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Enhancing nutrient use efficiency through nano-fertilizer in Barley (*Hordium vulgare* L.)

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Abstract
A field experiment was conducted during *Rabi* season of 2022-23 at Agricultural Research Farm, Department of Agronomy, R.B.S. College, Bichpuri, Agra (U.P.) the investigation entitled *'Enhancing nutrient use efficiency through nano-fertilizer in Barley (Hordeum vulgare L.)'*. The variables involved in this study were T_1 (Control (P+K) only),T_2 (Control (P+K) only+ 1000 ml NN/ha at 30-35 DAS+1000 ml NN/ha at 60-65 DAS), T_3 (50% RDN+500 ml NN/ha at 30-35 DAS+500 ml NN/ha at 60-65 DAS), T_4 (50% RDN+1000 ml NN/ha at 30-35 DAS+1000 ml NN/ha at 60-65 DAS), T_5 (75% RDN+500 ml NN/ha at 30-35 DAS+500 ml NN/ha at 60-65 DAS), T_6 (75% RDN+1000 ml NN/ha at 30-35 DAS+1000 ml NN/ha at 60-65 DAS), T_7 (RDN+500 ml NN/ha at 30-35 DAS+500 ml NN/ha at 60-65 DAS), T_8 (RDN+1000 ml NN/ha at 30-35 DAS+1000 ml NN/ha at 60-65 DAS) and T_9 (Recommended doses of fertilizers). These 9 treatments were compared in a "Randomized Block Design" with three replications. The experimental result revealed that 100% RDN (@ 60 kg ha^{-1}) when applied with two spray of nano-nitrogen fertilizer @1000 ml ha^{-1} at 30-35 and 60-65 DAS (T_8) played a vital role for overall improvement in crop growth and development and the maximum grain yield (56.88 q ha^{-1}) and maximum net return was obtained with crop fertilized with 100% RDN + two foliar sprays of nano-nitrogen fertilizer @1000 ml ha^{-1} at 30-35 and 60-65 DAS followed by T_7 (100% RDN + foliar spray of nano-nitrogen fertilizer @ 500 ml ha^{-1} at 30-35 and 60-65 DAS). The maximum net return ₹ 120448 ha^{-1} and B:C ratio (3.71) were also obtained.

Keywords: Barley, foliar spray, nutrient, nano-nitrogen (NN), yield

Introduction
Barley (*Hordeum vulgare* L.) is widely grown across a range of environments as a rain-fed or irrigated crop. It is considered as one of the most suitable cereal crops, which can survive and grow over a wide range of soils and under many adverse climatic conditions compared with many other cereal crops. The economically valuable product is grain, which is used for food and feed, but also for industrial processing. Singh *et al.* (2024). Every farmer concentrates on crop production to feed the family. (Harish *et al.*, 2023) [7, 18].

The indispensable use of fertilizers has emerged as an essential practice for augmenting crop yields and preserving soil fertility. Conventional fertilizers, such as urea, nitrogen, phosphorous, potassium, mono-ammonium phosphate, and diammonium phosphate, are widely utilized to supplement essential nutrients in the soil. However, conventional fertilizers suffer from low nutrient utilization efficiency due to leaching, leading to substantial economic losses and decreased soil fertility. The leaching of these nutrients from the soil has resulted in a significant decrease in soil fertility. As mineral nitrogen is easily lost by leaching or de-nitrification, the N rate needs to be optimized for the actual year, while application of P and K can be based on the principles of substitution of harvest P and K because soil available P and K changes slowly. Virendra, *et al.*, (2024) [12].

The nano-fertilizers deal with the elements in nano- meter dimensions (1-100 nm). When minimized to the nano-scale, these nutrients show some characteristics that differ from the presence of the nutrients in the macro scale, allowing unique applications. Nano-formulated fertilizers can release nutrients more slowly in cooperation with other fertilizers which may lead to improvement of nutrient use efficiency. (Singh *et al.*, 2024) [18]. Use of higher level of fertilizers, irrigation and sometimes reverting to older cultivars for specific needs and increase in the mechanized harvesting may lead to further losses due to lodging.

(Archna, *et al.*, 2023) [1]. One of the biggest obstacles to raising the commercial yield of crops is the current increase in fertilizer prices. Therefore, measures to reduce its losses and improve its economic utilization are required (Lokendra et el., 2024) [12]. Phosphorus regulates protein synthesis in plants, because it is a component of the complex nucleic acid structure. (Ramesh *et al.*, 2023, Sonia, *et al.*, 2023) [22]. Phosphorus is also important in cell division and development of new tissues. (Singh *et al.*, 2022) [20]. These changes persist over long periods, frequently spanning decades or even longer. But over the past few centuries, human activity particularly since the industrial revolution has significantly altered the makeup of the atmosphere. In spite of a changing climate, climate-resilient agronomy aims to maintain sustainable food production and stable livelihoods for farmers. (Singh *et al.*, 2023) [21].

Materials and Methods

The field experiment was carried out during winter (Rabi) season of 2022-23 at Agricultural Research Farm, Department of Agronomy, R.B.S. College, Bichpuri, Agra (U.P.). The soil of experimental field was moderately fertile, being low in organic carbon (0.31%), available nitrogen (181.50 kg ha-1), available phosphorus (27.5 kg P2O5 ha-1) and rich in available potassium (285.0 kg K ha-1). The variables involved in this study were T_1 (Control (P+K) only),T_2 (Control (P+K) only+ 1000 ml NN/ha at 30-35 DAS+1000 ml NN/ha at 60-65 DAS), T_3 (50% RDN+500 ml NN/ha at 30-35 DAS+500 ml NN/ha at 60-65 DAS), T_4 (50% RDN+1000 ml NN/ha at 30-35 DAS+1000 ml NN/ha at 60-65 DAS), T_5 (75% RDN+500 ml NN/ha at 30-35 DAS+500 ml NN/ha at 60-65 DAS), T_6 (75% RDN+1000 ml NN/ha at 30-35 DAS+1000 ml NN/ha at 60-65 DAS), T_7 (RDN+500 ml NN/ha at 30-35 DAS+500 ml NN/ha at 60-65 DAS), T_8 (RDN+1000 ml NN/ha at 30-35 DAS+1000 ml NN/ha at 60-65 DAS) and T_9 (Recommended doses of fertilizers). These 9 treatments were compared in a “Randomized Block Design” with three replications. The full dose of Nitrogen (60 kg ha-1), P2O5 (30kg ha-1) and K2O (20 kg ha-1) as per treatment applied as basal dressing at the time of sowing through DAP (46% P205+18% N), Urea (46% N) and MOP (60% K2O). Foliar application of different doses of nano fertilizers was applied at 30-35 and 60-65 DAS as per treatment.

Results and Discussion

Yield attributes

In case of barley, the main yield contributing characters are Stand count m-2, No. of earhead m-2, No. of grains/ earhead and 1000 grain weight. The variation in these yield attributes due to various levels of nano fertilizers and RDN were measured and results obtained were analyzed statistically. The respective data of yield attributes have been presented in Table 1. The data presented in table 1 reveal that application of various levels of nano fertilizer alone and with recommended levels of nitrogen produced significantly higher stand count meter-2 by 8.52 to 23.11 per cent than the control. The maximum stand count m-2 was recorded with the application of RDN+1000ml NN/ha at 30-35 DAS+1000 ml at 60-65 DAS (T_8) and it differed nominally with Recommended doses of fertilizers (T_9) and RDN+500ml NN/ha at 30-35 DAS+500 ml at 60-65 DAS (T_7) and could not reach the level of significance and resulted in significantly higher stand count m-2 by 5.52 to 30.06 per cent than rest of the treatments (T_1 to T_6). Application of 75% RDN+1000ml NN/ha at 30-35 DAS+1000 ml at 60-65 DAS (T_6) did not differ appreciably with 75% RDN+500ml NN/ha at 30-35 DAS+500 ml at 60-65 DAS (T_5) but both the treatments increased stand count meter-2 significantly by 5.05 to 23.26 per cent and 3.55 to 21.51 per cent, respectively over T_4 (50% RDN+1000ml NN/ha at 30-35 DAS+1000 ml at 60-65 DAS), T_3 (50% RDN+500ml NN/ha at 30-35 DAS+500 ml at 60-65 DAS), T_2 (Control(P+K) only +1000ml NN/ha at 30-35 DAS+1000 ml at 60-65 DAS) and T_1 (Control (P+K) only). In contrast, T_1, being the control treatment with only phosphorus (P) and potassium (K), had the lowest stand count, indicating that the absence of nitrogen (N) application limited plant density.

Table 1: Yield attributes as influenced by various treatments.

Treatments	Stand count m^{-2}	No. of earhead m^{-2}	No. of grains/ earhead	1000-grains weight (g)
T_1	288.33	244.50	35.08	36.16
T_2	315.17	304.11	37.52	37.50
T_3	327.50	315.50	38.60	38.01
T_4	338.33	325.47	39.01	39.68
T_5	350.35	340.34	40.53	40.87
T_6	355.40	346.53	40.67	41.20
T_7	366.31	348.75	40.91	41.80
T_8	375.01	364.00	43.08	43.50
T_9	365.50	347.14	40.87	41.67
SEm ±	4.43	5.82	0.89	0.76
CD at 5%	10.95	14.38	2.19	1.87

An examination of the data computed in Table 1 reveals that application of levels of nano fertilizers alone and with different rate of recommended doses of nitrogen produced significantly higher number of earhead m-2 by 19.60 to 32.83 per cent over the control (T_1). Maximum number of earhead m-2 (364.0) was recorded with the application of RDN+1000ml NN/ha at 30-35 DAS+1000 ml at 60-65 DAS (T_8) which was significantly higher by 4.37 to 48.88 percent over all other treatments. Application of Recommended doses of fertilizers (T_9), RDN+500ml NN/ha at 30-35 DAS+500 ml at 60-65 DAS (T_7), 75% RDN+1000ml NN/ha at 30-35 DAS+1000 ml at 60-65 DAS (T_6) and 75% RDN+500ml NN/ha at 30-35 DAS+500 ml at 60-65 DAS (T_5) were nominal among themselves and could not reach the level of significance and resulted in significantly higher number of earhead m-2 when compared with rest of the treatments (T_1 to T_4).

The data summarized in Table 4.5 indicate that all the levels of nano fertilizer and different rates of RDN increased number of grains/ earhead by 6.50 to 18.57 per cent over the control. Application of RDN+1000ml NN/ha at 30-35 DAS+1000 ml at 60-65 DAS (T_8) significantly increased number of grains/ earhead over all other treatments and the magnitude of increase was 5.30 to 22.81 percent. Treatment T_9 (Recommended doses of fertilizers) and T_7 (RDN+500ml NN/ha at 30-35 DAS+500 ml at 60-65 DAS) were statistically at par with T_5 (75% RDN+500ml NN/ha at 30-35 DAS+500 ml at 60-65 DAS) and T_6 (75% RDN+1000ml NN/ha at 30-35 DAS+1000 ml at 60-65 DAS), recorded significantly a greater number of grains / earhead by 4.77 to 16.51 and 4.87 to 16.62 percent, respectively over rest of the treatments (T_1 to T_4). T_8 (RDN+1000ml NN/ha at 30-35 DAS+1000 ml at 60-65 DAS) superior performance suggests that the combination of full recommended nitrogen dose (RDN) and multiple applications of NN fostered better pollination and grain filling. In contrast, T_1, with only P and K, resulted in the lowest grain count, likely due to limited nitrogen availability. The similar finding recorded by Karan *et al.* 2023 and Babu and Singh (2024) [3, 8, 18].

The table under reference further indicates that the maximum 1000 grain weight (43.50g) was recorded with the application of RDN+1000ml NN/ha at 30-35 DAS+1000 ml at 60-65 DAS (T_8) and it differed marginally with RDN+500ml NN/ha at 30-35 DAS+500 ml at 60-65 DAS (T_7) and Recommended doses of fertilizers (T_9) but produced significantly higher 1000 grains weight by 5.58 to 20.30 percent than rest of the treatments (T_1 to T_6). The heavier grain weight in T_8 highlights the beneficial impact of the RDN and NN applications, which likely enhanced nutrient uptake and allocation to grain development. The lighter grains in T_1 indicate suboptimal nutrient conditions, particularly the lack of nitrogen, which is crucial for grain filling. The increment in one or more characters due to application of Nitrogen along with nano-nitrogen have also been reported by Kumar *et al.*, (2023) Shubham, *et al.*, (2023), Babu and Singh (2024) and Kumar *et al.* (2025) [4, 9, 10, 16, 18].

Yield (q ha-1)

The data summarized in Table 2 indicate that application of different levels of nano fertilizers and recommended doses of nitrogen increased biological yield appreciably by 12.55 to 37.66 per cent over the control (T_1). The maximum biological yield was recorded with the application of RDN+1000ml NN/ha at 30-35 DAS+1000 ml at 60-65 DAS (T_8) which was significantly higher than all other treatments and the magnitude of increase was 3.44 to 60.40 percent. The differences in biological yield recorded with the application of RDN+500ml NN/ha at 30-35 DAS+500 ml at 60-65 DAS (T_7) and Recommended doses of fertilizers (T_9) were not appreciable among themselves produced significantly higher biological yield by 7.14 to 55.06 and 6.82 to 54.60 per cent than rest of the treatments including control (T_6 to T_1). Application of 75% RDN+1000ml NN/ha at 30-35 DAS+1000 ml at 60-65 DAS (T_6) was statistically at par with 75% RDN+500ml NN/ha at 30-35 DAS+500 ml at 60-65 DAS (T_5), gave appreciably higher biological yield by 9.13, 13.83, 26.56 and 44.73 per cent, respectively than T_4, T_3, T_2 and T_1. Control treatment (T_1) proved its significant inferiority over all other treatments. In contrast, T1, with only phosphorus (P) and potassium (K), had the lowest biological yield, reflecting suboptimal nutrient conditions. The data presented in Table 2 reveals that application of levels of nano fertilizers and rates of RDN produced significantly higher grain yield by 13.32 to 39.35 per cent over the control.

The significantly higher grain yield was noted with the application of RDN+1000ml NN/ha at 30-35 DAS+1000 ml at 60-65 DAS (T_8) which was 4.06 to 64.87 percent higher than all other treatments. The variation in grain yield per hectare with the application of RDN+500ml NN/ha at 30-35 DAS+500 ml at 60-65 DAS (T_7) was not well mark with Recommended doses of fertilizers (T_9) but both the treatments resulted in conspicuously higher grain yield by 9.78 to 58.74 and 7.91 to 55.74 per cent over rest of the treatments (T_1 to T_6), respectively. Application of 75% RDN+1000ml NN/ha at 30-35 DAS+1000 ml at 60-65 DAS (T_6) and 75% RDN+500ml NN/ha at 30-35 DAS+500 ml at 60-65 DAS (T_5) did not differ appreciably and both the treatments produced significantly higher grain yield by 8.05 to 44.32 and 5.25 to 40.38 per cent, respectively than remaining treatments T_4 to T_1. The higher grain yield in T8 can be attributed to the optimal nitrogen supply, which enhanced photosynthesis, nutrient uptake, and grain filling. The control treatment Control (P+K) only (T_1) had significantly lower grain yield due to the absence of nitrogen, which is critical for reproductive growth and grain development.

Table 2: Biological, grain and straw yields and harvest index as influenced by various treatments.

Treatments	Biological yield (qha^{-1})	Grain yield (qha^{-1})	Straw yield (qha^{-1})	Harvest index (%)	Gross return (₹ ha^{-1})	Cost of cultivation (₹ ha^{-1})	Net return (₹ ha^{-1})	B C ratio
T_1	87.08	34.50	52.58	39.62	101922	42336	59586	2.41
T_2	99.58	39.80	59.78	39.97	116877	43696	73181	2.67
T_3	110.72	44.15	66.57	39.88	129856	43607	86249	2.98
T_4	115.49	46.08	69.41	39.90	135477	44087	91390	3.07
T_5	122.22	48.50	73.72	39.68	143124	43803	99321	3.27
T_6	126.03	49.79	76.24	39.51	147378	44283	103095	3.33
T_7	135.03	54.66	80.37	40.48	159131	43999	115133	3.62
T_8	139.68	56.88	82.80	40.72	164927	44479	120448	3.71
T_9	134.63	53.73	80.90	39.91	157942	43119	114823	3.66
SEm ±	1.64	0.88	0.86	0.33	101922	42336	59586	2.41
CD at 5%	4.05	2.18	2.12	NS	116877	43696	73181	2.67

The Table under references further indicates that straw yield increased by 12.04 to 36.50 per cent with various treatments of nano fertilizers and rates of RDN over the control. The application of RDN+1000ml NN/ha at 30-35 DAS+1000 ml at 60-65 DAS (T_8) produced significantly higher straw yield (82.80 q ha-1) over all other treatments and the magnitude of increase was 2.35 to 57.47 percent. Application of RDN+500ml NN/ha at 30-35 DAS+500 ml at 60-65 DAS (T_7) did not differ appreciably with Recommended doses of fertilizers (T_9) and both the treatments increased significantly higher straw yield by 5.42 to 52.85 and 6.11 to 53.86 per cent, respectively than rest of the treatments. Treatment T_6 (75% RDN+1000ml NN/ha at 30-35 DAS+1000 ml at 60-65 DAS) also gave significantly higher straw yield by 3.42 to 45.00 percent than treatments T_5 to T_1, suggests that the treatment promoted not only reproductive growth but also vegetative growth, leading to more biomass production. The lowest straw yield in T_1 reflects limited vegetative growth due to nutrient deficiencies. The harvest index, which reflects the proportion of economic yield (grain) to total biomass, showed minimal variation across treatments, with values ranging from 39.51% in T_6 to 40.72% in T_8. Although the biological and grain yields increased with nitrogen and NN applications, the effect of various treatments of nano fertilizers and rates of recommended doses of nitrogen on harvest index was nominal and could not reach the level of significance. However, the highest harvest index (40.72%) was recorded with the application of RDN+1000ml NN/ha at 30-35 DAS+1000 ml at 60-65 DAS (T_8) and minimum (39.62%) with the Control (P+K) only (T_1). Similar results were also being reported by Aziz *et al.*, (2016), Gomaa *et al.*, (2018) and Kumar *et al.* (2023) Babu and Singh (2024), Kumar, *et al.* (2025) and Verma *et al.* (2025) [2, 4, 6, 9, 10, 18, 24].

Economic

Application of RDN+ foliar spray 1000ml NN/ha at 30-35 DAS+1000 ml at 60-65 DAS T_8 produced the highest net income (₹ 120,448 ha-1), followed by RDN+500ml NN/ha at 30-35 DAS+500 ml at 60-65 DAS (T_7) gave net return of ₹ 115133 ha-1 while T1 generated the lowest (₹ 59,586 ha-1). The benefit-cost ratio followed a similar pattern, with RDN+1000ml NN/ha at 30-35 DAS+ foliar spray 1000 ml at 60-65 DAS (T_8) achieving the highest B:C ratio (3.71) in T_1 the lowest (2.41). The higher B ratio in T_8 indicates that the additional investments in NN and nitrogen were highly effective in increasing returns, making it a highly profitable option for farmers. Similar results were also being reported by Aziz *et al.*, (2016), Gomaa *et al.*, (2018) and Kumar *et al.* (2023) Babu and Singh (2024), Kumar, *et al.* (2025) and Singh, *et al.* (2025) [2, 4, 6, 9, 10].

Conclusion

The study found that nano-fertilizers, particularly the application of recommended doses of nitrogen (RDN) combined with two foliar sprays of nano-nitrogen (NN) at critical growth stages, significantly enhance the growth, yield, and profitability of barley (*Hordeum vulgare* L.). Among the treatments, RDN with 1000 ml NN/ha applied at 30-35 DAS and 60-65 DAS (T_8) showed the best performance, resulting in the highest grain yield (56.88 q ha^{-1}), biological yield (139.68 q ha^{-1}), and net returns (₹ 120,448/ha), along with an excellent B:C ratio of 3.71. This underscores the potential of integrating nano-fertilizer technology for efficient nutrient use, higher productivity, and economic benefits. The findings advocate adopting nano-fertilizers as an innovative and sustainable approach to optimize nutrient management in cereal crops, addressing both agronomic and economic challenges effectively.

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