Impact of different levels of zinc and nitrogen on growth, productivity, and quality of aromatic rice cultivated under various irrigation regimes in two districts of Pakistan

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Rice is a staple food for more than 50% of the global population and it is one of the most valuable cereal crops. To fulfill the dietary requirement of the ever-growing world population, an increase in per-unit production of rice is direly required. In Pakistan, it stands as the 2nd in consumption after wheat, which is a staple food. A huge gap is observed between yield potential and actual yield of the aromatic rice cultivars at a farmer-field level. The significant limitations responsible for this gap are shortage of irrigation water, inappropriate application of fertilizers, less plant population, deficiency of micronutrients, and improper and poor plant protection measures. A field study was planned to assess the yield response and quality attributes of aromatic rice to three levels of zinc (Zn) and nitrogen (N) under three irrigation regimes (8-, 12-, and 16-acre inches) in the Sheikhupura and Sargodha districts of Pakistan. Irrigation treatments significantly influenced the growth, yield, and quality attributes; however, maximum improvement was observed by the application of irrigation at 12-acre inches. Among the Zn treatments, application of Zn at 10 kg ha$^{-1}$ was observed to be more responsive to improving the growth and quality parameters of aromatic rice crops. In the case of N treatments, application of N at 140 kg ha$^{-1}$ produced the maximum total tillers, as well as productive tillers per hill, spikelets per panicle, leaf area index, leaf area duration, crop growth rate, total dry matter, harvest
Introduction

Rice is a prominent cereal crop and staple food of masses around the globe. Among agricultural commodities, its cultivation requires an ample quantity of water. In Pakistan, it is the second most consumed food after wheat. In 2021, it was cultivated on an area of 3,335 thousand hectares with a production of 8.419 million tonnes (Government of Pakistan, 2021). For the cooking purposes, aromatic rice (basmati) is mainly preferred because of its long fluffy grains and unique taste. Least kernel dimension, aroma, fine texture, maximum elongation of the kernel during cooking, and high palatability with longer shelf life are some of the dynamic features of basmati rice (Ahmad et al., 2005). New basmati varieties, such as basmati super, basmati-2000, and shaheen basmati developed through different breeding approaches, have higher yield potential and improved quality characteristics. There is a huge yield gap between the potential yield and the actual yield of rice cultivars attained by the farmers. The potential yield of various basmati cultivars ranges from 4.5 to 6-ton ha\(^{-1}\), while farmers are getting only 2–2.8-ton ha\(^{-1}\), which is quite low (Ahmad et al., 2005; Shivay et al., 2010). Rice straw is commonly considered an agricultural waste that is a good source of sugar (Singhajutha et al., 2020). Pakistan is earning foreign exchange by exporting aromatic rice despite its actual yield being quite low than its genetic potential. Therefore, it is a timely need to strengthen research and planning to improve food production and quality to meet the standards of the international market.

The yield of basmati rice is low because of many factors, including water shortage, less plant population, non-judicious use of chemical fertilizers, zinc (Zn) deficiency, and poor plant protection measures. Among these factors, deficiency of water irrigation (Xie et al., 2008), nitrogen (N) fertilizer management (Wang et al., 2008), deficiency of Zn (Shivay et al., 2010), and weed infestation (Hossain et al., 2021a) have crucial effects to the growth, yield, and quality attributes of aromatic rice. Excess or deficiency of any input limits the growth and yield of field crops. Worldwide, water scarcity is a burning issue these days and sufficient irrigation of water supply is among the important factors for enhancing the yield of field crops (Xie et al., 2008). Prasad et al. (2008) reported that irrigation management had a significant impact on the growth, yield, and quality of rice. Sharma et al. (2008) reported the significant effects of irrigation regimes on grain, straw yield, and nutrient concentration of rice. There was a synergistic effect between irrigation levels and growth, quality, and nutrient concentration of upland rice (Crusciol et al., 2003).

Zinc (Zn) is an important micronutrient with vital roles in rice growth and metabolism. Its deficiency is a major concern in achieving target yield of field crops. Sarwar et al. (2020) and Anwar et al. (2022) reported that mineral fertilization, particularly micronutrients (Zn and Fe), is responsible for improved crop productivity and enhanced quality (Hussan et al., 2022). Its deficiency is mainly reported in rice-growing areas worldwide, including Pakistan. Paddy yield is reduced (25–50%) because of its deficiency, therefore, it is imperative to apply Zn in adequate quantity and at the proper time to attain maximum yield of rice and vegetable crops as well (Zafar et al., 2022). Mirzavand (2007) reported that an adequate supply of Zn to rice crops resulted in higher protein contents in grain. In Asian countries, it is a major health risk factor where rice is a staple food, and Zn nutrition for human and animal health has recently attained significant attention (WHO, 2002). Little work has been carried out and less information is available on the impact of Zn fertilization on kernel quality of basmati rice in Pakistan (Khan et al., 2009).

In modern agriculture, intensive cultivation is mandatory to meet the demands of ever-increasing population. In this scenario, N is dynamic macronutrient that has major role in crop production and improves the defensive system under competitive environment (Imran et al., 2021;
Experimental particulars and crop agro-environmental conditions in Pakistan. Rice crop cultivated under various irrigation regimes at diverse application on the growth, production, and quality of aromatic rice. In the light of rationale, the current experiment was designed to depict an increase in rice yield with increased N concentration to a certain level, while an N with very high rate resulted in low yield and N utilization by the rice. According to Ren et al. (2020), the difference in rice yield is mainly because of the difference between seed setting and several effective panicles. Meng and Du (2013) showed that an appropriate N application rate could ensure that the rice canopy population reached a higher leaf area index. It was investigated in a study of rice that nitrogenous fertilizer, amended with bacteria, was responsible for the variation in the various biochemical activities (Fatma et al., 2021). Breeding techniques are also under consideration in developing new varieties of field crops, particularly rice (Darwish et al., 2021; Herawati et al., 2021; Rahman et al., 2021), with respect to enhanced nitrogen use efficiency (Javed et al., 2022a,b). Various management approaches are being adopted by the farmers’ community to enhance the productivity of agronomic and horticultural crops (Khasanah and Rachmawati, 2020; Hossain M. A. et al., 2021b; Rehman et al., 2021), including the intercropping, application mineral elements, synthetic compounds (Nurhidayati et al., 2020; Abello et al., 2021), organic amendments (IJbal et al., 2020; Tabaxi et al., 2021), plants extracts, and biostimulants (Makawita et al., 2021; Khan et al., 2022) via soil (Rahim et al., 2020), seed coating (Javed et al., 2021), seed priming agents, and foliar spray (Khan et al., 2017; Batool et al., 2019; Farooq et al., 2021). These practices are not only responsible for productivity enhancement, but they significantly mitigate the adverse impacts of abiotic and biotic stresses (Shareef, 2020). It was hypothesized that the integrated application of N and Zn may enhance the productivity and quality of rice crops. In the light of rationale, the current experiment was designed to explore the impact of various levels of N along with Zn application on the growth, production, and quality of aromatic rice crop cultivated under various irrigation regimes at diverse agro-environmental conditions in Pakistan.

Materials and methods

Experimental particulars and crop husbandry

The Adaptive Research Farm, Sheikhupura (31.6°N, 74.6°E, and 217 m asl) and Adaptive Research Farm, Sargodha (32.04°N, 72.67°E and 188 m asl) were selected to conduct the designed experiments during the rice cultivation season. Geographical maps of the study areas are given in Figure 1. Aromatic rice nursery was sown after 20th May and nursery was transplanted after 40 days of nursery sowing. A recommended seed rate of 10 kg per ha was used to raise the nursery. For raising the nursery, the wet bed method was used. For this purpose, on the pulverized soil, rice seeds were spread manually. Regarding fertilization of rice nursery, 1.5 kg/6 marlas of N was applied. Super Basmati cultivar of aromatic rice was selected to observe the impact of treatments regarding growth, yield, and quality traits. Before, conducting the experiment, composite soil samples were collected from the study area with the help of an auger up to the depth of 30 cm. Physical and chemical properties of the experimental soils are presented in Table 1. Before transplanting, at the time of puddling, required doses of fertilizers applied to fulfill the nutrient required of rice crop. Urea, single superphosphate, potassium sulfate, and zinc sulfate were used as the sources of nutrients. Half dose of nitrogen was applied at the puddling, remaining half was applied at the tillering stage of the rice crop for maximum utilization of applied fertilizer. Depths of irrigation water, i.e., 8-, 12-, and 16-acre inches, were measured by installing the cut-throat flume at the field channel and calculations were made as described by Boman and Shukla (2006). To avoid the seepage effect or boarder impact, buffers plants were designed and maintained throughout the course of experimentation. Agronomic practices, including weeding and plant protection measures, etc., were uniformly performed during the growth period of rice crop. Flooded conditions were also observed regularly and maintained during the study. In the current experimentation, three factors, i.e., irrigation, zinc, and nitrogen, were under study with three levels of each factor (Irrigation; 8, 12, and 16-acre inches, Zn; 5, 10, and 15 kg ha⁻¹, and N; 70, 140, and 210 kg ha⁻¹).

Measurement of agronomic yield and quality attributes

Before the harvesting of crop, five hills were tagged randomly in each experimental unit to collect the data regarding total number of tillers per hill, number of panicle-bearing tillers, spikelet per panicle, and percentage of spikelet sterility. Total number of tillers per hill was counted manually from five tagged hills and the average was calculated. Tillers having panicles were separated and counted to record the number of panicle-bearing tillers (productive tillers). Number of spikelets per panicle was also counted manually from the productive tillers and the average was calculated. Spikelet sterility was recorded by observing the spikelet without grain and percentage was calculated. To record the data of yield and its components, an area of 7.5 m² was selected and harvested manually. Before threshing, all the harvested stuff...
was sun-dried for a week. Harvest index was expressed in percentage after calculating the ratio of grain yield to total dry matter. Thousand (1,000) kernels were counted manually from each experimental unit and weighed by electric balance to record the 1,000-kernel weight. A digital caliper was used to record the dimensions (length and width) of kernels. Tillers were randomly selected from each experimental unit to observe normal, opaque, abortive, and chalky kernels according to the procedure described by Nagato and Chaudhry (1969).
Measurement of growth parameters

Destructive sampling was done to record the data related to leaf area index, leaf area duration, crop growth rate, net assimilation rate, and photosynthetically active radiation. With an interval of fortnightly duration, four plants were harvested at ground level from each experimental unit to record the data regarding growth attributes. Fresh and dry weights of all parts of plant (stem, leaves, and panicle) were recorded. To record the dry weight, samples were dried in oven at 70°C up to a constant weight. Leaf area was recorded according to the protocols of Watson (1952). Leaf area duration, crop growth rate, and net assimilation rate were measured according to the formulas described by Hunt (1978). Photosynthetically active radiations were measured by following the method of Szeicz (1974). Radiation use efficiency, with respect to total dry matter (RUE_{TDM}) and grain yield (RUE_{KY}), was calculated according to following equations:

\[ \text{RUE}_{\text{TDM}} = \frac{\text{TDM}}{\Sigma \text{Sa}} \]
\[ \text{RUE}_{\text{KY}} = \frac{\text{Kernel yield}}{\Sigma \text{Sa}} \]

Where Sa is amount of intercepted light.

Statistical analysis

Normal data distribution assumption was tested using SPSS v. 17.0 software 195 packages according to the Shapiro and Wilk (1965) method. The combined ANOVA was carried out according to Snedecor and Cochran (1994), to estimate the main effects of the different sources of variation and their interactions. F-test was used to test treatment significance at 5% probability level using "MSTAT-C" software package. Mean separation was done using least significant difference (LSD) test when significant differences were found (Steel et al., 1997).

Results

Irrigation treatments significantly influenced the growth attributes, i.e., total number of tillers per hill, panicle bearing tillers per hill (productive tillers), spikelets per panicle, and spikelet sterility percentage (Table 2). Among all the irrigation treatments, application of irrigation at 12-acre inches produced maximum total tillers per hill, productive tillers per hill, and spikelets per panicle at both sowing places. Same treatment also reduced the spikelet sterility percentage as well (Table 2). Zn treatments significantly affected the total tillers per hill, productive tillers per hill, and spikelet sterility percentage except for spikelets per panicle. Application of Zn at 15 kg ha\(^{-1}\) was observed to be more responsive as compared to other treatments regarding growth attributes. N levels significantly influenced the growth parameters except for spikelet sterility percentage, and application of nitrogen at 140 kg ha\(^{-1}\) produced the maximum number of total tillers per hill, productive tillers per hill, and spikelets per panicle (Table 2). Interactive impact of irrigations, such as Zn and N applications, is also presented in the Table 2.

Irrigation treatments significantly affected the harvest index, kernel length and width, and 1,000- kernel weight of rice cultivated under three irrigation levels (Table 3). Among all irrigation treatments, application of irrigation at 12-acre inches produced maximum harvest index, kernel length and width, and 1,000-kernel weight at both sowing regions. Zn treatments significantly affected the harvest index, kernel length and width, and 1,000-kernel weight. Application of Zn at 10 kg ha\(^{-1}\) was observed more responsive as compared to other treatments. N levels also significantly improved these attributes and application of nitrogen at 140 kg ha\(^{-1}\) produced maximum harvest index, kernel length and width, and 1,000-kernel weight. Interactive impact of irrigations, such as Zn and N applications, is also presented in the Table 3.

Irrigation treatments significantly influenced the percentage of normal, opaque, and abortive kernel of rice cultivated under three irrigation levels at Sheikhupura and Sargodha districts of Pakistan (Table 4). Among all the irrigation treatments, application of irrigation at 12-acre inches produced maximum percentage of normal kernel. Same treatment also reduced the opaque and abortive kernel, while maximum rate of opaque and abortive kernel was observed at irrigation level of 8-acre inches. Zn treatments also significantly affected these attributes. Application of Zn at 10 kg ha\(^{-1}\) improved the maximum percentage of normal kernel as compared to other treatments. Similarly, highest reduction in opaque and abortive kernel was also noted at 10 kg ha\(^{-1}\) Zn application level, while maximum rate of these parameters was observed at 5 kg ha\(^{-1}\) Zn.

| TABLE 1 Physical and chemical characteristics of experimental soil. |
|---------------------------------------------------------------|
| **Determination** | **Unites** | **Sheikhupura** | **Sargodha** |
| **Physical characteristics** | | | |
| Sand (%) | 14 | 23 |
| Silt (%) | 70 | 60 |
| Clay (%) | 16 | 17 |
| Texture class | Loam | Silty loam |
| **Chemical characteristics** | | | |
| pH | 8.4 | 7.6 |
| Total soluble salts (%) | 10.1 | 15.02 |
| Organic matter (%) | 0.80 | 0.96 |
| Total nitrogen (%) | 0.07 | 0.06 |
| Available phosphorus ppm | 10.4 | 16.80 |
| Available potassium ppm | 204 | 235 |
TABLE 2 Impact of zinc and nitrogen rates on number of tillers per hill, panicle bearing tillers, spikelets per panicle, and percentage of spikelet sterility of rice cultivated under three irrigation levels at Sheikhupura (D1) and Sargodha (D2) districts of Pakistan.

| Parameters                  | Tillers per hill | Panicle bearing tillers | Spikelets per panicle | Percentage of spikelet sterility |
|-----------------------------|------------------|--------------------------|------------------------|----------------------------------|
| A = Irrigation levels       | D1               | D2                       | D1                     | D2                              |
| I1 = 8                      | 14.73c           | 14.52b                   | 13.80b                 | 12.61b                            |
| I1 = 12                     | 15.92a           | 15.98a                   | 14.93a                 | 13.94a                            |
| I1 = 16                     | 15.28b           | 15.03ab                  | 14.12b                 | 13.38ab                           |
| SE                          | 0.18             | 0.39                     | 0.27                   | 0.34                              |
| LSD                         | 0.50*            | 1.08*                    | 0.74*                  | 0.93*                            |
| B = Zinc rates              |                  |                          |                        |                                  |
| Zn1 = 5 kg ha⁻¹             | 13.79b           | 13.46b                   | 12.80b                 | 12.22b                            |
| Zn2 = 10 kg ha⁻¹            | 16.09a           | 16.11a                   | 15.07a                 | 13.97a                            |
| Zn3 = 15 kg ha⁻¹            | 16.04a           | 15.97a                   | 14.98a                 | 13.73a                            |
| SE                          | 0.15             | 0.17                     | 0.16                   | 0.20                              |
| LSD                         | 0.34**           | 0.37**                   | 0.36**                 | 0.43**                           |
| C = Nitrogen rates          |                  |                          |                        |                                  |
| N1 = 70 kg ha⁻¹             | 15.13b           | 14.96b                   | 14.12b                 | 12.95c                            |
| N2 = 140 kg ha⁻¹            | 15.49a           | 15.47a                   | 14.49a                 | 13.56a                            |
| N3 = 210 kg ha⁻¹            | 15.3ab           | 15.11ab                  | 14.25b                 | 13.41b                            |
| SE                          | 0.13             | 0.20                     | 0.12                   | 0.06                              |
| LSD                         | 0.27*            | 0.41*                    | 0.24**                 | 0.12**                           |
| Interactive effect of irrigation (A), zinc (B), and nitrogen (C) rates |                  |                          |                        |                                  |
| A × B                       | *                | *                        | **                     | NS                               |
| A × C                       | NS               | NS                       | **                     | NS                               |
| B × C                       | NS               | NS                       | **                     | NS                               |
| A × B × C                   | NS               | NS                       | **                     | NS                               |

Means sharing the same alphabet within the column are not statistically significant.

SE, standard error; LSD, least significant difference value for comparison; NS, statistically non-significant.

* and ** Significant at P < 0.05 and 0.01, respectively.
TABLE 3 Impact of zinc and nitrogen rates on harvest index, kernel length, and width, and 1,000-kernel weight of rice cultivated under three irrigation levels at Sheikhupura (D1) and Sargodha (D2) districts of Pakistan.

| Parameters | Harvest index | Kernel length | Kernel width | 1000-kernel weight |
|------------|---------------|---------------|--------------|-------------------|
| Treatments | D1            | D2            | D1           | D2               | D1           | D2           |
| A = Irrigation levels |               |               |              |                  |              |              |
| $I_1 = 8$  | 25.79c        | 24.53b        | 6.43b        | 6.52b            | 1.65b        | 1.71b        | 16.63b       | 19.01b |
| $I_1 = 12$ | 33.95a        | 32.18a        | 6.73a        | 6.88a            | 1.84a        | 1.96a        | 18.50a       | 20.37a |
| $I_1 = 16$ | 30.25b        | 27.36b        | 6.54ab       | 6.76a            | 1.78a        | 1.80ab       | 17.64b       | 19.71b |
| SE         | 0.01          | 0.01          | 0.08         | 0.09             | 0.04         | 0.06         | 0.46         | 0.36   |
| LSD        | 0.03**        | 0.04**        | 0.21*        | 0.24*            | 0.12*        | 0.17*        | 1.27*        | 1.00*  |
| B = Zinc rates |             |               |              |                  |              |              |
| $Zn_1 = 5$ | 26.61b        | 25.16c        | 6.48b        | 6.52b            | 1.72b        | 1.75b        | 17.03b       | 19.43b |
| $Zn_2 = 10$| 32.54a        | 30.93a        | 6.68a        | 6.89a            | 1.82a        | 1.90a        | 18.00a       | 19.83a |
| $Zn_3 = 15$| 30.84a        | 27.97b        | 6.54ab       | 6.74a            | 1.73b        | 1.82ab       | 17.74a       | 19.82a |
| SE         | 0.006         | 0.005         | 0.07         | 0.09             | 0.03         | 0.06         | 0.32         | 0.24   |
| LSD        | 1.85**        | 1.24**        | 0.14*        | 0.19**           | NS           | NS           | 0.70*        | 0.35*  |
| C = Nitrogen rates |           |               |              |                  |              |              |
| $N_1 = 70$ | 28.67b        | 26.84b        | 6.47b        | 6.57b            | 1.71b        | 1.72c        | 17.15b       | 19.06c |
| $N_2 = 140$| 31.13a        | 29.75a        | 6.67a        | 6.86a            | 1.79a        | 1.92a        | 17.99a       | 20.18a |
| $N_3 = 210$| 30.19a        | 27.48b        | 6.57ab       | 6.72ab           | 1.76ab       | 1.84b        | 17.63ab      | 19.84b |
| SE         | 0.003         | 0.004         | 0.07         | 0.11             | 0.03         | 0.04         | 0.33         | 0.08   |
| LSD        | 1.56**        | 1.93**        | 0.13*        | 0.23*            | 0.06*        | 0.08**       | 0.66*        | 0.16*  |

Interactive effect of irrigation (A), zinc (B), and nitrogen (C) rates

| A × B      | NS            | NS            | **           | NS               | **           | NS           | NS           | NS            |
| A × C      | NS            | NS            | NS           | NS               | NS           | NS           | NS           | NS            |
| B × C      | NS            | NS            | NS           | NS               | NS           | NS           | NS           | NS            |
| A × B × C  | NS            | NS            | NS           | NS               | NS           | NS           | NS           | NS            |

Means sharing the same alphabet within the column are not statistically significant.
SE, standard error; LSD, least significant difference value for comparison; NS, statistically non-significant.
* and ** Significant at $P < 0.05$ and 0.01, respectively.

Discussion

Water consumption in agriculture sector is increasing day by day while its resources are declining, so using irrigation water for rice production in areas of high-water stress can be a challenging issue. Water requirement for rice irrigation needs continuous flooding to maximize kernel yields (Du et al., 2022). In fact, without full immersion, weeds are difficult to control, and yield is adversely affected. Water quality has a significant impact on rice growth, yield characteristics, and yield (Prasad et al., 2008; Rezaei et al., 2013). The results of present experimentation showed that increasing the irrigation level significantly increased the TDM compared to the lower irrigation level. However, the results also showed that the difference between 12-acre inches and 16-acre inches was not significant. These findings are supported by Mukherjee and Mandal (1995), who conducted a field trial to study the effect of full immersion and nitrogen fertilization on rice yield. They observed that flooding conditions were positively correlated with grain yield and nitrogen yield. Similarly, Thanunathan and Sivasubramanian (2002) showed that the highest number of high-density grains was recorded in continuous submergence. Sharma et al. (2008) concluded that pre-sowing irrigation and gradual fertilization have a positive effect on straw yield and nutrient content of straw crops.
TABLE 4 Impact of zinc and nitrogen rates on percentage of normal, opaque, and abortive kernel of rice cultivated under three irrigation levels at Sheikhupura (D1) and Sargodha (D2) districts of Pakistan.

| Parameters                  | Percentage of normal kernel | Percentage of opaque kernel | Percentage of abortive kernel | Percentage of chalky kernel |
|-----------------------------|-----------------------------|----------------------------|-------------------------------|-----------------------------|
| Treatments                  | D1                          | D2                         | D1                            | D2                          |
| **A = Irrigation levels**   |                             |                             |                               |                             |
| $I_1 = 8$                   | 65.02b                      | 71.82b                     | 10.99a                        | 12.35a                      |
| $I_1 = 12$                  | 69.02a                      | 74.28a                     | 10.03b                        | 10.67c                      |
| $I_1 = 16$                  | 66.44b                      | 73.66a                     | 10.44b                        | 11.48b                      |
| SE                          | 0.82                        | 0.65                       | 0.19                          | 0.23                        |
| LSD                         | 2.29*                       | 1.81*                      | 0.52*                         | 0.64*                       |
| **B = Zinc rates**          |                             |                             |                               |                             |
| $Zn_1 = 5$ kg ha$^{-1}$     | 66.04                       | 72.11                      | 11.27a                        | 11.97a                      |
| $Zn_2 = 10$ kg ha$^{-1}$    | 67.87                       | 73.97                      | 9.49c                         | 11.17b                      |
| $Zn_3 = 15$ kg ha$^{-1}$    | 66.58                       | 73.68                      | 10.70b                        | 11.37b                      |
| SE                          | 0.63                        | 0.86                       | 0.20                          | 0.24                        |
| LSD                         | NS                          | NS                         | 0.43**                        | 0.52**                      |
| **C = Nitrogen rates**      |                             |                             |                               |                             |
| $N_1 = 70$ kg ha$^{-1}$     | 65.65b                      | 72.15b                     | 10.68a                        | 11.79a                      |
| $N_2 = 140$ kg ha$^{-1}$    | 67.98a                      | 74.37a                     | 10.28c                        | 11.26b                      |
| $N_3 = 210$ kg ha$^{-1}$    | 66.89b                      | 73.23b                     | 10.49b                        | 11.46b                      |
| SE                          | 0.76                        | 0.54                       | 0.09                          | 0.12                        |
| LSD                         | 1.54*                       | 1.09**                     | 0.18**                        | 0.25**                      |
| **Interactive effect of irrigation (A), zinc (B), and nitrogen (C) rates** |                             |                             |                               |                             |
| $A \times B$                | NS                          | **NS**                     | NS                            | *                           |
| $A \times C$                | NS                          | NS                         | NS                            | *                           |
| $B \times C$                | NS                          | NS                         | NS                            | **NS**                      |
| $A \times B \times C$       | NS                          | NS                         | NS                            | NS                          |

Means sharing the same alphabet within the column are not statistically significant. SE, standard error; LSD, least significant difference value for comparison; NS, statistically non-significant.

* and ** Significant at $P < 0.05$ and 0.01, respectively.

Similarly, increasing Zn application levels also increased TDM, a response commonly seen in Punjab rice (Ahmad et al., 2009). Therefore, irrigation and Zn fertilization possibly increase TDM yield due to the increase in LAI, LAD, and, hence, CGR (Ahmad et al., 2009). These results also confirmed that under the current environmental and soil conditions, 12-acre inches and 10 kg Zn ha$^{-1}$ were sufficient to achieve higher TDM. The amount of water needed to water plants depends on climate, plant, and soil conditions. However, water requirements can be modified by changing irrigation schedules and cultivation methods (Kim et al., 1992; Sharma and Sarkar, 1994). A study in Punjab (Pakistan) (Ahmad et al., 2009) compared five irrigation patterns (62.5, 77.5, 92.5, 107.5, and 1,122.5 cm) with Basmati-385 cultivar of basmati rice.

Nitrogen (N) plays a key role in plant growth in intensive agriculture as an essential component of cellular components. Therefore, insufficient nitrogen intake has profound effects on food production. Some early researchers reported that the rate and timing of nitrogen application played an important role in improving the yield of rice and other field crops (Habtergebrial et al., 2013; Khan et al., 2021). These authors found the highest yields (4–5 ton ha$^{-1}$) of basmati rice and its components at 130–140 kg N ha$^{-1}$. The outcomes of current experiments are in line with the results of Rajarathinam and Balasubramaniyan (1999) who found that the components of rice yield (such as number of ears m$^{-2}$, number of ears$^{-1}$, and thousand kernel weight), rice yield, and index yield were highest and amounted to 200 kg N ha$^{-1}$. Nitrogen is an integral part of protein, an important component of protoplasm and enzymes, and a biological catalyst that accelerates the life process. It is also an important component of organic compounds, such as core proteins, amino acids, amines, amino sugars, and plant polypeptides. Iqbal et al. (2020) reported that application of farmyard manure was responsible to improve the growth of maize crop. Nitrogen fertilization significantly affects the yield of super hybrid rice (Zheng et al., 2008; Yoseftabar et al., 2012). Kavitha et al. (2008) concluded that using 200 kg N ha$^{-1}$ improves nutrient uptake, yield, and economics of rice.
TABLE 5 Impact of zinc and nitrogen rates on leaf area index, leaf area duration, total dry matter and crop growth rate of rice cultivated under three irrigation levels at Sheikhupura (D1) and Sargodha (D2) districts of Pakistan.

| Parameters | Treatments | Leaf area index | Leaf area duration | Crop growth rate | Total dry matter |
|------------|------------|-----------------|--------------------|------------------|-----------------|
|            |            | D1              | D2                 | D1               | D2              |
| A = Irrigation levels | I$_1$ = 8 | 4.77b           | 5.21b              | 257.1b           | 282.9b          | 10.35b           | 10.60b          | 13.87c           | 14.12b           |
|            | I$_1$ = 12| 5.34a           | 5.82a              | 285.0a           | 321.2a          | 11.29a           | 11.89a          | 15.35a           | 15.76a           |
|            | I$_1$ = 16| 5.05ab          | 5.48ab             | 271.5ab          | 299.5ab         | 10.63b           | 11.45ab         | 14.98b           | 15.46a           |
|            | SE         | 0.14            | 0.16               | 5.75             | 9.68            | 0.20             | 0.35            | 0.12             | 0.12             |
|            | LSD        | 0.39*           | 0.44*              | 15.95*           | 26.87*          | 0.57*            | 0.96*           | 0.34**           | 0.23**           |
| B = Zinc rates | Zn$_1$ = 5 kg ha$^{-1}$ | 4.95b           | 5.38b              | 261.7b           | 291.9b          | 9.89c            | 10.57c          | 13.52b           | 13.81c           |
|            | Zn$_2$ = 10 kg ha$^{-1}$ | 5.21a           | 5.64a              | 280.02a          | 308.18a         | 11.73c           | 12.21a          | 15.36a           | 16.18a           |
|            | Zn$_3$ = 15 kg ha$^{-1}$ | 5.00b           | 5.50b              | 271.9ab          | 303.7ab         | 10.65b           | 11.17b          | 15.33a           | 15.35b           |
|            | SE         | 0.09            | 0.06               | 4.94             | 5.97            | 0.31             | 0.23            | 0.09             | 0.18             |
|            | LSD        | 0.20*           | 0.12**             | 10.77*           | 13.02*          | 0.68*            | 0.51*           | 0.19**           | 0.38**           |
| C = Nitrogen rates | N$_1$ = 70 kg ha$^{-1}$ | 4.85b           | 5.41b              | 257.54c          | 295.13c         | 10.25b           | 10.81c          | 15.58b           | 14.88b           |
|            | N$_2$ = 140 kg ha$^{-1}$ | 5.34a           | 5.57a              | 285.29a          | 307.76a         | 11.13a           | 11.82a          | 14.92a           | 15.30a           |
|            | N$_3$ = 210 kg ha$^{-1}$ | 4.98b           | 5.54a              | 270.8b           | 300.88b         | 10.88a           | 11.32b          | 14.70ab          | 15.17a           |
|            | SE         | 0.08            | 0.05               | 4.08             | 2.63            | 0.14             | 0.15            | 0.14             | 0.10             |
|            | LSD        | 0.20**          | 0.12*              | 8.27**           | 5.34*           | 0.25**           | 0.31**          | 0.27*            | 0.21**           |

Interactive effect of irrigation (A), zinc (B), and nitrogen (C) rates

|          | A × B | A × C | B × C | A × B × C |
|----------|-------|-------|-------|-----------|
| NS       | NS    | NS    | NS    | NS        |

Means sharing the same alphabet within the column are not statistically significant.

SE, standard error; LSD, least significant difference value for comparison; NS, statistically non-significant.

* and ** Significant at P < 0.05 and 0.01, respectively.
TABLE 6 Impact of zinc and nitrogen rates on net assimilation rate (NAR), photosynthetically active radiation (PAR), and radiation use efficiency (RUE) with respect to total dry matter (TDM) and kernel yield (KY) of rice cultivated under three irrigation levels at Sheikhupura (D1) and Sargodha (D2) districts of Pakistan.

| Parameters | NAR | PAR | RUE to TDM | RUE to KY |
|------------|-----|-----|------------|----------|
| Treatments | D1  | D2  | D1         | D2       | D1         | D2       |
| A = Irrigation levels |
| $I_1 = 8$ | 5.51c | 4.97b | 826.41b | 873.29b | 1.73b | 1.63b | 0.66b | 0.57c |
| $I_1 = 12$ | 5.72a | 5.44a | 861.72a | 919.57a | 1.82a | 1.81a | 0.71a | 0.61a |
| $I_1 = 16$ | 5.59b | 5.18ab | 846.86a | 890.03ab | 1.77ab | 1.73ab | 0.68b | 0.58b |
| SE | 0.02 | 0.13 | 7.06 | 9.05 | 0.02 | 0.04 | 0.01 | 0.01 |
| LSD | 0.06* | 0.35* | 19.61* | 25.13* | 0.06* | 0.10* | 0.03* | 0.02* |
| B = Zinc rates |
| $Zn_1 = 5$ kg ha$^{-1}$ | 5.38b | 5.05b | 829.95b | 880.62b | 1.68b | 1.63b | 0.65b | 0.54c |
| $Zn_2 = 10$ kg ha$^{-1}$ | 5.85a | 5.42a | 857.79a | 897.36a | 1.88a | 1.83a | 0.70a | 0.65a |
| $Zn_3 = 15$ kg ha$^{-1}$ | 5.59ab | 5.11ab | 847.25a | 895.91a | 1.76ab | 1.71b | 0.69a | 0.58b |
| SE | 0.22 | 0.16 | 7.02 | 5.60 | 0.04 | 0.04 | 0.03 | 0.02 |
| LSD | 0.47* | 0.34* | 15.29* | 12.21* | 0.09** | 0.80** | 0.03* | 0.04* |
| C = Nitrogen rates |
| $N_1 = 70$ kg ha$^{-1}$ | 5.41b | 5.06b | 826.66c | 884.67b | 1.70c | 1.67c | 0.65b | 0.57b |
| $N_2 = 140$ kg ha$^{-1}$ | 5.75a | 5.36a | 863.33a | 901.72a | 1.83a | 1.81a | 0.71a | 0.62a |
| $N_3 = 210$ kg ha$^{-1}$ | 5.66a | 5.16b | 845.06b | 887.56b | 1.79b | 1.71b | 0.68a | 0.57b |
| SE | 0.09 | 0.08 | 6.31 | 3.02 | 0.02 | 0.02 | 0.02 | 0.01 |
| LSD | 0.18** | 0.16** | 12.79** | 6.12** | 0.03** | 0.04** | 0.03* | 0.02* |

Interactive effect of irrigation (A), zinc (B), and nitrogen (C) rates

| A × B | NS | NS | NS | NS | NS | NS | NS | NS |
| A × C | NS | NS | NS | NS | NS | NS | NS | NS |
| B × C | NS | NS | NS | NS | NS | NS | NS | NS |
| A × B × C | NS | NS | NS | NS | NS | NS | NS | NS |

Means sharing the same alphabet within the column are not statistically significant.
SE, standard error; LSD, least significant difference value for comparison; NS, statistically non-significant.
* and ** Significant at $P < 0.05$ and 0.01, respectively.

occurs, and this additional LAI provides no benefit to the crop. Nitrogen fertilization plays critical roles in physiomorphological traits of field crops, which are directly and/or indirectly linked with economical yield (Kumar et al., 2022).

The mean crop growth rate (CGR) was affected by increased doses of zinc and nitrogen at both sites. However, the difference in mean CGR between irrigation levels was not significant. The average CGR values for Basmati rice reported here compare favorably to those from other regions. Ahmad et al. (2009) reported mean CDRs ranging from 12 to 14.50 g/m$^2$ day$^{-1}$ at the Faisalabad, Kala Shah Kaku, and Gujranwala sites. The results showed that increasing zinc and nitrogen doses significantly improved the efficacy of CT irradiation (RUE). Averaging these two sites, Sheikhupura and Sargodha had ERU averages of 1.77 and 1.73 g MJ$^{-1}$, respectively. Similar dependencies have been reported by others (Ahmad et al., 2009) who also reported ERU values ranging from 1.41 to 1.44 g MJ$^{-1}$.

Data on quality parameters of transplanted fine rice affected by increased rehydration, zinc, and nitrogen levels showed significant but quadratic responses for all treatments. The results presented in this experiment generally show that higher doses of irrigation, zinc, or nitrogen application decrease the appearance of most grades. Similar results have been reported by others (Ahmad et al., 2009). Treatments, such as slower watering rates, zinc, and nitrogen consumption, may be too low to cause nutritional stress, which can increase grain size reduction. Shivay et al. (2008) and Khan et al. (2009) reported that using zinc in an amount of 10–15 kg ha$^{-1}$ can improve the yield and quality of milled rice.

**Conclusion**

In an intensive rice production system, rice productivity is significantly influenced by several factors, including low plant population, irrigation water shortage, zinc deficiency, imbalanced use of fertilizers, and inadequate plant protection measures. Experiments were conducted to examine the impact of three levels of zinc and nitrogen under three irrigation regimes on the growth and quality of rice crop. The outcomes of current experimentations showed that application of irrigational water, zinc, and nitrogen at 12-acre inches, 10, and 140 kg ha$^{-1}$, respectively, are responsible to achieve maximum kernel yield and quality of produce. Further studies
regarding integrated application of macro and micronutrients are required to enhance the resources use efficiency with improved crop productivity.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

All authors actively participated in designing and conducting the experiment, data collection, statistically analysis, and manuscript preparation.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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