Effect of Nitrogen and Zinc Fertilizer Application on Growth and Yield of Rice (*Oryza sativa* L.)

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ABSTRACT

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| Nitrogen (N) and zinc (Zn) are critical nutrients that often limit yield in flooded rice systems. To investigate the effects of varying N and Zn fertilizer rates on the growth, yield, and nutrient use efficiency of rice (*Oryza sativa* L. cv. Sinthuka) during both dry and wet seasons through pot experiments conducted at the Yezin Agricultural University farm. The experiment was designed as a 4×3 factorial arrangement with three replications, evaluating four nitrogen application rates (0, 40, 80, and 120 kg ha⁻¹) and three zinc application rates (0, 10, and 20 kg ha⁻¹). Nitrogen application significantly enhanced plant height, tiller number, and grain yield. While the maximum grain yield was achieved at 120 kg N ha⁻¹ during the dry season, no statistically significant differences were observed between 120 kg N ha⁻¹ and 80 kg N ha⁻¹ across key growth and yield parameters, indicating that 80 kg N ha⁻¹ is likely the optimal rate for sustainable productivity in both seasons. Zinc application at 10 kg ha⁻¹ significantly increased filled grain percentages (71.20% compared to 61.97% in the control) and exhibited a synergistic interaction with nitrogen, further enhancing grain yield. The highest yields were recorded with 120 kg N ha⁻¹ combined with 10 kg Zn ha⁻¹ (71.05 g hill⁻¹) in the dry season and 80 kg N ha⁻¹ combined with 10 kg Zn ha⁻¹ (43.43 g hill⁻¹) in the wet season. Therefore, the application of 80 kg N ha-1 and 10 kg Zn ha-1 might be the appropriate rate to maximize the rice production. Considering the increased grain yield of rice, nitrogen rate 80 kg N ha-1 and zinc rate 10 kg Zn ha-1 should be used in this study area. |

*Keywords: Rice, Nitrogen, Zinc and Yield components, grain,* *synergistic interaction*

**1. INTRODUCTION**

Rice is one of the staple food crops for about half of the world's population, making its production critical for global food security. The global demand for rice is expected to increase significantly, from 439 million tons in 2010 to 496 million tons by 2020 and 553 million tons by 2035 [1]. To meet this growing demand, enhancing rice productivity while addressing both agronomic and environmental challenges is vital.

Nitrogen (N) is the most critical nutrient for rice growth, yield, and grain quality [2]. However, limited nitrogen availability often restricts crop performance [3], while excessive use of N fertilizers can lead to increased costs, reduced profitability, and environmental issues such as soil acidification, eutrophication, and micronutrient imbalances [4]. Continuous rice cultivation without proper fertilizer management has also resulted in nutrient depletion, further complicating efforts to sustainably boost yields. Additionally, unpredictable weather patterns, such as droughts and floods, affect fertilizer efficiency and rice productivity [5].

Zinc (Zn) deficiency is another significant challenge that limits rice production and poses risks to human health, particularly in regions where populations rely heavily on cereal-based diets. Cereals like rice are more susceptible to Zn deficiency than legumes, leading to yield losses and reduced grain quality [6]. Zinc is essential for metabolic processes, enzymatic activity, chlorophyll synthesis, and stress tolerance in rice [7]. In Asia, Zn deficiency is a major nutritional stress affecting yields, influenced by factors such as soil pH, redox potential, bicarbonate levels, and interactions with phosphorus (P), iron (Fe), and manganese (Mn) [8].

Interestingly, nitrogen fertilization, particularly with urea, has been found to enhance zinc uptake in flooded rice systems, performing better than ammonium nitrate (NH₄NO₃) in increasing grain Zn concentrations [9]. However, the rising cost of urea poses challenges for smallholder farmers, emphasizing the need for precise nutrient management strategies. While extensive research has explored rice's response to nitrogen, the interactions between nitrogen and zinc remain underexplored.

Farmers in Myanmar, for example, primarily focus on macronutrients when growing rice, with minimal attention given to micronutrients. This highlights the broader need for balanced nutrient management practices that address both macronutrient and micronutrient deficiencies to improve rice productivity and grain quality.

Against this backdrop, the present study aims to investigate the effects of nitrogen (N) and zinc (Zn) fertilizer application on rice growth and yield. The goal is to identify optimal nutrient combinations that can enhance productivity while ensuring sustainable agricultural practices and improved grain quality.

2. materials and method

The pot experiments were conducted over two seasons: the dry season from January to June and the wet season from July to November in 2024. All experiments were performed at the Yezin Agricultural University farm. A factorial arrangement of 4×3 was implemented within a Randomized Complete Block Design (RCBD), comprising three replications, resulting in a total of twelve treatments.

Pot size used for rice cultivation was 31 cm diameter × 30 cm height. Thirty-six black plastic pots, each pot filled with 15 kg of thoroughly mixed soil to a depth of 20 cm, allowing for a 10 cm space at the top for irrigation purposes. In the second season experiment, the same treatments were applied to the same plots as in the first season. The rice variety tested in this experiment was Sinthuka, 21- day old seedlings were transplanted one plant per pot.

Prior to the initiation of the experiment, soil samples were collected to analyze key physicochemical properties, with results documented in Table 1. The applied fertilizers were urea, triple superphosphate (TSP), and muriate of potash (MOP) as sources of nitrogen (N), phosphorus (P), and potassium (K), respectively. The triple superphosphate (TSP) was applied as a basal fertilizer. Urea and MOP were applied in three equal splits: during basal application, tillering, and panicle initiation stage.

Zinc sulfate heptahydrate (ZnSO₄·7H₂O), which contains 22% zinc, was used as the zinc source. Different zinc application rates were applied as a basal treatment at transplanting, except in the control treatment. Normal agronomic practices, including irrigation, weed control, and pest and disease management, were employed throughout the experiment as necessary to ensure optimal growth conditions.

2.1 DATA COLLECTION

Data collection was conducted systematically to evaluate growth parameters and yield characteristics of the plants. Growth parameters, including plant height, the number of tillers per hill, and SPAD readings, were recorded from each pot at two-week intervals, commencing from 14 days after transplanting (DAT) and continuing until the heading stages. Upon reaching maturity, comprehensive assessments were conducted to determine yield and its component traits. The grain yield was measured from each pot at harvest using a digital balance, with the values adjusted to a standard moisture content of 14%.

2.2 DATA ANALYSIS

The data were analyzed using ANOVA with Statistix 8 software, and the treatment means were compared using the least significant difference (LSD) test at a 5% level.

Table 1. Some physicochemical properties of experimental soil

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Characteristics** | **Rating** | | **Analytical methods** | |
| % sand | 82.27 |  | | |
| % silt | 11.10 | |  |
| % clay | 6.63 | |  |
| Texture class | Loamy sand | | [10] |
| pH | 6.2 (Slightly acid) | | [11] |
| CEC (cmol kg-1) | 2.73 (Very low) | | [12] |
| EC (dS m-1) | 0.01 (Non-saline) | | [11] |
| OM (%) | 1.52 (Low) | | [13] |
| Total Nitrogen (%) | 0.13 | | [11] |
| Available P (mg kg-1) | 3 (low) | | [11] |
| Available K (mg kg-1) | 23 (low) | | [14] |
| DTPA Zn (mg kg-1) | 0.6 (marginal) | |  |

3. results

3.1 Growth Parameter

3.1.1 Plant Height (cm)

In both seasons, plant height exhibited a progressive increase across all treatments, ranging from 14 DAT to 84 DAT. During the dry season, plant height varied from 15 cm to 71 cm, with the minimum plant height recorded in the N0Zn0 treatment and the maximum in the N3Zn1 treatment (Figure 1). In the wet season, the plant height ranged from 23.33 cm to 102 cm, with statistically significant differences observed at both the 5% and 1% levels at 42 DAT and 84 DAT. The minimum plant height was obtained from N0Zn0 and the maximum in N2Zn1.

3.1.2 Number of tillers hill-1

The number of tillers per hill showed a statistically significant difference at 28 DAT. The maximum number of tillers was recorded in the N3Zn1 treatment, while the minimum was observed in N0Zn0 during the dry season (Figure 2). Similarly, during the wet season, significant differences were noted at 28 DAT, with the highest tiller number was recorded in the N2Zn1 treatment and the lowest in N0Zn0. Across both seasons, the number of tillers per hill increased from 42 DAT to 70 DAT.

3.1.3 SPAD reading

Statistical analyses indicated no significant differences in SPAD reading among treatments at all growth stages (Figure 3). During the dry season, the highest SPAD reading was recorded in the N2Zn1 treatment at 56 DAT, while the lowest was in the N0Zn0 treatment at 70 DAT. All treatments showed significantly higher SPAD readings compared to the control (N0Zn0). In the wet season, SPAD readings ranged from 33.53 to 44.30, with the lowest observed at 84 DAT and the highest at 56 DAT.

3.2 YIELD AND YIELD CONTRIBUTING CHARACTERS

3.2.1 Panicle length (cm)

During the dry season, panicle length ranged from 18.67 cm (control, 0 kg N ha-1) to 21.47 cm (120 kg N ha-1) (Table 2). Although increasing nitrogen rates corresponded to longer panicle lengths, no statistical differences were noted between the 80 kg ha-1 and 120 kg ha-1 treatments. Zinc fertilizer application did not result in significant differences in panicle length; however, the application of 20 kg Zn ha-1 resulted in the longest panicle lengths, contrasting with the control (0 kg Zn ha-1). No significant interaction between nitrogen and zinc fertilizer application were observed.

In the wet season, panicle length ranged from 19.10 cm to 21.40 cm across nitrogen treatments (Table 3) with the longest panicles recorded in the 80 kg N ha-1 treatment, which did not differ significantly from the 120 kg N ha-1 treatment. Similarly, the highest panicle length was achieved with 20 kg Zn ha-1, with no statistical difference from the 10 kg Zn ha-1 treatment. Consistent with the dry season, no significant interaction between nitrogen and zinc fertilizer application were observed.

3.2.2 Number of panicles hill-1

A significant difference (Pr < 0.01) was noted in the number of panicles per hill among treatments during the dry season, ranging from 28.78 to 36.22. The maximum number of panicles per hill was associated with the 120 kg N ha-1 treatment, while the minimum was observed in the control (0 kg N ha-1) (Table 2). No significant differences were found in the number of panicles per hill attributable to zinc fertilizer rates, with varying between 31.50 and 34.75. There was no significant interaction between nitrogen and zinc fertilizer application on number of panicles per hill.

During the wet season, significant differences were observed at both the 1% and 5% levels for the number of panicles per hill among nitrogen and zinc treatments (Table 3). The number of panicles per hill ranged from 11.56 to 20.11 across nitrogen treatments and 15.58 to 18.13 among zinc treatments. As the dry season, there was no significant interaction between nitrogen and zinc fertilizer application on number of panicles per hill.

3.2.3 Number of spikelets panicle-1

In the dry season, no significant differences were noted in the number of spikelets per panicle due to varied nitrogen and zinc fertilizer treatments (Table 2). The maximum number of spikelets per panicle was recorded in the 120 kg N ha-1 treatment, which did not differ statistically from the 80 kg N ha-1 treatment. The control treatment (0 kg N ha-1, 0 kg Zn ha-1) yielded the minimum spikelets number, which ranged from 141.08 to 146.83 due to varied zinc fertilizer treatments. There was no significant interaction between nitrogen and zinc fertilizer application on number of spikelets per panicle.

The wet season data revealed statistically significant differences at the 1% level in the number of spikelets per panicle across treatments (Table 3). The maximum spikelets number were noted with the 80 kg N ha-1 and 10 kg Zn ha-1 treatments, with no statistically significant difference from the 120 kg N ha-1 and 20 kg Zn ha-1 treatments. Similar to previous findings, no significant interaction between nitrogen and zinc fertilizer application was observed.

3.2.4 Filled grain percentage (%)

In the dry season, a significant difference in the percentage of filled grains was noted among nitrogen and zinc fertilizer at both the 1% and 5% significance levels (Table 2). The filled grain percentage ranged from 61.97% to 74.52%, with the maximum percentage (74.52%) recorded in the 120 kg N ha-1 but it was not statistically different from 80 kg N ha-1. Regarding zinc treatment, the maximum filled grain percentage was achieved with 10 kg Zn ha-1. No significant interaction between nitrogen and zinc fertilizer application was observed.

During the wet season, similar results were observed with a significant difference in the filled grain percentage at 1% level among nitrogen and zinc treatments (Table 3). The maximum filled grain percentage among nitrogen treatments was observed in 120 kg N ha-1, with no statistical difference from the 80 kg N ha-1 treatment. In terms of zinc treatment, the maximum filled grain percentage was also recorded at 10 kg Zn ha-1, showing no significant difference from the 20 kg Zn ha-1 treatment. There was no significant interaction between nitrogen and zinc fertilizer application on filled grain percentage.

3.2.5 1000 grain weight (g)

In the dry season, analysis revealed no significant differences in 1000 grain weight across varying rates of nitrogen fertilizers (Table 2). The maximum 1000 grain weight, recorded at 20.09 g, was found in the 120 kg N ha-1 treatment, which did not significantly differ from the 80 kg N ha-1 treatment. Similarly, the effect of zinc treatments showed no statistical difference among treatments, with the maximum 1000 grain weight observed in the 10 kg Zn ha-1 treatment. Furthermore, no significant interaction between nitrogen and zinc fertilizer application were detected.

During the wet season, the same trend persisted, as no significant differences were found among treatments due to varying nitrogen fertilizer rates (Table 3). The maximum 1000 grain weight was achieved with the 120 kg N ha-1 treatment, whereas the control treatment (0 kg N ha-1) exhibited the minimum weight. Likewise, there were no statistically significant differences among zinc treatments, with the maximum weight again recorded at 10 kg Zn ha-1. The interaction between nitrogen and zinc treatments remained statistically non-significant.

3.2.6 Grain yield (g hill-1)

In the dry season, varying rates of nitrogen fertilizer significantly impacted grain yield at the 1% level (Table 2). Nitrogen rate, 120 kg N ha-1 resulted in the maximum grain yield of 71.05 g per hill, which was not statistically different from that of 80 kg N ha-1. The effect of zinc fertilizers also indicated a significant impact on grain yield at the 1% level, with the maximum yield recorded from the 10 kg Zn ha-1. Notably, significant interaction effects between nitrogen and zinc fertilizer applications were evident at the 5% level (Figure 4). Grain yield showed a noticeable response to nitrogen application both with and without zinc. Without zinc, increasing nitrogen rates led to a moderate increase in grain yield, but the response plateaued at higher nitrogen levels. With zinc, the grain yield was consistently higher at each nitrogen level compared to treatments without zinc. Combination of N3Zn1 treatment produced maximum grain yield which was not statistically significant from N2Zn1 treatment. On the other hand, the lowest grain yield was found with the combination of N0Zn0 treatment.

During the wet season, statistically significant differences in grain yield were found at the 1% level due to the varying rates of nitrogen fertilizers (Table 3). The 80 kg N ha-1 treatment produced the maximum grain yield, whereas the lowest yield was observed with the control treatment (0 kg N ha-1). Additionally, the effect of zinc fertilizers demonstrated significant impacts on grain yield at the 1% level, and significant interaction between nitrogen and zinc fertilizer application was also found at this level of significance (Figure 4). Combination of N2Zn1 treatment produced the highest grain yield which was statistically significant from N3Zn1 treatment. On the other hand, the minimum grain yield was found with the combination of N0Zn0 treatment which was not statistically significant from N0Zn1 treatment.

1.  (b)



**42 DAT,**

**Pr > F = (\*)**

**84 DAT,**

**Pr > F = (\*\*)**

Figure.1 Mean value of plant height as affected by combined application of nitrogen and zinc fertilizer application in (a) dry season, (b) wet season, 2024

1.  (b)



**28 DAT,**

**Pr > F = (\*)**

**28 DAT,**

**Pr > F = (\*)**

Figure.2 Mean value of number of tillers hill-1 as affected by combined application of nitrogen and zinc fertilizer application in (a) dry season, (b) wet season, 2024

1. (b)



Figure.3 Mean value of SPAD reading as affected by combined application of nitrogen and zinc fertilizer application in (a) dry season, (b) wet season, 2024

Table.2 Yield and yield contributing characters of rice as affected by nitrogen and zinc fertilizer application in dry season, 2024

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Treatments** | **Panicle  length  (cm)** | | **No. of panicle  hill-1(no.)** | | **No. of spikelets  panicle-1 (no.)** | | **Filled grain %** | | **1000grain  weight(g)** | | **Grain yield (g hill-1)** | |
|  |
| 0 kg N ha-1 | 18.67 | b | 28.78 | c | 133.89 |  | 61.97 | c | 19.31 |  | 44.74 | c |  |
| 40 kg N ha-1 | 19.43 | b | 32.22 | bc | 142.56 |  | 65.94 | b | 19.68 |  | 58.33 | b |  |
| 80 kg N ha-1 | 21.19 | a | 35.67 | ab | 148.78 |  | 72.04 | a | 19.93 |  | 70.11 | a |  |
| 120 kg N ha-1 | 21.47 | a | 36.22 | a | 152.56 |  | 74.52 | a | 20.09 |  | 71.05 | a |  |
| LSD 0.05 | 1.06 |  | 3.74 |  | 14.79 |  | 3.82 |  | 0.58 |  | 3.40 |  |  |
| 0 kg Zn ha-1 | 19.91 |  | 31.50 |  | 141.08 |  | 65.87 | b | 19.52 |  | 54.09 | b |  |
| 10 kg Zn ha-1 | 20.31 |  | 34.75 |  | 146.83 |  | 71.20 | a | 20.02 |  | 65.99 | a |  |
| 20 kg Zn ha-1 | 20.35 |  | 33.42 |  | 145.42 |  | 68.77 | ab | 19.71 |  | 63.10 | a |  |
| LSD 0.05 | 0.92 |  | 3.24 |  | 12.81 |  | 3.31 |  | 0.50 |  | 2.95 |  |  |
| Pr ≥ F |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Nitrogen | \*\* |  | \*\* |  | ns |  | \*\* |  | ns |  | \*\* |  |  |
| Zinc | ns |  | ns |  | ns |  | \* |  | ns |  | \*\* |  |  |
| N × Zn | ns |  | ns |  | ns |  | ns |  | ns |  | \* |  |  |
| CV% | 5.36 |  | 11.51 |  | 10.47 |  | 5.70 |  | 3.01 |  | 5.71 |  |  |

In a column, means having the same letters are not significantly different at 5% level.

\* Significant difference at 5% level, \*\* Significant difference at 1% level

Table.3 Yield and yield contributing characters of rice as affected by nitrogen and zinc fertilizer application in wet season, 2024

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Treatments** | **Panicle  length  (cm)** | | **No. of panicle  hill-1(no.)** | | **No. of spikelets  panicle-1 (no.)** | | **Filled grain %** | | **1000grain  weight(g)** | | **Grain yield (g hill-1)** | |
|  |
| 0 kg N ha-1 | 19.10 | c | 11.56 | c | 118.00 | c | 68.84 | c | 19.98 |  | 18.76 | c |  |
| 40 kg N ha-1 | 20.15 | b | 16.28 | b | 123.00 | b | 73.09 | b | 20.18 |  | 29.60 | b |  |
| 80 kg N ha-1 | 21.40 | a | 20.11 | a | 131.00 | a | 79.68 | a | 20.37 |  | 43.43 | a |  |
| 120 kg N ha-1 | 21.29 | a | 19.78 | a | 129.11 | a | 81.49 | a | 20.48 |  | 42.43 | a |  |
| LSD 0.05 | 1.02 |  | 1.87 |  | 3.41 |  | 3.57 |  | 0.47 |  | 3.51 |  |  |
| 0 kg Zn ha-1 | 20.33 |  | 15.58 | b | 122.42 | b | 72.95 | b | 20.10 |  | 28.59 | c |  |
| 10 kg Zn ha-1 | 20.49 |  | 18.13 | a | 127.92 | a | 77.96 | a | 20.38 |  | 38.48 | a |  |
| 20 kg Zn ha-1 | 20.64 |  | 17.08 | ab | 125.50 | a | 76.41 | a | 20.28 |  | 33.76 | b |  |
| LSD 0.05 | 0.88 |  | 1.62 |  | 2.95 |  | 3.09 |  | 0.40 |  | 3.04 |  |  |
| Pr ≥ F |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Nitrogen | \*\* |  | \*\* |  | \*\* |  | \*\* |  | ns |  | \*\* |  |  |
| Zinc | ns |  | \* |  | \*\* |  | \*\* |  | ns |  | \*\* |  |  |
| N × Zn | ns |  | ns |  | ns |  | ns |  | ns |  | \*\* |  |  |
| CV% | 5.08 |  | 11.27 |  | 2.79 |  | 4.82 |  | 2.41 |  | 10.68 |  |  |

In a column, means having the same letters are not significantly different at 5% level.

\* Significant difference at 5% level, \*\* Significant difference at 1% level

1. (b)

**Pr > F = (\*\*)**

**LSD 0.05 = 6.08**

**CV % = 10.68**

**Pr > F = (\*)**

**LSD 0.05 = 5.90**

**CV % = 5.71**

N0 – 0 kg N ha-1, N1- 40 kg N ha-1, N2 – 80 kg N ha-1, N3 – 120 kg N ha-1

Zn0  – 0 kg Zn ha-1, Zn1 – 10 kg Zn ha-1, Zn2 – 20 kg Zn ha-1

Figure.4 Mean value of grain yield as affected by combined application of nitrogen and zinc fertilizer application in (a) dry season, (b) wet season, 2024

**4. DISCUSSION**

The findings of this study point out the critical roles of nitrogen (N) and zinc (Zn) fertilization in optimizing rice growth, yield components, and grain productivity, while highlighting their main effect and interactive effect under pot conditions. The results align with prior research on nutrient management in rice systems [15] while also offering new perspectives on the synergistic potential of N and Zn combinations, particularly in regions where micronutrient deficiencies and imbalanced fertilization practices persist [16].

**4.1 Growth parameters**

Plant height and tiller production exhibited significant responses to both N and Zn applications, with the highest values observed under combined treatments (e.g., N3Zn1 in the dry season and N2Zn1 in the wet season). These results corroborate earlier studies demonstrating N’s role in promoting vegetative growth and Zn’s function in enhancing cell elongation and meristematic activity [17].

**4.1.1 Plant height (cm)**

The progressive increase in plant height across treatments highlights N’s dominance in driving vegetative growth, particularly at higher rates (120 kg N ha-1 in the dry season and 80 kg N ha-1 in the wet season). The synergistic effect of Zn (10 kg ha-1) in amplifying N’s impact suggests that Zn mitigates structural limitations to growth, possibly by enhancing auxin activity or cell wall integrity [18]. Seasonal variations in optimal N-Zn combinations (N3Zn1 vs. N2Zn1) may reflect differences in temperature and light intensity of the two seasons, which influence nutrient uptake efficiency [19].

**4.1.2 Number of tillers hill-1 (no.)**

Tiller numbers peaked at 70 DAT before declining, likely due to self-shading and resource competition among tillers. The highest tiller number under N3Zn1 (dry season) and N2Zn1 (wet season) indicate that Zn alleviates N-induced tiller senescence, possibly by improving root oxidative capacity [20]. Zn-modulated root exudates promote the proliferation of beneficial microbes in the rhizosphere. These microbes, such as nitrogen-fixing bacteria, contribute to N mineralization and increase the availability of ammonium and nitrate ions for plant uptake [21]. No significant difference between Zn rates (10 vs. 20 kg ha-1) suggests a threshold effect, beyond which additional Zn does not enhance tillering [22].

**4.1.3 SPAD reading**

SPAD reading values were consistently higher in treated plants compared to the control, highlighting the positive effect of fertilization on chlorophyll content. Although zinc fertilization is known to increase chlorophyll concentration in rice leaves [23] and plays a role in chlorophyll biosynthesis through nutrient regulation [24], no significant differences were observed among zinc fertilizer rates in this study. The increase in SPAD readings was mainly attributed to nitrogen fertilization, as nitrogen is a fundamental component of chlorophyll and directly influences leaf greenness. This result agrees with the findings of [25], who reported that SPAD-502 chlorophyll meter readings were significantly affected by different nitrogen fertilizer sources. Similarly, [26] found that nitrogen application led to a significant increase in SPAD values with nitrogen application.

**4.2 Yield contributing characters and grain yield**

Nitrogen application significantly influenced panicle length, spikelet number, and filled grain percentage, particularly at rates of 80 kg N ha-1 and 120 kg N ha-1. These findings align with [27], who emphasized N’s dominance in determining sink capacity. Zinc, applied at 10 kg ha-1 and 20 kg Zn ha-1 enhanced filled grain percentages and panicle length, likely by mitigating oxidative stress and improving pollen viability [28]. Notably, the interaction between N and Zn significantly boosted grain yield in both seasons, with the maximum grain yield achieved at 120 kg N ha-1 (dry season) and 80 kg N ha-1 (wet season) combined with 10 kg Zn ha-1 [29].

**4.2.1 Panicle length and spikelet number**

Panicle elongation and spikelet formation were maximized at 120 kg N ha-1 in the dry season, however, 80 kg N ha-1 in the wet season; this author [30] revealed that increase in spikelet number by N is the result of increase in panicle length. Recent study [31] showed that the increase in the number of spikelets panicle-1 by nitrogen fertilization is associated with an increase in cytokinin contents. Zinc’s marginal effect on panicle length (20 kg ha-1) suggests that Zn’s primary contribution lies in post-anthesis processes, such as grain filling, rather than structural development [32].

**4.2.2 Filled grain percentage (%)**

Zn’s enhancement of filled grains (71.2% at 10 kg ha-1) pointed out its role in reducing spikelet sterility. Previous studies confirmed that Zn fertilizer enhanced the number of grains panicle-1 through improving physiological processes of the crop such as photosynthesis and nutrient translocation [33]. The interaction effect (N × Zn) further highlights that Zn may alleviate N-induced oxidative stress, which can impair grain filling under high-N conditions [22].

**4.2.3 Grain yield (g hill-1)**

The dry season’s maximum yield at 120 kg N ha-1 which was not statistically different from 80 kg N ha-1 and the wet season’s optimal at 80 kg N ha-1 reflects seasonal differences in solar radiation and temperature. The sufficiency of 80 kg N/ha in the wet season is primarily due to lower solar radiation and different temperature conditions, rather than pest pressure. These findings align with previous research showing how environmental factors influence nitrogen use efficiency in rice cultivation [2]. Higher dose of N with Zn at early stage contributing more in growth and development resulted higher grain yield. This might be owing to the fulfilment of the requirement of N and Zn and a positive interaction between nitrogen and zinc. These findings also corroborate the finding of [34]. Zinc’s consistent yield boost (10 kg ha-1) confirms its role in stabilizing N efficiency, particularly under suboptimal conditions [35]. In many cases, the relationship between nutrient application rate and crop yield follows the law of diminishing returns. Beyond a certain point, additional nutrient input does not translate into proportional yield increases and may even cause yield reductions [36].

**4.2.4 Nutrient Interactions**

The significant N × Zn interaction for grain yield (5% level in dry season, 1% in wet season) suggests that Zn enhances N recovery efficiency. This synergy reduces N losses via volatilization or leaching, aligning with findings that Zn stabilizes ammonium (NH₄⁺) in flooded soils [37]. Zn stabilizes enzymes involved in N metabolism, such as urease and glutamine synthetase. By regulating urease activity, Zn can reduce urea hydrolysis rates, thereby minimizing ammonia volatilization [38]. This ensures that more N remains in the soil for plant uptake [38].

5. Conclusion

The study demonstrated that integrated nitrogen and zinc fertilization significantly enhanced rice growth and yield components in both dry and wet seasons. In the dry season, although 120 kg N ha⁻¹ combined with zinc resulted in the maximum plant growth and yield, it was not statistically different from the 80 kg N ha⁻¹ treatment, making 80 kg N ha⁻¹ as the recommended optimal rate for sustaining favorable growth and yield components. In the wet season, the combination of 80 kg N ha⁻¹ with 10 kg Zn ha⁻¹ (N2Zn1) also produced the highest performance. The study further demonstrates that zinc application (10 kg Zn ha-1) significantly increases number of panicles, spikelets number and filled grain percentage, addressing both agronomic productivity and human nutritional needs in regions where Zn deficiency is prevalent. Overall, the study confirms that 80 kg N ha⁻¹, in combination with zinc (10 kg ha-1), is adequate for optimizing rice productivity, thereby reducing fertilizer input costs and limiting environmental risks.

Integrated nutrient management for rice production under micronutrient-deficient soils is a very important research aspect, this study contributes a lot to the scientific community in understanding and reaffirming the interaction effect of both nutrients, zinc and nitrogen on rice production.

The significant N and Zn interaction highlights the importance of balanced nutrient management. From an environmental perspective, this synergy reduces nitrogen losses and soil degradation risks, offering a sustainable strategy to balance productivity with ecological health. For smallholder farmers, particularly in micronutrient-deficient regions like Myanmar, integrating zinc with optimized nitrogen rates presents a cost-effective approach to enhance profitability and food security. Future research should investigate these nutrient interactions across diverse soil and climatic conditions.

Disclaimer (Artificial intelligence)

Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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