**Optimising growth and development by integrating water management practices and nano-fertilizers application in rice (*Oryza Sativa* L.)**


## Abstract

Rice (*Oryza sativa* L.) is a vital staple crop, feeding over half of the global population. Despite its significance, rice cultivation faces challenges due to its high-water demand and reliance on conventional fertilizers, which can degrade soil health and increase environmental pollution. This study, conducted at the Student's Instructional Farm, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, over two consecutive Kharif seasons (2022 and 2023), aimed to evaluate the effects of water management practices and nano fertilizers on different rice varieties. A split-plot design was used, with water management systems ($I_1$- Flooding throughout crop growth (3+/-2cm), $I_2$- Saturation maintenance up to PI and (3+/-2cm) after PI, and $I_3$- Alternate wetting and drying) in main plot, three varieties ($V_1$- NDR 2064, $V_2$- Pusa Basmati 1509 and $V_3$- Arize 6444 Gold) in sub plot and five nano fertilizers treatments ($F_1$- 100% RD- $N_{120kg/h}$ $P_{60kg/h}$ $K_{40kg/h}$ + $Zn_{25kg/h}$, $F_2$- 100% RD- $N_{120kg/h}$ $P_{60kg/h}$ $K_{40kg/h}$ + $Zn_{25kg/h}$ + Nano fertilizers ($Urea_{4ml/l}$ + $DAP_{4ml/lit}$ + $Zn_{0.5ml/l}$, $F_3$- 75% RD- $N_{90kg/ha}$ $P_{45kg/ha}$ $K_{30kg/ha}$ + $Zn_{18.75kg/ha}$ + Nano fertilizers ($Urea_{4ml/l}$ + $DAP_{4ml/lit}$ + $Zn_{0.5ml/l}$), $F_4$- 50% RD- $N_{60kg/ha}$ $P_{30kg/ha}$ $K_{20kg/ha}$ + $Zn_{12.5kg/ha}$ + Nano fertilizers ($Urea_{4ml/l}$ + $DAP_{4ml/lit}$ + $Zn_{0.5ml/l}$) and $F_5$- Nano fertilizers ($Urea_{4ml/l}$ + $DAP_{4ml/lit}$ + $Zn_{0.5ml/l}$)) in sub- sub plotswith three replications.Results advocated that saturation irrigation significantly improved plant height, tiller count, dry matter accumulation, and leaf area index as compared to continuous flooding and alternate wetting and drying. Among the rice varieties, Arize-6444 Gold outperformed others in terms of tiller number and dry matter accumulation. Nano fertilizers, especially at 75% RD- $N_{90kg/ha}$ $P_{45kg/ha}$ $K_{30kg/ha}$ + $Zn_{18.75kg/ha}$ + Nano fertilizers ($Urea_{4ml/l}$ + $DAP_{4ml/lit}$ + $Zn_{0.5ml/l}$) improved nutrient efficiency, leading to increased tiller counts, reduced tiller mortality, and higher dry matter accumulation. The combined use of optimized water management practices and nano fertilizers showed potential to reduce water use and improve rice productivity, offering a more sustainable approach to rice cultivation. These findings suggest that integrating saturation irrigation practice and nano-fertilizers can enhance rice yields while conserving water and minimizing the environmental footprint, addressing critical challenges in modern rice production.



**Keywords:** Water management, nano fertilizers, saturation irrigation, alternate wetting and drying, continuous flooding and rice.

## 1. INTRODUCTION

Rice (*Oryza sativa* L.) is a staple food crop, sustaining over half of the world's population [1]. It is grown across 165 million hectares globally, producing 516.02 million metric tons of paddy in 2022/2023 [2]. The Asia-Pacific region accounts for over 90% of global rice production and consumption, with China leading in 2022-23, producing 146 million metric tons of milled rice. India, the second-largest producer and consumer after China, cultivates rice on 46 million hectares, yielding 135 million tons with a productivity of 28.05 quintals per hectare [3]. In financial year 2022, India exported $3.54 billion worth of Basmati rice and $6.12 billion of non-Basmati rice [4]. The top rice-producing states in India include West Bengal, Uttar Pradesh, and Punjab, with Uttar Pradesh contributing 12.81% of the total rice production covering acreage of 6.02 million hectares [5]. Rice adaptability allows it to thrive in diverse habitats, soil types, and climatic conditions. Its optimal growth temperatures range from 26.5°C to 29.5°C, while ripening occurs best between 20°C and 25°C. However, rice is a water-intensive crop, requiring 3,000-5,000 litters of water per kilogram of grain. Conventional irrigation methods, such as continuous flooding, deplete water resources and harm ecosystems, posing significant challenges as water scarcity intensifies [6]. Sustainable irrigation practices like Saturation Irrigation and Alternate Wetting and Drying (AWDI) have been developed to conserve water and maintain yields. Saturation irrigation maintains soil moisture without flooding, optimizing nutrient absorption and reducing water use [7]. The AWDI, which alternates periods of drying and re-flooding, reduces water usage by up to 23% with minimal impact on yield [8]. India's agricultural growth, spurred by the 1970s Green Revolution, heavily relies on inorganic fertilizers like urea, DAP, and MOP. However, these inputs often lead to nutrient inefficiency, soil degradation, and increased greenhouse gas emissions [8]. Nano fertilizers offer a more sustainable alternative, delivering nutrients via nanoparticles under 100 nm, encapsulated in polymers for gradual with targeted release. Nano urea, developed by the Nano Biotechnology Research Center and Indian Farmers Fertilizers Cooperative Limited, enhances nitrogen uptake through stomatal absorption, while Nano DAP supplies nitrogen and phosphorus, improving seedling vigor and reducing phosphorus use by 60 per cent[9]. Nano zinc further supports nutrient efficiency by enhancing phosphorus conversion and maintaining plant membrane integrity. These innovations improve fertilizer use efficiency, reduce environmental impacts, and sustain crop productivity in India [10]. The present investigation was therefore undertaken to integrate water management practices with nano fertilizers application on different groups of rice varieties in order to sustain rice production.

## 2. MATERIALS AND METHODS

The present investigation was conducted at the Student's Instructional Farm of the Department of Agronomy, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur (U.P.) over two consecutive years during *Kharif* 2022 and 2023 as presented in Fig. 1. Kanpur is located in the sub-tropics, which has a semi-arid climate, positioned between latitudes 25.26° to 28.58° North and longitudes 79.31° to 80.34° East, at an elevation of approximately 125.9 meters above sea level. The experimental plot was adequately levelled, properly drained, and equipped with reliable irrigation via a tube well. It is located in the alluvial Gangetic region of central Uttar Pradesh.

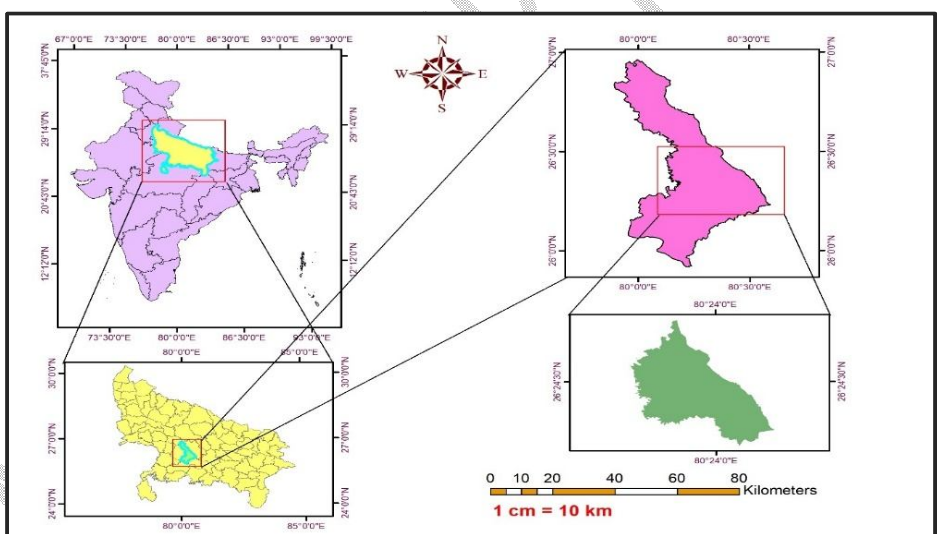


**Fig. 1:** Study area map.

### 2.1 Experimental Details

The experiment was conducted in the split plot design, with three replications during both the years. The water management system was implemented in the main plot ($I_1$- Flooding throughout crop growth (3+/-2cm), $I_2$- Saturation Maintenance up to PI and (3+/-2cm) after PI and $I_3$- Alternate wetting and drying), while promising varieties were allotted to the sub-plot ($V_1$- NDR- 2064,$V_2$- PB-1509 and $V_3$- Arize-6444 Gold) and nano fertilizers were assigned to the sub sub-plot ($F_1$- 100% RD-N120kg/h P60kg/h K40kg/h + Zn25kg/h, $F_2$- 100% RD- N120kg/h P60kg/h K40kg/h + Zn25kg/h +

Nano Fertilizers (Urea4ml/l + DAP4ml/lit + Zn0.5ml/l), $F_3$- 75% RD- N90kg/ha P45kg/ha K30kg/ha + Zn18.75kg/ha + Nano Fertilizers (Urea4ml/l + DAP4ml/lit + Zn0.5ml/l), $F_4$- 50% RD- N60kg/ha P30kg/ha K20kg/ha + Zn12.5kg/ha + Nano Fertilizers (Urea4ml/l + DAP4ml/lit + Zn0.5ml/l) and $F_5$- Nano Fertilizers (Urea4ml/l + DAP4ml/lit + Zn0.5ml/l). The following observations wererecorded under study.

**2.2.Growth Characters**

**2.1.1 Plant height(cm):** Five plants were randomly selected and labelled from each experimental plot. The height of the rice plant was measured using a meter scale, from the base of the plant to the apex of the highest leaf before panicle emergence, and to the tip of the panicle after heading. Their average is recorded in centimetres.

**2.1.2 Number of tillers ($m^{-2}$):** The tiller count was assessed by enumerating the number of tillers per 1.0 m² at five randomly selected sites within each plot at 30, 60, and 90 days after transplanting (DAT), in addition to the harvest stage. The average tiller count was subsequently quantified as the number of tillers per square meter (m²).

**2.1.3 Tiller Mortality (%):** Tiller mortality, which affects both the field stand and the final productive tillers at harvest, is regulated by internal hormonal factors, genotype characteristics, and environmental conditions during the growth phase, was calculated as below.

$$\text{Tiller mortality (\%)} = \frac{\text{Number of a live tillers}}{\text{Total number of tillers}} \times 100$$

**2.1.4 *Dry matter accumulation (g hill$^{-1}$)*:** The weights of dry biomass (measured in g hill$^{-1}$) and the growth parameters of rice plants were recorded subsequent to the application of various treatments. Measurements were documented at 30, 60 and 90 days after transplantation, as well as during the harvest stage. The samples underwent an automated drying procedure at 70°C for 24 hours to determine the dry weight and recorded accordingly.

**2.1.5 *Leaf Area Index (LAI)*:** The aggregate number of leaves from three random hills was categorized into three distinct classifications: small, medium, and large. Subsequently, the maximum dimensions of each leaf group were documented, encompassing both length and width. The leaf area for an individual leaf from each group was calculated using a designated formula, subsequently multiplied by the total number of leaves in each group.

$$\boldsymbol{Leaf\ area} = K \times length\ of\ leaf \times width\ of\ leaf$$

The adjustment factor, designated as K, was set at 0.75 for all stages of crop growth, except for the seedling and maturity phases, which employed a value of 0.67. The leaf area per hill was determined by aggregating the leaf area index values derived from the leaf area data using the formula proposed by Watson (1947).

$$\textbf{Leaf area index} = \frac{Total\ leaf\ area}{Unit\ ground\ area}$$

## 3. RESULTS AND DISCUSSION

### 3.1 Water management practice

#### 3.1.1 Plant height (cm)

Plant height serves as a crucial indicator of plant development, influencing its anatomical structure, dry matter production, and yield [12]. Rice plant height, measured at 30-day intervals until harvest, showed a rapid increase up to 90 days post-transplanting, followed by a decline due to biological activity and senescence (Table No.1) [13]. The highest plant height was recorded under the Saturation Maintenance treatment (38.73, 72.14, 103.07 and 99.11 cm (2022); 41.64, 75.94, 106.04 and 101.76 cm (2023) at 30, 60, 90 at harvest, respectively) followed by flooding (35.57, 68.45, 97.92 and 94.16 cm (2022); 38.25, 72.05, 100.74 and 96.67 cm (2023) at 30, 60, 90 at harvest, respectively), while the lowest was observed under alternate wetting and drying (34.15, 65.71, 93.59 and 90.01 cm (2022); 36.72,69.17, 96.29 and 92.41 cm (2023) at 30, 60, 90 at harvest, respectively). This variation was likely due to differences in water availability, aeration, and root establishment, confirming findings by [14] and [15].

#### 3.1.2 Number of tillers ($m^{-2}$)

Tillering is an important growth phase that contributes to the rice plant's overall yield. The highest number of tillers was observed in Saturation Maintenance (167.19, 258.32, 284.85 and 269.55 $m^{-2}$ (2022); 177.26, 269.23, 291.72 and 277.89 $m^{-2}$ (2023) at 30, 60, 90 and at harvest, respectively) followed by alternate wetting and drying (174.55, 269.71, 295.47, and 281.47$m^{-2}$ (2022); 185.06, 281.83, 302.82 and 290.18 $m^{-2}$(2023) at 30, 60, 90 and at harvest, respectively) with the lowest tiller count recorded under the flooding treatment 167.19, 258.32, 284.85 and 269.55 $m^{-2}$ (2022); 177.26, 269.23, 291.72 and 277.89 $m^{-2}$ (2023) at 30, 60, 90 and at harvest, respectively (Table No.2). Tillering is highly sensitive to water stress, which affects leaf elongation and reduces active tillering sites [16] Enhanced nutrient uptake and metabolic activities under adequate moisture conditions promoted the production of tillers, leading to higher counts under optimal irrigation treatments.

### 3.1.3 Tiller mortality (%)

The flooding treatment resulted in higher tiller mortality 5.38% (2022) and 4.75 % (2023), followed by alternate wetting and drying 4.70 % (2022) and 4.15 % (2023)(Table No.3), attributed to moisture and nutrient deficiencies and unfavourable climatic factors. The availability of water enhances leaf area and ear production, which contribute to better tiller productivity, as reported by [17].

### 3.1.4 Dry matter accumulation (g hill$^{-1}$)

Dry matter accumulation peaked during at harvest stage under Saturation Maintenance treatment being10.46, 16.39, 23.44 and 34.65 g hill$^{-1}$ (2022);11.62, 17.44, 24.41 and 39.10 g hill$^{-1}$ (2023) at 30, 60, 90 and at harvest, respectively followed by alternate wetting and drying (9.29, 14.55, 20.80 and 30.75 g hill$^{-1}$ (2022); 10.32, 15.48, 21.67 and 32.03 g hill$^{-1}$ (2023) at 30, 60, 90 and at harvest, respectively). Theflooding treatment, however, led to lower dry matter accumulation (8.88, 13.92, 19.90 and 29.46 g hill$^{-1}$ (2022); 9.88, 14.82, 20.75 and 30.69 g hill$^{-1}$ (2023) at 30, 60, 90 and at harvest, respectively (Table No.4) due to reduced root activity and relevant metabolic processes. During the ripening stage, low soil moisture reduced dry matter production, with translocation to panicles increasing [18]. These findings are consistent with the reports of [19].

### 3.1.5 Leaf area index (LAI)

The leaf area index (LAI), which reflects the plant's vegetative plasticity, was highest under Saturation Maintenance (1.47, 4.82, and 4.31 (2022); 1.49, 4.92, 4.39 (2023) at 30,60,90 and at harvest, respectively), followed by alternate wetting and drying (1.43, 4.72, and 4.22 (2022); 1.46, 4.82 and 4.30 (2023) at 30,60,90 and at harvest, respectively). Flooding led to a lower LAI 1.41, 4.64 and 4.14 (2022); 1.44, 4.73 and 4.23 (2023) at 30,60,90 and at harvest, respectively (Table 1), These finding are in accordance to the result of [20]. Water management strategies had a significant impact on LAI, with adequate irrigation supporting better leaf area and consequently improving dry matter accumulation and yield.

## 3.2. Varieties

### 3.2.1. Plant height (cm)

Plant height being, a key indicator of rice plant development, is reflecting genetic differences and environmental influences. The growth of rice plants across varieties showed a rapid increase up to 90 days after transplanting (DAT), followed by a slight decline as harvest approached due to senescence. The NDR 2064 exhibited the maximum plant height at 90 DAT (42.11, 83.45, 106.96 and 102.08 cm (2022); 45.28, 87.84, 110.05 and 104.81 cm (2023) at 30, 60, 90 at harvest, respectively) followed by Arize 6444 Gold (37.84, 69.55, 98.73 and 95.12 cm (2022); 40.69, 73.21, 101.57 and 97.66 cm (2023) at 30, 60, 90 at harvest, respectively). The PB 1509 recorded the smallest plant height during the same period (Table No.1). These differences in plant height are primarily attributed to genetic variations among the rice varieties, as similar results have noted by [21].

### 3.2.2. Number of tillers ($m^{-2}$)

The Arize 6444 Gold showing the maximum number of tiller (213.76, 336.53, 368.59 and 350.12 $m^{-2}$(2022); 224.09, 348.14, 377.64 and 360.95 $m^{-2}$(2023) at 30, 60, 90 and at harvest, respectively), followed by NDR 2064 175.72, 274.90, 303.35 and 290.08$m^{-2}$ (2022); 186.31, 287.12, 311.04 and 299.05 $m^{-2}$ (2023) at 30, 60, 90 and at harvest, respectively (Table 2). This variation in tiller count is linked to the genetic composition of the rice varieties, influencing nutrient uptake and plant metabolism. Adequate moisture throughout the growth stages played a significant role in promoting higher tiller counts.

### 3.2.3. Tiller mortality (%)

The highest tiller mortality was observed in Arize 6444 Gold (5.07 % (2022); 4.48 % (2023) respectively), followed by NDR 2064 (4.47 % (2022); 3.94 % (2023) respectively) and PB 1509 (4.29 % (2022); 3.78 % (2023) respectively) (Table 3). This mortality was largely due to moisture deficiency, nutrient limitations, and climatic factors that affected tiller growth and metabolism. Reduced moisture availability likely contributed to the unproductive outcomes which leads to higher mortality rates.

### 3.2.4. Dry matter accumulation (g $hill^{-1}$)

Dry matter accumulation in plants increased as growth progressed, peaking at harvest. The Arize 6444 Gold showed the highest dry matter accumulation (12.73, 19.95, 28.52 and 42.17 g $hill^{-1}$ (2022); 14.15, 21.22, 29.71 and 43.93 g $hill^{-1}$ (2023) at 30, 60, 90 and at harvest, respectively) followed by NDR 2064 (9.63, 15.09, 21.58 and 31.95 g $hill^{-1}$ (2022); 10.72, 16.08, 22.51 and 33.28

g hill$^{-1}$ (2023) at 30, 60, 90 and at harvest, respectively). PB 1509 recorded the lowest dry weight (6.26, 9.81, 14.03 and 20.74 g hill$^{-1}$ (2022); 6.96, 10.44, 14.61 and 21.61 g hill$^{-1}$ (2023) at 30, 60, 90 and at harvest, respectively) (Table 4). These differences in dry weight are influenced by moisture availability, with increased water promoting greater dry matter accumulation. Water stress, on the other hand, reduces photosynthesis and nitrogen metabolism, ultimately stunting plant growth.

#### 3.2.5. Leaf area index (LAI)

The leaf area index (LAI) varied significantly among varieties.TheArize 6444 Gold possessed the highest LAI (1.69, 5.15 and 5.03 (2022); 1.73, 5.26 and 5.13 (2023) at 30, 60 and 90, respectively), followed by NDR 2064 (1.69, 4.88 and4.13 (2022); 1.72, 4.98 and 4.21 (2023) at 30, 60 and 90,respectively), and PB 1509 (0.93, 4.15 and 3.51 (2022); 0.95, 4.23 and 3.59 at 30, 60 and 90, respectively) (Table 5). The LAI highest at 60 DAT and slightly declined at 90 DAT. Genetic differences, along with environmental factors, significantly influenced LAI, which directly affects the plant's photosynthetic capacity and dry matter production.

### 3.3. Nano fertilizers

#### 3.3.1. Plant Height (cm)

The plant height of rice increased rapidly until 90 days after transplanting (DAT), thereafter, it slowed as photosynthates were directed toward reproductive parts. The tallest plants were recorded with the application of 100% RD (N120kg/ha P60kg/ha K40kg/ha + Zn25kg/ha) plus nano fertilizers (Urea 4ml/l, DAP 4ml/l, Zn 0.5ml/l), reaching heights of 39.37, 73.50, 105.03 and 100.56 cm (2022); 42.26, 77.34, 108.02 and 103.21 cm (2023) at 30, 60, 90 DAT, and at harvest, respectively. These results were followed by 100% RD without nano fertilizers (37.61, 71.54, 102.10, 98.18 cm (2022); 40.44, 75.30, 105.04, 100.81 cm (2023) at 30, 60, 90 DAT, and at harvest, respectively, and 75% RD with nano fertilizers (36.48, 69.39, 99.60, 95.77 cm (2022); 39.22, 73.04, 102.47 and 98.33 cm (2023) at 30, 60, 90 DAT, and at harvest, respectively) (Table 1). The increase in plant height is attributed to rapid mineralization from nano-fertilizers, enhancing nutrient availability and promoting cell elongation and division [22, 23].

#### 3.3.2. Number of tillers (m$^{-2}$)

The number of tillers increased by the 90 DAT and declined thereafter due to the diversion of nutrients toward reproductive growth. The highest number of tillers was observed with 75% RD (N90kg/ha P45kg/ha K30kg/ha + Zn18.75kg/ha) and nano fertilizers (189.04, 292.15, 317.20 and

304 $m^{-2}$ (2022); 200.41, 305.26, 325.40 and 314.32 $m^{-2}$(2023) at 30, 60, 90 and at harvest, respectively), followed by 100% RD with nano fertilizers (183.55, 284.84, 309.25, 297.38 $m^{-2}$ (2022);194.70, 297.69, 317.23 and 306.64 $m^{-2}$ (2023) at 30, 60, 90 and at harvest, respectively) (Table 2). It indicating the positive impact of nano-fertilizers on nutrient absorption and tiller development [24].

### 3.3.3. Tiller mortality (%)

Tiller mortality was the lowest in the treatment of 75% RD with nano fertilizers treatment (3.87 % (2022); 3.40 % (2024)), followed by application of 100% RD with nano fertilizers (4.11 % (2022) and 3.61 % (2023) respectively) (Table 3). The lower mortality is likely due to the enhanced nutrient availability provided by nano-fertilizers, which sustained tiller growth and reduced stress-induced mortality [25].

### 3.3.4. Dry matter accumulation (g $hill^{-1}$)

The dry matter accumulation increased steadily over time, peaking at harvest (Table 4). The highest dry weight was recorded with 75% RD and nano fertilizers (10.07, 15.77, 22.55, 33.34 g $hill^{-1}$ (2022); 11.18, 16.78, 23.49 and 34.73 g $hill^{-1}$ (2023) at 30, 60, 90 and at harvest, respectively). The continuous supply of nutrients being facilitated by the application of nano-fertilizers, improved the vegetative growth and nutrient use efficiency of plants, resulting in greater dry matter production.

### 3.3.5. Leaf area index (LAI)

The leaf area index increased until 60 DAT and declined by 90 DAT due to leaf aging (Table 5). The highest LAI was observed with the application of 75% RD and nano fertilizers (1.52, 4.93 and 4.39 (2022); 1.55, 5.03 and 4.48 (2023) respectively), followed by 100% RD with nano fertilizers (1.48, 4.71 and 4.25 (2022); 1.51, 4.81 and 4.34 (2023), respectively). Nano-fertilizers improved chlorophyll content and photosynthesis, contributing to greater leaf area and overall growth [29]. These results highlight the role of nano-fertilizers in enhancing nitrogen availability and promoting efficient nutrient utilization throughout the growth cycle.

## 4. CONCLUSION

Keeping above findings in view, it is concluded that the among all the treatments, saturation maintenance up to PI and (3+/-2cm) after PI of water management practice with combination treatment of 75% RD- $N_{90kg/ha}$ $P_{45kg/ha}$ $K_{30kg/ha}$ + $Zn_{18.75kg/ha}$ + Nano Fertilizers ($Urea_{4ml/l}$ + $DAP_{4ml/lit}$ + $Zn_{0.5ml/l}$) was found most appropriate irrespective of promising varieties and hybrid to optimize growth and development in rice.



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**Table 1: Effect of water management practices, varieties and nano-fertilizers on plant height (cm) in rice.**

| Treatment | Plant height (cm) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 30 DAT | | 60 DAT | | 90 DAT | | At harvest | |
| | 2022 | 2023 | 2022 | 2023 | 2022 | 2023 | 2022 | 2023 |
| **A. Water Management Practices** | | | | | | | | |
| **$I_1$-** Flooding throughout crop growth (3+/-2cm) | 35.57 | 38.25 | 68.45 | 72.05 | 97.92 | 100.74 | 94.16 | 96.67 |
| **$I_2$-** Saturation Maintenance up to PI and (3+/-2cm) after PI | 38.73 | 41.64 | 72.14 | 75.94 | 103.07 | 106.04 | 99.11 | 101.76 |
| **$I_3$-** Alternate wetting and drying | 34.15 | 36.72 | 65.71 | 69.17 | 93.59 | 96.29 | 90.01 | 92.41 |
| **SE ± (d)** | 0.20 | 0.21 | 0.38 | 0.40 | **0.44** | **0.45** | **0.41** | **0.43** |
| **CD (*P*= 0.05)** | **0.54** | **0.59** | **1.05** | **1.11** | **1.22** | **1.24** | **1.14** | **1.18** |
| **B. Varieties** | | | | | | | | |
| **$V_1$-** NDR- 2064 | 42.11 | 45.28 | 83.45 | 87.84 | 106.96 | 110.05 | 102.08 | 104.81 |
| **$V_2$-** PB-1509 | 28.49 | 30.64 | 53.30 | 56.11 | 88.90 | 91.46 | 86.07 | 88.37 |
| **$V_3$-** Arize-6444 Gold | 37.84 | 40.69 | 69.55 | 73.21 | 98.73 | 101.57 | 95.12 | 97.66 |
| **SE ± (d)** | 0.028 | 0.30 | 0.53 | 0.56 | **0.77** | **0.79** | **0.74** | **0.76** |
| **CD (*P*= 0.05)** | **0.61** | **0.65** | **1.16** | **1.23** | **1.67** | **1.72** | **1.61** | **1.18** |
| **C. Nano-fertilizers** | | | | | | | | |
| **$F_1$-** 100% RD- $N_{120kg/h}$ $P_{60kg/h}$ $K_{40kg/h}$ + $Zn_{25kg/h}$ | 37.61 | 40.44 | 71.54 | 75.30 | 102.10 | 105.04 | 98.18 | 100.81 |
| **$F_2$-** 100% RD- $N_{120kg/h}$ $P_{60kg/h}$ $K_{40kg/h}$ + $Zn_{25kg/h}$ + Nano Fertilizers ($Urea_{4ml/l}$ + $DAP_{4ml/lit}$ + $Zn_{0.5ml/l}$) | 39.37 | 42.26 | 73.50 | 77.34 | 105.03 | 108.02 | 100.56 | 103.21 |
| **$F_3$-** 75% RD- $N_{90kg/ha}$ $P_{45kg/ha}$ $K_{30kg/ha}$ + $Zn_{18.75kg/ha}$ + Nano Fertilizers ($Urea_{4ml/l}$ + $DAP_{4ml/lit}$ + $Zn_{0.5ml/l}$) | 36.48 | 39.22 | 69.39 | 73.04 | 99.60 | 102.47 | 95.77 | 98.33 |
| **$F_4$-** 50% RD- $N_{60kg/ha}$ $P_{30kg/ha}$ $K_{20kg/ha}$ + $Zn_{12.5kg/ha}$ + Nano Fertilizers ($Urea_{4ml/l}$ + $DAP_{4ml/lit}$ + $Zn_{0.5ml/l}$) | 35.02 | 37.65 | 66.62 | 70.12 | 95.75 | 98.51 | 92.07 | 94.53 |
| **$F_5$-** Nano Fertilizers ($Urea_{4ml/l}$ + $DAP_{4ml/lit}$ + $Zn_{0.5ml/l}$) | 33.27 | 35.77 | 63.29 | 66.62 | 90.00 | 92.59 | 86.54 | 88.85 |
| **SE (d)** | 0.44 | 0.48 | 0.84 | 0.89 | **1.19** | **1.22** | **1.14** | **1.17** |
| **CD (P= 0.05)** | **0.88** | **0.95** | **1.68** | **1.77** | **2.37** | **2.44** | **2.28** | **2.34** |

**Table 2: Effect of water management practices, varieties and nano-fertilizers on Tiller ($m^{-2}$) in rice.**

| Treatment | Tiller ($m^{-2}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 30 DAT | | 60 DAT | | 90 DAT | | At harvest | |
| | 2022 | 2023 | 2022 | 2023 | 2022 | 2023 | 2022 | 2023 |
| **A. Water Management Practices** | | | | | | | | |
| **$I_1$-** Flooding throughout crop growth (3+/-2cm) | 167.19 | 177.26 | 258.32 | 269.23 | 284.85 | 291.72 | 269.55 | 277.89 |
| **$I_2$-** Saturation Maintenance up to PI and (3+/-2cm) after PI | 196.73 | 208.59 | 303.99 | 317.67 | 329.73 | 338.32 | 317.28 | 327.09 |
| **$I_3$-** Alternate wetting and drying | 174.55 | 185.06 | 269.71 | 281.83 | 295.47 | 302.82 | 281.47 | 290.18 |
| **SE ± (d)** | **0.97** | **1.00** | **1.54** | **1.603** | **1.74** | **1.74** | **1.63** | **1.68** |
| **CD (*P*= 0.05)** | **2.67** | **2.77** | **4.25** | **4.43** | **4.80** | **4.80** | **4.49** | **4.64** |
| **B. Varieties** | | | | | | | | |
| **$V_1$-** NDR- 2064 | 175.72 | 186.31 | 274.90 | 287.12 | 303.35 | 311.04 | 290.08 | 299.05 |
| **$V_2$-** PB-1509 | 148.99 | 160.51 | 220.58 | 234.16 | 238.11 | 244.19 | 228.09 | 235.15 |
| **$V_3$-** Arize-6444 Gold | 213.76 | 224.09 | 336.53 | 348.14 | 368.59 | 377.64 | 350.12 | 360.95 |
| **SE ± (d)** | **1.39** | **1.47** | **2.13** | **2.23** | **2.32** | **2.38** | **2.22** | **2.29** |
| **CD (*P*= 0.05)** | **3.02** | **3.21** | **4.63** | **4.85** | **5.05** | **5.80** | **4.83** | **4.98** |
| **C. Nano-fertilizers** | | | | | | | | |
| **$F_1$-** 100% RD- $N_{120kg/h}$ $P_{60kg/h}$ $K_{40kg/h}$ + $Zn_{25kg/h}$ | 174.25 | 184.76 | 269.22 | 281.33 | 294.80 | 302.13 | 280.95 | 289.65 |
| **$F_2$-** 100% RD- $N_{120kg/h}$ $P_{60kg/h}$ $K_{40kg/h}$ + $Zn_{25kg/h}$ + Nano Fertilizers ($Urea_{4ml/l}$ + $DAP_{4ml/lit}$ + $Zn_{0.5ml/l}$) | 183.55 | 194.7 | 284.84 | 297.69 | 309.25 | 317.23 | 297.38 | 306.64 |
| **$F_3$-** 75% RD- $N_{90kg/ha}$ $P_{45kg/ha}$ $K_{30kg/ha}$ + $Zn_{18.75kg/ha}$ + Nano Fertilizers ($Urea_{4ml/l}$ + $DAP_{4ml/lit}$ + $Zn_{0.5ml/l}$) | 189.04 | 200.41 | 292.15 | 305.26 | 317.20 | 325.40 | 304.88 | 314.32 |
| **$F_4$-** 50% RD- $N_{60kg/ha}$ $P_{30kg/ha}$ $K_{20kg/ha}$ + $Zn_{12.5kg/ha}$ + Nano Fertilizers ($Urea_{4ml/l}$ + $DAP_{4ml/lit}$ + $Zn_{0.5ml/l}$) | 178.69 | 189.87 | 283.17 | 293.07 | 306.71 | 314.61 | 295.57 | 304.77 |
| **$F_5$-** Nano Fertilizers ($Urea_{4ml/l}$ + $DAP_{4ml/lit}$ + $Zn_{0.5ml/l}$) | 163.92 | 173.78 | 253.32 | 264.69 | 281.80 | 288.42 | 264.37 | 272.55 |
| **SE (d)** | **2.19** | **2.32** | **3.40** | **3.54** | **3.72** | **3.82** | **3.55** | **3.66** |
| **CD (P= 0.05)** | **4.36** | **4.617** | **6.77** | **7.06** | **7.42** | **7.61** | **7.07** | **7.29** |

**Table 3: Effect of water management practices, varieties and nano-fertilizers on mortality percentage in rice.**

| Treatment | Tiller mortality (%) | |
|---|---|---|
| | **2022** | **2023** |
| **A. Water Management Practices** | | |
| **$I_1$-** Flooding throughout crop growth (3+/-2cm) | 5.38 | 4.75 |
| **$I_2$-** Saturation Maintenance up to PI and (3+/-2cm) after PI | 3.74 | 3.29 |
| **$I_3$-** Alternate wetting and drying | 4.70 | 4.15 |
| **SE ± (d)** | 0.03 | 0.02 |
| **CD (*P*= 0.05)** | **0.07** | **0.07** |
| **B. Varieties** | | |
| **$V_1$-** NDR- 2064 | 4.47 | 3.94 |
| **$V_2$-** PB-1509 | 4.29 | 3.78 |
| **$V_3$-** Arize-6444 Gold | 5.07 | 4.48 |
| **SE ± (d)** | 0.04 | 0.03 |
| **CD (*P*= 0.05)** | **0.08** | **0.07** |
| **C. Nano-fertilizers** | | |
| **$F_1$-** 100% RD- $N_{120kg/h}$ $P_{60kg/h}$ $K_{40kg/h}$ + $Zn_{25kg/h}$ | 4.70 | 4.13 |
| **$F_2$-** 100% RD- $N_{120kg/h}$ $P_{60kg/h}$ $K_{40kg/h}$ + $Zn_{25kg/h}$ + Nano Fertilizers ($Urea_{4ml/l}$ + $DAP_{4ml/lit}$ + $Zn_{0.5ml/l}$) | 4.11 | 3.61 |
| **$F_3$-** 75% RD- $N_{90kg/ha}$ $P_{45kg/ha}$ $K_{30kg/ha +}$ $Zn_{18.75kg/ha}$ + Nano Fertilizers ($Urea_{4ml/l}$ + $DAP_{4ml/lit}$ + $Zn_{0.5ml/l}$) | 3.87 | 3.40 |
| **$F_4$-** 50% RD- $N_{60kg/ha}$ $P_{30kg/ha}$ $K_{20kg/ha +}$ $Zn_{12.5kg/ha}$ + Nano Fertilizers ($Urea_{4ml/l}$ + $DAP_{4ml/lit}$ + $Zn_{0.5ml/l}$) | 4.19 | 3.68 |
| **$F_5$-** Nano Fertilizers ($Urea_{4ml/l}$ + $DAP_{4ml/lit}$ + $Zn_{0.5ml/l}$) | 6.19 | 5.50 |
| **SE ± (d)** | 0.06 | 0.05 |
| **CD (*P*= 0.05)** | **0.12** | **0.12** |

**Table 4: Effect of water management practices, varieties and nano-fertilizers on dry weight (g hill$^{-1}$) in rice.**

| Treatment | Dry weight (g $hill^{-1}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 30 DAT | | 60 DAT | | 90 DAT | | At harvest | |
| | 2022 | 2023 | 2022 | 2023 | 2022 | 2023 | 2022 | 2023 |
| **A. Water Management Practices** | | | | | | | | |
| **$I_1$-** Flooding throughout crop growth (3+/-2cm) | 8.88 | 9.88 | 13.92 | 14.82 | 19.90 | 20.75 | 29.46 | 30.69 |
| **$I_2$-** Saturation Maintenance up to PI and (3+/-2cm) after PI | 10.46 | 11.62 | 16.39 | 17.44 | 23.44 | 24.41 | 34.65 | 39.10 |
| **$I_3$-** Alternate wetting and drying | 9.29 | 10.32 | 14.55 | 15.48 | 20.80 | 21.67 | 30.75 | 32.03 |
| **SE ± (d)** | 0.06 | 0.07 | 0.10 | 0.10 | 0.14 | 0.15 | 0.21 | 0.22 |
| **CD (*P*= 0.05)** | **0.17** | **0.19** | **0.27** | **0.29** | **0.39** | **0.41** | **0.58** | **0.60** |
| **B. Varieties** | | | | | | | | |
| **$V_1$-** NDR- 2064 | 9.63 | 10.72 | 15.09 | 16.08 | 21.58 | 22.51 | 31.95 | 33.28 |
| **$V_2$-** PB-1509 | 6.26 | 6.96 | 9.81 | 10.44 | 14.03 | 14.61 | 20.74 | 21.61 |
| **$V_3$-** Arize-6444 Gold | 12.73 | 14.15 | 19.95 | 21.22 | 28.52 | 29.71 | 42.17 | 43.93 |
| **SE ± (d)** | 0.07 | 0.08 | 0.11 | 0.12 | 0.16 | 0.17 | 0.24 | 0.25 |
| **CD (*P*= 0.05)** | **0.16** | **0.18** | **0.25** | **0.26** | **0.35** | **0.37** | **0.52** | **0.54** |
| **C. Nano-fertilizers** | | | | | | | | |
| **$F_1$-** 100% RD- $N_{120kg/h}$ $P_{60kg/h}$ $K_{40kg/h}$ + $Zn_{25kg/h}$ | 8.24 | 9.29 | 14.48 | 15.44 | 20.71 | 21.62 | 30.68 | 31.96 |
| **$F_2$-** 100% RD- $N_{120kg/h}$ $P_{60kg/h}$ $K_{40kg/h}$ + $Zn_{25kg/h}$ + Nano Fertilizers ($Urea_{4ml/l}$ + $DAP_{4ml/lit}$ + $Zn_{0.5ml/l}$) | 8.91 | 10.99 | 15.1 | 16.19 | 21.16 | 22.08 | 32.26 | 33.62 |
| **$F_3$-** 75% RD- $N_{90kg/ha}$ $P_{45kg/ha}$ $K_{30kg/ha +}$ $Zn_{18.75kg/ha}$ + Nano Fertilizers ($Urea_{4ml/l}$ + $DAP_{4ml/lit}$ + $Zn_{0.5ml/l}$) | 10.07 | 11.18 | 15.77 | 16.78 | 22.55 | 23.49 | 33.34 | 34.73 |
| **$F_4$-** 50% RD- $N_{60kg/ha}$ $P_{30kg/ha}$ $K_{20kg/ha +}$ $Zn_{12.5kg/ha}$ + Nano Fertilizers ($Urea_{4ml/l}$ + $DAP_{4ml/lit}$ + $Zn_{0.5ml/l}$) | 8.79 | 9.88 | 14.34 | 15.32 | 20.93 | 21.84 | 31.42 | 32.77 |
| **$F_5$-** Nano Fertilizers ($Urea_{4ml/l}$ + $DAP_{4ml/lit}$ + $Zn_{0.5ml/l}$) | 7.73 | 8.7 | 13.67 | 14.54 | 19.55 | 20.36 | 28.90 | 30.11 |
| **SE (d)** | 0.12 | 0.13 | 0.19 | 0.20 | 0.27 | 0.28 | 0.40 | 0.42 |
| **CD (P= 0.05)** | **0.24** | **0.27** | **0.38** | **0.40** | **0.54** | **0.56** | **0.80** | **0.83** |

**Table 5: Effect of water management practices, varieties and nano-fertilizers on leaf area index in rice.**

| Treatment | Leaf area index |
|---|---|

| | 30 DAT | | 60 DAT | | 90 DAT | |
|---|---|---|---|---|---|---|
| | **2022** | **2023** | **2022** | **2023** | **2022** | **2023** |
| **A. Water Management Practices** | | | | | | |
| **$I_1$-** Flooding throughout crop growth (3+/-2cm) | 1.41 | 1.44 | 4.64 | 4.73 | 4.14 | 4.23 |
| **$I_2$-** Saturation Maintenance up to PI and (3+/-2cm) after PI | 1.47 | 1.49 | 4.82 | 4.92 | 4.31 | 4.39 |
| **$I_3$-** Alternate wetting and drying | 1.43 | 1.46 | 4.72 | 4.82 | 4.22 | 4.30 |
| **SE ± (d)** | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 |
| **CD (*P*= 0.05)** | **0.03** | **0.03** | **0.06** | **0.06** | **0.06** | **0.06** |
| **B. Varieties** | | | | | | |
| **$V_1$-** NDR- 2064 | 1.69 | 1.72 | 4.88 | 4.98 | 4.13 | 4.21 |
| **$V_2$-** PB-1509 | 0.93 | 0.95 | 4.15 | 4.23 | 3.51 | 3.59 |
| **$V_3$-** Arize-6444 Gold | 1.69 | 1.73 | 5.15 | 5.26 | 5.03 | 5.13 |
| **SE ± (d)** | 0.01 | 0.01 | 0.04 | 0.04 | 0.03 | 0.03 |
| **CD (*P*= 0.05)** | **0.02** | **0.03** | **0.08** | **0.08** | **0.07** | **0.07** |
| **C. Nano-fertilizers** | | | | | | |
| **$F_1$-** 100% RD- $N_{120kg/h}$ $P_{60kg/h}$ $K_{40kg/h}$ + $Zn_{25kg/h}$ | 1.41 | 1.44 | 4.58 | 4.68 | 4.11 | 4.20 |
| **$F_2$-** 100% RD- $N_{120kg/h}$ $P_{60kg/h}$ $K_{40kg/h}$ + $Zn_{25kg/h}$ + Nano Fertilizers ($Urea_{4ml/l}$ + $DAP_{4ml/lit}$ + $Zn_{0.5ml/l}$) | 1.48 | 1.51 | 4.71 | 4.81 | 4.25 | 4.34 |
| **$F_3$-** 75% RD- $N_{90kg/ha}$ $P_{45kg/ha}$ $K_{30kg/ha}$ + $Zn_{18.75kg/ha}$ + Nano Fertilizers ($Urea_{4ml/l}$ + $DAP_{4ml/lit}$ + $Zn_{0.5ml/l}$) | 1.52 | 1.55 | 4.93 | 5.03 | 4.39 | 4.48 |
| **$F_4$-** 50% RD- $N_{60kg/ha}$ $P_{30kg/ha}$ $K_{20kg/ha}$ + $Zn_{12.5kg/ha}$ + Nano Fertilizers ($Urea_{4ml/l}$ + $DAP_{4ml/lit}$ + $Zn_{0.5ml/l}$) | 1.46 | 1.49 | 4.60 | 4.70 | 4.20 | 4.29 |
| **$F_5$-** Nano Fertilizers ($Urea_{4ml/l}$ + $DAP_{4ml/lit}$ + $Zn_{0.5ml/l}$) | 1.31 | 1.34 | 4.47 | 4.57 | 4.01 | 4.10 |
| **SE (d)** | 0.02 | 0.02 | 0.06 | 0.06 | 0.05 | 0.05 |
| **CD (P= 0.05)** | **0.04** | **0.04** | **0.11** | **0.12** | **0.10** | **0.11** |