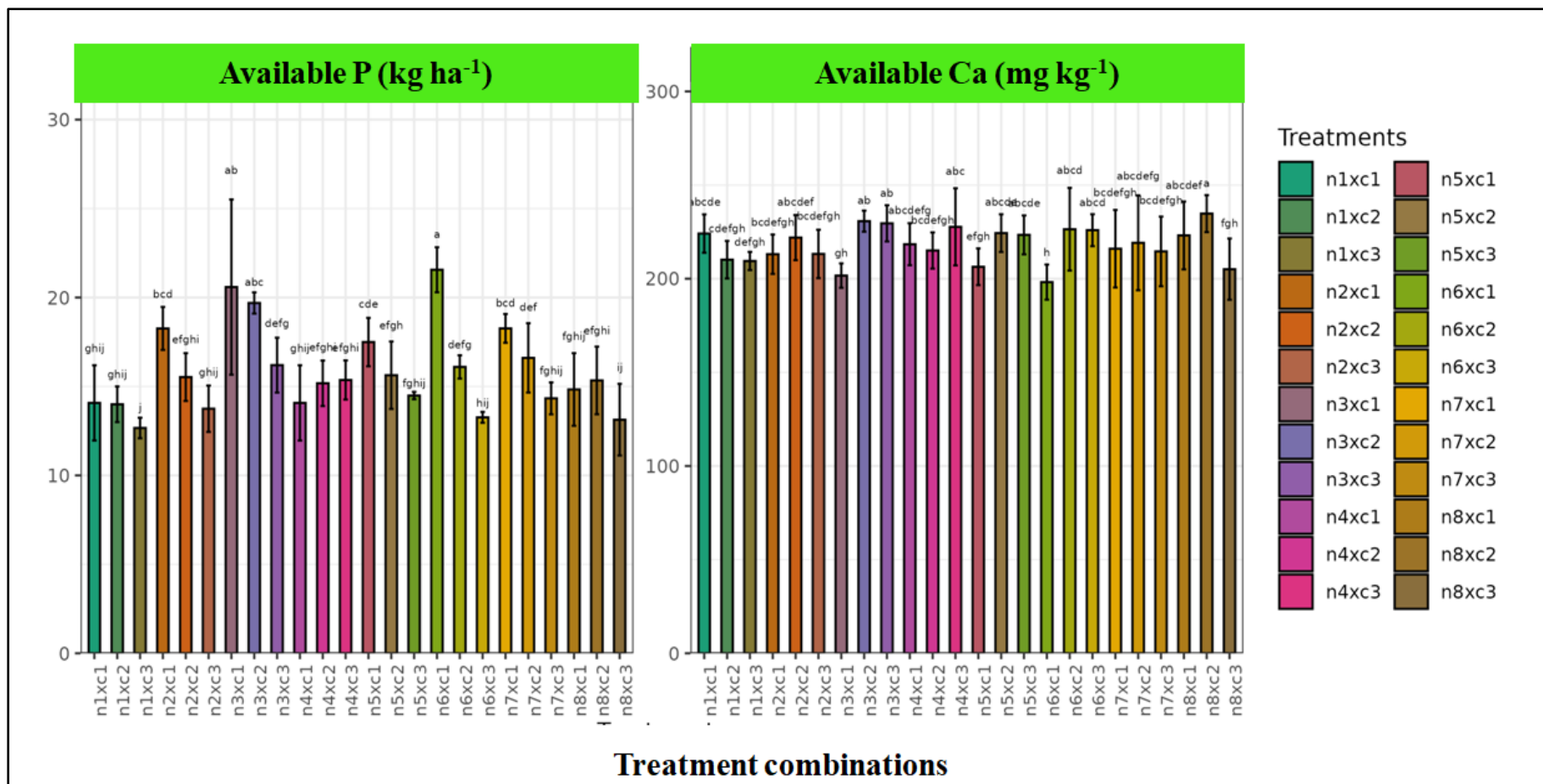


Fig. 14. Interaction effect of residual nutrients and crop sequences on available phosphorus and calcium status of the soil after the experiment

soil, aligning with the findings of Nakhate *et al.* (2024) who reported that nano zinc applications minimized nutrient antagonism and enhanced P uptake in cereals. Similar results were also observed in wheat (Jalal *et al.*, 2023). Furthermore, the significant interaction effect observed, particularly in combinations such as n₆c₁, highlights the synergistic advantage of integrating efficient zinc application with leguminous crops. Legumes, through their biological nitrogen fixation and root exudation, are known to stimulate microbial activity and organic acid production, thereby facilitating greater phosphorus solubilization (Richardson *et al.*, 2009b; Shruthi *et al.*, 2023).

Enhancement in residual phosphorus availability, particularly in treatments involving nano zinc applications, can be attributed to the synergistic effects of nano zinc on phosphorus mobilization and uptake. Balanced nutrient cycling under nano zinc regimes may have contributed to better maintenance of soil cation exchange capacity (CEC), facilitating K retention. This aligns with findings from Lahari *et al.* (2021), who reported that foliar application of nano zinc in rice significantly increased phosphorus availability in the soil. Similarly, Nakhate *et al.* (2024) demonstrated that foliar application of nano zinc in wheat under zinc-sufficient soils enhanced the availability of phosphorus.

In the present study, the available calcium (Ca) content in the soil was not significantly influenced by the residual nutrient treatments or crop sequences individually but exhibited a significant variation due to their interaction (Fig. 12.). Notably, the highest available Ca was observed in the n₈c₂ interaction (control treatment without P and Zn application under rice-rice-bhindi sequence), recording 234.74 mg kg⁻¹ available Ca. The elevated Ca availability in this combination may be attributed to lower nutrient uptake demand by crops grown without additional phosphorus and zinc inputs, leading to a relative accumulation of exchangeable calcium in the soil. Additionally, the bhindi crop, being less exhaustive for calcium compared to legumes like cowpea, may have contributed to higher residual Ca levels. According to White and Broadley (2003), calcium availability and retention in soils are strongly influenced by plant uptake rates and soil cation exchange dynamics, where reduced competition from other cations can favor higher soil Ca status. Furthermore, Assmann *et al.* (2017) reported that in nutrient-

depleted systems, non-leguminous crops often leave behind higher residual calcium levels due to lower biological demand and slower cycling of base cations, supporting the findings observed in this study.

The present study clearly demonstrated that soil-applied zinc remained available and accessible to crops during the third season. Treatments involving nano zinc formulations (N₆, N₃ and N₅) exhibited higher available Zn levels, suggesting efficient residual persistence. However, the overall trend indicated that although zinc was initially available, its concentrations had begun to decline, implying substantial plant uptake during the third cropping season. Particularly, conventional ZnSO₄ soil-applied treatment (N₁) showed the lowest residual zinc availability, likely because a significant portion had already been absorbed by the preceding crops. This observation aligns with the findings of Alloway (2008b), who noted that zinc applied to soils with active cropping systems is gradually depleted over seasons due to plant uptake and reduced soil reserve replenishment. Furthermore, the rice-rice-grain cowpea sequence (C₁) consistently maintained higher residual Zn compared to non-legume sequences, highlighting the role of legumes in enhancing micronutrient cycling through root exudation and improved soil biological activity (Dakora and Phillips, 2002). The significant interaction between nano zinc treatments and crop sequence (Fig. 13.), with the highest Zn levels observed in n₃c₁, denotes the efficient mobilization and recycling of zinc are not solely dependent on the fertilizer form, but also on biological processes triggered by specific crop combinations.

Crop sequence significantly influenced the availability of iron (Fe) and boron (B) in the soil after the third season, whereas residual nutrient treatments and their interactions did not show any significant effect. Notably, higher available Fe concentrations were recorded in the rice-grain cowpea (C₁) and rice- rice-rice-bhindi (C₂) sequences, while the rice-rice-fallow (C₃) sequence exhibited the lowest Fe availability. Similarly, the available B content was significantly higher in C₁ and C₂ compared to C₃. The enhanced availability of Fe and B under the C₁ and C₂ sequences could be attributed to continuous cropping and active root systems promoting rhizosphere microbial activity and organic acid exudation, which are known to solubilize micronutrients (Dakora and Phillips, 2002;

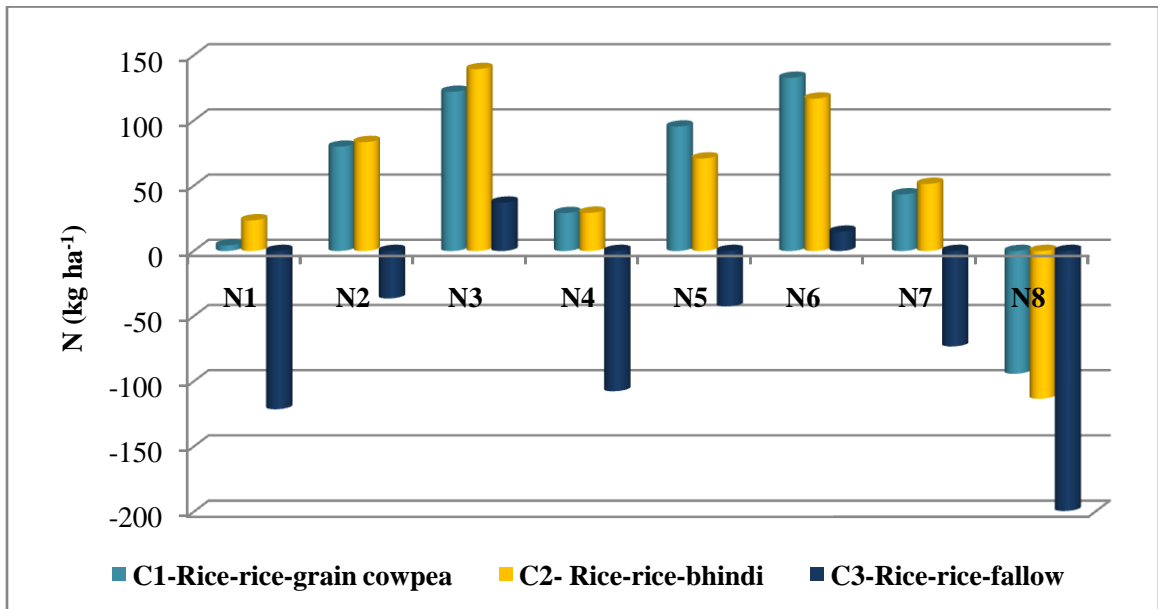


Fig. 15. Effect of residual nutrients and crop sequences on N balance sheet, kg ha⁻¹

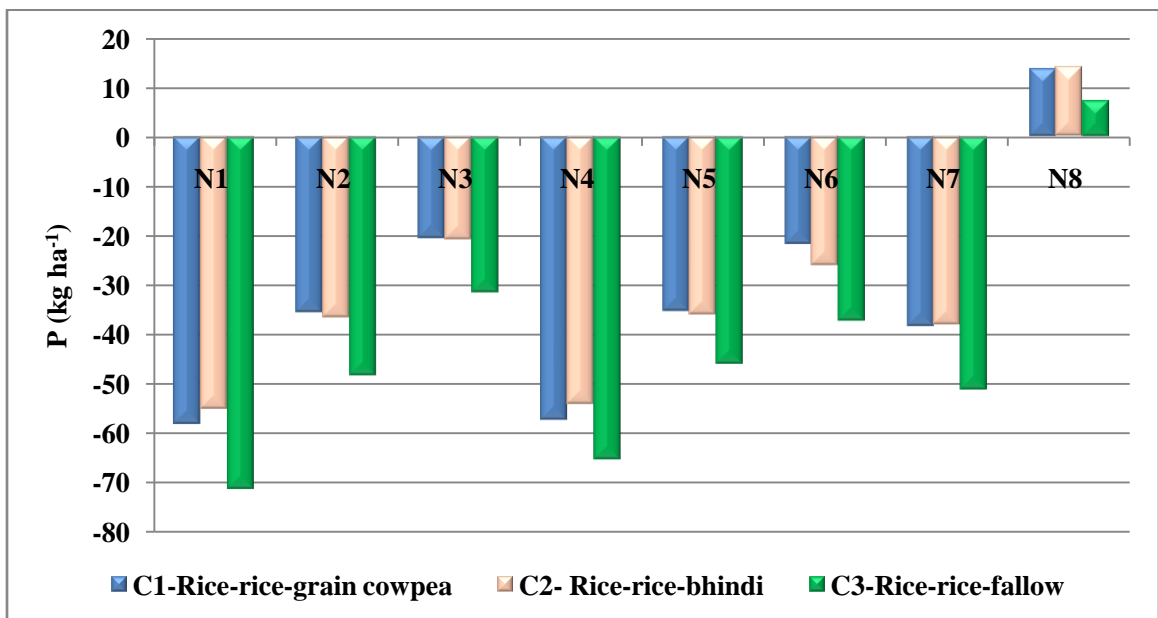


Fig. 16. Effect of residual nutrients and crop sequences on P balance sheet, kg ha⁻¹

Marschner, 2012). In contrast, the fallow sequence (C₃) lacked active plant-microbe interactions, likely leading to reduced micronutrient mobilization and bioavailability. Moreover, legume-based sequences, such as rice-rice-grain cowpea, may have contributed to better micronutrient dynamics through biological nitrogen fixation and associated soil biological processes, which have been shown to improve the cycling and availability of micronutrients in the soil (Rengel, 2015).

5.4.3 Nutrient Balance of the System

The nitrogen balance across the rice-rice-grain cowpea, rice-rice-bhindi, and rice-rice-fallow systems showed that nano zinc application significantly improved nitrogen retention compared to conventional treatments (Fig. 15.). In rice-rice-grain cowpea and rice-rice-bhindi sequences, all treatments except N₈ showed a positive nitrogen balance, with the highest gains under N₃ and N₆. This results proved that nano zinc improved nitrogen use efficiency by enhancing enzymatic activities and plant uptake (Dimkpa and Bindraban, 2016; Baral *et al.*, 2023b). Conversely, in the rice-rice-fallow system, nitrogen losses were observed in all treatments, except N₃ and N₇. The control treatment (N₈) observed the highest loss that may be due to reduced plant uptake and greater leaching or volatilization losses (Adhikari *et al.*, 2016; Raliya *et al.*, 2016). Additionally, nano zinc enhanced residual soil Zn, which promotes microbial nitrogen fixation during fallow periods, further contributing to nitrogen conservation in the system (Baral *et al.*, 2024).

The phosphorus balance in the system showed a net loss across all treatments, except control (N₈) in rice-rice-grain cowpea, rice-rice-bhindi and rice -rice-fallow systems (Fig. 16.). Treatments receiving soil-applied ZnSO₄ alone (N₁), experienced the highest phosphorus depletion, while those involving nano zinc applications (N₃ and N₆) recorded lower losses, suggesting improved phosphorus uptake efficiency due to enhanced root activity and rhizosphere processes (Dimkpa and Bindraban, 2016). In contrast, N₈, which did not receive any phosphorus addition, showed a net gain due to poor crop growth and minimal phosphorus removal, possibly supported by mineralization of native soil

phosphorus (Shen *et al.*, 2011; Richardson *et al.*, 2009b). The results highlight the role of zinc, particularly in nano form, in optimizing phosphorus use by crops (Alloway, 2008b).

The potassium balance in the system showed that treatments with nano zinc application (N₃ and N₆) had better potassium retention across rice-rice-cowpea, rice-rice-bhindi, and rice-rice-fallow sequences (Fig. 17.). In the rice-rice-cowpea and bhindi systems, nano zinc treatments maintained a positive potassium status highlighting improved K use efficiency. Research on bio-resource recycling of nutrients in rice-wheat cropping system indicated that legume residues improve soil K availability and microbial activity, reducing depletion (Nazir *et al.*, 2021). Conversely, the rice-rice-fallow sequence showed higher potassium depletion, particularly in N₈ (-70.84 kg ha⁻¹), due to the absence of a third crop that otherwise supports nutrient recycling (Dinesh *et al.*, 2010). Similar studies where continuous monocropping without residue return depleted non-exchangeable K reserves in rice was reported by Begum *et al.* (2024).

The calcium balance across rice-rice-cowpea, rice-rice-bhindi, and rice-rice-fallow sequences revealed net loss of Ca, ranging from -383.33 to -469.66 kg ha⁻¹ over three cropping seasons, despite lime applications of 600 kg ha⁻¹ during *virippu* and *mundakan* seasons. In Kerala's lateritic soils, water-soluble and exchangeable Ca fractions, which constitute 40–60 per cent of total soil Ca, are highly susceptible to leaching, particularly under conditions of high rainfall and acidic pH ~5.15) (Bhindhu and Sureshkumar, 2021). Annual leaching losses in these soils have been estimated at 100-300 kg ha⁻¹, drastically reducing available calcium for crop uptake. Even though calcium is not fixed in the soil like phosphorus, its high mobility in acidic soils results in losses that outpace replenishment through lime amendments (Ylivainio *et al.*, 2024). Additionally, the applied lime also plays a vital role in neutralizing exchangeable and soluble aluminum (Al³⁺), further diminishing available Ca²⁺ in the soil solution (Olego *et al.*, 2021). A similar trend was observed in liming trials in Ethiopia, where repeated lime applications were necessary to sustain soil Ca levels, as the initial amendment was insufficient to offset continued leaching in acidic soils (Tunebo *et al.*, 2023).

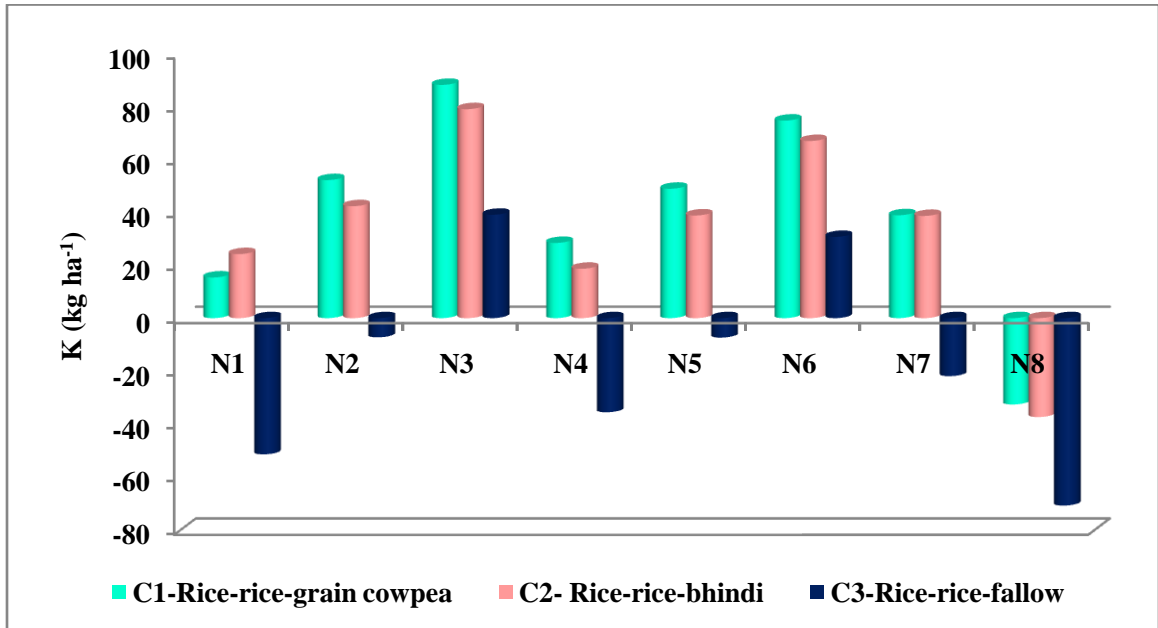


Fig. 17. Effect of residual nutrients and crop sequences on K balance sheet, kg ha⁻¹

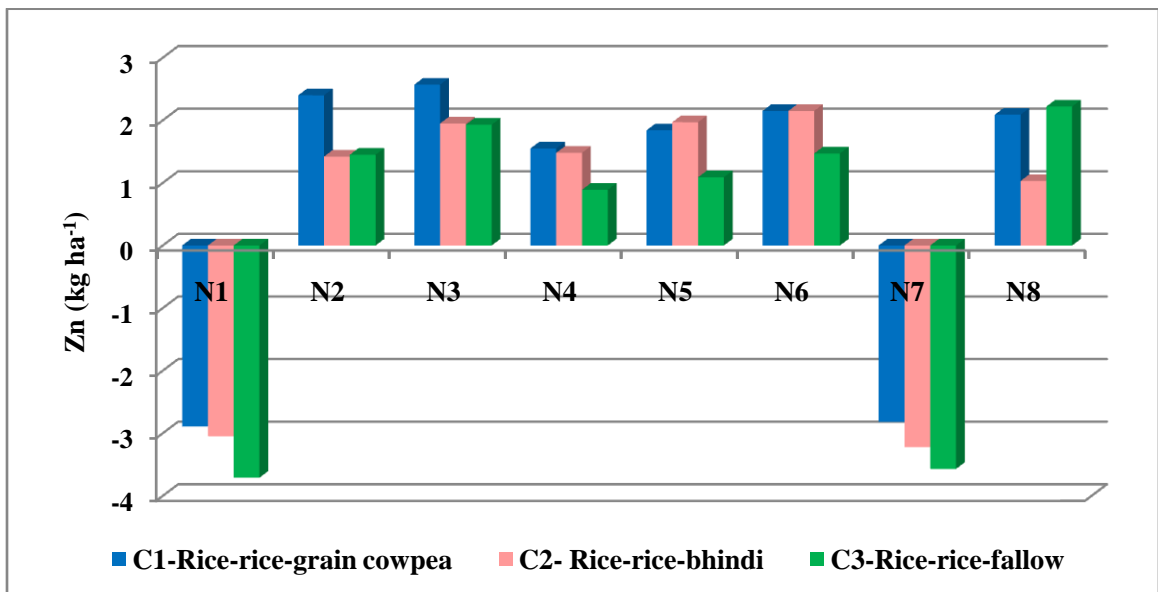


Fig. 18. Effect of residual nutrients and crop sequences on Zn balance sheet, kg ha⁻¹

The zinc balance in the system demonstrated that foliar application of nano zinc (N₂, N₃ and N₆) consistently resulted in a positive net zinc gain across the rice-rice-cowpea, rice-rice-bhindi, and rice-rice-fallow sequences (Fig. 18.). In the high phosphorus soils where the experiment was conducted, zinc availability to crops can be inherently limited due to phosphorus-induced zinc antagonism. Foliar application of nano zinc effectively bypassed this soil constraint by delivering zinc directly to the foliage, enhancing crop Zn uptake while reducing extraction pressure on soil reserves, thus supporting a favorable residual zinc balance. Integration of legumes such as cowpea further improved nutrient cycling and biological activity, aiding in the maintenance of soil zinc status. In contrast, treatment involving conventional soil-applied ZnSO₄ (N₁) recorded substantial zinc depletion, particularly in the rice-rice-fallow system, likely due to the absence of a third crop and lower nutrient recycling potential. These observations align with previous reports that nano fertilizers improve nutrient use efficiency under challenging soil chemical conditions (Zhang *et al.*, 2025a; Wang *et al.*, 2023), while continuous cropping without biomass return accelerates micronutrient depletion (Dinesh *et al.*, 2010; Begum *et al.*, 2024).

The iron balance in the system showed that across the rice-rice-grain cowpea and rice-rice-bhindi sequence, a positive net gain in Fe was observed. In contrast, in the rice-rice-fallow system, treatments N₈ (-35.20 kg ha⁻¹), N₄ (-26.54 kg ha⁻¹), N₇ (-10.58 kg ha⁻¹) and N₁ (-9.80 kg ha⁻¹) experienced a net loss of Fe, while N₆ (23.07 kg ha⁻¹), N₃ (13.18 kg ha⁻¹), N₂ (2.59 kg ha⁻¹), and N₅ (0.17 kg ha⁻¹) maintained a positive Fe balance. The overall results suggested that crop sequencing with legumes like cowpea, and appropriate nutrient interventions like nano-fertilizers, particularly foliar applications, can enhance iron retention in soil systems, consistent with findings by Qureshi *et al.* (2018) and (Wang *et al.*, 2021) who emphasized improved micronutrient efficiency through nano-fertilizer use. The depletion of iron in rice-rice-fallow systems aligns with findings that continuous cropping and the return of crop residues are critical for maintaining soil micronutrient status (Upadhaya *et al.*, 2022).

The boron balance across the rice-rice-grain cowpea sequence showed positive net gains in all treatments, except for N₈ and N₂, which showed net losses. The net loss in N₈ was likely due to the absence of boron application, leading to depletion in soil boron reserves. In N₂, the low-dose nano zinc application likely resulted in competitive interactions between zinc and boron, causing a minimal loss of boron. In the rice-rice-bhindi sequence, all treatments showed net gains in boron, except for N₈, which had a minimal net loss. In the rice-rice-fallow sequence, all treatments except N₆ and N₃ showed negative boron balance, highlighting the importance of continuous cropping and nutrient management for sustaining boron levels in soil. These findings suggest that nutrient interventions, including nano-fertilizers, can enhance boron retention and improve soil micronutrient status, consistent with studies by Laik *et al.* (2021) and Panda *et al.* (2024).

5.5 EFFECT OF RESIDUAL NUTRIENT STATUS AND CROP SEQUENCE ON SYSTEM ENERGETICS OF RBCS

System energetics is a crucial measure in evaluating the sustainability, productivity, and input-use efficiency of a cropping system. Parameters like energy efficiency, specific energy, energy productivity, and energy intensity reflect how effectively the energy inputs (fertilizers, seeds, labor, irrigation, and machinery) are converted into agricultural outputs. A cropping system that shows high energy efficiency and productivity with low specific energy and optimal energy intensity is considered more sustainable, profitable, and environmentally sound. Understanding how residual nutrient status and crop sequences influence these energy parameters provides important insights for long-term nutrient management and crop planning strategies.

The highest energy efficiency was observed in N₃ (9.12), followed by N₆ (8.65). Interestingly, cowpea and bhindi yields were not highest in N₃, but rather in N₁. However, the superior performance of N₃ and N₆ in terms of system energetics can be attributed to their higher outputs in the previous two rice seasons (Fig. 19 and 20.). The residual nutrient status in N₃ and N₆, combined with strong performances of the rice crops in earlier seasons, contributed significantly to cumulative system productivity.

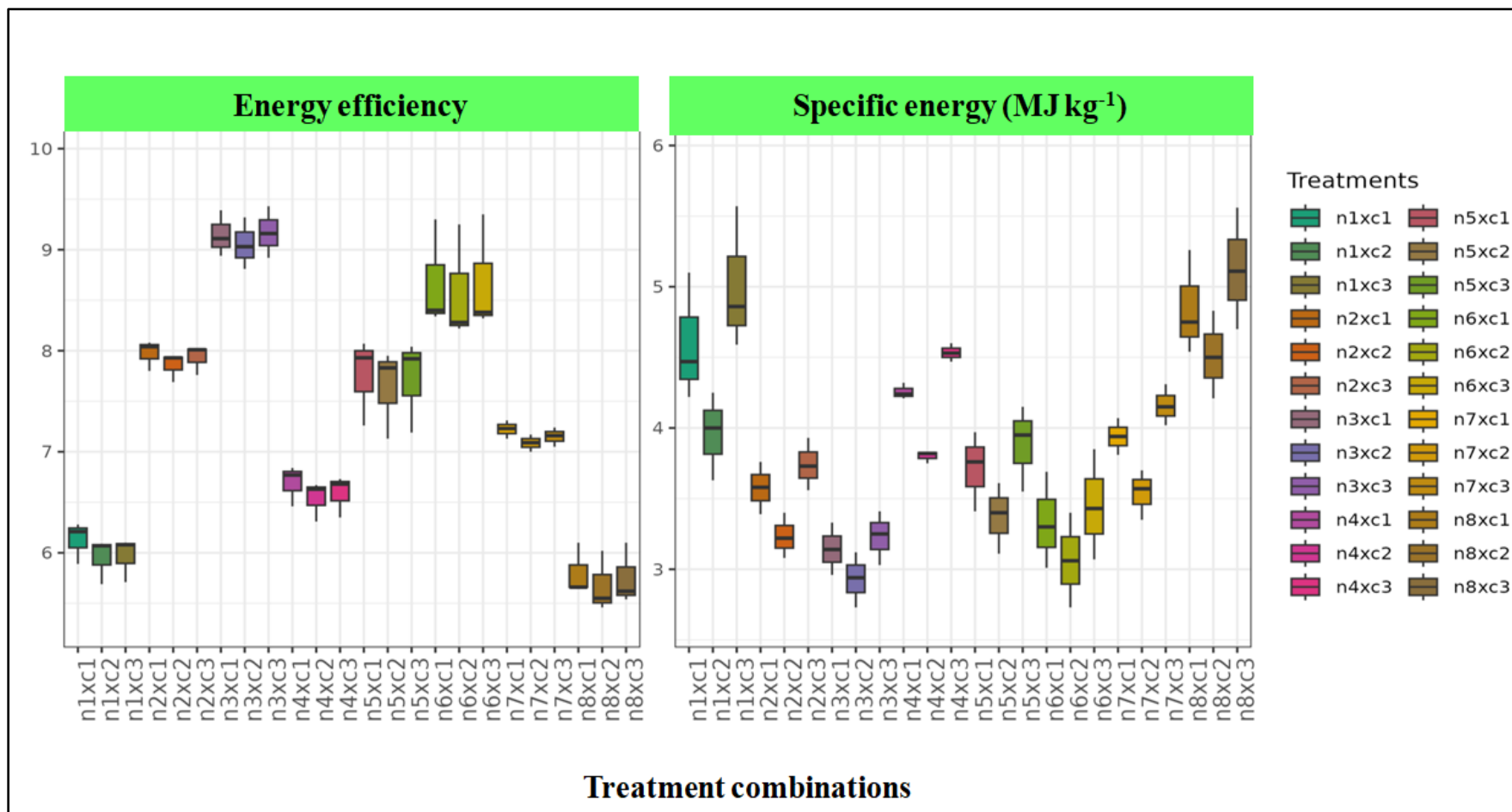


Fig. 19. Effect of residual nutrients and crop sequences on energy efficiency and specific energy

Thus, although cowpea and bhindi yields were slightly lower in N₃ compared to N₁, the overall energy output across all three crops (rice-rice-grain cowpea, rice-rice-bhindi) was much higher in N₃, improving system energy efficiency. The lowest energy efficiency was recorded in N₈ (5.75), where poor residual nutrient status led to lower rice yields in earlier seasons and consistently low cowpea and bhindi yields, thereby drastically reducing the system's overall output. Among crop sequences, rice-rice-grain cowpea recorded the highest energy efficiency due to the lower energy input requirements and better yield performance of cowpea compared to fallow, while rice-rice-fallow showed the least efficiency as no productive output was obtained from the third season. In treatment combinations, n₃c₃ (9.17) and n₃c₁ (9.15) had the highest energy efficiency, further confirming that the combination of a productive residual nutrient status with a suitable third season crop grain cowpea optimizes system outputs and energy conversion. Here, in case of the n₃c₃ combination the highest energy efficiency can be attributed to the no energy input in the third season as it is left fallow. Paramesh *et al.* (2023) revealed that incorporating a pulse crop like cowpea in the rice based cropping system was found to be energy efficient. Singh *et al.* (2017) found variations in the energy efficiency in diversified cropping systems and found that more efficient were being including vegetables and pulses in the system. Vigovskis *et al.* (2012) and Soni *et al.* (2018) also reported similar results.

Specific energy was the lowest in N₃ (3.10 MJ kg⁻¹), indicating efficient use of energy inputs per unit output. On the contrary, N₈ recorded the highest specific energy (4.83 MJ kg⁻¹) due to its consistently poor yields across all seasons, especially in the final season crops. Among crop sequences, the rice-rice-bhindi sequence had lower specific energy values compared to the fallow sequence, indicating that even moderate yields of bhindi contributed more favorably to system energetics than no crop at all. Among treatment combinations, n₃c₂ (2.93 MJ kg⁻¹) indicated least specific energy, suggesting that bhindi grown under the favorable residual nutrient conditions of N₃ required less energy input per unit of produce. Ray *et al.* (2009) reported better energy use efficiency in the cropping sequences which were diversified with vegetables like bhindi.

Energy productivity was the highest in N₃ (0.71 kg MJ⁻¹), and the lowest in N₈ (0.46 kg MJ⁻¹). Although cowpea and bhindi individually yielded higher under N₁, the cumulative output across the system favored N₃. This highlights that system productivity depends on the whole sequence of crops, not only the final crop. Among crop sequences, rice-rice-bhindi had better energy productivity than fallow systems, reflecting that inclusion of a vegetable crop, even with moderate input requirements, enhances overall system efficiency. The highest energy productivity among treatment combinations was recorded in n₃c₂ (0.74 kg MJ⁻¹), aligning with the earlier observations of efficient energy conversion when residual nutrient benefits were combined with an energy-efficient third crop. Vigovskis *et al.* (2012) also reported similar results.

Energy intensity, which measures the energy output gained per unit of economic input, was the highest in N₃ (1.34 MJ ₹⁻¹) and the lowest in N₈ (0.78 MJ ₹⁻¹). Here again, the superior cumulative yields under N₃ justified the higher energy investment. Among crop sequences, the fallow sequence (C₃) had higher energy intensity compared to grain cowpea and bhindi sequence and it can be inferred that the energy equivalent which is fixed on the dry weight basis may not substantiate for the bhindi yield, moreover the cost of cultivation for the fallow sequence is nil for the third season crop which would have reflected in the energy intensity. The same would be the reason for the better performance of the treatment combination n₃c₃ (1.47 MJ ₹⁻¹).

5.6 EFFECT OF RESIDUAL NUTRIENT STATUS AND CROP SEQUENCE ON SYSTEM PRODUCTIVITY AND SYSTEM PROFITABILITY

5.6.1 System Yield and System Productivity

System yield and system productivity are critical parameters for evaluating the overall performance of cropping systems over a complete cycle. System yield reflects the cumulative harvestable output from all the crops grown, while system productivity (expressed as yield per day) measures the efficiency of land use over time. Together, they provide a comprehensive picture of how well nutrients, time, and resources are utilized, and how sustainable and profitable a cropping system is in the long term.

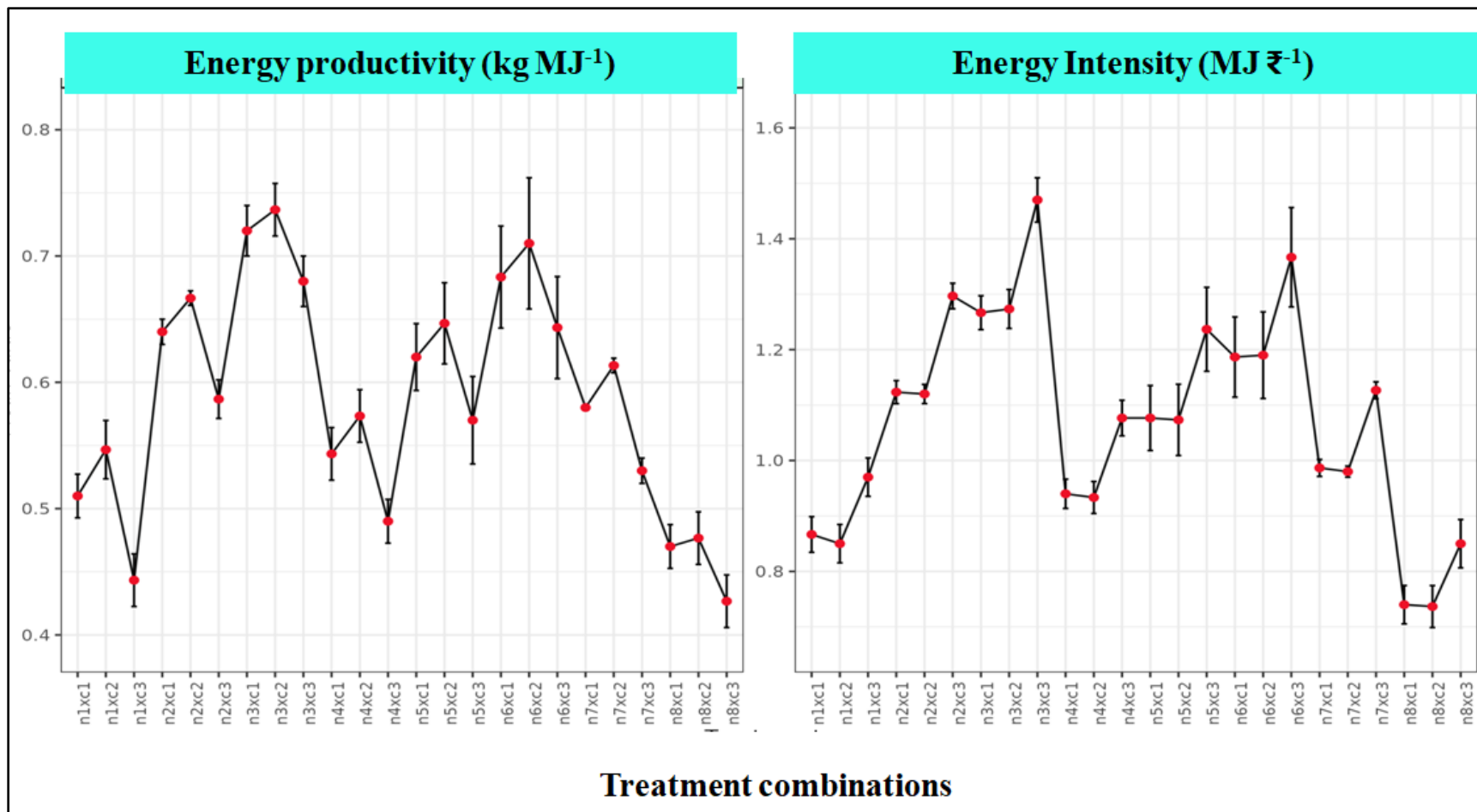


Fig. 20. Effect of residual nutrients and crop sequences on energy productivity and energy intensity

In the present study, significant differences were observed among residual nutrient treatments, crop sequences, and their interactions. The highest system yield was recorded in N₃ (11504 kg ha⁻¹), closely followed by N₆ (11015 kg ha⁻¹), while lower yields were observed in N₁, N₇, and N₈ (Fig. 21.). Similarly, higher system productivity was noted in N₃ and N₆ (32 and 30 kg ha⁻¹ day⁻¹) treatments compared to others. Among crop sequences, rice-rice-bhindi resulted in highest system yield and productivity, whereas rice-rice-fallow showed the lowest. Supported by the studies of Upadhaya *et al.* (2022).

The superior performance of N₃ and N₆ can be attributed to the highest growth and cumulative yield contributions across seasons, resulting from the improved impact of nano zinc nutrition applied during the earlier phases of two previous rice crops. The nano zinc enhanced nutrient uptake efficiency, soil biological health, and overall plant vigor, establishing a strong residual nutrient base that sustained higher productivity in the subsequent cowpea and bhindi crops. Thus, strategic residual nutrient management coupled with appropriate crop sequencing, proved to be beneficial for optimizing system productivity. Similar results where the diversification of the system with different crops to utilize the resources and land resulted in better system yield and productivity were observed by Soni *et al.* (2018); Sudhalakshmi *et al.* (2021) and Samant *et al.* (2023).

5.6.2 System Profitability

System economics, particularly net returns and benefit-cost (B:C) ratio, serve as crucial indicators of the sustainability and profitability of cropping systems (Fig. 22.). These parameters reflect the efficiency with which inputs are converted into economic gains and guide the selection of crop sequences and nutrient management practices for maximizing returns. In the present study, significant variations were observed among the treatments and crop sequences with respect to system economics. The treatment N₃ [Residual nutrient status of the soil for T₃-NP with Nano Zn at 0.05% + FS with Nano Zn at 0.05% at MT stage] recorded the highest net returns of ₹ 173627 ha⁻¹ and the highest B:C ratio of 1.49, whereas the lowest net returns (₹ 11024 ha⁻¹) and B:C ratio (0.91) were observed in the control treatment N₈. Among the crop sequences, the rice-rice-bhindi

sequence (C₂) registered the highest net returns of ₹ 114127 ha⁻¹ and was superior in terms of profitability compared to the rice-rice-grain cowpea (C₁) and rice-rice-fallow (C₃) sequences with the latter showing the least returns (₹ 88065 ha⁻¹). Considering treatment combinations, n₃c₂ recorded the highest net returns (₹ 182091 ha⁻¹), while the lowest net returns were obtained in n₈c₃ (₹ 8425 ha⁻¹). Interestingly, the highest B:C ratio was observed in the n₃c₃ combination (1.79), despite a lower gross return, indicating higher cost efficiency in this sequence, the cost of cultivation for the fallow season remained nil which would have reflected in the B:C ratio.

The superior performance of N₃ can be attributed to the effective residual impact of nano Zn applications, which enhanced nutrient availability, improved crop vigour, and ultimately led to higher yields and better marketable produce. Nano-formulated zinc fertilizers are known for their higher nutrient use efficiency, sustained release, and better plant uptake, resulting in cumulative positive effects on soil fertility and crop productivity over multiple seasons which ultimately reflected in the profitability (Baral *et al.*, 2023a). The rice-rice-bhindi sequence (C₂) outperformed other sequences due to the high economic value of bhindi, which was a high-demand vegetable crop that contributed significantly to system profitability. On the other hand, the rice-rice-fallow sequence (C₃) due to the absence of an income-generating crop during the third season remained unprofitable. Overall, the integration of efficient nutrient management practices, particularly the application of nano Zn, coupled with profitable crop sequence of rice-rice-bhindi, proved highly effective in enhancing system economics and ensuring the sustainability of the cropping system, which was also reported by Upadhaya *et al.* (2022).

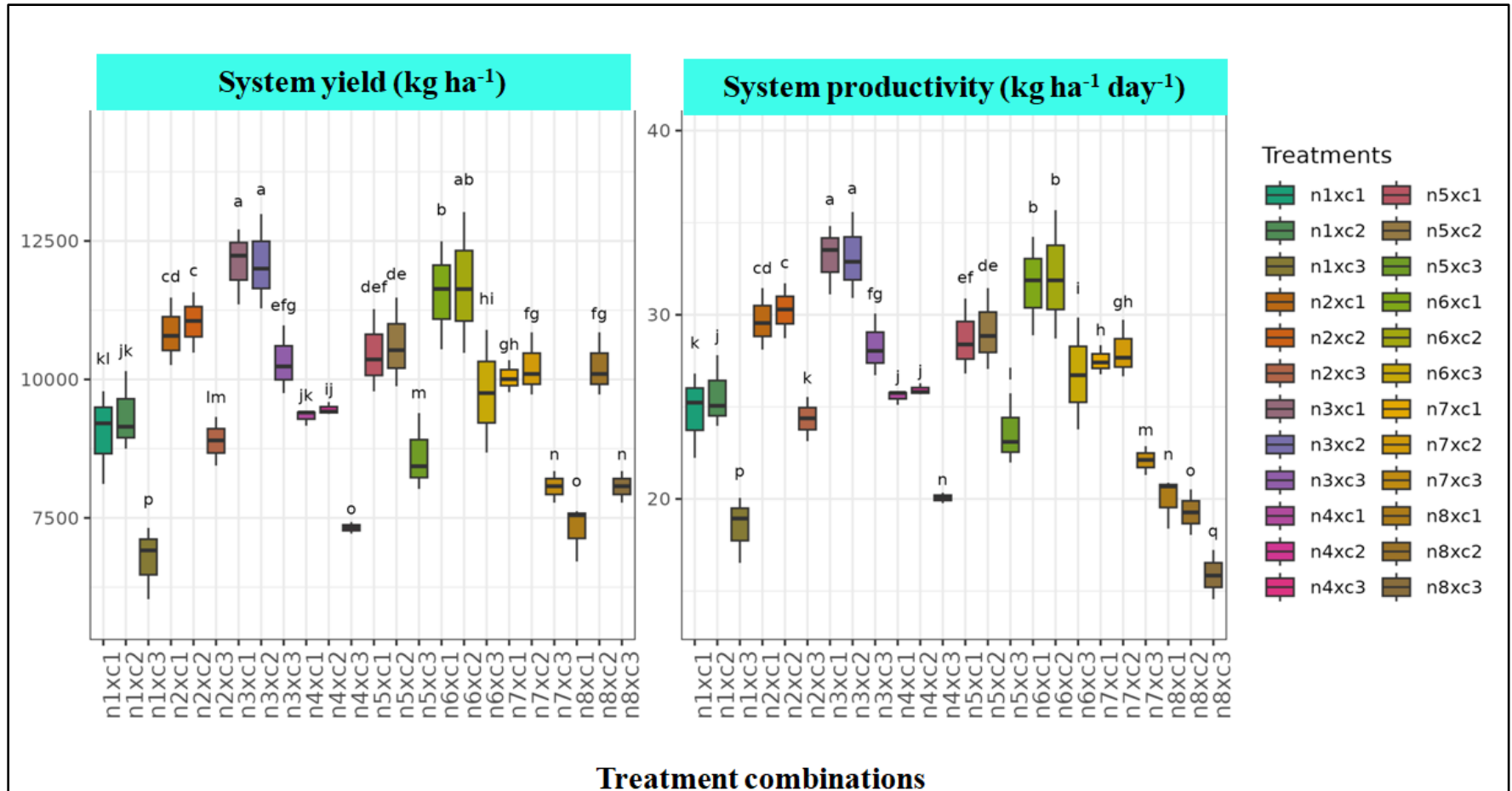


Fig. 21. Interaction effect of residual nutrients and crop sequences on system yield and system productivity

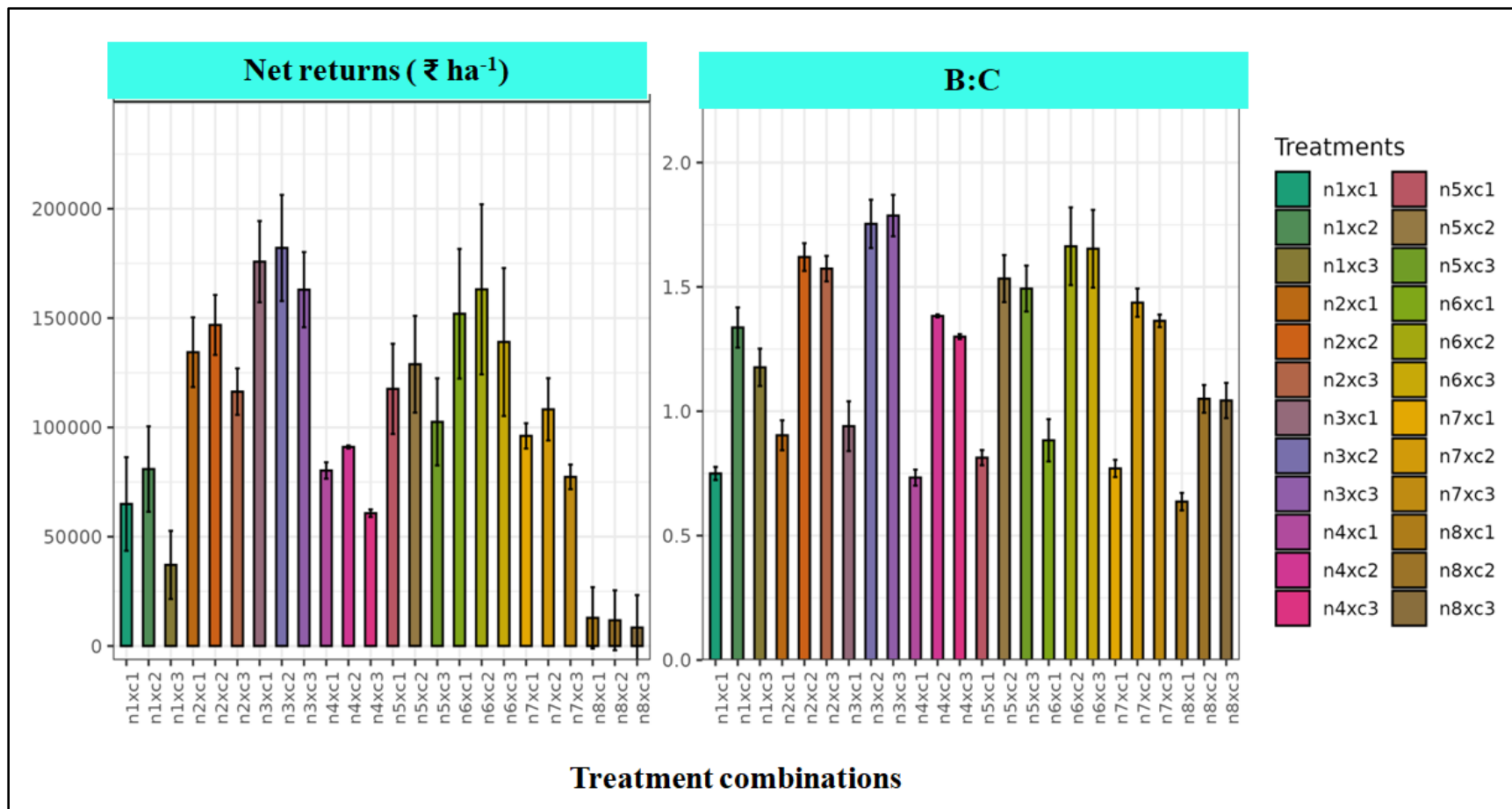


Fig. 22. Effect of residual nutrients and crop sequences on economics of rice based cropping system

SUMMARY

6. SUMMARY

A field experiment entitled “Nano zinc nutrition in rice based cropping systems in high phosphorus soils” was conducted during the period from April 2022 to May 2023 at Integrated Farming System Research Station (IFSRS), Karamana, Thiruvananthapuram, Kerala. The objectives of the study were to evaluate the response of rice to nano zinc in high P soils, study the residual effect of nano zinc nutrition on growth and yield of succeeding crops, study the P - Zn interactions and identify the promising crop sequence in terms of system productivity and profitability.

The experiment comprised three parts of which Part 1 and 2 were carried out in rice. The first and second parts of the experiment were laid out in randomized complete block design with three replications using variety Uma (Mo 16) in *virippu* and *mundakan* season. The treatments are T₁- [Soil application (SA) of ZnSO₄ at 20 kg ha⁻¹ (applied only in *virippu* season)], T₂- [Nutri priming (NP) with nano Zn at 0.05%], T₃- [NP with nano Zn at 0.05% + Foliar spray (FS) with nano Zn at 0.05% at maximum tillering (MT) stage], T₄- [NP with ZnSO₄ at 0.5%], T₅- [NP with ZnSO₄ at 0.5% + FS with nano Zn at 0.05% at MT stage], T₆-[FS with nano Zn at 0.05% at MT and panicle initiation (PI) stages], T₇- [FS with ZnSO₄ at 0.5% at MT and PI stages], T₈- [Control (Recommended Dose of Nutrients (RDN) without application of P and Zn)]. The RDN were 90:45:45 (N:P₂O₅:K₂O) kg ha⁻¹ modified to 64:22:53 kg ha⁻¹ on soil test basis.

The growth attributes of rice during *virippu* and *mundakan* were significantly affected by zinc nutrition. At all growth stages of rice taller plants were observed with nutri priming with nano Zn at 0.05% + foliar spray with nano Zn at 0.05% at maximum tillering stage -T₃ (60.17 cm, 73.82 cm, 112.45 cm and 124.87 cm, respectively) during *virippu*, (58.60 cm, 74.70cm, 97.70cm and 118.20 cm) during *mundakan* which was on par with T₆ at harvest stage. Tillers per m² were significantly influenced by the treatments, the higher number of tillers per m² at maximum tillering stage were observed in T₂ (486 and 701, respectively in *virippu* and *mundakan*) and T₃ (468 and 689, respectively in *virippu* and *mundakan*), at panicle initiation stage, flowering and at

harvest higher number of tillers m^{-2} were observed in T₃ (654, 677 and 658, respectively in *virippu*; 828, 868 and 711, respectively in *mundakan*) which were comparable with the treatments T₂ and T₆ during *virippu* and T₆ in *mundakan*. Leaf area per hill during *virippu* was higher in T₂ (776.53 cm^2) and T₃ (774.52 cm^2) at the maximum tillering stage whereas, at panicle initiation stage, flowering and at harvest the higher leaf area per hill was recorded in T₃ (1101.41 cm^2 , 1379.20 cm^2 and 1187.25 cm^2 , respectively). Similarly, during *mundakan*, at all growth stages, T₃ recorded higher leaf area per hill (706.65 cm^2 , 981.49 cm^2 , 1112.11 cm^2 and 935.70 cm^2 at maximum tillering, panicle initiation, flowering and at harvest, respectively) which was on par with T₆ at flowering and at harvest. The highest leaf area index at panicle initiation stage during *virippu* and *mundakan* were observed in T₃ (3.67 and 4.91, respectively). Dry matter production at harvest was higher in T₃ (37.38 g per hill and 34.27 g per hill, respectively during *virippu* and *mundakan*) which was on par with T₆ during both the seasons, the lowest dry matter production was recorded in T₈ (20.13 g per hill and 15.99 g per hill, respectively during *virippu* and *mundakan*).

The yield and yield attributes of rice during *virippu* and *mundakan* were significantly influenced by the treatments. Nutri priming with nano zinc at 0.05% followed by foliar spray with nano zinc at 0.05% at maximum tillering stage (T₃) recorded lower sterility percentage of (6.51% and 4.83%, respectively during *virippu* and *mundakan*) which was at par with T₆. The yield attributes *viz.*, productive tillers per hill, no. of grains per panicle, grain weight per panicle were significantly higher in T₃ (19, 217 and 6.15g, respectively in *virippu*) (18, 204 and 5.62g, respectively in *mundakan*) and were comparable with T₆. Grain yield of rice during *virippu* and *mundakan* were significantly influenced by the treatments and the highest grain yield during both the seasons were observed in T₃ (5025 $kg\ ha^{-1}$ and 5297 $kg\ ha^{-1}$, respectively) which was on par with T₆ (4753 $kg\ ha^{-1}$) and T₂ (4494 $kg\ ha^{-1}$), whereas in *mundakan* T₃ was found on par with T₆ (5023 $kg\ ha^{-1}$). Grain yield was lower in T₈ during both the seasons (*virippu*- 2988 $kg\ ha^{-1}$, *mundakan*- 2807 $kg\ ha^{-1}$) and in *virippu* it was on par with

T₁ (3222 kg ha⁻¹) and T₄ (3272 kg ha⁻¹), respectively. Similarly, the straw yield was higher in T₃ (5864 kg ha⁻¹, 6432 kg ha⁻¹, respectively during *virippu* and *mundakan*) which was statistically at par with T₆ during both the seasons and the lowest straw yield was recorded in T₈ (3519 kg ha⁻¹ and 3271 kg ha⁻¹, respectively during *virippu* and *mundakan*) and in *virippu* it was on par with T₁ and T₄. The pooled mean over two seasons on grain and straw yield revealed that the highest grain yield was recorded in T₃ (5161 kg ha⁻¹ and 6148 kg ha⁻¹, respectively) and it was found on par with T₆.

The nutrient uptake of N, P, K, Ca and Zn by rice at panicle initiation and at harvest were significantly influenced by zinc nutrition. The total N uptake at panicle initiation was higher in T₃ (97.73 kg ha⁻¹ and 110.03 kg ha⁻¹, respectively during *virippu* and *mundakan*) and at harvest the total N uptake was higher in T₃ (121.94 kg ha⁻¹) which was on par with T₆ (112.08 kg ha⁻¹). The lower uptake was observed in T₈ (57.36 kg ha⁻¹), T₁ (65.72 kg ha⁻¹) and T₄ (68.44 kg ha⁻¹) during *virippu* whereas, and in *mundakan* the highest N uptake was reported in T₃ (154.97 kg ha⁻¹) and T₆ (145.68 kg ha⁻¹) and the lowest uptake was reported in T₈. The total P uptake at panicle initiation stage was significantly higher in the treatment T₃ (17.82 kg ha⁻¹) which was on par with T₂ (16.33 kg ha⁻¹), whereas in *mundakan*, the highest uptake was reported in T₃ (17.73 kg ha⁻¹) and T₂ (17.30 kg ha⁻¹). At harvest the total uptake of P during *virippu* was the highest in T₃ (27.41 kg ha⁻¹) whereas, during *mundakan* the total uptake of P was higher in T₃ (27.90 kg ha⁻¹) and T₆ (20.92 kg ha⁻¹). The total K uptake by the rice during panicle initiation is significantly higher in T₃ (83.88 kg ha⁻¹ and 86.74 kg ha⁻¹) which was comparable to T₂ (79.50 kg ha⁻¹ and 84.18 kg ha⁻¹) and T₆ (77.40 kg ha⁻¹ and 75.74 kg ha⁻¹) during *virippu* and *mundakan*, respectively. At harvest the total uptake of K was higher in T₃ (74.50 kg ha⁻¹) and T₆ (69.35 kg ha⁻¹) which were on par with T₂ (66.39 kg ha⁻¹) during *virippu*. The total uptake of K at harvest during *mundakan* was the highest in T₃ (92.30 kg ha⁻¹) and T₆ (85.17 kg ha⁻¹). The total Ca uptake at panicle initiation was higher in T₃ (32.02 kg ha⁻¹), T₆ (30.04 kg ha⁻¹) and T₂ (28.17 kg ha⁻¹) during *virippu*. The total uptake of Ca was higher in T₃ (34.36 kg ha⁻¹) and T₂ (32.63 kg ha⁻¹) during

mundakan. At harvest the total uptake of Ca was higher in T₃ (26.35 kg ha⁻¹) which was on par with T₆ (23.49 kg ha⁻¹) and T₂ (22.70 kg ha⁻¹) during *virippu*. In *mundakan*, Ca uptake was higher in T₃ (26.61 kg ha⁻¹) which was found on par with T₆ (24.77 kg ha⁻¹). The total Zn uptake at panicle initiation stage during *virippu* was significantly higher in T₃ (0.30 kg ha⁻¹) which was on par with T₆ (0.27 kg ha⁻¹) and T₂ (0.27 kg ha⁻¹) whereas, in *mundakan*, the highest Zn uptake was observed in T₃ (0.30 kg ha⁻¹) which was on par with T₂. At harvest, the total Zn uptake was significantly higher in T₃ (0.39 kg ha⁻¹) which was on par with T₆ (0.36 kg ha⁻¹) whereas, the lower uptake was observed in T₈ (0.18 kg ha⁻¹) which was on par with T₁ (0.21 kg ha⁻¹) during *virippu*. The total uptake of Zn was the highest in T₃ (0.40 kg ha⁻¹) and the lowest was recorded in T₈ (0.15 kg ha⁻¹) during *mundakan*.

The nutrient use efficiency of the phosphorus and zinc were calculated in terms of agronomic efficiency (AE), physiological efficiency (PE) and apparent recovery efficiency (ARE). The highest AE of P was recorded in T₃ (94.29, 58.87) and highest AE of Zn was recorded in T₂ (30116.45, 31780 kg kg⁻¹), respectively during *virippu* and *mundakan*). The PE_P was higher in T₁ (160.78 kg kg⁻¹) during *virippu* and in T₄ (162.08 kg kg⁻¹) during *mundakan* whereas, PE_{Zn} was higher in T₃ during *virippu* and in T₁ during *mundakan*. The ARE_P during *virippu* and *mundakan* seasons, was higher in T₃ (0.63 and 0.45 kg kg⁻¹, respectively), whereas ARE_{Zn} was higher in T₂ (3.20 and 2.81 kg kg⁻¹, respectively during *virippu* and *mundakan* seasons).

The results on post experiment soil analysis after *virippu* and *mundakan* rice revealed that there was a significant variation in available N, P, K and Zn in response to different zinc nutrition concentrations and application methods. The available N was higher in the treatments T₆ (373.37 kg ha⁻¹) and T₃ (356.14 kg ha⁻¹) during *virippu*, whereas during *mundakan* the highest available nitrogen was recorded in T₃ (353.33 kg ha⁻¹) and T₆ (347.93 kg ha⁻¹). The available P during *virippu* were higher in T₃, T₇, T₆, T₅ (18.12, 17.51, 17.37, 17.28 kg ha⁻¹, respectively) whereas, in *mundakan*, T₃ showed the

highest available P (19.87 kg ha⁻¹). During *virippu*, the highest available K was recorded in T₆ (79.54 kg ha⁻¹) whereas, in *mundakan*, the highest available K was observed in T₅ (75.81 kg ha⁻¹). During *virippu*, higher available Zn was recorded in T₃ (1.47 kg ha⁻¹) and T₂ (1.40 kg ha⁻¹) whereas, in *mundakan*, higher available zinc was recorded in T₃ (1.76 kg ha⁻¹), T₆ (1.74 kg ha⁻¹) and T₅ (1.68 kg ha⁻¹). The dehydrogenase activity of the soil after *virippu* and *mundakan* seasons were significantly higher in T₃ (54.80 and 54.13 g⁻¹ soil 24h⁻¹, respectively) which was comparable to T₆ (50.23 and 51.57 g⁻¹ soil 24h⁻¹, respectively). During both *virippu* and *mundakan* seasons, higher phosphatase activity was noted in T₈ (29.80 and 25.97g⁻¹soil h⁻¹, respectively) which was on par with T₄ (27.53 and 23.37g⁻¹soil h⁻¹, respectively).

The highest net returns (₹ 76622 ha⁻¹ and ₹ 86368 ha⁻¹) were observed in nutri priming with nano Zn at 0.05% + Foliar spray with nano Zn at 0.05% at maximum tillering stage (T₃) during *virippu* and *mundakan*, respectively. The highest B:C ratio was recorded in T₃ (1.74 and 1.82, respectively during *virippu* and *mundakan*).

The third part of the experiment was conducted during summer season to study the residual effect of nano zinc nutrition on growth and yield of succeeding crops. The experiment was laid out in strip plot design wherein, each individual plots of previous crop were divided to three sub plots and crops *viz.*, grain cowpea (variety-Kanakamony (PTB 1)) and bhindi (Anjitha) were grown and one sub plot was kept as fallow. The main plot treatments were residual nutrients of the previous seasons (N₁ to N₈) and the sub plot treatments were three crop sequences (C₁- rice-rice-grain cowpea, C₂- rice-rice-bhindi, C₃- rice-rice-fallow).

The growth attributes of grain cowpea were recorded at harvest and the results revealed that tallest plant (81.03 cm) with the highest number of branches per plant (9.33) and the highest dry matter production (38.90 g per plant) were recorded in N₁ (Residual nutrient status of the soil of the treatment T₁). Yield attributes of cowpea such as no of pods per plant (12), 100 seed weight (12.57 g), seed yield per plant (32.27 g), seed yield

ha⁻¹ (855 kg ha⁻¹), haulm yield per plant (43.63 g) and haulm yield ha⁻¹ (2030 kg ha⁻¹) were highest in N₁.

The growth attributes of bhindi at harvest such as plant height (96.30 cm), number of branches per plant (3.67), dry matter production (95.13 g per plant) were higher N₁ (Residual nutrient status of the soil of the treatment T₁). Yield attributes of bhindi *viz.*, no of fruits per plant (25), fruit weight (16.70 g), fruit yield per plant (299.37 g), fruit yield ha⁻¹ (1945 kg ha⁻¹), haulm yield per plant (51.17 g) and haulm yield ha⁻¹ (1897 kg ha⁻¹) were higher in N₁.

The soil analysis of the experimental site after the conduct of experiment revealed that the soil reaction (pH), electrical conductivity (EC) and organic carbon (OC) did not vary significantly, whereas the available nutrients of the soil after the experiment varied significantly due to residual nutrient status and crop sequences. Available N was significantly affected by the residual nutrients and crop sequences whereas, their interactions were not significant. Among the residual nutrients, the higher available N was observed in N₆ (339.25 kg ha⁻¹) and N₅ (338.43 kg ha⁻¹). Available P among the residual nutrients was the highest in N₃ (18.33 kg ha⁻¹) and among the crop sequences, the highest available P of 17.40 kg ha⁻¹ was observed in the rice-rice-grain cowpea sequence. Available K was higher in N₃ (79.18 kg ha⁻¹) and N₆ (78.61 kg ha⁻¹) among the residual nutrients and C₁ (76.21 kg ha⁻¹) recorded the highest available K and the interactions were non significant. Available Ca was not affected by the residual nutrients and crop sequences whereas, it varied significantly for their interactions. Among the interactions, the highest available Ca was observed in n₈c₂ (234.74 kg ha⁻¹). Among the residual nutrients, the highest available Zn was observed in N₆ (1.67 kg ha⁻¹) and among the crop sequences the highest was in C₁ (1.70 kg ha⁻¹), whereas in interactions, n₃c₁ was observed to have the highest available Zn (1.87 kg ha⁻¹). Available Fe did not vary significantly among residual nutrients and their interactions whereas, crop sequences significantly influenced available Fe and higher available Fe was found in C₂ (232.53 kg

ha⁻¹) and C₁ (226.22 kg ha⁻¹). Similarly, available B did not vary significantly among residual nutrients and their interactions but varied significantly among crop sequences, where higher available B was found in C₁ (1.85 kg ha⁻¹) and C₂ (1.78 kg ha⁻¹). The soil enzymes dehydrogenase and phosphatase activities varied significantly to the residual nutrient status of the soil and crop sequences. Among residual nutrients, N₃ (56.25 g⁻¹soil 24h⁻¹) recorded the highest dehydrogenase activity which was found comparable with the treatment N₆ (53.01 g⁻¹soil 24h⁻¹) and the highest activity among crop sequences was observed in C₁ (50.16). The highest phosphatase activity was observed in N₁ (31.99 g⁻¹soil h⁻¹) which was on par with N₄ (30.64 g⁻¹soil h⁻¹) in residual nutrients and among the interactions, n₁c₁ (34.97 g⁻¹soil h⁻¹) recorded the highest phosphatase activity and it did not vary with the crop sequences.

The data on system analysis revealed that the system yield and system productivity were influenced by the residual nutrients and the cropping sequences. Higher system yield among the residual nutrients was observed in N₃ (11504 kg ha⁻¹) which was found comparable with N₆ (11015 kg ha⁻¹). Among the crop sequences, the highest system yield was recorded in rice-rice-bhindi and among the interactions, n₃c₁ (12100 kg ha⁻¹) and n₃c₂ (12090 kg ha⁻¹) recorded the highest system yield. The highest system productivity of 32 kg ha⁻¹ day⁻¹ was recorded in N₃ which was found on par with N₆ (30 kg ha⁻¹ day⁻¹) and among the crop sequences, higher system productivity was reported in C₂-rice-rice-bhindi and C₁- rice-rice-grain cowpea and among the interactions, n₃c₂ and n₃c₁ recorded the highest system productivity of 33 kg ha⁻¹ day⁻¹.

The system energetics varied among the residual nutrients, crop sequences and their combinations. The highest energy efficiency was found in N₃ (9.12) and C₁ (7.42) among residual nutrients and crop sequences, respectively. Among the treatment combinations, n₃c₃ (9.17) recorded the highest energy efficiency. The lowest specific energy among the residual nutrients was recorded in N₃ (3.10 MJ kg⁻¹) and the highest specific energy was recorded in N₈ (4.83 MJ kg⁻¹) and among the crop sequences, C₂ and

among interactions, n_6c_2 recorded the lowest specific energy. The energy productivity among residual nutrients, crop sequences and their interactions was higher in N_3 (0.71 kg MJ^{-1}), C_2 (0.62) and n_3c_2 (0.74 kg MJ^{-1}) respectively. The highest energy intensity was observed in the treatment N_3 (1.34 MJ ₹^{-1}), C_3 (1.17 MJ ₹^{-1}) and n_3c_3 (1.47 MJ ₹^{-1}) among residual nutrients, crop sequences and their interactions respectively.

The nutrient balance in the system among different crop sequences for various nutrients revealed that the nitrogen balance has shown net gain in all the treatments in rice- rice-grain cowpea system except in N_8 . In rice-rice-bhindi sequence, a net gain of N was observed in all the treatments except in N_8 . The highest net gain of nitrogen was reported in N_3 (37.04 kg ha^{-1}) in rice-rice-fallow sequence. Among the three sequence, net loss of phosphorus was observed in all the treatments except N_8 . Potassium balance in the system revealed that there was a positive balance of potassium in rice-rice-grain cowpea in all the treatments except N_8 which recorded a net loss of 32.64 kg ha^{-1} . The highest net gain of K (79.00 kg ha^{-1}) in N_3 was observed in rice-rice-bhindi sequence. In rice-rice-fallow sequence, there was a net gain of K in N_3 (39.08 kg ha^{-1}) and N_6 (30.72 kg ha^{-1}) and all other treatments showed a net loss in potassium. Calcium balance among the crop sequences revealed that there was a net loss of calcium in all sequences. Zinc balance of the system in rice-rice-grain cowpea showed a positive balance except for N_1 and N_7 treatments. Rice-rice-bhindi sequence was observed with a net gain of Zn in N_6 (2.15 kg ha^{-1}). In rice- rice-fallow sequence, the highest net gain of zinc was observed in the treatment N_3 (1.93 kg ha^{-1}). Iron balance in the rice-rice-grain cowpea sequence was positive with the highest net gain in N_6 (55.24 kg ha^{-1}) and in rice-rice-bhindi sequence, there was a net gain of iron in all treatments where, N_3 recorded the highest net gain of 80.60 kg ha^{-1} and in rice-rice-fallow sequence there was a net gain in N_6 (23.07 kg ha^{-1}), N_3 (13.18 kg ha^{-1}), N_2 (2.59 kg ha^{-1}) and N_5 (0.17 kg ha^{-1}), respectively.

The evaluation of profitability of the system in terms of net returns and B:C ratio varied among residual nutrient status, crop sequence and their combinations. The highest net returns of ($\text{₹ } 173627 \text{ ha}^{-1}$) was observed in the treatment N_3 residual nutrient status

and among crop sequences, C₂- rice-rice-bhindi sequence (₹ 114127 ha⁻¹) recorded the highest net returns. Among the treatment combinations, n₃c₂ (₹ 182091 ha⁻¹) recorded the highest net returns. The treatment N₃ recorded the highest B:C ratio of 1.49 among the residual nutrients whereas, rice-rice-bhindi sequence recorded the highest B:C ratio (1.47). Among the treatment combinations, the highest B:C ratio was observed in n₃c₃ (1.79)

From the study it can be concluded that nutri-priming with nano zinc at 0.05% (50 ml ha⁻¹) combined with a foliar spray of nano zinc at 0.05% (250 ml ha⁻¹) at the maximum tillering stage (T₃) was the most effective treatment for enhancing the productivity and profitability of rice during both the *virippu* and *mundakan* seasons in high phosphorus soils. Treatment T₃ was adjudged as the most effective in mitigating P-Zn interactions, resulting in higher nutrient uptake during both the *virippu* and *mundakan*. The residual nutrient status under N₁ [resulting from the soil application of ZnSO₄ at 20 kg ha⁻¹ (applied during *virippu* season)] led to improved performance of the succeeding crops (grain cowpea and bhindi). Among the cropping sequences evaluated, the rice-rice-bhindi sequence emerged as the most productive and profitable cropping sequence.

FUTURE LINE OF WORK

- Different concentrations of ZnSO₄ and nano zinc could be explored.
- Evaluation of microbially mediated nutrient management of P and Zn in high P soils. Diversification of summer fallows with high value crops (sweet corn, oil seeds *etc.*).
- Evaluation of soil applied ZnSO₄ in reduced rate of application (5 and 10 kg ha⁻¹)
- Effect of zinc nutrition on mitigating stress in plants could be studied.

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APPENDICES

APPENDIX-Ia

**Weather data during *virippu*
(3 April 2022 to 22 August 2022)**

St. Met Week	Period (2022)	Temperature (°C)		R.H. (%)			Rainfall (mm)	No. of rainy days
		Min.	Max.	RH I	RH II	Mean		
14	Apr 2-8	24.18	32.15	88.6	70.91	79.76	42.93	2
15	Apr 9-15	23.73	31.42	91	73.63	82.32	85.6	4
16	Apr 16-22	25.16	31.88	88.25	71.77	80.01	35.81	2
17	Apr 23-29	25.8	32.41	89.13	68.53	78.83	20.07	2
18	Apr 30-May 6	26.79	32.80	84.86	70.20	77.53	18.54	1
19	May 7-13	25.24	31.93	86.23	68.04	77.14	37.34	3
20	May 14-20	23.94	29.35	93.16	80.10	86.63	185.93	6
21	May 21-27	24.93	30.22	90.86	77.06	83.96	55.12	3
22	May 28-Jun 3	24.59	30.23	91.00	77.60	84.30	58.67	6
23	Jun 4 - 10	25.62	30.27	89.47	77.55	83.51	18.80	2
24	Jun 11 - 17	24.53	30.52	88.24	76.98	82.61	34.29	3
25	Jun 18 - 24	24.63	30.45	86.21	71.33	78.77	19.81	1
26	Jun 25-Jul 1	24.47	29.84	87.67	77.04	82.36	40.39	4
27	Jul 2-8	23.61	29.35	86.77	74.36	80.57	69.34	5
28	Jul 9-15	24.14	29.05	91.09	80.13	85.61	27.18	4
29	Jul 16-22	24.51	29.27	88.28	78.47	83.38	5.08	1
30	Jul 23-29	24.58	30.31	88.21	76.03	82.12	4.32	1
31	Jul 30-Aug 5	23.92	28.02	89.23	83.25	86.24	108.20	6
32	Aug 6-12	24.82	29.37	88.23	77.44	82.84	0.76	0
33	Aug 13-19	25.02	30.79	86.93	72.57	79.75	0.00	0
34	Aug 20-26	24.08	29.08	91.11	79.16	85.14	28.96	3

APPENDIX-Ib

**Weather data during *mundakan*
(12 September 2022 to 14 January 2023)**

St. Met Week	Period (2022-2023)	Temperature (°C)		R.H. (%)			Rainfall (mm)	No. of rainy days
		Min.	Max.	RH I	RH II	Mean		
37	Sep 10-16	25.00	29.84	90.22	76.30	83.26	3.81	0
38	Sep 17-23	24.97	30.89	88.90	69.75	79.33	0	0
39	Sep 24-30	25.18	31.53	83.17	66.49	74.83	0	0
40	Oct 1-7	24.64	30.15	88.60	71.59	80.10	14.47	2
41	Oct 8-14	24.32	30.54	87.15	75.02	81.09	53.34	3
42	Oct 15-21	24.09	29.36	92.09	80.10	86.10	183.64	4
43	Oct 22-28	24.00	30.04	93.04	74.67	83.86	43.43	2
44	Oct 29-Nov 4	24.22	30.21	92.25	76.81	84.53	37.34	2
45	Nov 5-11	23.97	30.02	93.32	72.11	82.72	37.34	3
46	Nov 12-18	23.94	30.01	91.38	72.12	81.75	34.04	2
47	Nov 19-25	22.69	30.18	89.75	63.62	76.69	0.25	0
48	Nov 26-Dec 2	24.16	30.49	90.48	70.98	80.73	0.00	0
49	Dec 3-9	24.23	30.10	92.21	73.37	82.79	17.53	2
50	Dec 10-16	22.92	29.83	88.68	69.32	79.00	47.75	2
51	Dec 17-23	23.39	31.30	89.61	64.78	77.20	0.25	0
52	Dec 24-31	23.51	30.68	91.82	70.57	81.20	16.76	1
1	Jan 1-7	21.77	29.80	92.21	62.49	77.35	0.00	0
2	Jan 8-14	22.21	29.80	89.63	66.14	77.89	0.00	0

APPENDIX-Ic

**Weather data during *puncha*
(15 February 2023 to 4 May 2023)**

St. Met Week	Period (2023)	Temperature (°C)		R.H. (%)			Rainfall (mm)	No. of rainy days
		Min.	Max.	RH I	RH II	Mean		
7	Feb 12-18	21.87	30.10	90.49	62.15	76.32	0	0
8	Feb 19-25	22.42	31.52	88.40	61.30	74.85	0	0
9	Feb 26-Mar 4	22.21	31.33	83.11	57.43	70.27	0	0
10	Mar 5-11	23.72	31.69	89.35	63.01	76.18	0	0
11	Mar 12-18	24.90	31.73	86.96	65.78	76.37	0	0
12	Mar 19-25	25.28	32.21	83.37	66.95	75.16	1.02	0
13	Mar 26-Apr 1	26.08	32.50	83.52	69.18	76.35	12.70	1
14	Apr 2-8	25.38	32.33	86.32	68.52	77.42	10.41	1
15	Apr 9-15	25.29	32.40	89.14	70.20	79.67	0.25	0
16	Apr 16-22	26.97	33.09	86.85	70.56	78.705	3.56	1
17	Apr 23-29	26.02	33.06	86.45	71.03	78.74	49.53	3
18	Apr 30-May 6	25.02	32.32	90.20	69.58	79.89	86.87	4
19	May 7-13	25.51	32.18	87.85	73.30	76.32	13.72	1

APPENDIX-II

Average input cost and market price of produce

Sl. No	Items	Cost (₹)
I	INPUT	
A	Seed	
	Paddy Seed	42 per kg
	Cowpea	450 per kg
	Bhindi	1500 per kg
B	Labour	
	Men / Women	1046 per day
C	Fuel	
	Diesel	96.48 per litre
D	Manures, fertilizers and biofertilizers	
	FYM	1 per kg
	Lime	20 per kg
	Urea	7 per kg
	Rock phosphate	15 per kg
	Muriate of Potash	40 per kg
	Nano zinc (Liquid)	600 per 500 mL
	Zinc sulphate	140 per kg
II	OUTPUT	
	Market price of paddy grains	30 per kg
	Market price of paddy straw	5 per kg
	Market price of cowpea	80 per kg
	Market price of bhindi	40 per kg

APPENDIX-III

Standard energy equivalent per unit values for inputs and outputs

Sl. No	Particulars	Unit	Energy Equivalent per unit input or output (MJ unit ⁻¹)	Reference
A	INPUT			
1.	Human labour	hr	1.96	Taki and Yildizhan (2018)
2.	Machinery			
a)	Power tiller	hr	62.70	Patel <i>et al.</i> , (2017)
b)	Electric motor	hr	64.80	Patel <i>et al.</i> , (2017)
3.	Fuel			
a)	Diesel	L	56.31	Yildizhan and Taki, (2019)
4.	Planting material			
a)	Paddy Seed	kg	14.7	Patel <i>et al.</i> , (2017)
b)	Cowpea	kg	14.7	Dey <i>et al.</i> (2024)
c)	Bhindi	kg	2.9	Devasenapathy <i>et al.</i> (2009)
5.	Water	m ³	0.63	Elhami <i>et al.</i> (2021)
6.	Chemical fertilizers			
a)	Nitrogen	kg	60.6	Abdi <i>et al.</i> (2012)
b)	Phosphorus	kg	11.1	Abdi <i>et al.</i> (2012)
c)	Potassium	kg	6.7	Abdi <i>et al.</i> (2012)
d)	Lime	kg	1.320	Pimentel, (1980)
e)	Zinc sulphate	kg	20.9	Taewichit, (2012)
f)	Nano zinc	ml	0.102	Devasenapathy <i>et al.</i> 2009
7.	Farm yard manure	kg	0.3	Unakitan and Aydın, (2018)
8.	PP chemicals			
a)	Insecticides	L	199	Elhami <i>et al.</i> (2021)
b)	Herbicides	L	238	Elhami <i>et al.</i> (2021)
c)	Fungicides	L	92	Elhami <i>et al.</i> (2021)
B	OUTPUT			
1.	Paddy grain	kg	14.7	Patel <i>et al.</i> , (2017)
2.	Paddy straw	kg	12.5	Patel <i>et al.</i> , (2017)
3.	Cowpea grain	kg	14.7	Dey <i>et al.</i> (2024)
4.	Bhindi	kg	1.9	Devasenapathy <i>et al.</i> (2009)

APPENDIX-IVa

Fixed energy input (MJ ha⁻¹) of *virippu* rice

No	Operation	Requirement	Rate of energy, MJ ha ⁻¹
1.	Pre planting operations		
	Land preparation using power tiller	Power tiller	$\frac{\text{Wt of power tiller (kg) X MJ X hr. of operation}}{\text{Life span (hrs)}}$ = $\frac{400 \times 62.7 \times 8}{6000} = 33.44$
		Diesel	(1 l/hr)- for 8 hr $8 \times 1 \times 56.31 = 450.48$
		Labour	(1 Men) = $1 \times 8 \text{ hr} \times 1.96 = 15.68$
	Layout, bund preparation, levelling	Labour	(8 Men) = $9 \times 8 \text{ hr} \times 1.96 = 141.12$
	FYM application	Labour	(1 Men) = $1 \times 8 \text{ hr} \times 1.96 = 15.68$
		FYM	$5000 \times 0.3 = 1500$
	Lime application	Labour	(1 Men) = $1 \times 8 \text{ hr} \times 1.96 = 15.68$
		Lime	$600 \times 1.320 = 792$
	Total energy, MJ ha⁻¹		$33.44+450.48+15.68+141.12+15.68+1500+15.68+792 = 2964.08$
2.	Planting operations		
	Nursery management	Labour	$1 \text{ Men} \times 1.96 \times 8 \text{ hrs} = 15.68$
	Seeds	Seed	$65 \text{ kg} \times 14.7 = 955.50$
	Transplanting	Labour	$12 \text{ women} \times 1.96 \times 8 \text{ hrs} = 188.16$
	Gap filling	Labour	$2 \text{ women} \times 1.96 \times 8 \text{ hrs} = 31.36$
	Total energy, MJ ha⁻¹		$15.68+955.50+188.16+31.36 = 1190.70$
3.	Cultural operations		
	Weeding	Labour	$20 \text{ women} \times 1.96 \times 8 \text{ hrs} = 313.60$
	Fertilizer application	Labour	$4 \text{ Women} \times 1.96 \times 8 \text{ hrs} = 62.72$
		Nitrogen	$139 \text{ kg} \times 60.6 = 8423.4$
		Potassium	$88 \text{ kg} \times 6.7 = 589.6$

	Irrigation	Diesel	For 16 hr (1 litre/hr) = 16 x 1 x 56.31 = 900.96
		Pump (Diesel 5 HP)	Wt of engine (kg) x MJ x hrs of operation = $\frac{150 \times 64.8 \times 16}{10500}$ = 14.81
		Water	192 m ³ x 0.6 = 115.20
	Insecticide / fungicide application	Labour	3 Men x 1.96 x 8 hrs = 47.04
		Insecticide	1 lit x 199 = 199
		Fungicide	1 lit x 92 = 92
	Total energy, MJ ha⁻¹		313.60+62.72+8423.4+589.6+900.96+14.81+115.20+47.04+199+92 = 10758.33
4.	Harvest operations		
	Harvest	Labour	12 Women x 1.96 x 8 hrs = 188.16
	Threshing	Labour	3 Women x 1.96 x 8 hrs = 47.04
	Total energy, MJ ha⁻¹		188.16+47.04 = 235.20
	Grand total, MJ ha⁻¹		15148.31

APPENDIX-IVb

Variable energy input (MJ ha⁻¹) of *virippu* rice

Operation	Variable energy input	Variable energy. MJ ha ⁻¹							
		T ₁	T ₂	T ₃	T ₄	T ₅	T ₆	T ₇	T ₈
1. Pre-planting operations									
Nutri-priming	Nano zinc	-	50 ml x 0.102 = 5.1	50 ml x 0.102 = 5.1					
	ZnSO ₄	-	-	-	0.5 kg x 20.9 = 10.45	0.5 kg x 20.9 = 10.45			
2. Cultural operations									
Fertilizer application	ZnSO ₄ (SA)	20 kg x 20.9 = 418	-	-	-	-	-	-	-
	Phosphorus	120 kg x 11.1 = 1332	120 kg x 11.1 = 1332	120 kg x 11.1 = 1332	120 kg x 11.1 = 1332	120 kg x 11.1 = 1332	120 kg x 11.1 = 1332	120 kg x 11.1 = 1332	-
	ZnSO ₄ (FA)	-	-	-	-	-	-	5 kg x 20.9 = 104.5	-
	Nano Zinc (FA)	-		250 ml x0.102 = 25.5		250 ml x 0.102 = 25.5	500 ml x 0.102 = 51		
	Labour			2 x 8 hr x 1.96 = 31.36		2 x 8 hr x 1.96 = 31.36	4 x 8hr x 1.96 = 62.72	4 x 8hr x 1.96 = 62.72	
Weeding	Labour	-	-	-	-	-	-	-	1 x 8 hr x 1.96 = 15.68
Total variable input		1750.00	1337.10	1393.96	1342.50	1399.31	1445.72	1499.22	15.68

APPENDIX-Va

Fixed energy input (MJ ha⁻¹) of *mundakan* rice

No	Operation	Requirement	Rate of energy, MJ ha ⁻¹
1.	Pre planting operations		
	Land preparation using power tiller	Power tiller	$\frac{\text{Wt of power tiller (kg)} \times \text{MJ} \times \text{hr. of operation}}{\text{Life span (hrs)}}$ $= \frac{400 \times 62.7 \times 5}{6000} = 20.9$
		Diesel	(1 l/hr)- for 5 hr $5 \times 1 \times 56.31 = 281.55$
		Labour	(1 Men) = 1 x 8 hr x 1.96 = 15.68
	Bund preparation, levelling	Labour	(5 Men) = 5 x 8 hr x 1.96 = 78.4
	FYM application	Labour	(1 Men) = 1 x 8 hr x 1.96 = 15.68
		FYM	5000 x 0.3 = 1500
	Lime application	Labour	(1 Men) = 1 x 8 hr x 1.96 = 15.68
		Lime	600 x 1.320 = 792
	Total energy, MJ ha⁻¹		20.9+281.55+15.68+78.4+15.68+1500+15.68+792 = 2719.89
2.	Planting operations		
	Nursery management	Labour	1 Men x 1.96 x 8 hrs = 15.68
	Seeds	Seed	75 kg x 14.7 = 1102.5
	Transplanting	Labour	15 women x 1.96 x 8 hrs = 235.2
	Gap filling	Labour	2 women x 1.96 x 8 hrs = 31.36
	Total energy, MJ ha⁻¹		15.68+1102.5+235.2+31.36 = 1384.74
3.	Cultural operations		
	Weeding	Labour	20 women x 1.96 x 8 hrs = 313.60
	Fertilizer application	Labour	4 Women x 1.96 x 8 hrs = 62.72
		Nitrogen	124 kg x 60.6 = 7514.4
		Potassium	80 kg x 6.7 = 536.0
	Irrigation	Diesel	For 20 hr (1 litre/hr) $= 20 \times 1 \times 56.31 = 1126.2$
		Pump (Diesel 5 HP)	$\frac{\text{Wt of engine (kg)} \times \text{MJ} \times \text{hrs of operation}}{\text{Life span (hrs)}}$ $= \frac{150 \times 64.8 \times 20}{10500} = 18.51$
		Water	240 m ³ x 0.6 = 144.0

	Insecticide / fungicide application	Labour	3 Men x 1.96 x 8 hrs = 47.04
		Insecticide	1 lit x 199 = 199
		Fungicide	1 lit x 92 = 92
	Total energy, MJ ha⁻¹		313.60+62.72+7514.4+536+1126.2+18.51+144+47.04+199 +92 = 10053.47
4.	Harvest operations		
	Harvest	Labour	12 Women x 1.96 x 8 hrs = 188.16
	Threshing	Labour	3 Women x 1.96 x 8 hrs = 47.04
	Total energy, MJ ha⁻¹		188.16+47.04 = 235.2
	Grand total, MJ ha⁻¹		14393.3

APPENDIX-Vb
Variable energy input (MJ ha⁻¹) of *mundakan* rice

Operation	Variable energy input	Variable energy. MJ ha ⁻¹							
		T ₁	T ₂	T ₃	T ₄	T ₅	T ₆	T ₇	T ₈
1. Pre-planting operations									
Nutri-priming	Nano zinc	-	50 ml x 0.102 = 5.1	50 ml x 0.102 = 5.1					
	ZnSO ₄	-	-	-	0.5 kg x 20.9 = 10.45	0.5 kg x 20.9 = 10.45			
2. Cultural operations									
Fertilizer application	Phosphorus	208 kg x 11.1 = 2308.8	208 kg x 11.1 = 2308.8	208 kg x 11.1 = 2308.8	208 kg x 11.1 = 2308.8	208 kg x 11.1 = 2308.8	208 kg x 11.1 = 2308.8	208 kg x 11.1 = 2308.8	-
	ZnSO ₄ (FA)	-	-	-	-	-	-	5 kg x 20.9 = 104.5	-
	Nano Zinc (FA)	-		250 ml x 0.102 = 25.5		250 ml x 0.102 = 25.5	500 ml x 0.102 = 51	-	-
	Labour			2 x 8 hr x 1.96 = 31.36		2 x 8 hr x 1.96 = 31.36	4 x 8hr x 1.96 = 62.72	4 x 8hr x 1.96 = 62.72	-
Total variable input		2308.8	2313.9	2370.76	2319.25	2376.11	2422.52	2476.02	-

APPENDIX-VI
Energy input (MJ ha⁻¹) of *puncha* grain cowpea

No	Operation	Requirement	Rate of energy, MJ ha ⁻¹
1.	Pre planting operations		
	Land preparation, bund preparation, levelling	Labour	(6 Men) = 6 x 8 hr x 1.96 = 94.08
	Total energy, MJ ha⁻¹		94.08
2.	Planting operations		
	Seeds	Seed	40 kg x 14.7 = 588
	Sowing	Labour	6 women x 1.96 x 8 hrs = 94.08
	Total energy, MJ ha⁻¹		588+94.08 = 682.08
3.	Cultural operations		
	Herbicide application	Labour	1 Men x 1.96 x 8 hrs = 15.68
		Herbicide	1 lit x 238 = 238
	Total energy, MJ ha⁻¹		15.68+238 = 253.68
4.	Harvest operations		
	Harvest	Labour	8 Women x 1.96 x 8 hrs = 125.44
	Total energy, MJ ha⁻¹		125.44
	Grand total, MJ ha⁻¹		1155.28

APPENDIX-VII
Energy input (MJ ha⁻¹) of *puncha bhindi*

No	Operation	Requirement	Rate of energy, MJ ha ⁻¹
1.	Pre planting operations		
	Land preparation, bund preparation, levelling	Labour	(6 Men) = 5 x 8 hr x 1.96 = 78.4
	Total energy, MJ ha⁻¹		78.4
2.	Planting operations		
	Seeds	Seed	8 kg x 2.9 = 23.2
	Sowing	Labour	6 women x 1.96 x 8 hrs = 94.08
	Total energy, MJ ha⁻¹		15.2+94.08 = 117.28
3.	Cultural operations		
	Herbicide application	Labour	1 Men x 1.96 x 8 hrs = 15.68
		Herbicide	1 lit x 238 = 238
	Total energy, MJ ha⁻¹		15.68+238 = 253.68
4.	Harvest operations		
	Harvest	Labour	17 Women x 1.96 x 8 hrs = 266.56
	Total energy, MJ ha⁻¹		266.56
	Grand total, MJ ha⁻¹		715.92

**NANO ZINC NUTRITION IN RICE BASED CROPPING
SYSTEMS IN HIGH PHOSPHORUS SOILS**

by

BODDU ARCHANA

(2020-21-046)

ABSTRACT

**Submitted in partial fulfilment of the requirement for the degree of
DOCTOR OF PHILOSOPHY IN AGRICULTURE**

Faculty of Agriculture

Kerala Agricultural University



DEPARTMENT OF AGRONOMY

COLLEGE OF AGRICULTURE

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KERALA, INDIA

2025

ABSTRACT

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The project entitled “Nano zinc nutrition in rice based cropping systems in high phosphorus soils” was conducted at College of Agriculture, Vellayani, Thiruvananthapuram, Kerala, during 2020-2025. The objectives of the study were to evaluate the response of rice to nano zinc in high P soils, study the residual effect of nano zinc nutrition on growth and yield of succeeding crops, study the P - Zn interactions and to identify the promising crop sequence in terms of system productivity and profitability.

The study comprised three parts which were carried out at Integrated Farming System Research Station (IFSRS), Karamana, Thiruvananthapuram, Kerala during 2022-23. The first and second parts of the experiment were laid out in randomized complete block design with three replications using variety Uma (Mo 16) in *virippu* and *mundakan* seasons. The treatments comprised T₁- [Soil application (SA) of ZnSO₄ at 20 kg ha⁻¹ (applied only in *virippu* season)], T₂- [Nutri priming (NP) with nano Zn at 0.05%], T₃- [NP with nano Zn at 0.05% + Foliar spray (FS) with nano Zn at 0.05% at maximum tillering (MT) stage], T₄- [NP with ZnSO₄ at 0.5%], T₅- [NP with ZnSO₄ at 0.5% + FS with nano Zn at 0.05% at MT stage], T₆-[FS with nano Zn at 0.05% at MT and panicle initiation (PI) stages], T₇- [FS with ZnSO₄ at 0.5% at MT and PI stages], T₈- [Control (Recommended Dose of Nutrients (RDN) without application of P and Zn)]. The RDN were 90:45:45 (N:P₂O₅:K₂O) kg ha⁻¹ modified as 64:22:53 kg ha⁻¹ on soil test basis.

The growth and yield attributes of rice were significantly influenced by nano zinc nutrition. Taller plants with the highest number of tillers per m², higher leaf area per hill, leaf area index and dry matter production were recorded in T₃ and was on par with T₆ during both the seasons. The yield attributes *viz.*, higher numbers of productive tillers per hill, grains per panicle, grain weight per panicle and lower sterility percentage were observed in T₃ and was on par with T₆ during both the seasons. The pooled mean over the seasons revealed that the grain yield (5161 kg ha⁻¹) and straw yield (6148 kg ha⁻¹) of rice

were higher in T₃ and was on par with T₆. The grain yield increased by 78 and 69 per cent in T₃ and T₆, respectively over control.

The nutrient uptake by plants at panicle initiation and harvest were significantly affected by zinc nutrition. The higher uptake of N, P, K, Ca and Zn by the rice plants at panicle initiation and harvest were observed in T₃ which was comparable to T₂ and T₆ at panicle initiation and comparable to T₆ at harvest during both *virippu* and *mundakan*. The nutrient use efficiency of P and Zn in terms of agronomic efficiency was the highest in T₃ and T₆, respectively during *virippu* and *mundakan*.

The available nutrient status of the soil after each season was significantly influenced by nano zinc nutrition. The available N, P, K and Zn were higher in T₃ and T₆ during both *virippu* and *mundakan*. The dehydrogenase and phosphatase activities were significantly higher in T₃ and were on par with T₆. The highest net returns (₹ 76622 ha⁻¹ and ₹ 86368 ha⁻¹) and B:C ratio (1.74 and 1.82) were recorded in T₃ during *virippu* and *mundakan*, respectively.

The third part of the experiment was conducted during summer season to study the residual effect of nano zinc nutrition on growth and yield of succeeding crops. The experiment was laid out in strip plot design and was replicated thrice wherein, each individual plots of previous crop were divided to three sub plots and crops *viz.*, grain cowpea (Kanakamony (PTB 1)) and bhindi (Anjitha) were grown in two sub plots and one sub plot was kept as fallow. The main plot treatments were residual nutrients of the previous seasons (N₁ to N₈) and the sub plot treatments were three crop sequences (C₁- rice-rice-grain cowpea, C₂- rice-rice-bhindi, C₃- rice-rice-fallow).

Growth, yield attributes and yield of summer crops *viz.*, grain cowpea and bhindi were higher in N₁. Available N, P, K, Zn, and soil enzyme activities were influenced by the residual nutrient status of the soil and crop sequences. Higher available N was observed in N₆ and N₅, available P, K and dehydrogenase activity were higher in N₃, available Zn was the highest in N₆, and phosphatase activity was higher in N₁. Among the

crop sequences, available P, Zn and dehydrogenase activity were the highest in C₁. Among the interactions, the highest available Ca, available Zn and phosphatase activity were observed in n₈c₂, n₃c₁ and n₁c₁, respectively.

The highest system yield (11504 kg ha⁻¹) and system productivity (32 kg ha⁻¹ day⁻¹) were observed in N₃ which was on par with N₆. The crop sequence C₂ recorded the highest system yield (10592 kg ha⁻¹), while both C₂ and C₁ sequences showed higher system productivity. Among the interactions, n₃c₁ and n₃c₂ recorded the highest system yield (12100 and 12090 kg ha⁻¹, respectively) and system productivity (33 kg ha⁻¹ day⁻¹, respectively).

The highest energy efficiency, the lowest specific energy, the highest energy productivity and the highest energy intensity were recorded in N₃. Among the crop sequences, C₁ recorded the highest energy efficiency (7.42) and energy productivity was higher in C₂ (0.62 kg MJ⁻¹). Among the interactions, n₃c₃ recorded the highest energy efficiency.

The data on nutrient balance showed a net gain of nitrogen in all treatments in C₁ and C₂, except N₈. The rice-rice-fallow sequence showed a net gain in N₃, and N₆. Available phosphorus showed a net loss among all sequences and all treatments except N₈. Potassium had a positive balance in the rice-rice-grain cowpea and rice-rice-bhindi in all treatments except N₈. In rice-rice-fallow sequence, net gain of K was observed in N₃ and N₆. Zinc balance was positive in all the crop sequences and all the treatments except N₁ and N₇ which recorded net loss of Zn.

Among the residual nutrients, the highest system net returns (₹ 173627 ha⁻¹) and B:C ratio (1.49) were observed in N₃ whereas, among crop sequences, rice-rice-bhindi (C₂) showed the highest net returns (₹ 114127 ha⁻¹) and B:C ratio (1.47). Among the treatment combinations, n₃c₂ recorded the highest net returns (₹ 182091 ha⁻¹) and the highest B:C ratio (1.79) in n₃c₃.

From the study, it can be concluded that nutri priming with nano zinc at 0.05% (50 ml ha⁻¹) followed by foliar spray of nano zinc at 0.05% (250 ml ha⁻¹) at maximum tillering stage along with soil test basis recommended dose of nutrients was effective way in enhancing the productivity and profitability of rice in high phosphorus soils. The growth and yield of grain cowpea and bhindi were the highest in residual nutrient with soil application of ZnSO₄ at 20 kg ha⁻¹ [applied only in *virippu*]. Rice-rice-bhindi was identified as the promising crop sequence in terms of system productivity and system profitability.

സംഗ്രഹം

“ഫോസ്ഫറസ് കൂടിയ മണ്ണിലെ നെല്ല്വിഷ്ഠിത വിളസമ്പ്രദായത്തിൽ നാനോ സിങ്ക് പോഷണം” എന്ന വിഷയത്തിൽ തിരുവനന്തപുരം വെള്ളായണി കാർഷിക കോളേജിൽ 2020-2025 കാലയളവിൽ ഒരു ഗവേഷണം നടത്തുകയുണ്ടായി. ഫോസ്ഫറസ് കൂടിയ മണ്ണിൽ നാനോ സിങ്ക്നോട് നെല്ല്വിഷ്ഠിത പ്രതികരണം, നാനോ സിങ്ക് പോഷണത്തിന്റെ അവശിഷ്ടത്തിൽ അടുത്ത വിളയുടെ വളർച്ച, ഫോസ്ഫറസ്-സിങ്ക് പാരസ്പര്യം, വിള സമ്പ്രദായത്തിന്റെ ഉല്പാദനക്ഷമത, ലാഭസാധ്യത എന്നിവയുടെ അടിസ്ഥാനത്തിൽ മികച്ച വിളകൃമം തിരിച്ചറിയുക തുടങ്ങിയവയായിരുന്നു ഈ പഠനത്തിന്റെ പ്രധാന ലക്ഷ്യങ്ങൾ.

കേരള കാർഷിക സർവ്വകലാശാലയുടെ കീഴിൽ കരമനയിൽ പ്രവർത്തിക്കുന്ന സംയോജിത കൃഷി സമ്പ്രദായ ഗവേഷണ കേന്ദ്രത്തിൽ 2022-2023 കാലയളവിൽ ഫീൽഡ് പഠനം നടത്തി. മൂന്ന് ഭാഗങ്ങളായി തിരിച്ച് നടത്തിയ ഈ ഗവേഷണത്തിന്റെ ആദ്യ രണ്ടു ഭാഗങ്ങൾ വിരിപ്പ്, മൂണ്ടകൻ കാലങ്ങളിൽ റാൻഡമൈസ്ഡ് കമ്പ്ളിറ്റ് ബ്ലോക്ക് ഡിസൈനിൽ മൂന്നു ആവർത്തനങ്ങളിലായി ഉമ വിത്തിനം ഉപയോഗിച്ച് ചെയ്തു. T₁ - [ZnSO₄ @20 kg ha⁻¹ മണ്ണിലൂടെ നൽകുക (വിരിപ്പ് സീസണിൽ മാത്രം)]; T₂ - [0.05% നാനോ സിങ്ക് ഉപയോഗിച്ച് ന്യൂട്രീപ്രെമിംഗ്]; T₃ - [0.05% നാനോ സിങ്ക് ഉപയോഗിച്ച് ന്യൂട്രീപ്രെമിംഗ് + പരമാവധി ചിനപ്പ് പൊട്ടുന്ന സമയത്ത് 0.05% നാനോ സിങ്ക് പത്ര പോഷണമായി നൽകുക]; T₄ [ZnSO₄ 0.5% ഉപയോഗിച്ച് ന്യൂട്രീപ്രെമിംഗ് ചെയ്യുക] T₅ - [ZnSO₄ 0.5% ഉപയോഗിച്ച് ന്യൂട്രീപ്രെമിംഗ് ചെയ്യുക + 0.05% നാനോ സിങ്ക് പത്ര പോഷണമായി നൽകുക]; T₆ - [പരമാവധി ചിനപ്പ് പൊട്ടുന്ന സമയത്തും കതിർ വരുന്ന സമയത്തും 0.05% നാനോ സിങ്ക് പത്ര പോഷണമായി നൽകുക]; T₇ - [ZnSO₄ 0.5% പത്ര പോഷണമായി പരമാവധി ചിനപ്പ് പൊട്ടുന്ന സമയത്തും കതിർ വരുന്ന സമയത്തും നൽകുക]; T₈ - [കൺട്രോൾ -ശുപാർശ പ്രകാരമുള്ള പോഷകങ്ങൾ ഫോസ്ഫറസും സിങ്ക് ഉൾപ്പെടുത്താതെ നൽകുക] തുടങ്ങിയവയാണ് ആദ്യരണ്ടു ഭാഗങ്ങളിലെ ട്രീറ്റ്മെന്റുകൾ.

ഗവേഷണത്തിന്റെ മൂന്നാം ഭാഗം നാനോ സിങ്ക് പോഷണത്തിന്റെ അവശിഷ്ടത്തിൽ അടുത്ത വിളയുടെ വളർച്ചയും ഉൽപ്പാദനവും പഠിക്കുക എന്നതായിരുന്നു. വേനൽക്കാലത്ത് നടത്തിയ ഈ പഠനം സ്ട്രിപ് പ്ലോട്ട് ഡിസൈനിൽ മൂന്നു

ആവർത്തനങ്ങളിലായി ചെയ്തു. ഇതിൽ ആദ്യം കൃഷി ചെയ്ത പ്ലോട്ടുകൾ മൂന്ന് സബ്പ്ലോട്ടുകളായി തിരിച്ച് അതിൽ രണ്ടു പ്ലോട്ടിൽ വൻപയർ (കനകമണി (PTB1)), വെണ്ട(അഞ്ചിത) എന്നിവ വളർത്തി, മറ്റൊരു സബ് പ്ലോട്ട് തരിശായി ഇടുകയും ചെയ്തു. മെയിൻ പ്ലോട്ട് ട്രീറ്റ്‌മെന്റുകൾ കഴിഞ്ഞ സീസണിലെ അവശിഷ്ട പോഷകങ്ങളും, സബ് പ്ലോട്ട് ട്രീറ്റ്‌മെന്റുകൾ മൂന്ന് വിള ക്രമങ്ങളുമായിരുന്നു (C₁ - നെല്ല്-നെല്ല്-വൻപയർ ,C₂- നെല്ല്-നെല്ല്-വെണ്ട, C₃- നെല്ല്-നെല്ല്-തരിശ് നിലം).

മണ്ണു പരിശോധനയുടെ അടിസ്ഥാനത്തിൽ ശുപാർശ പ്രകാരമുള്ള പോഷകങ്ങൾ നൽകുന്നതോടൊപ്പം നെൽവിത്ത് നാനോ സിങ്ക് 0.05 ശതമാനം ന്യൂട്രീ പ്രൈമിംഗ് ചെയ്യുകയും തുടർന്ന് പരമാവധി ചിനപ്പ് പൊട്ടുന്ന സമയത്ത് നാനോ സിങ്ക് 0.05 ശതമാനം പത്രപോഷണം നൽകുന്നത് വഴി ഫോസ്ഫറസ് കൂടിയ മണ്ണിൽ നെല്ലിന്റെ ഉല്പാദനക്ഷമതയും, ലാഭസാധ്യതയും വർദ്ധിക്കുന്നതായി പ്രസ്തുത പഠനത്തിൽ നിന്നും കണ്ടെത്തി. കൂടാതെ, P-Zn പാരസ്പര്യം ലഘൂകരിക്കാൻ മേൽപറഞ്ഞ രീതി വളരെയധികം പ്രായോഗികമാണെന്നും മനസ്സിലായി. ZnSO₄@20 കിലോഗ്രാം ഒരു ഹെക്ടറിന് എന്ന തോതിൽ മണ്ണിൽ നൽകിയതിന്റെ അവശിഷ്ട പോഷണത്തിൽ വൻപയറിനും വെണ്ടയ്ക്കും കൂടുതൽ വിളവ് ലഭിച്ചു. തിന്റെ ഉല്പാദനക്ഷമത, ലാഭസാധ്യത എന്നിവയുടെ അടിസ്ഥാനത്തിൽ നെല്ല്-നെല്ല്-വെണ്ട എന്ന വിളക്രമമാണ് ഏറ്റവും മികച്ചതെന്ന് ഈ പഠനത്തിലൂടെ കണ്ടെത്തി.