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IMPROVING RICE PRODUCTIVITY AND QUALITY THROUGH OPTIMUM PLANT POPULATION AND NITROGEN MANAGEMENT

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ABSTRACT

Rice yield can be improved with optimum plant population and nitrogen levels. A field experiment was conducted at Krishi Vigyan Kendra, Panipat (Haryana) during *kharif* 2023 to explore the effect of plant population dynamics and nitrogen management in Basmati rice. In this study three different plant populations, *viz*, P_1, P_2 and P_3 (33, 25, 20) plant m^{-2} and five nitrogen levels, *viz*., N_1, N_2, N_3, N_4, and N_5 (100% RDN, 100 RDN + two sprays of nano nitrogen at 40-50 and 60-70 DAT, LCC based nitrogen scheduling, 125% RDN and 150% RDN) keeping as main plot and sub plot respectively, were replicated thrice in split plot design Results revealed that P_2N_5 had highest yield (5292 kg ha^{-1}) which was higher than (3.14~11.05) other treatments. It can be attributed to higher number of $panicle^{-1}$ and number of grains $panicle^{-1}$. However, the combination of P_2N_5 leads to better gross returns and benefit: cost. This study suggests that P_2N_5 treatments could enhance rice yield up to a significant level.
***Keyword* :** LCC, Nano Nitrogen, Nitrogen Management, Plant Population

Introduction

Rice is a vital global crop, providing a primary food source for approximately half of the world's population. It accounts for over 21% of global caloric intake and serves as the main calorie source for up to 76% of individuals in Southeast Asia (Zhao *et al*., 2020; GRiSP, 2013). Originating from Asia, particularly the areas around the Yangtze River in China and the Ganges Delta in India, rice cultivation has significantly influenced civilizations for thousands of years (Wang *et al*., 2022). India has the largest rice acreage, covering 43.8 million hectares, and ranks second in production after China, with an estimated output of over 135 million metric tons in the financial year 2023 (Statista, 2024). Furthermore, projections indicate that the global population is expected to surpass 9 billion by 2050 and exceed 10 billion by 2080 (UN, 2022). Given the widespread consumption of rice among a significant portion of the global population, there is an urgent need to increase rice production to ensure food security on a global scale.

Rice has a higher potential for greenhouse gas emissions compared to other cereals, with a Global Warming Potential (GWP) 467% greater than wheat and 169% higher than maize (Linquist *et al*., 2012). Imbalanced nitrogen fertilizer application significantly limits rice quality and yield (Wang e*t al*., 2008). The yield and quality of basmati rice depends upon several factors such as growing environment, cultural practices, varieties etc, but the application of nitrogen has paramount importance. Insufficient application of nitrogen in rice causes reduction in yield due to poor accumulation of photosynthates (Hasegawa *et al*., 1994; Yoshida *et al*., 2006) and quality i.e. low grain protein content (Dou *et al*., 2017) in basmati rice. Contemporary cultivars of basmati rice are input responsive and have potential to give better yield with reasonable application of nitrogen fertilizer (Pooniya and Shivay 2013; Sravan and Neupane, 2021). However excess application of nitrogen in Basmati rice makes it more susceptible to pests and diseases, lodging; thus, excessive nitrogen can reduce yield and quality such as amylose content (Li *et al*., 2003; Xu e*t al*., 2005 and aroma (Kaur, Mahal, and Kaur 2016). Careful utilization of nitrogen fertilizer is crucial for promoting robust rice growth and improving the overall grain yield (Liang, 2022; Ravi *et al*., 2024).

Plant population, in addition to nitrogen, plays a crucial role in determining crop yield. The practice of transplanting rice at wider spacing by migratory labour leads to low plant density, which results in excessive nitrogen application in basmati rice. This is done to enhance tillering and make up for the sub-optimal plant population. The plant population plays a crucial role in determining the interception of solar radiation, the extent of canopy coverage, the accumulation of dry matter, and the overall growth rate (Anwar *et al*., 2011). When rice seedlings are transplanted too closely, they engage in competition for essential resources such as light, water, and nutrients, which can adversely affect their growth and lead to a decrease in grain yield. Sub optimal plant population leads to reduction in overall yield due to less number plant per unit area (Li, 2016), less number of panicle per unit area (Liu, 2017). So, optimal plant population fosters the robust development of both above-ground and below-ground plant structures by enhancing the effective utilization of solar radiation, nutrients, and water.

Optimum Plant population and reasonable nitrogen levels are two most critical factors for optimum yield, quality and returns in basmati rice (Gong *et al.,* 2022; Wei *et al*., 2024). Farmers can enhance production and economic benefits by rationalizing the plant population and nitrogen levels. The yield potential can't be realised if plant population is too dense or sparse. This study investigates the effect of plant population and nitrogen levels on quality, yield components and economics of basmati rice in Trans Gangetic plains of India. It is anticipated that this study will contribute to the enhancement of production systems (including seed rates and fertilization practices) and improve the profitability of rice cultivation in India and other rice-producing nations globally.

Materials and Methods

Site description, Soil properties and weather parameters

Field experiment was conducted at experiment farm of Krishi Vigyan Kendra, Panipat (29º22' N 76º58' E 263 m altitude) Haryana (India) in 2023-2024. Soil samples were gathered from 0-60 cm depth for analysis of soil properties before application of fertilizers as indicated in Table 1. The station lies under the eastern agroclimatic zone of Haryana. Weather data such as rainfall, maximum temperature, minimum temperature, bright sunshine hours etc. were collected from nearby observatory (CSSRI, Karnal) and shown in Figure 1.

Experimental and treatment details

Field experiment was arranged in a split plot design. The treatment comprising of 3 different plant population (P_1- 33 plant m^{-2}; P_2- 25 plant m^{-2} and P_3- 20 plant m^{-2}) in main plot and 5 different levels of nitrogen (N_1- 100% RDN (90 Kg ha^{-1}); N_2- 100% RDN + two spray of nano-nitrogen at 40-50 and 60-70 DAT; N_3- LCC based nitrogen scheduling (4 splits of 22.5 kg N ha^{-1}); N_4- 125% RDN; and N_5- 150% RDN) at subplot with three replications. The gross plot size was 6 m x 3 m.

Crop management

Pre germinated seeds of PB 1718 (Basmati rice) were sown in a seedbed with sowing date of 8 June in 2023 and thirty-days old seedlings with four leaves were manually transplanted in main field on 8 July 2023 by using a labelled rope. For treatment N_1, 90 kg N was applied in three splits, 1/3rd dose of N for each level was applied at 0, 21 and 42 DAT. For treatment $N_{2,}$ 4 splits of 22.5 kg N ha^{-1} was applied based on leaf color chart reading at 0, 21, 49 and 63 DAT. In treatment N_3, Foliar spray of nano urea @ 4ml l^{-1} was used in 125-liter water at 40 and 60 DAT. In treatment $N_{4\,(}$112.5 kg ha^{-1}) and N_5 (135 kg ha^{-1}), 1/3rd dose of N for each level was applied at 0, 21 and 42 DAT. The protein content in grains was determined by total N measured by Kjeldahl (1883) method in grains multiplied by Jones factor i.e. 6.25 (Jones *et al.,* 1942). The grain and straw yield at maturity was determined by harvesting individual plot of 18 m^{-2} by using a sickle. The harvest index was calculated from given formula:

Harvest Index= Economical Yield /Biological yield X 100

Statistical analysis

The analysis of variance (ANOVA) as outlined by Panse and Sukhtane (1978) was used to evaluate all data from experiment. The significant treatment effects were calculated using the least significant difference at $p<0.05$. Finally, the data analysis done through 'OPSTAT' available on official website of CCS Haryana Agricultural University, Hisar. The figures were generated through RStudio software and MS Office.

Results and Discussion

Yield attributes and yield components

Yield attributes

The result revealed that plant population has no significant effect on the yield attributes, i.e. panicle length, number of panicle m^{-2}, number of grains panicle^{-1} and test weight (Table 2). However, the number of panicle m^{-2} and number of grains $panicle^{-1}$ was significantly influenced with increase in levels of nitrogen up to 150% RDN, being highest in N_5. In contrary to this, lowest yield attributed were recorded under treatment N_1. With increasing the nitrogen levels, the yield components improved but the higher application of nitrogen showed maximum improvement (Deng *et al.,* 2011). The total number of spikelets as crucial determinant of yield also improved with nitrogen application (Zhou *et al.,* 2017). The overall quantity of spikelet was determined by the number of panicles and the number of grains present in each panicle Liu *et al.,* 2022). Nitrogen has non-significant effect on panicle length and test weight, although treatment N_5 resulted into superior panicle length and test weight as compared to other treatments. Maximum panicle length (31.0 cm) was achieved under higher application of nitrogen. Similar results were confirmed by findings of Metwally *et al.*, 2011; Metwally *et al*., 2017; Yoseftabar, 2013.

Yield components

The Figure 2 demonstrates the significant effect of plant population and nitrogen levels on yield parameters. The present study revealed that basmati rice cultivated with moderate plant population *i.e.* 25 plant $^{-2}$ resulted in significantly higher grain yield (5028 kg ha^{-1}) which was 2.8% higher as compared to treatment P_1. On the other hand, dense plant population resulted into maximum straw (8051 kg ha^{-1}) and biological yield (13029 kg ha^{-1}). Under dense plant population better solar radiation inception resulted into better accumulation of photosynthetic matter which ultimately leads to maximum straw yield. But the competition for resources like water, nutrients etc. are more under dense plant population (Ngouajio, 2011, Liu *et al.,* 2021). On the other hand, plant population below the optimum level has better access to the available resources so yield of a single plant usually reaches its maximum but yield per unit area reduces to a greater extent due to a smaller number of numbers of plants per unit area. Yield is dependent upon interspecific and intraspecific competition for available resources, highest yield is achieved when such competition is low (Khajepour, 2008). So, the highest grain yield was achieved under moderate plant population due to better utilization of resources and less competition among plants for resources.

The N_5 treatment gives highest grain, straw, and biological yield (5556, 8946 and 14503 kg ha^{-1} respectively) in comparison to the treatments. The lowest yield parameters were recorded under N_1 treatment. Nitrogen helps in proper filling of seeds which leads to higher seed production. When nitrogen is not applied in sufficient quantity then it hampers yield attributes mainly number of panicle m^{-2} (Eagle *et al.*, 2000; Slaton *et al.*, 2003). Highest number of grains $panicle^{-1}$ and number of panicle m^{-2} was recorded under highest level of nitrogen dose. This is confirmed by findings of Rajput *et al.,* 2020; Lar *et al.*, 2007, Kumar *et al*, 2025; Ye *et al.,* 2019; Sorour *et al.,* 2016). Hence, yield components improved with increase in nitrogen levels upto 150% RDN as nitrogen leads to better translocation and accumulation of photosynthates from vegetative to reproductive parts.

Interaction effect of plant population and nitrogen on grain yield

A two-factor interaction plot (Fig. 4) illustrates how three plant populations (P_1, P_2, P_3) respond to five nitrogen levels (N_1–N_5) in terms of rice grain yield. Across all populations, yield rose progressively as nitrogen increased, with the largest jump occurring between N_3 and N_5. Under the lowest nitrogen treatment (N_1), P_2 slightly out yielded P_1 (4588 vs. 4669kg ha^{-1}), while P_3 recorded the lowest output (4338 kg ha^{-1}), suggesting P_2's relative advantage when nitrogen is scarce. With higher nitrogen rates, P_2 not only stayed ahead of P_1 but also extended its lead over P_3, peaking at 5608 kg ha^{-1} under N_5.

Notably, the lines for each population do not run parallel, indicating a significant interaction between population and nitrogen ($p<0.05$). In practical terms, this means each population's yield gains from added nitrogen differ in magnitude.

Quality parameters

The effect of plant population on quality parameters was found non-significant. Table 3 depicted that with increasing in the nitrogen content the kernel length and protein content has improved significantly. The treatment N_5 leads to highest kernel length (7.79 mm) which was 1.6% higher as compared to N_1. The maximum protein content in grains was observed in treatment N_5 (6.9) followed by N_4 (6.7). The protein content has improved with nitrogen levels (Chen *et al.*, 2023; Yang *et al.,* 2024)). A high nitrogen level favours high protein content with reduced adhesiveness that can be due to protein affects the water absorption (Martin and Fitzgerald, 2002; Ding *et al*., 2021).

Economics

The treatment P_2 gets maximum gross returns (241806 Rs ha^{-1}), net returns (120746 Rs ha^{-1}) and B: C (1.99) followed by treatment P_1. In contrary to this, the minimum gross returns (120659 Rs ha^{-1}), net returns

(113469 Rs ha^{-1}) and B: C (1.94) was found in the treatment P_3.

In case of various nitrogen level, the treatment N_5 resulted into higher cost of cultivation (120959 Rs ha^{-1}), gross returns (267966 Rs ha^{-1}), net returns (147007 Rs ha^{-1}) and B:C (2.2) which was followed by treatment N_4. The lowest gross returns (217633 Rs ha^{-1}, net returns (97480 Rs ha^{-1}), and B:C (1.81) was obtained in treatment N_1.(Table 4)

Conclusion

Optimum combination of plant population and nitrogen levels can result in better performance of basmati rice. Many researches across the worked showed that plant population, nitrogen application and their positive interaction significantly impact the grain yield. Therefore, moderate plant population with optimizing the nitrogen levels can improve various agronomic traits in basmati rice and lead to better utilization of resources. The appropriate combination as revealed by this study is 25 plants m^{-2} with 150% RDN for better yield and quality in basmati rice. However, grain yield in this combination is at par with 20 plants m^{-2} with 150% RDN. The substantial yield gain with additional application of nitrogen even at the highest plant population reveals that there is strong case for upward revision of nitrogen doses in basmati rice.

The farmer practice of using nitrogen more than the RDN is corroborated by this study. However, any dose exceeding 150% RDN would be undesirable because the aggravating biotic stresses may lead to yield plateau or yield penalty.

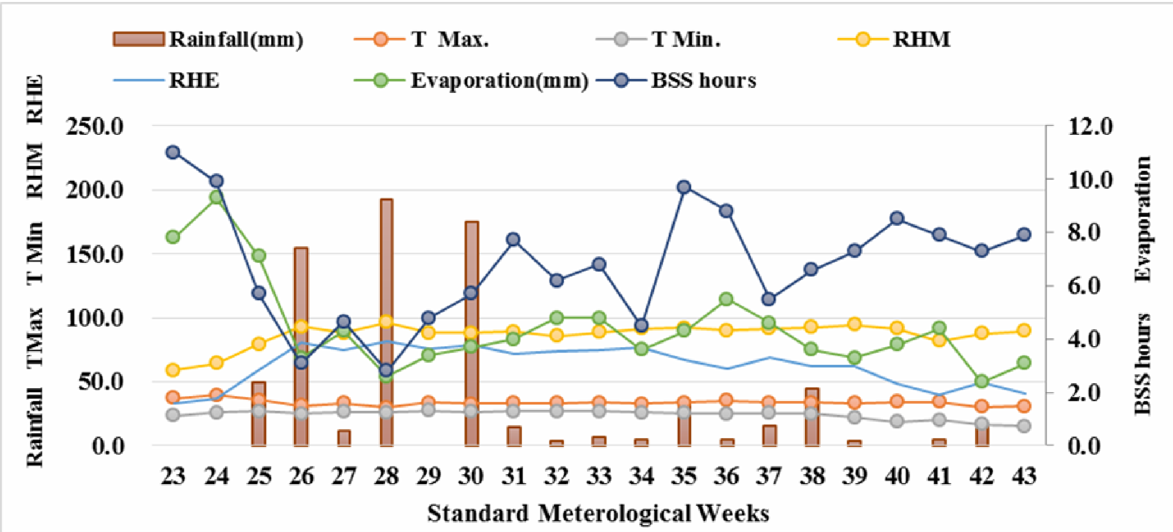

Fig. 1 : Weekly weather data collected nearby observatory (CSSRI, Karnal) during *kharif* 2023

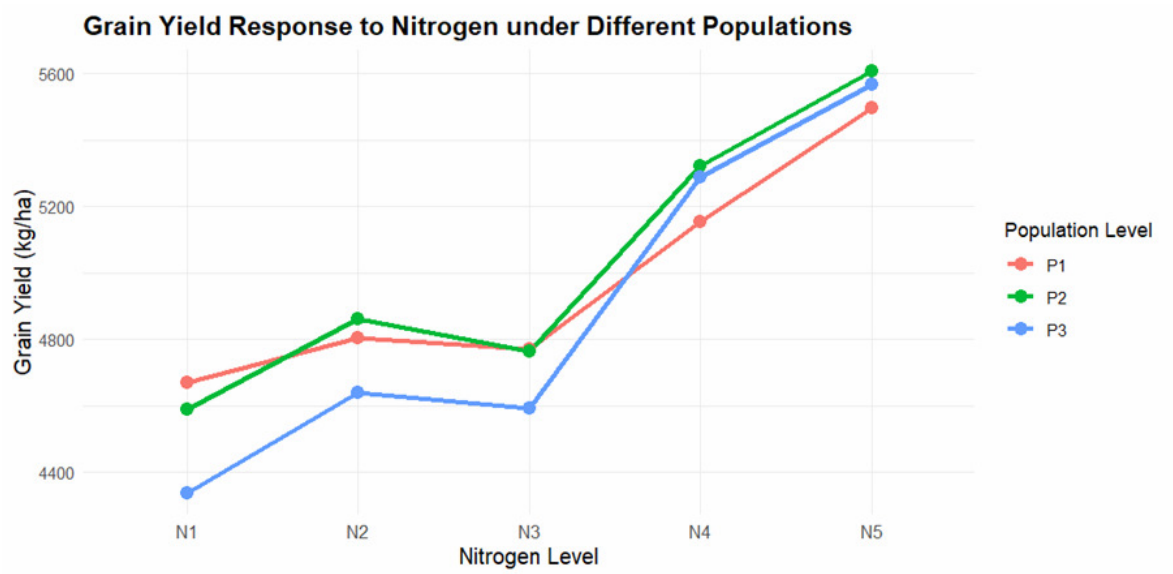

Fig. 2 : Influence of plant population and nitrogen levels on grain yield

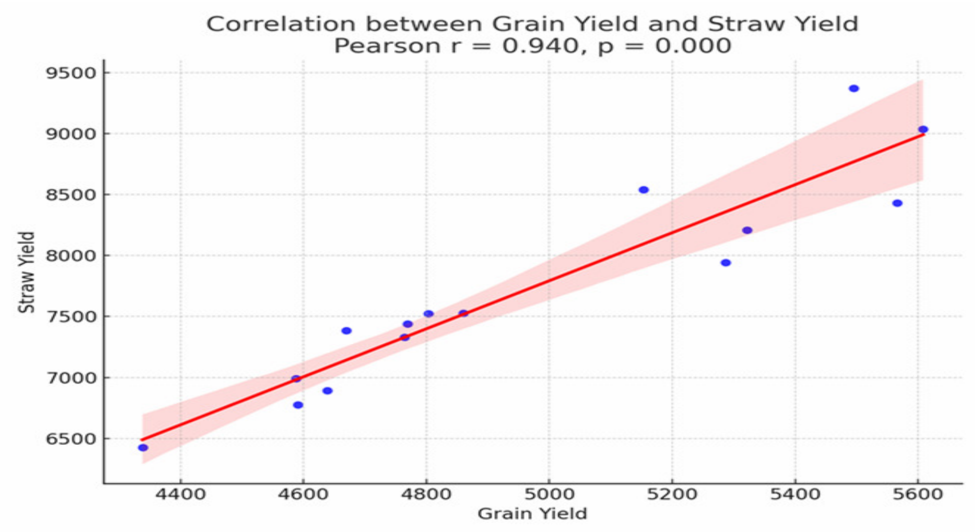

Fig. 3 : Correlation analysis between grain and straw yield in basmati rice

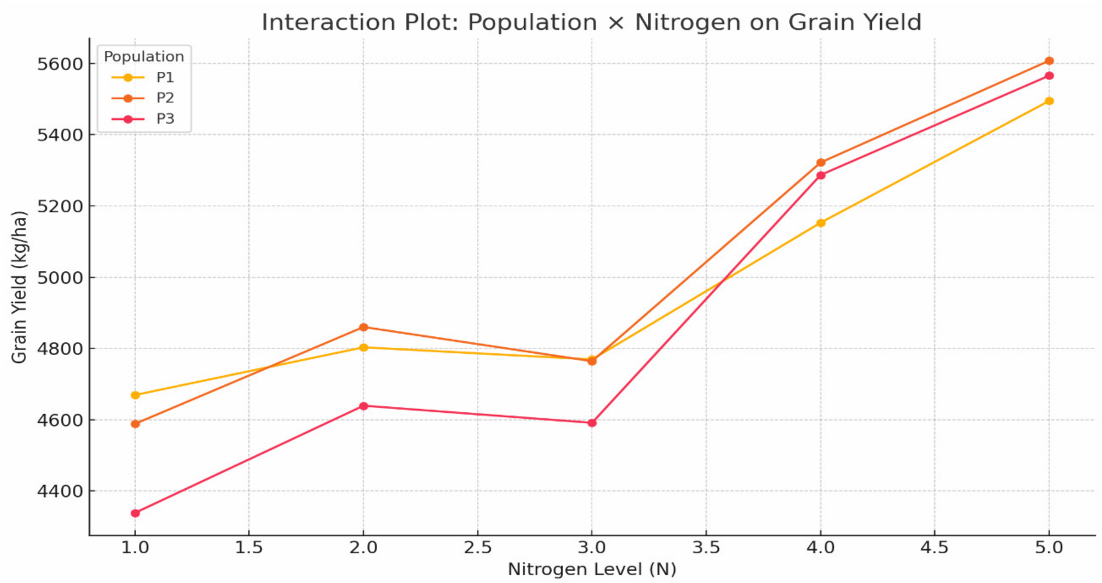

Fig. 4 : Interaction effect of population dynamics and nitrogen management on grain yield of basmati rice

Table 1 : Initial Physio-Chemical characteristics of soil in 2023

Year	Organic Matter	pH	EC	Available N	Available P	Available K
2023	0.63%	8.3	0.33	127 kg ha^{-1}	37 kg ha^{-1}	166 kg ha^{-1}

Table 2 : Effect of population dynamics and nitrogen management on yield attributes of basmati rice

Treatments	**Yield attributes**			
Plant Population	Panicle length	Number of panicle (m^{-2})	Number of grains panicle^{-1}	1000 grain weight
P_1-20 cm x 15 cm (33 plant m^{-2})	30.1	287.8	82.3	25.4
P_2-20 cm x 20 cm (25 plant m^{-2})	30.5	285.0	82.8	25.4
P_3-20 cm x 25 cm (20 plant m^{-2})	30.9	278.2	82.7	25.6
SE(m) ±	0.3	2.1	0.3	0.05
CD (p=0.05)	NS	NS	NS	NS

Nitrogen levels (kg ha^{-1})				
N_1- 100% RDN (90 kg ha^{-1})	29.7	270.0	80.8	25.2
N_2- 100%RDN+two spray of nano nitrogen at 40-50 and 60-70 DAT	30.6	277.2	82.1	25.3
N_3- LCC based nitrogen scheduling (Tentative 4 splits of 22.5 kg N ha^{-1})	30.5	276.8	81.2	25.5
N_4- 125% RDN	30.8	291.7	84.2	25.6
N_5- 150% RDN	31.0	302.6	84.6	25.6
SE(m) ±	0.3	2.1	0.5	0.2
CD (p=0.05)	NS	6.2	1.4	NS

Table 3 : Effect of population dynamics and nitrogen management on quality of basmati rice

Treatments	Quality Parameters			
Plant Population	**Kernel length (mm)**	**Kernel breadth (mm)**	**Kernel length: breadth**	**Protein content (%)**
P_1-20 cm x 15 cm (33 plant m^{-2})	7.55	1.93	3.90	6.44
P_2-20 cm x 20 cm (25 plant m^{-2})	7.65	1.93	3.94	6.49
P_3-20 cm x 25 cm (20 plant m^{-2})	7.73	1.95	3.96	6.51
SE(m) ±	0.03	0.01	0.02	0.02
CD (p=0.05)	NS	NS	NS	NS
Nitrogen levels (kg ha^{-1})				
N_1- 100% RDN (90 kg ha^{-1})	7.45	1.90	3.90	6.14
N_2- 100%RDN+two spray of nano nitrogen at 40-50 and 60-70 DAT	7.59	1.93	3.92	6.40
N_3- LCC based nitrogen scheduling	7.66	1.94	3.94	6.2
N_4- 125% RDN	7.74	1.95	3.95	6.7
N_5- 150% RDN	7.79	1.97	3.96	6.9
SE(m) ±	0.07	0.01	0.02	0.06
CD (p=0.05)	0.2	NS	NS	0.18

Table 4 : Effect of population dynamics and nitrogen management on economics of basmati rice

Treatments	Economics			
Plant Population	**Cost of cultivation (Rs ha^{-1})**	**Gross return (Rs ha^{-1})**	**Net return (Rs ha^{-1})**	**Benefit: cost (B:C)**
P_1- 20 cm x 15 cm (33 plant m^{-2})	121459	240148	118688	1.97
P_2- 20 cm x 20 cm (25 plant m^{-2})	121059	241806	120746	1.99
P_3- 20 cm x 25 cm (20 plant m^{-2})	120659	234128	113469	1.94
Nitrogen levels (kg ha^{-1})				
N_1- 100% RDN (90 kg ha^{-1})	120153	217633	97480	1.81
N_2- 100%RDN+two spray of nano nitrogen at 40-50 and 60-70 DAT	123278	229001	105723	1.85
N_3- LCC based nitrogen scheduling (Tentative 4 splits of 22.5 kg N ha^{-1})	120353	226062	105709	1.87
N_4- 125% RDN	120556	252808	132252	2.0
N_5- 150% RDN	120959	267966	147007	2.2

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Authors' contributions: All authors were actively involved in the experimental design, analysed the findings, participated in discussions, contributed to paper preparation, did an extensive review and approved the final version

Conflict of interest: Authors declare that there are no conflicts of interest.

References

Chen, H., Yang, G., Xiao, Y., Zhang, G., Yang, G., Wang, X. and Hu, Y., (2023). Effects of nitrogen and phosphorus fertilizer on the eating quality of indica rice with different amylose content. *Journal of Food Composition and Analysis*, **118**, 105167 https://doi.org/10.1016/j. jfca.2023 .105167

Deng, J., Zhou, Z.X., Zhu, B., Zheng, X.H., Li, C.S., Wang, X. and Jian, Z. (2011). Modeling nitrogen loading in a small watershed in southwest China using a DNDC model with hydrological enhancements. *Biogeosciences*, **8**, 2999–3009.

Ding, Y. Y., Cheng, J. J., Lin, Q. Y., Wang, Q. Y., Wang, J. R. and Yu, G. P. (2021). Effects of endogenous proteins and lipids on structural, thermal, rheological, and pasting properties and digestibility of adlay seed (*Coix lacryma-jobi* L.) starch. *Food Hydrocolloids,* **111**, 106254.

Dou, Z., Tang, S., Li, G., Liu, Z., Ding, C. and Chen, L. (2017). Application of nitrogen fertilizer at heading stage improves rice quality under elevated temperature during grain-filling stage. *Crop Science,* **57**(4), 2183–2192.

Eagle, A. J., Bird, J. A., Horwath, W. R., Linquist, B. A., Brouder, S. M., Hill, J. E. and van Kessel, C. (2000). Rice yield and nitrogen utilization efficiency under alternative straw management practices. *Agronomy Journal,* **92**, 1096–1103.

Gong, Y. L., Lei, Y., Zhang, X. P., Yan, B. C., Ju, X. T., Cheng, X. Y., Zhang, J. D., Sun, X. Y., Xu, H. and Chen, W. F. (2022). Nitrogen rate and plant density interaction enhances grain yield by regulating the grain distribution of secondary branches on the panicle axis and photosynthesis in japonica rice. *Photosynthetica,* **60**, 179–189.

GRiSP. (2013). *Rice almanac* (4th ed.). International Rice Research Institute.

Hasegawa, T., Koroda, Y., Seligman, N. A. G. and Horie, T. (1994). Response of spikelet number to plant nitrogen concentration and dry weight in paddy rice. *Agronomy Journal,* **86**(4), 673–676.

Jones, D. B., Munsey, V. E. and Walker, L. E. (1942). Report of committee on protein factors. *Journal of the Association of Agricultural Chemists,* **25**, 118–120.

Kaur, J., Mahal, S. S. and Kaur, A. (2016). Yield and quality evaluation of direct seeded basmati rice (*Oryza sativa* L.) under different irrigation and nitrogen regimes. *Cereal Research Communications,* **44**(2), 330–340. https://doi.org/10.1556/0806.43.2015.047

Khajepour, M. R. (2008). *Principles and foundations of agronomy*. Isfahan University of Technology Press.

Kjeldahl, J. (1883). A new method for the determination of nitrogen in organic matter. *Zeitschrift für Analytische Chemie,* **22**, 366–382.

Kumar, P., Sewhag, M., Singh, D., Kumar, S., Kumar, P., Rahul and Kumar, S. (2025). Impact of integrated nano and non-nano urea on nitrogen efficiency and uptake in grain and straw in late-sown wheat. *Biological Forum – An International Journal,* **17**(5), 22–26.

Li, G. H., Zhang, J., Yang, C. D., Liu, Z. H., Wang, S. H. and Ding, Y. F. (2016). Population characteristics of high-yielding rice under different densities. *Agronomy Journal,* **108**, 1415–1423.

Li, Y. X., Wang, Z., Gu, Y. J. and Chen, Z. Z. (2003). Effects of various nitrogen treatments on starch accumulation in caryopsis during the rice grain filling. *Journal of Nanjing Normal University (Natural Science),* **26**(3), 68–71.

Liang, G. (2022). Nitrogen fertilization mitigates global food insecurity by increasing cereal yield and its stability. *Global Food Security,* **34**, 100652.

Linquist, B., Van Groenigen, K. J., Adviento-Borbe, M. A., Pittelkow, C. and Van Kessel, C. (2012). An agronomic assessment of greenhouse gas emissions from major cereal crops. *Global Change Biology,* **18**, 194–209.

Lar, O. P., Shivay, Y. S. and Kumar, D. (2007). Effect of nitrogen and sulphur fertilization on yield attributes, productivity and nutrient uptake of aromatic rice (*Oryza sativa* L.). *Indian Journal of Agricultural Sciences,* **77**(11), 772–775.

Liu, K., Chen, Y., Huang, J., Qiu, Y., Li, S., Zhuo, X. and Yang, J. (2022). Spikelet differentiation and degeneration in rice varieties with different panicle sizes. *Food and Energy Security,* **11**(1), e320.

Liu, Q. H., Zhou, X. B., Li, J. L. and Xin, C. Y. (2017). Effects of seedling age and cultivation density on agronomic characteristics and grain yield of mechanically transplanted rice. *Scientific Reports,* **7**, 14072.

Liu, Y., Liao, Y. C. and Liu, W. Z. (2021). High nitrogen application rate and planting density reduce wheat grain yield by reducing filling rate of inferior grain in middle spikelets. *The Crop Journal,* **9**, 412–426.

Martin, M. and Fitzgerald, M. A. (2002). Proteins in rice grains influence cooking properties. *Journal of Cereal Science,* **36**, 285–294.

Metwally, T. F., Gabr, W. E. and Hashem, I. M. (2017). Growth performance of genotypes at suboptimal level of nitrogen fertilizer and effect of rice blast and white tip nematode diseases. *Egyptian Journal of Plant Protection Research,* **5**, 47–74.

Metwally, T. F., Gewaily, E. E. and Naeem, S. S. (2011). Nitrogen response curve and nitrogen use efficiency of Egyptian hybrid rice. *Journal of Agricultural Research, Kafr El-Shaikh University,* **37**, 73–84.

Ngouajio, M. (2011). Using the right planting density is critical for optimum yield and revenue for vegetable crops. *Michigan State University Extension*.

Panse, V. G. and Sukhatme, P. V. (1978). *Statistical methods for agricultural workers*. ICAR.

Pooniya, V. and Shivay, Y. S. (2013). Enrichment of basmati rice grain and straw with zinc and nitrogen through ferti-fortification and summer green manuring under Indo-Gangetic plains of India. *Journal of Plant Nutrition,* **36**(1), 91–117. https://doi.org/10.1080/01904167.2012. 733052

Rajput, P., Singh, A. K., Rajput, R. K. and Singh, A. (2020). Effect of nitrogen levels on yield and yield attributes of rice (*Oryza sativa*) grown under different planting geometry. *Indian Journal of Agronomy,* **65**(2), 235–241.

Ravi, Sutaliya, J. M., Dhaka, A. K., Kamal, Phogat, P. and Singh, D. (2024). Effect of precision nitrogen management using nano urea and optical sensor on the nitrogen use efficiency of basmati rice and soil properties under different establishment methods. *Biological Forum–An International Journal,* **16**(7), 98–102.

Slaton, N. A., Cartwright, R. D., Meng, J., Gbur, E. E., Jr. and Norman, R. J. (2003). Sheath blight severity and rice yield as affected by nitrogen fertilizer rate, application method, and fungicide. *Agronomy Journal,* **95**, 1489–1496.

Sravan, U. S., Singh, S. P. and Neupane, M. P. (2021). Response of basmati rice varieties to integrated nutrient management. *Journal of Plant Nutrition,* **44**(3), 351–365. https://doi.org/10.1080/01904167.2020.1822394

Statista. (2024). *Production volume of rice in India from financial year 2010 to 2023*.

United Nations. (2022). *World population prospects 2022: Ten key messages*. UN Department of Global Communications.

Wang, J., Zhu, J., Lei, D. and Jiang, L. (2022). New evidence for rice harvesting in the early Neolithic Lower Yangtze River, China. *PLoS ONE,* **7**, 12–17.

Wang, Y., Zhu, B., Shi, Y. and Hu, C. (2008). Effects of nitrogen fertilization on upland rice based on pot experiments. *Communications in Soil Science and Plant Analysis,* **39**(11–12), 1733–1749.

Wei, J. G., Chai, Q., Yin, W., Fan, H., Guo, Y., Hu, F. L., Fan, Z. L. and Wang, Q. M. (2024). Grain yield and nitrogen uptake of maize in response to increased plant density under reduced water and nitrogen supply conditions. *Journal of Integrative Agriculture,* **23**, 122–140.

Xu, R. L., Dai, Q. G., Huo, Z. Y. and Wang, X. Q. (2005). Effects of nitrogen fertilizer quantity on rice variety quality. *Journal of Nanjing Normal University (Agriculture & Life Science),* **26**(1), 66–68.

Yang, G., Chen, H., Zhang, G., Yang, G., Wang, X. and Hu, Y. (2024). Effect of nitrogen fertilizers on starch and protein contents and physicochemical characteristics of rice noodles. *Journal of Food Composition and Analysis,* **135**, 106565.

Yoseftabar, S. (2013). Effect of nitrogen management on panicle structure and yield in rice (*Oryza sativa* L.). *International Journal of Agriculture and Crop Sciences,* **5**, 1224–1227.

Yoshida, H., Horie, T. and Shiraiwa, T. (2006). A model explaining genotypic and environmental variation of rice spikelet number per unit area measured by cross-locational experiments in Asia. *Field Crops Research,* **97**(2–3), 337–343.

Zhao, M., Lin, Y. and Chen, H. (2020). Improving nutritional quality of rice for human health. *Theoretical and Applied Genetics,* **133**, 1397–1413.

Zhu, D. W., Zhang, H. C., Guo, B. W., Xu, K., Dai, Q. G., Wei, H. Y. and Huo, Z. Y. (2017). Effects of nitrogen level on yield and quality of japonica soft super rice. *Journal of Integrative Agriculture,* **16**(5), 1018–1027.