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Nitrogen Use Efficiency of Modern Rice Variety Influenced by Integrated Nutrient Management Options in Dry Season

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A B S T R A C T

Nitrogen (N) is the most limiting nutrient element affecting yield and performances of modern rice varieties. However, efficient use of nitrogen by a modern rice variety might be improved through integrated fertilizer management options. To explore this, a field experiment was conducted over two consecutive dry seasons (2021-22 and 2022-23) from December to June at the experimental field of Sher-e-Bangla Agricultural University (SAU), Dhaka, Bangladesh. Modern rice variety, BRRI dhan100 was used in the experiment. The objectives of the experiments were to investigate the responses of BRRI dhan100 under different N fertilizer rates as well as to assess N use efficiencies of the variety. The experiment comprised seven treatments such as N1 = Researcher's Practice (RP): N-P-K-S- Zn @ 124-22-75-20-4 kg ha^{-1}, N_2 = N_1 + 33% more N over N_1, N_3 = N_1 – 33% less N than N_1, N_4 = N_1 but no nitrogen was used (-N), N_5 = N_1 + Cowdung @ 5 t ha^{-1}, N_6 = Soil test based (STB) dose: N-P-K-S-Zn @ 130-20-83-21-3 kg ha^{-1} and N_7 = Absolute control (No fertilizers applied). The experimental design was RCB (randomized complete block) with three replicates. Standard management practices were maintained across treatments. Yield and yield components data were collected following standard methods at maturity. Collected grain and straw samples were analyzed to estimate N use efficiencies. The treatments had significant ($p<0.01$ to 0.05) effects on yield, yield components, and N use efficiencies of BRRI dhan100 in both years. Among the treatments, N_1, N_5 and N_6 showed statistically similar performances of BRRI dhan100 in respect of yield, yield components and nitrogen efficiencies. Irrespective of years, the highest mean grain yield (6.76-6.83 t ha^{-1}) was obtained from N_5 (N_1 + Cowdung), which were statistically identical with those in N1 (Researcher's Practice: RP) and N_6 (STB) but significantly ($p<0.01$) higher than other four treatments (N_2, N_3, N_4 and N_7). N use efficiencies of BRRI dhan100 were significantly (p = 0.01) affected by the treatments. Agronomic (AEN: 21.63 to 23.98 kg grain kg^{-1} applied N) and physiological efficiencies (PEN: 36.99 to 40.36 kg grain kg^{-1} N uptake) of N_1, N_5 and N_6 were statistically identical but significantly ($p<0.01$) higher than that in N_2 and N_3. Therefore, considering overall performances especially grain yield and nitrogen use efficiencies, BRRI dhan100 may be grown applying the fertilizer treatments N_1 (Researcher's Practice: RP), N_5 (N1 + 5 t ha^{-1} Cowdung) and N_6 (STB) to achieve higher yield, improve N use efficiencies ensure food security of the country and expectantly to maintain soil health.

1. Introduction

Rice (*Oryza sativa* L.) is the most important staple food crop, feeding more than half of the global population, and ranks as the second most widely traded agricultural commodity worldwide (Gondwal et

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al., 2024; Jahan et al., 2017). It plays a vital role in ensuring food security, particularly in economically developing nations (Dass et al., 2016; Wasaya et al., 2022). Globally rice is grown in ~164.19 million hectares of land producing ~756.74 million tons per year (World Food and Agriculture – Statistical Yearbook, 2023). In Bangladesh, rice is grown in three distinct seasons i.e. Boro/dry (Dec-May), Aus (Apr-Aug), and Aman (Jul-Dec) covering almost 11.7 million hectares of land (World Food and Agriculture – Statistical Yearbook, 2022). Sustenance and enhancement in rice production of Bangladesh is a major challenge due to the continual loss of cultivable land, which is declining at a rate of approximately 0.7% per year (Statistical-Yearbook-of-Bangladesh, 2019). This requires either vertical increase by increasing yield and productivity per unit area through improve management practices and cropping intensity or horizontal increase by exploring new area for rice cultivation which is very difficult in Bangladesh with land scarcity. The average rice yield in Bangladesh (3.25 t ha^{-1}) remains lower compared to other major rice-producing countries such as China (4.74 t ha^{-1}) and Japan (5.00 t ha^{-1}) (World Food and Agriculture – Statistical Yearbook, 2022). However, lower yield has not indicated by low yield potentiality instead it can be influenced by several biotic and abiotic factors (Mahbub et al., 2017; Singh et al., 2014). Among abiotic factors N fertilizer management is the most important factors for rice cultivation. Nitrogen (N) is an essential macronutrient and integral part of genetic material, amino acids, chlorophyll, and proteins (Anas et al., 2020; Azimi et al., 2021) via its involvement in the photosynthesis, enzyme activity and carbon–nitrogen metabolism (Anas et al., 2020; Ma et al., 2022). Hence, efficient N management in high-yielding rice cultivars is essential to achieve their genetic yield potential (Jahan et al., 2022; Mahajan et al., 2010; Rezaei et al., 2009). Therefore, determining the optimal N rate and evaluating nitrogen use efficiency (NUE) for each rice variety is vital for fertilizer recommendations (Noor, 2017).

Generally N use efficiency is defined as the N output by the crop per unit nitrogen input (Meena et al., 2014; Mitra, 2017). Inefficient or imbalanced N fertilizer application reduces N utilization efficiency, decreases yield, deteriorates grain quality, and contributes to environmental pollution, posing risks to human health and sustainable agriculture (Lü et al., 2009). Appropriate fertilizer management can remarkably enhance rice yield and quality (Mahender et al., 2016), whereas excessive use of fertilizers especially N fertilizer diminishes NUE and increases N losses. As such higher N application rates increase pest incidence and intensify the risk of nitrogen losses through volatilization, leaching and denitrification, leading to environmental degradation, global warming and health hazards (Thorburn et al., 2017; Hu et al., 2018). Balance N, P, K, S and Zn fertilizers application in producing good rice yield is crucial and efficient use of nutrients especially N is important to sustain rice production and healthier environment. In Bangladesh, N requirement for paddy rice is approximately 80 kg N ha^{-1}, but due to limited knowledge of N mineralization, farmers generally rely exclusively on costly mineral N fertilizers, which typically have an efficiency of less than 40% (Kader et al., 2013). In many rice-growing regions, fertilizer recommendations follow generalized prescriptive models that do not consider site-specific variations in soil N-supplying capacity or varietal requirements (Fan et al., 2012; Kader et al., 2013, 2017; Meisinger et al., 2008). Such blanket recommendations often lead to inefficient N use, increased production costs, yield decline, and environmental pollution (Fan et al., 2012; Peng et al., 2009). Total N was found to inconsistently relate to indigenous soil N supplying capacity (Kader et al., 2013), however, previous studies have primarily focused on yield response to N rates and mechanisms of N loss, rather than optimizing fertilizer rates in line with the soil's inherent N-supplying ability (Saha et al., 2012 and Zhao et al., 2010). Several studies have assessed NUE among rice genotypes globally (Karmakar et al, 2021; Wu et al., 2016; Haefele et al., 2008), but limited research has been conducted with newly released modern rice variety, BRRI dhan100 with only chemical and integrated nutrient fertilizer management to evaluate its N use efficiency and performance. Therefore, this study was conducted to evaluate performances and nitrogen use efficiency (NUE) of BRRI dhan100 with fertilizers management options including chemical and integrated fertilizer management practices during dry (Boro) season.

2. Materials and methods

2.1. Experimental site, weather and soil

The field experiments with same treatments were carried out for two consecutive years (December 2021 to May 2022 and December 2022 to May 2023) at the experimental field of Sher-e-Bangla Agricultural University, Sher-e-Bangla Nagar, Dhaka (Latitude: 23°46´19.9´´N, Longitude: 90°22´15.1´´ E and Altitude: 9.0 m above from sea level). The experimental site has fallen under subtropical climatic condition with high temperatures and humidity, moderate rainfall and occasional winds during the kharif season (March-September), as well as low temperatures and limited precipitation in the rabi season (October-February) (BMD, 2024).

2.2. Soil properties of the experimental site

The experiment was carried out in typical rice growing silty clay loam soil at the Soil Science Division experimental field at SAU, Dhaka. The physical and chemical properties of the surface soil (0-20 cm) are shown in the Table 1.

Table 1

Physical and chemical properties of the initial soil (0-20 cm depth).

Characteristics	Value
% Sand (2.0-0.05 mm)	19
% Silt (0.05-0.002 mm)	45
% Clay (<0.002 mm)	36
Textural class	Silty Clay Loam
Consistency	Granular and friable when dry
pH-H_2O (1: 2.5)	6.1
Organic Matter (%)	1.38
Total N (%)	0.09
Available P (mg kg^{-1})	19.85
Exchangeable K (cmol (+) kg^{-1})	0.12
Available S (mg kg^{-1})	14.40

2.3. Experimental set up, crop establishment, management practices and crop harvest

The modern high yielding Zinc enriched BRRI dhan100 (Grain yield: 7.7 t ha^{-1}, growth duration: 148 d, amylose: 26.8% and grain Zn content: 25.7 mg kg^{-1}) was used in the experiment. This rice cultivar was developed for dry (Boro) season in 2021 by the Bangladesh Rice Research Institute (BRRI) from the cross between BR7166-5B-5/BG305/BRRI dhan29. Seeds of BRRI dhan100 were sown uniformly in well prepared wet nursery bed on December 11, 2021 (in first year) and December 07, 2022 (in second-year). In both years, seven treatments such as N_1 = Researcher's Practice (RP): N-P-K-S-Zn @ 124-22-75-20-4 kg ha^{-1}, resp. (equalling 270-112-150-112-11 kg ha^{-1} Urea-TSP-MoP-Gypsum-$ZnSO_4.H_2O$, resp.), N_2 = N_1 + 33% more N over N_1, N_3 = N_1- 33% less N than N_1, N_4 = N_1 but no N was applied (-N), N_5 = N_1 + Cowdung@5 t ha^{-1}, N_6 = Soil test based (STB) N-P-K-S-Zn @ 130-20-83-21-3 kg ha^{-1}, respectively and N_7 = Absolute control (No fertilizers applied) were tested. The experiment was laid out in Randomized Complete Block Design (RCBD) with three replicates and unit plot size of 3 m × 4 m. Full amount of P, K, S and Zn fertilizers were applied during final land preparation and thoroughly mixed with soil in six treatments (N_1, N_2, N_3, N_4, N_5 and N_6), except N_7. Except N_4 and N_7, urea was top dressed in all other five treatments into three equal splits on 15 days after transplanting (DAT), 30 DAT and 45 DAT, respectively in both experimental years. Cowdung was applied on 20 days before transplanting in both years, and 35 days old 2-3 seedlings $hill^{-1}$ were transplanted at 25 cm x 15 cm spacing on January 26 (2022) and January 13 (2023). Other standard management practices were followed for all treatments. Plant protection measures were followed as and when necessary.

The crop was harvested when approximately 85-90% of the grains had turned golden yellow, indicating physiological maturity. A central area of 6 m^2 from each plot was harvested to determine grain and straw yields. The harvested plants from each plot were bundled separately, properly labeled, and transported to the threshing floor. The bundles were sun-dried, threshed, and the grains were subsequently cleaned. Grain and straw weights along with their respective moisture contents, were recorded after adequate sun drying. Yields were then expressed in tons per hectare (t ha^{-1}) and adjusted to 14% and 3% moisture content for grain and straw, respectively. For calculating the yield attributes, six hills $plot^{-1}$ outside the sampling area were cut at ground level.

2.4. Analysis of plant samples

Collected grain and straw samples were analyzed for total N content by micro Kjeldahl method (Bremner and Mulvaney, 1982). Also di-acid (HNO3:HClO4 =3:1) digestion for grain and straw samples were performed to measure P concentrations calorimetrically using the molybdovanadate yellow color method (Yoshida et al.,1976), K concentration directly using a flame photometer (Yoshida et al., 1976) and S concentration by the turbidity method (Chaman and Pratt, 1964).

2.5. Calculation of N use efficiencies

Nitrogen use efficiencies were assessed using the following formulae.

Agronomic Efficiency of N (AE_N)

Agronomic efficiency of N (AEN) is the incremental efficiency of applied N reflecting how much additional yield was produced for each kg N applied (Dobermann & Fairhurst, 2000; Karmakar et al., 2021). Formula used for AE_N was:

$$AE_N\ (\text{kg kg}^{-1}) = \frac{(GY_{+N} - GY_{-N})}{FN} \quad \text{---------------}\ (1)$$

Where, AE_N = Agronomic Efficiency of N, GY_{+N} = Grain yield (kg ha^{-1}) with N fertilizer application, GY_{-N}

= Grain yield (kg ha^{-1}) without N fertilizer application and FN = Amount of N fertilizer applied (kg ha^{-1}).

Physiological Efficiency of N (PE_N)

Physiological efficiency of N (PE_N) equates how much additional grain yield is produced for each additional kg of N uptake. PEN from applied N is the ratio of kg grain yield increase per kg N uptake (Dobermann and Fairhurst, 2000; Karmakar et al., 2021). The following formula was used:

$$PE_N\ (\text{kg kg}^{-1}) = \frac{(GY_{+N} - GY_{-N})}{(UN_{+N} - UN_{-N})} \quad \text{-------------- (2)}$$

Where, PE_N = Physiological efficiency of N; GY_{+N} = Grain yield (kg ha^{-1}) with N application; GY_{-N} = Grain yield (kg ha^{-1}) without N application; UN_{+N} = N uptake (kg ha^{-1}) from N fertilized plot and UN_{-N} = N uptake (kg ha^{-1}) from N unfertilized plot.

Internal Efficiency of N (IE_N)

Internal efficiency of N (IE_N) is the utilization efficiency of the N taken up by the crop indicating how much yield is produced per kg N taken up from both fertilizer and indigenous (soil) sources. The IEN is the ratio of kg grain per kg N taken up (Dobermann & Fairhurst, 2000; Karmakar et al., 2021). Formula for IE_N was:

$$IE_N\ (\text{kg kg}^{-1}) = \frac{GY}{UN} \quad \text{-------------- (3)}$$

Where, IE_N = Internal efficiency of N; GY = Grain yield (kg ha^{-1}) in N fertilized plot; UN = Total N uptake (kg ha^{-1}) in N fertilized plot from both indigenous soil and N fertilizer sources.

Nitrogen Harvest Index (NHI)

Nitrogen harvest index (NHI) is computed as the ratio of total grain N uptake and total plant N uptake. NHI was estimated using following formula (Fageria et al., 2010; Karmakar et al., 2021; Singh et al., 2014):

$$NHI = \frac{GN}{TN} \quad \text{-------------- (4)}$$

Where, NHI = Nitrogen harvest index, GN = Grain N uptake (kg ha^{-1}) and TN = Total plant N uptake (kg ha^{-1}).

2.6. Data Analysis

Data collected on yield, different parameters and N use efficiencies were analyzed using statistical software Statistix 10, and the least significant difference (LSD) test was performed according to Gomez and Gomez (1984).

3. Results and discussion

3.1. Variability in plant growth and yield contributing characters

Except 1000 grain weight, plant height, tiller production and other yield attributes were significantly ($p < 0.01$ to < 0.05) affected by different levels of N fertilizer application in both years (Table 2). Plant height of the treatments N_1, N_2, N_3, N_5 and N6 were statistically identical, which were again significantly higher than that in treatments N_4 and N_7 in both the experimental years Boro 2022 and 2023 (Table 2). Compared to N_4 and N_7, the plant height increased by 12.00-19.05 cm (in 2022 and 8.52–18.65 cm in 2023 across five N fertilizer applied treatments N1, N2, N3, N5 and N6. Enhanced N levels improved plant growth and development via stimulating numerous physiological processes like induced cell division and elongation with maximizing vegetative growth and plant height (Kumar et al., 2015; Timilsina et al., 2023). Nitrogen levels had significant effect (P = 0.01) on tiller production per unit area in both experimental years Boro 2022 and 2023 (Table 2). Significantly higher number of tillers per square meter were counted in the treatments N_2, N_5 and N_6, with its second higher values attained from N_1 and N_3 and the lowest values from N_4 and N_7 treatments in both years (Table 2). Number of tiller m^{-2} increased from 10 to 92 for different levels of N over no fertilizers which were equivalent to 4.50 to 41.44% increase in Boro 2022. Similar trends were also observed in Boro 2023 that corresponded to 1.73 to 38.96% increase. Panicle production of BRRI dhan100 was significantly affected by different nitrogen management options in both experimental years Boro 2022 and 2023 (Table 2). In Boro 2022, panicles m^{-2} were significantly greater in the treatments N_2, N_5 and N_6 ranging from 281 to 288 with their second higher values obtained from N_1 and N_3 (255 and 257, respectively). Accordingly, lower number of panicles m^{-2} were found in the without N treatments N_4 and N_7 (208 and 201, respectively). Hence, panicle production was higher in the treatments with N fertilizer applications than without N fertilizer applied treatments. Similar trends were also observed in Boro 2023. Rakotoson et al. (2017) found that panicles per square meter was consistently and positively correlated with N rates. These results were again in alignment with Karmakar et al. (2021) who reported that panicles production remarkably reduced with decreasing N rates. It was found that the panicle m^{-2} increased from 7-87 (equivalent to 3.4-43.28% increase in 2022) and 1-82 (equivalent to 0.48-39.05% increase in 2023) for different levels of N over no N fertilizer. Rajesh et al. (2017) reported that application of 120 kg N ha^{-1} recorded significantly higher values for morpho-physiological parameters. Irrespective of years, significantly longer panicles (25.38-27.34 cm) were measured in all five treatments with N fertilizer application compared to the treatments without N fertilizer application and no fertilizer application (21.06-22.32 cm) (Table 2). As the rate of N fertilizer increases, more nitrogen is contributed to the development, elongation, and length of the panicle (Islam et al., 2008). Number of grains panicle^{-1} varied from 73 to 112 across the treatments. Irrespective of years, significantly higher number of grains panicle^{-1} (100-112) were measured in all five treatments with N fertilizer application compared to the treatments without N fertilizer application and no fertilizer application (73-81) (Table 2). Number of grains panicle^{-1} increased by 1-34 in Boro 2022 and 8-9 in Boro 2023 across six treatments with different levels of nitrogen and no N over absolute control treatment. Similar results also reported by Dass et al. (2016) and Islam et al. (2008). Both the fertility and sterility percentage of BRRI dhan100 were significantly influenced by the treatments (Table 2). Moreover, grain fertility percentages were significantly greater in the treatments N_1, N_3, N_5 and N_6 in both years than other treatments. Thousand grain weight of BRRI dhan100 was not affected by nutrients/N rates (Table 2) which might be due to the fact that grain weight has been considered as one of the genetically controlled characteristics. These findings are in agreement with Karmakar et al. (2021) who reported that N rates had no significant effect on rice grain weight.

Table 2

Effect of different N level on growth and yield attributes of BRRI dhan100 during 2022 and 2023 dry (Boro) season rice at SAU Dhaka, Bangladesh.

Treatment	Plant height (cm)	Tillers m^{-2} (no.)	Panicles m^{-2} (no.)	Panicle length (cm)	Grains panicle^{-1} (no.)	Fertility (%)	Sterility (%)	1000-grain wt. (g)
				2022 Dry (Boro) Season				
N_1	97.45 ab	276 b	255 b	25.76 a	104 a	79.4 a	20.6 bc	16.98
N_2	101.76 a	309 a	285 a	25.45 a	101 a	75.4 b	24.6 a	16.42
N_3	98.03 ab	279 b	257 b	25.38 a	102 a	79.1 a	20.9 bc	16.43
N_4	85.45 bc	232 c	208 c	21.26 b	77 b	75.5 b	24.5 a	15.69
N_5	100.37 a	314 a	288 a	26.09 a	110 a	82.1 a	17.9 c	16.89
N_6	101.21 a	304 a	281 a	26.49 a	105 a	80.8 a	19.2 bc	16.64
N_7	82.71 c	222 c	201 c	21.06 b	76 b	73.1 b	26.9 a	15.58
$LSD_{(0.05)}$	13.63	24.53	21.18	2.372	10.13	3.961	2.092	--
F-test	0.05	0.01	0.05	0.01	0.01	0.05	0.01	NS
				2023 Dry (Boro) Season				
N_1	100.11 ab	272 b	250 b	25.68 a	106 a	79.7 ab	20.3 b	16.84
N_2	103.21 a	315 a	289 a	26.09 a	100 a	73.5 c	26.5 a	16.08
N_3	97.24 ab	290 ab	269 ab	25.42 a	105 a	80.8 ab	19.2 b	16.38
N_4	88.72 bc	235 c	211 c	22.32 b	81 b	78.4 b	20.6 b	15.86
N_5	100.19 ab	321 a	292 a	27.34 a	112 a	84.2 a	15.8 c	16.72
N_6	100.88 a	297 ab	275 ab	26.87 a	104 a	80.6 ab	19.4 b	16.70
N_7	84.56 c	231 c	210 c	21.70 b	73 b	71.6 c	28.4 a	15.25
$LSD_{(0.05)}$	10.94	36.75	26.32	2.690	13.45	4.051	3.561	--
F-test	0.05	0.01	0.01	0.01	0.01	0.01	0.01	NS

Means within a column with similar letter(s) were statistically identical, whereas different letter(s) differed significantly at $p < 0.01$ and $p < 0.05$.

N_1 = Researcher's Practice (RP): N-P-K-S-Zn @ 124-22-75-20-4 kg ha^{-1}, resp. (equalling 270-112-150-112-11 kg ha^{-1} Urea-TSP-MoP-Gypsum-$ZnSO_4.H_2O/7H_2O$, resp.), N_2 = N_1 + 33% more N over N_1, N_3 = N_1- 33% less N than N_1, N_4 = N_1 but no N was applied (-N), N_5 = N_1 + Cowdung@5 t ha^{-1}, N_6 = Soil test based (STB) N-P-K-S-Zn @ 130-20-83-21-3 kg ha^{-1}, respectively and N_7 = Absolute control (No fertilizers applied)

3.2. Variability in Grain, Straw, Biological yields, and Harvest Index

Grain, straw and biological yields, and harvest index of BRRI dhan100 were significantly ($p < 0.01$ to < 0.05) affected by the treatments in both the experimental years Boro 2022 and 2023 (Table 3). Mean grain yield of the treatments N_1, N_5 and N_6 were statistically similar and significantly higher ($p < 0.01$) than the other treatments. Grain yield of N_2 found lower than N_1 although 33% higher N was applied in N_2. This was likely due to lodging of the crop in the plots of treatments N_2 for excess N application. Grain yields were lower in the treatments where no or lower amount of N was applied. These findings were similar to those of Karmakar et al. (2021) who stated that grain yield decreased with application of excess N. These enhancements in grain yield in N_1, N_5 and N_6

may be resulted from balanced nitrogen application rates which stimulated dry matter accumulation, accelerated plant growth rate, promoted internode elongation and enhanced gibberellin activity (Ghoneim et al., 2018). Furthermore, the observed grain yields improvement in N_1, N_5 and N_6 than other N treatments could be associated with nitrogen's pivotal role in increasing the most striking yield components especially higher number of grains per panicle and fertility percent, and lower sterility percent (Table 2) matching with findings of Karmakar et al. (2021) and Gueye and Becker (2011). Straw yield was significantly ($p<0.01$) affected by different treatments in both years, Boro 2022 and 2023 (Table 3). Among the treatments, the highest straw yield (7.56 and 7.78 t ha^{-1} in Boro 2022 and 2023, respectively) in the treatment N_5 were due to the application of additional organic manure i.e. 5 t ha^{-1} cowdung that might be contributed to enhance vegetative growth as well as straw yield compared to the other treatments. The production of higher straw might be increased in N_5 due to application of additional N from 5 t ha^{-1} cowdung with 100% chemical N fertilizer. The results are in line with the findings of Karmakar et al. (2021) and Swain et al. (2006) who reported that increasing N rates increased rice straw yield. Biological yield (Grain + Straw) was statistically affected by the treatments and also follow the similar trend of straw yield as the treatment N_5 produced the highest biological yield. Moreover, it was statistically similar in the treatments N_1 and N_6. In general, biological yield was higher in the N applied treatments compared to without N fertilizer applied treatments. These results on biological yields mostly due to more straw yields in N_5, N_1 and N_6 with balanced and integrated N fertilizer applications compare to imbalanced (over or under N rates and absence) N fertilizer managements (Karmakar et al., 2021; Peng et al., 2006). Harvest index of BRRI dhan100 was significantly affected by the treatments (Table 3). In both years, harvest index was higher and statistically identical across N_1, N_4, N_5 and N_6 treatments. Harvest index was the lowest in N_7 (without fertilizers) that might be due to lower grain yield. While Rakotoson et al. (2017) found that harvest index was consistently positively correlated with N rates.

Table 3

Effect of different N levels on grain, straw, biological yields and harvest index of BRRI dhan100 during Boro 2022 and 2023 season at SAU Dhaka, Bangladesh.

Treatment	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	Biological yield (t ha^{-1})	Harvest index (%)
		2022 Dry (Boro)Season		
N_1	6.36 a	6.76 b	13.12 b	48.48 a
N_2	5.56 b	6.83 b	12.38 c	44.91 ab
N_3	4.67 c	5.71 c	10.38 d	44.99 ab
N_4	4.13 c	4.62 d	8.75 e	47.20 a
N_5	6.76 a	7.56 a	14.32 a	47.21 a
N_6	6.39 a	6.91 b	13.30 b	48.05 a
N_7	3.46 d	4.59 d	8.06 e	42.93 b
$LSD_{(0.05)}$	0.587	0.534	0.696	2.781
F-test	0.01	0.01	0.01	0.05
		2023 Dry (Boro) Season		
N_1	6.57 a	6.87 b	13.45 b	48.85 a
N_2	5.63 b	6.91 b	12.54 b	44.90 b
N_3	4.74 c	5.86 c	10.60 c	44.72 b
N_4	4.34 c	4.74 d	9.09 d	47.74 a
N_5	6.83 a	7.78 a	14.62 a	46.72 ab
N_6	6.52 a	7.05 b	13.57 b	48.05 a
N_7	3.60 d	4.68 d	8.28 d	43.48 b
$LSD_{(0.05)}$	0.568	0.696	1.011	2.391
F-test	0.01	0.01	0.01	0.05

In a column means with similar letter(s) were statistically identical and those having dissimilar letter(s) differed significantly at $p<0.01$ and $p<0.05$.

N_1 = Researcher's Practice (RP): N-P-K-S-Zn @ 124-22-75-20-4 kg ha^{-1}, respectively (equalling 270-112-150-112-11 kg ha^{-1} Urea-TSP-MoP-Gypsum-$ZnSO_4.H_2O/7H_2O$, respectively), N_2 = N_1 + 33% more N over N_1, N_3 = N_1- 33% less N than N_1, N_4 = N_1 but no N was applied (-N), N_5 = N_1 + Cowdung@5 t ha^{-1}, N_6 = Soil test based (STB) N-P-K-S-Zn @ 130-20-83-21-3 kg ha^{-1}, respectively and N_7 = Absolute control (No fertilizers applied)

3.3. Nitrogen use efficiencies (NUE)

Nitrogen use efficiencies (NUE) such as Agronomic efficiency of N (AEN), Physiological efficiency of N (PEN), Internal efficiency of N (IEN) and Nitrogen harvest index (NHI) of BRRI dhan100 were significantly ($p<0.01$) affected by fertilizer management options (Table 4). Irrespective of year, significantly ($p<0.01$) higher agronomic N use efficiency, AEN (in kg grain kg^{-1} N applied) of BRRI dhan100 was recorded in N_1, N_5 and N_6 (21.63 to 23.98) treatments than that in N_2 (12.28 to 12.69) and N_3 (13.69 to 14.50) with 33% higher and lower N application rates, respectively. Ladha et al. (2005) reported AEN values of 22 kg kg^{-1} N for rice. The optimum use of nitrogen fertilizer had a significant effect on AEN. Moreover, Cai et al. (2022) reported that AEN was dominated by the ability of the plant to mobilize N rather than N uptake. Physiological efficiency of N (PEN) of BRRI dhan100 was statistically influenced by the treatments in both experimental years 2022 and 2023 Boro seasons (Table 4). Overall PEN ranged from 24.51 to 40.36 kg kg^{-1} among the treatments. These results were also parallel with the findings of Dobermann and Fairhurst (2000) who reported that PEN ranged from 22 to 49 kg kg^{-1} with an average of 35 kg kg^{-1}. In both years, significantly ($p<0.01$) higher PEN (about 40 kg kg^{-1}) was recorded in N_5, which was again statistically identical with that in N_1 (about 37 kg kg^{-1}) and N_6 (about 38 kg kg^{-1}) but differed from that in N_3 (~29 to 34 kg kg^{-1}) and N_2 (about 25 kg kg^{-1}). Yesuf and Balcha (2014) reported the PEN of 38 to 29 when N rate increased from 3.5 to 14 g m^{-2}, respectively. In both years, internal efficiency of N (IEN) of BRRI dhan100 was the highest in N_4 (273 and 310 kg kg^{-1}) followed by N_7 (242 and 257 kg kg^{-1}), while the lowest IEN (57 and 58 kg kg^{-1}) was found in N_2. Across the N fertilizer applied treatments, the sequence of IEN (kg kg^{-1}) was N_3 (88-89) $>N_1$, N_5 and N_6 (67-71), $>N_2$ (57-58) in two years. In both years, the IEN (kg kg^{-1}) in N_1, N_5 and N_6 were also statistically identical but greater than that in N_2 and lower than that in N_3. Chiranjeeb et al. (2022) reported that 50% N through urea + 50% N through vermicompost registered the highest internal efficiency of nitrogen (IRN). Irrespective of year, nitrogen harvest index (NHI) of BRRI dhan100 ranged from 0.43 to 0.55 kg kg^{-1} across the treatments having the highest ($p<0.01$) NHI (0.55 kg kg^{-1}) was recorded in N_2 (Table 4). The lowest NHI (0.41-0.43 kg kg^{-1}) was found in N_3 which was statistically identical with that in N_4 (0.44-0.46 kg kg^{-1}) and N_7 (0.43-0.45 kg kg^{-1}) (Table 4). Moreover, the second higher and statistically identical NHI was recorded across N_1, N_5 and N_6 treatments (0.47-0.50 kg kg^{-1}) in both years. The variations in NHI are related with the capacity of rice genotype to utilize N and N levels for growth and development (Swain et al., 2006 and Singh et al., 1998). Our results corroborated with findings of Swain et al. (2006) and Karmakar et al. (2021) who found that the NHI ranged from 0.45 to 0.69 kg kg^{-1} and 0.52 to 0.58 kg kg^{-1}, respectively.

Table 4

Treatments effect on different N use efficiency of BRRI dhan100 during Boro 2022 and 2023 growing season at SAU Dhaka, Bangladesh.

Treatments	AE_N (kg kg^{-1})	PE_N (kg kg^{-1})	IE_N (kg kg^{-1})	NHI (kg kg^{-1})
		2022 Dry (Boro) Season		
N_1	22.72 a	36.99 ab	67 d	0.48 b
N_2	12.69 b	25.42 c	57 e	0.55 a
N_3	14.50 b	33.90 b	88 c	0.43 c
N_4	0.00 c	0.00 d	273 a	0.44 c
N_5	23.55 a	40.36 a	70 d	0.50 b
N_6	21.68 a	38.01 ab	69 d	0.49 b
N_7	0.00 c	0.00 d	242 b	0.43 c
$LSD_{(0.05)}$	3.280	5.848	9.17	0.041
F-test	0.01	0.01	0.01	0.01
		2023 Dry (Boro) Season		
N_1	23.98 a	37.26 a	70 d	0.47 bc
N_2	12.28 b	24.51 c	58 e	0.55 a
N_3	13.69 b	29.31 b	89 c	0.41 c
N_4	0.00 c	0.00 d	310 a	0.46 bc
N_5	23.09 a	40.09 a	71 d	0.50 b
N_6	21.63 a	38.21 a	71 d	0.49 b
N_7	0.00 c	0.00 d	257 b	0.45 bc
$LSD_{(0.05)}$	3.454	3.846	11.78	0.038
F-test	0.01	0.01	0.01	0.01

Means within a column having similar letter(s) are statistically similar, whereas those with different letter(s) differ significantly at $p<0.01$.

AEN = Agronomic efficiency of N, PEN = Physiological efficiency of N, IEN = Internal efficiency of N and NHI = Nitrogen harvest index.

N_1 = Researcher's Practice (RP): N-P-K-S-Zn @ 124-22-75-20-4 kg ha^{-1}, resp. (equalling 270-112-150-112-11 kg ha^{-1} Urea-TSP-MoP-Gypsum-$ZnSO_4.H_2O/7H_2O$, resp.), N_2 = N_1 + 33% more N over N_1, N_3 = N_1- 33% less N than N_1, N_4 = N1 but no N was applied (-N), N_5 = N_1 + Cowdung@5 t ha^{-1}, N_6 = Soil test based (STB) N-P-K-S-Zn @ 130-20-83-21-3 kg ha^{-1}, respectively and N_7 = Absolute control (No fertilizers applied).

4. Conclusion

Grain yield, yield attributes, different nitrogen use efficiency and overall performances of BRRI dhan100 had significantly affected by integrated nutrient management (N_5) as well as soil test based (STB: N_6) and Researcher's Recommended (N_1) N fertilizer management options. Among the treatment combinations, N_1 (Researcher's Practice: N-P-K-S- Zn @ 124-22-75-20-4 kg ha^{-1}), N_5: N_1 + Cowdung @5 t ha^{-1} and N_6 (Soil test-based dose: N-P-K-S-Zn @ 130-24-83-22-3 kg ha^{-1}) treatments consistently provided the higher potentiality in plant growth, yield attributes, yield and nitrogen use efficiencies of BRRI dhan100. Consequently, the treatment N_1, N_5 and N_6 may be recommended for BRRI dhan100 to achieve higher yield, improve N use efficiencies and ensure food security of the country. Further verifications by long-term experiments with studying changes in postharvest soil properties will provide detailed insights for sustainable soil health management.

Authors' contribution

CMHK and BK conceived the idea and carried out the experiments and data collection, drafting of manuscript. BK, MMH and AKP edited, interpretated and improved the manuscript. All authors read and approved the final manuscript.

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Competing interest

The authors declare that they have no competing interests.

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