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Improving Nitrogen Fertilizer Management for Yield and N Use Efficiency in Wetland Rice Cultivation in Bangladesh

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Abstract: Achieving high-yielding crops while also improving nitrogen use efficiency is a significant challenge for agricultural production in Bangladesh. We investigated the impacts of applying nitrogen (N) using different management options in wetland rice on a calcareous dark gray soil over three seasons. These included (1) the recommended dose of available N as prilled urea, (2) the recommended N dose plus 25% extra of available N as prilled urea, (3) 25% less than the recommended dose of available N as prilled urea, (4) the recommended dose of prilled urea in 2 t ha^{-1} cow dung, (5) the recommended dose as urea super granules (USGs) by deep placement, (6) 4 t ha^{-1} biochar with the recommended dose of prilled urea, and (7) Zero N. It was found that the growth, yield, and N use efficiency (NUE) were significantly different from the results obtained for prilled urea in all the alternative fertilizer options. The deep placement of USG consistently increased plant height, total number of tillers per plant, effective tillers per plant, chlorophyll content, panicle length, grains per panicle, and 1000-grain weight. The yield increases over recommended prilled urea were 5.22% for USG followed by biochar with the recommended dose. Similarly, using the deep placement of USG gave the highest yield and harvest index. In addition, compared to the recommended dose of prilled urea, the deep placement of USG increased NUE by 13%, agronomic N efficiency by 20%, and recovery N use efficiency by 19%. This suggests the rate of N application could be reduced by up to 8% without impacting yield by using deep placement of USG instead of prilled urea. The cost–benefit ratio was higher for the deep placement of USG than all other treatments. Biochar with the recommended dose of prilled urea also showed good results in terms of growth, yield, and NUE (41.8, 43.0, and 41.7, respectively, during three sequential years), but the extra cost of the biochar reduced the cost–benefit ratio. These findings suggest that the deep placement of USG is the best option for improving the yield of rice while also improving N use efficiency.

Keywords: rice yield; fertilization options; nitrogen use efficiency; urea super granule (USG); biochar

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Citation: Kamuruzzaman, M.; Rees, R.M.; Islam, M.T.; Drewer, J.; Sutton, M.; Bhatia, A.; Bealey, W.J.; Hasan, M.M. Improving Nitrogen Fertilizer Management for Yield and N Use Efficiency in Wetland Rice Cultivation in Bangladesh. *Agronomy* **2024**, *14*, 2758. https://doi.org/10.3390/agronomy14122758

Academic Editors: Bertrand Hirel and Claudio Ciavatta

Received: 23 September 2024
Revised: 12 November 2024
Accepted: 18 November 2024
Published: 21 November 2024

1. Introduction

Rice (*Oryza sativa* L.) is the most important staple food crop for more than 3 billion people in the world and 135 million people in Bangladesh. It is the most extensively cultivated cereal crop in Bangladesh, with about 75% of the total cropped area occupied by rice cultivation. Thus, rice plays a vital role in the livelihood of the people of Bangladesh [1].

The yield of rice largely depends upon the nutritional state of the soil and the availability of nutrients from chemical fertilizers. Most of the farmers in Bangladesh apply more N than is necessary to obtain a high yield. Urea is the most common N fertilizer, accounting for about 75% of the total N fertilizer used in Bangladesh [2]. Nitrogen is the most important and limiting nutrient in crop production worldwide. It is an essential constituent of protein or chlorophyll, promotes vegetative growth, and provides the green color to plants. On the other hand, the deficiency of N also hampers crop production. The growth and yield parameters of rice are strongly affected by N management [3].

Nitrogenous fertilizer application through traditional methods results in losses of 75–80% of the N applied [4,5]. Nitrogen use efficiency in rice cultivation is typically around 20–50% (Chivenge et al. [6]), while the average value for cereal grain production is about 40% [7]. It indicates that ~60–80% of the N used for rice is lost to the environment. Surplus N contributes to greenhouse gas (GHG) emissions (N_2O) [8], air pollution (NH_3, NO, and NO_2) [9], biodiversity loss [10], soil acidity development [11], groundwater pollution [12], surface water eutrophication [13], etc. The optimum rate of N fertilization plays a vital role in the growth and development of rice. On the other hand, unnecessary N fertilization promotes excessive vegetative growth, making the plant vulnerable to insects, pests, and diseases, ultimately reducing yield.

Warm climates significantly affect nitrogen (N) stocks in soils through various mechanisms, influencing both nitrogen availability and its long-term storage. The N stocks of Bangladesh soils are very low due to a warm climate accompanied by centuries of cultivation on the same land [14]. In Bangladesh, conventional fertilization (three splits of N fertilizer, one basal and two top dressing) is normally practiced in rice cultivation. Inappropriate fertilization and the excessive use of N fertilizers have resulted in considerable N losses. The loss of N through NH_3 volatilization, denitrification, surface runoff, leaching, chemical fixation, or immobilization by microbes is a severe problem in the wet low-lands of Bangladesh where rice fields are subjected to alternate submergence and drainage [15]. Therefore, it is crucial to improve NUE for minimizing adverse environmental issues through better N management practices for sustainable rice production. In this context, some improvements in N management have been reported in recent studies such as precision N management [16], controlled N release [17], and integrated nutrient management [18] that deliver optimum N and better NUE. Efficient fertilizer management gives not only a higher crop yield of crops but also increases NUE and reduces fertilizer cost [19–21].

Some effective measures have been reported for lowering N fertilizer rates and increasing N use efficiency such as applying the controlled release of N fertilizer [22,23], biochar [24,25], and combined application of inorganic and organic fertilizer [26,27]. Biochar, a kind of carbon-rich organic material produced from organic biomass through pyrolysis, i.e., under limited oxygen and high temperature, has been found to be efficient for enhancing NUE [28]. It has been reported to inhibit the nitrification process in soil, thereby contributing to lower losses [29]. The higher yield of grain of rice in the biochar-treated fields might be connected with higher soil nutrient retention [30], higher cation exchange capacity [31], and better soil fertility [32]. Reduced N_2O emissions with biochar application are connected with both the inhibition of nitrification and denitrification [33]. Therefore, this study assesses the hypothesis that suitable N fertilizer management options can allow reduced N inputs while maintaining or increasing yield and increasing N use efficiency. The objective was to compare the effect of different N fertilizer management options on the growth, yield, and N use efficiency of BRRI dhan28 (rice variety) in wetland rice cultivation under calcareous dark gray soil in Bangladesh.

2. Materials and Methods

Experiments were conducted in three consecutive years (2021, 2022, and 2023) at the Agronomy Research Farm, Department of Agronomy and Agricultural Extension, University of Rajshahi, Rajshahi-6205, Bangladesh. The experimental site location is 24°22′36″ N latitude and 88°38′27″ E longitude at an altitude of 20 m above sea level (Figure 1) and is within the Agro-Ecological Zone (AEZ) *'High Barind Tract'* (AEZ-11) of Bangladesh [34]. The properties of the soil at the start of the experiment are shown in Table 1. The rice variety was the high-yielding variety, BRRI dhan28, developed by the Bangladesh Rice Research Institute [35].

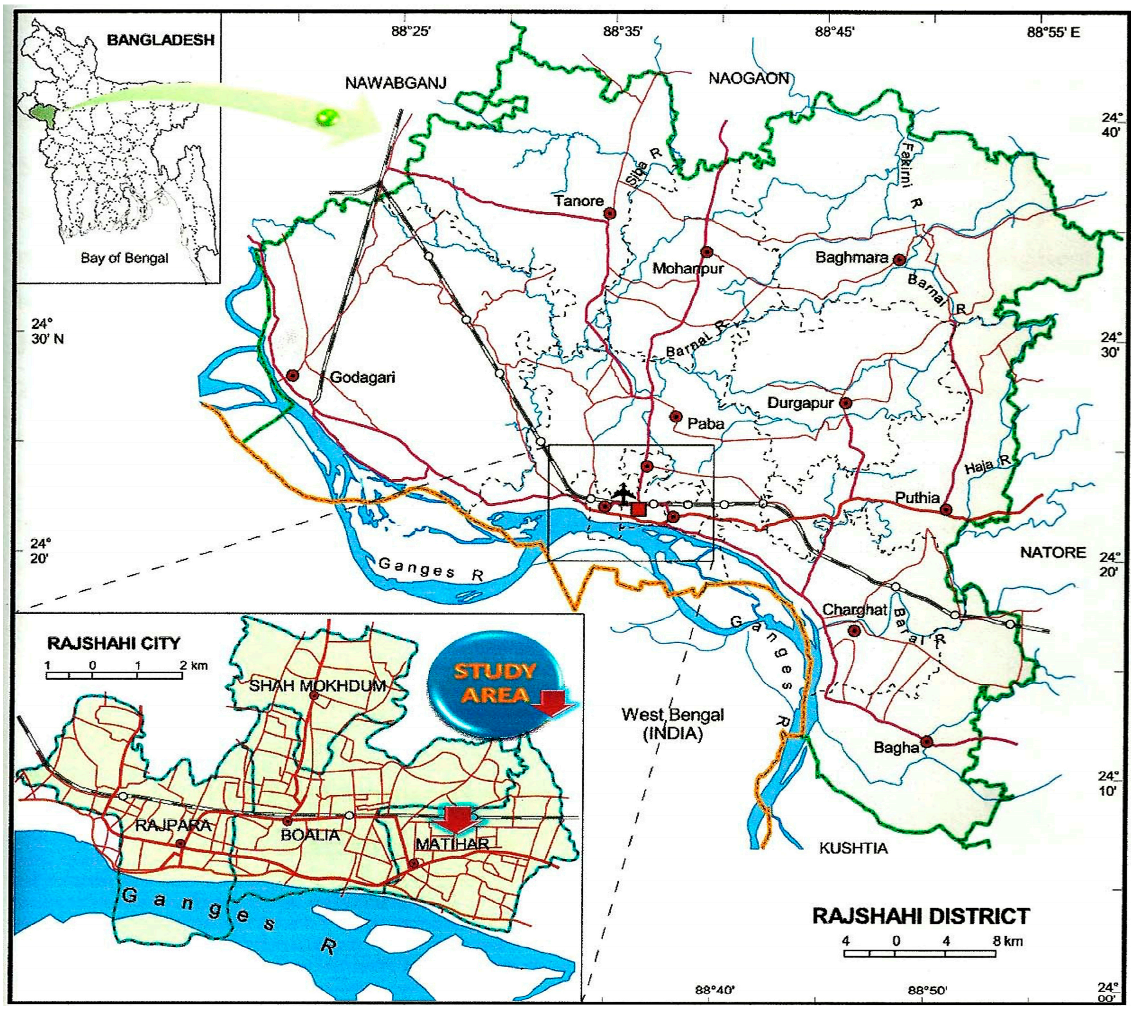

Figure 1. Location map of the study area.

Table 1. The initial soil properties of the experimental plot.

Parameter	Quantity
Soil Type	Calcareous dark gray soil
Sand	34%
Silt	36%
Clay	30%
Bulk density	1270 kg m^{-3}
Soil pH	7.62
Organic matter	12 g kg^{-1}
Total N	0.8 g kg^{-1}
Available Ca	32.4 g kg^{-1}
Available P (inorganic)	19.85 g kg^{-1}
Available K	0.47 g kg^{-1}
Available S	14.40 g kg^{-1}
Available Zn	0.78 g kg^{-1}

2.1. Climate of the Experimental Area

The climate of the experimental area is subtropical, characterized by a very hot summer and cool winter with the hottest months in March and June (maximum temperature 38 °C; average: 25–38 °C) and the coldest months in December and January (temperature often below 12 °C; average: 10–18 °C). The humidity is high with heavy rainfall (above 80% of the total rainfall) during January to May (*Rabi* season); the mean monthly average relative humidity is 72.9% and the average annual rainfall is 1524 mm. The air temperatures, sunshine hours, and rainfall amounts during the rice cultivation period were similar in the three successive years [36].

Other fertilizers viz. P, K, S, and Zn were applied 24–76–12–2.5 kg ha^{-1} as per the recommendation of the BARC Fertilizer Recommendation Guide (2018).

2.2. Experimental Design

The experimental area was divided into 4 replicated blocks and laid out using a randomized complete block design (RCBD) to reduce the effects of soil variability. Within each block, there were seven 15 m × 1.5 m (22.5 m^{-2}) plots, separated from each other by 75 cm borders (total of 28 plots). Treatments were assigned at random to each plot within the blocks (Table 2).

Table 2. Treatments used in the experiment.

	Treatments
T_1	Zero N/Control N
T_2	Recommended dose (RD) of N (180 kg ha^{-1} N) as prilled urea
T_3	125% of RD of N (225 kg ha^{-1} N) as prilled urea
T_4	75% of RD of N (135 kg ha^{-1} N) as prilled urea
T_5	The cow dung (2 t ha^{-1}) supplemented with prilled urea
T_6	Deep placement of urea super granule (USG) (165 kg ha^{-1}: 1 USG of 2.7 g)
T_7	Biochar (4 t ha^{-1}) supplemented with prilled urea

2.3. Application of Fertilizers

All the fertilizers except urea were applied during the final land preparation. No nitrogenous fertilizers were applied to the Zero N/CK. Prilled urea (PU) was applied in three equal splits at 15, 45, and 60 days after transplanting (DAT). Cow dung was applied at 2 t ha^{-1} (2.5% N) during final land preparation and the rest of the N was supplemented by PU. Urea super granules (USGs) (165 kg N ha^{-1}) were applied at 15 DAT and one USG pellet of 2.7 g was placed at 8–10 cm depth between four hills at alternate rows. Before the application of N fertilizers, the water in the rice plots was drained. Biochar was applied as a urease inhibitor at 4 t ha^{-1} during the final land preparation. The properties of the biochar applied are shown in Table 3.

Table 3. The characteristics of rice husk biochar.

Parameter	Quantity
The pyrolysis temperature	450 °C
Residence time:	100 min
pH	8.70
Carbon (C)	342 g kg^{-1}
Hydrogen (H)	20.8 g kg^{-1}
Oxygen (O)	230 g kg^{-1}
Nitrogen (N)	5 g kg^{-1}
Phosphorus (P)	0.9 g kg^{-1}
Cation exchange capacity (CEC)	24.6 cmol kg^{-1}

The biochar was collected from the Christian Commission for Development in Bangladesh (CCDB).

2.4. Land Preparation and Transplanting

After sufficient water had been applied, the soil was plowed and then cross plowed three times using a power tiller, followed by laddering to get the plots to the desired puddle state. The fertilizers were applied following practices recommended by BRRI [37]. The 30-day-old plants were transplanted at three seedlings per hill on the well-puddled plots after land preparation had been completed.

2.5. Intercultural Operations

Irrigation was applied to the experimental plots and insect pests, weeds, and diseases were controlled as needed.

2.6. Straw and Grain Analysis for Nitrogen Content

Randomly positioned samples of straw and grain from each sub-plot were taken at maturity and oven-dried at 60 °C for 72 h. The samples were ground and passed through a 0.5 mm sieve to prepare a sample of 10 g. The N concentrations of the straw and grain samples were measured using the *Kjeldahl* method as described by Jackson [38].

Nitrogen uptake in the grain and straw was calculated by multiplying the N content by the respective straw and grain yield. Total N uptake in whole biomass was obtained by summing up the N uptake by the grain and straw. The total N content of the straw and grain samples was used to estimate the N use efficiency according to Moll et al. [39], Ortiz-Monasterio et al. [40], and Guarda et al. [41].

Formulae to calculate different efficiencies of nitrogen:

- ➢ Nitrogen use efficiency (NUE) or $NUE_N = Y_N/F_N$;
- ➢ Agronomic efficiency of applied N, $AE_N = (Y_N - Y_0)/F_N$;
- ➢ Crop recovery efficiency of applied N, $RE_N = (U_N - U_0)/F_N$.

where F_N = amount of (fertilizer) N applied (kg ha^{-1})

Y_N = crop yield with applied N (kg ha^{-1});
Y_0 = crop yield (kg ha^{-1}) in a control treatment with no N;
U_N = total plant N uptake in aboveground biomass at maturity (kg ha^{-1}) in a plot that received N;
U_0 = the total N uptake in aboveground biomass at maturity (kg ha^{-1}) in a plot that received no N.

2.7. Recorded Data

For each hill from each plot, five plants were selected randomly and data on growth and yield were recorded. The data on plant growth parameters included plant height (cm); tillers per hill (no.); effective tillers per hill (no.); non-effective tillers per hill (no.); chlorophyll content (SPAD value); dry matter per plant (g); panicle length (cm); extrusion length (cm); yield and yield contributing parameters viz. filled grains per panicle (no.); unfilled grains per panicle (no.); weight of 1000 grains (g); grain yield (t ha^{-1}), straw yield (t ha^{-1}), biological yield (t ha^{-1}), and harvest index (%); N content of grain and straw (%); N uptake by grain, straw and plant (kg ha^{-1}); N use efficiency (NUE%); agronomic efficiency of N (AEN %); and recovery efficiency of N (REN %).

2.8. Estimation of Benefit–Cost Ratio (BCR)

To calculate the BCR for rice cultivation, the costs were divided into fixed costs (costs that do not change with the scale of production, such as land rent, and equipment depreciation like irrigation infrastructure) and variable costs (costs that vary with the production process, including seeds, fertilizers, pesticides, labor, irrigation, fuel, and transportation). The following formula was used to determine the benefit–cost ratio:

$$BCR = \frac{\text{Total Benefits}}{\text{Total Costs}}$$

2.9. Statistical Analysis

The data obtained for different parameters were statistically analyzed using a two-way analysis of variance to determine the significant difference in different treatments' effects on growth, yield and yield attributes, and N use efficiency of BRRI dhan28. The data recorded were compiled and analyzed statistically using the statistical package SPSS (Version 22) and

Excel program. The mean differences were adjudged by Duncan's Multiple Range Test. The data obtained are presented as mean values with the standard error (±SE) of the means.

3. Results

3.1. Plant Height

Plant height (cm) responded significantly ($p = 0.05$) to the different N fertilizer management options (Figure 2) during the three successive cropping years. The tallest plants at harvest (104.13, 101.13, and 109.50 cm) were from the T_6 (USG) treatment; at the same time, the shortest plants (66.18, 62.75, and 71.63 cm, respectively) were from the T_1 (control N) treatment during the three consecutive years.

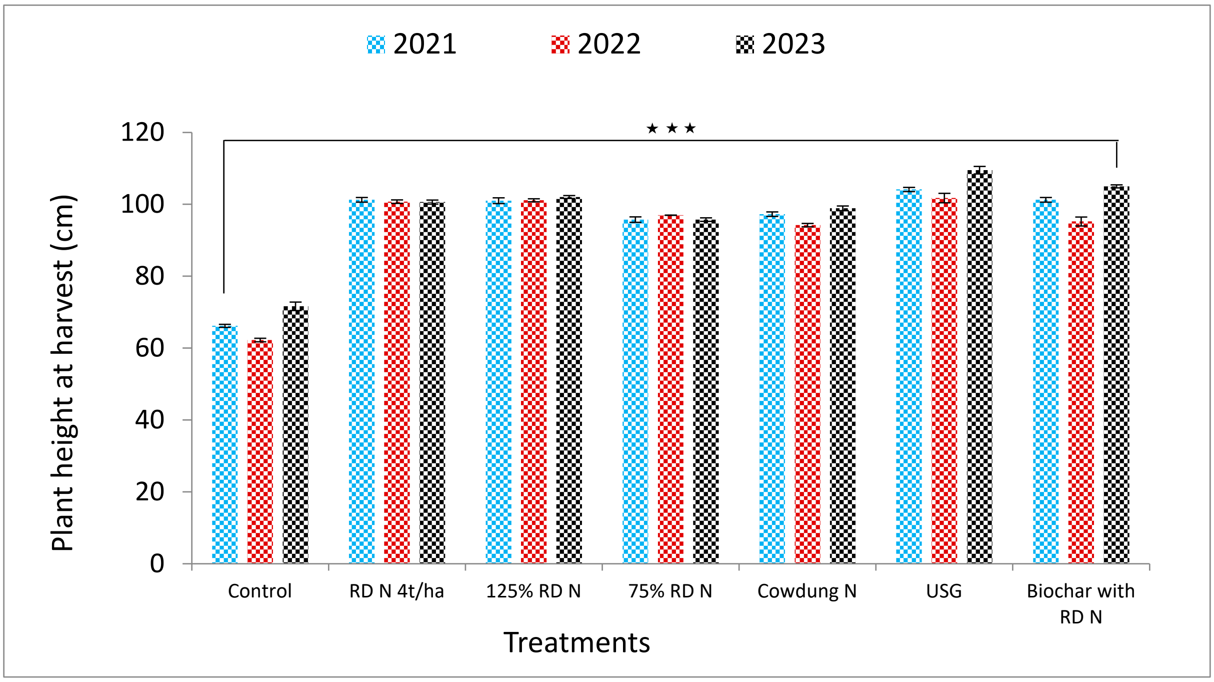

Figure 2. Plant height (cm) of rice (BRRI dhan28) at harvest during three successive cropping years. The mean average of four replications and the capped line represent standard error. Significance difference compared to control at $p = 0.05$. *** = 0.1% level of significance. RDN = Recommended dose of nitrogen.

3.2. Tillering

The number of effective tillers was significantly ($p = 0.05$) influenced by the treatments (Table 4). During 2021, the highest number of effective tillers per hill (14.75) was observed in the T_6 treatment (urea super granule—USG) and the minimum number of effective tillers per hill (5.50) in T_1 (Zero N). Similarly, during 2022 and 2023, the highest number of effective tillers per hill (14.75 and 13.17) was in the T_6 treatment while the minimum number of effective tillers per hill (4.75 and 6.25, respectively) was in T_1 (Zero N). From the responses to different nitrogenous fertilizer management options, the results can be ranked in the following order: $T_6 > T_7 > T_3 > T_2 > T_5 > T_4 > T_1$ in respect of the number of effective tillers over the three experimental years. Due to the deep placement of USG, the rice plants grew vigorously and produced more effective tillers compared to the recommended dose of N fertilizer. The treatments significantly influenced the number of non-effective tillers (Table 3). The lowest number (0.25 and 1) of non-effective tillers per hill was in the T_6 treatment during successive cropping years while the highest number (3.25, 4.25, and 5.0, respectively) was in the T_1 treatment (Zero N). The minimum number of non-effective tillers hill^{-1} was obtained in T_7 (biochar 4 t ha^{-1} with recommended N). This might be due to the slow release of N from USG and biochar and the supply of N as per the requirement of rice plants in their entire life span.

Table 4. Effects of nitrogenous fertilizer management options on effective tiller hill^{-1}, non-effective tiller hill^{-1} of rice (BRRI dhan28) at harvest.

	No. of Effective Tiller Hill^{-1}			No. of Non-Effective Tiller Hill^{-1}		
	2021	2022	2023	2021	2022	2023
T_1	5.50 ± 0.29 ^{d}	4.75 ± 0.63 ^{e}	5.25 ± 0.42 ^{d}	3.25 ± 0.29 ^{a}	4.25 ± 0.48 ^{a}	4.0 ± 0.41 ^{a}
T_2	10.50 ± 0.29 ^{c}	11.50 ± 0.65 ^{bc}	10.67 ± 0.56 ^{b}	0.50 ± 0.29 ^{bc}	2.25 ± 0.25 ^{b}	2.25 ± 0.25 ^{bc}
T_3	11.50 ± 0.48 ^{bc}	11.0 ± 0.71 ^{c}	9.67 ± 0.41 ^{bc}	0.25 ± 0.25 ^{c}	2.0 ± 0.41 ^{b}	2.67 ± 0.65 ^{b}
T_4	9.75 ± 0.85 ^{c}	8.75 ± 0.48 ^{d}	8.92 ± 0.25 ^{c}	1.25 ± 0.48 ^{b}	2.25 ± 0.48 ^{b}	1.50 ± 0.50 ^{bc}
T_5	10.25 ± 0.25 ^{c}	10.75 ± 0.48 ^{c}	9.92 ± 0.53 ^{bc}	0.25 ± 0.25 ^{c}	1.75 ± 0.25 ^{b}	2.17 ± 0.44 ^{bc}
T_6	14.75 ± 0.48 ^{a}	14.75 ± 0.63 ^{a}	13.17 ± 0.97 ^{a}	0.25 ± 0.25 ^{c}	1.0 ± 0.41 ^{b}	1.0 ± 0.41 ^{c}
T_7	12.25 ± 0.48 ^{b}	14.0 ± 0.41 ^{ab}	10.58 ± 0.21 ^{bc}	0.0 ^{c}	0.25 ± 0.25 ^{b}	1.92 ± 0.08 ^{bc}
LS	***	***	***	***	**	***

The mean was calculated from four replicates for each treatment. a, b, c, d, e, etc. indicate significant differences among the treatments. In a column, means having similar letter(s) are statistically similar and those having dissimilar letter(s) differ significantly by LSD at 0.05 levels of probability. T_1 = Zero N/Control N; T_2 = recommended N; T_3 = 125% of recommended N; T_4 = 75% of recommended N; T_5 = cow dung N 2 t ha^{-1} supplemented with prilled urea N; T_6 = deep placement of urea super granule (USG) 165 kg ha^{-1}; T_7 = biochar 4 t ha^{-1} with recommended N as prilled urea; LS = level of significance; *** = 0.1% level of significance; ** = 1% level of significance; ± = standard error.

3.3. Chlorophyll Content (SPAD Value)

The leaf chlorophyll content (SPAD value) responded significantly (p = 0.05) to the fertilizer treatments at 30, 45, 60, and 75 DAT in the three consecutive years (Table 5). During 2021, 2022, and 2023, the highest chlorophyll content (SPAD value) was from the T_6 (urea super granule—USG) treatment at almost all the sampling dates. This may have been due to the improving effects of USG on the chlorophyll content of rice plants attributed to its role in regulating the release of N to synchronize with plant demand. In T_2 (recommended dose of N), T_3 (125% of RD of N), and T_7 (biochar 4 t ha^{-1} with recommended N fertilizer), the SPAD values were also significantly higher than the control at 30, 45, 60, and 75 DAT for the increment of the SAPD value.

Table 5. Effect of N fertilizer management options on chlorophyll content of rice (BRRI dhan28) at 30, 45, 60, and 75 days after transplanting (DAT).

	Chlorophyll Content (SPAD Value)											
	30 DAT			45 DAT			60 DAT			75 DAT		
	2021	2022	2023	2021	2022	2023	2021	2022	2023	2021	2022	2023
T_1	32.28 ± 0.86 ^{d}	30.78 ± 0.35 ^{f}	31.90 ± 0.80 ^{d}	32.03 ± 0.42 ^{c}	29.78 ± 0.98 ^{e}	33.0 ± 0.44 ^{c}	31.98 ± 0.45 ^{d}	27.95 ± 0.41 ^{c}	34.38 ± 0.42 ^{d}	26.10 ± 0.43 ^{e}	26.93 ± 0.62 ^{d}	25.45 ± 0.52 ^{d}
T_2	41.48 ± 0.46 ^{b}	43.0 ± 0.37 ^{cd}	41.28 ± 0.48 ^{b}	42.33 ± 0.42 ^{a}	44.23 ± 0.21 ^{bc}	41.70 ± 0.58 ^{a}	44.35 ± 0.42 ^{ab}	42.35 ± 0.83 ^{b}	44.65 ± 0.46 ^{ab}	31.08 ± 0.45 ^{c}	35.48 ± 0.34 ^{b}	30.45 ± 0.27 ^{b}
T_3	43.30 ± 0.30 ^{a}	44.80 ± 0.78 ^{ab}	42.58 ± 0.53 ^{ab}	44.48 ± 0.19 ^{a}	44.98 ± 0.05 ^{b}	44.20 ± 0.44 ^{a}	43.50 ± 0.46 ^{bc}	41.60 ± 0.55 ^{b}	43.18 ± 0.60 ^{bc}	31.73 ± 0.19 ^{bc}	39.55 ± 0.76 ^{a}	31.58 ± 0.53 ^{ab}
T_4	37.50 ± 0.87 ^{c}	39.0 ± 0.42 ^{e}	36.83 ± 0.82 ^{c}	42.05 ± 1.15 ^{a}	41.0 ± 0.04 ^{d}	38.05 ± 1.24 ^{b}	41.65 ± 1.20 ^{c}	40.60 ± 0.55 ^{b}	41.90 ± 1.22 ^{c}	28.53± 0.52 ^{d}	32.0 ± 0.04 ^{c}	27.75 ± 0.54 ^{c}
T_5	41.25 ± 0.52 ^{b}	42.25 ± 0.60 ^{d}	41.23 ± 0.46 ^{b}	42.05 ± 2.27 ^{a}	44.50 ± 0.75 ^{bc}	42.33 ± 2.13 ^{a}	42.68 ± 0.53 ^{bc}	41.60 ± 0.55 ^{b}	42.80 ± 0.23 ^{bc}	30.83± 0.21 ^{c}	36.25 ± 0.60 ^{b}	30.65 ± 0.21 ^{b}
T_6	44.73 ± 0.52 ^{a}	45.73 ± 0.06 ^{a}	43.60 ± 0.52 ^{a}	44.55 ± 0.44 ^{a}	45.80 ± 0.48 ^{a}	44.88 ± 0.30 ^{a}	45.53 ± 0.38 ^{a}	45.18 ± 0.94 ^{a}	45.68 ± 0.60 ^{a}	40.10± 0.51 ^{a}	39.48 ± 0.15 ^{a}	39.30 ± 0.32 ^{a}
T_7	43.43 ± 0.57 ^{a}	43.95 ± 0.53 ^{bc}	43.08 ± 0.67 ^{ab}	42.85 ± 0.26 ^{a}	43.18 ± 0.62 ^{c}	43.03 ± 0.27 ^{a}	42.68 ± 0.61 ^{bc}	41.35 ± 0.83 ^{b}	42.33 ± 0.78 ^{c}	32.80 ± 0.35 ^{b}	39.68 ± 0.55 ^{a}	34.70 ± 0.25 ^{a}
LS	***	***	***	***	***	***	***	***	***	***	***	***

The mean was calculated from four replicates for each treatment. a, b, c, d, e, etc. indicate significant differences among the treatments. In a column, means having similar letter(s) are statistically similar and those having dissimilar letter(s) differ significantly by LSD at 0.05 levels of probability. T_1 = Zero N/Control N; T_2 = recommended N; T_3 = 125% of recommended N; T_4 = 75% of recommended N; T_5 = cow dung N 2 t ha^{-1} supplemented with prilled urea N; T_6 = deep placement of urea super granule (USG) 165 kg ha^{-1}; T_7 = biochar 4 t ha^{-1} with recommended N as prilled urea; LS = level of significance; *** = 0.1% level of significance; ± = standard error.

3.4. Dry Matter Production

Dry matter production was significantly (p = 0.05) affected by the fertilizer management options at 30, 45, 60, and 75 days after transplanting (DAT) (Table 6). At all the sampling dates, the treatment T_6 (urea super granule—USG) had the highest DM accumulation in the successive cropping years compared to the recommended dose of N fertilizer. The biochar treatment (T_7) was the nearest to the T_6 treatment for increasing dry matter production.

3.5. Panicle Length, Extrusion Length (cm), and Grain Weight (g)

There was a significant (p = 0.05) effect of the treatments on the length of panicles (Table 7). In the entire sequence of cropping seasons, the longest panicle length (23.95, 24.25, and 26.86 cm) was from the T_6 treatment and the shortest was from the T_1 treatment (Zero N). The extrusion length (cm) under different treatments varied significantly during

2021 but it did not vary during the 2022 and 2023 cropping seasons. The weight of 1000 grains (g) varied significantly across the treatments. The maximum 1000-grain weight was in the T_6 treatment and the minimum 1000-grain weight was in T_1 (Zero N) during the successive cropping years. The consistent nutrient supply helps maintain the accumulation of biomass and enhances the overall grain-filling process which might be attributed to increasing grain weight.

Table 6. Effect of N fertilizer management options on dry matter plant^{-1} (g) of rice (BRRI dhan28) at 30, 45, 60, and 75 days after transplanting (DAT).

	Dry Matter Plant^{-1} (g)											
	30 DAT			45 DAT			60 DAT			75 DAT		
	2021	2022	2023	2021	2022	2023	2021	2022	2023	2021	2022	2023
T_1	0.57 ± 0.02 ^{e}	0.58 ± 0.01 ^{c}	0.56 ± 0.02 ^{d}	1.26 ± 0.02 ^{f}	1.23 ± 0.02 ^{e}	1.25 ± 0.03 ^{e}	1.900.0 ^{e}	2.01 ± 0.04 ^{f}	1.92 ± 0.02 ^{e}	2.86 ± 0.02 ^{f}	3.0 ± 0.03 ^{d}	2.87 ± 0.03 ^{f}
T_2	1.09 ± 0.02 ^{b}	1.07 ± 0.05 ^{ab}	1.08 ± 0.03 ^{b}	2.03 ± 0.02 ^{bc}	1.85 ± 0.03 ^{b}	2.01 ± 0.03 ^{b}	2.53 ± 0.02 ^{c}	2.64 ± 0.12 ^{bc}	2.52 ± 0.02 ^{c}	3.59 ± 0.02 ^{bc}	3.66 ± 0.04 ^{b}	3.58 ± 0.03 ^{b}
T_3	1.11 ± 0.01 ^{b}	1.26 ± 0.11 ^{a}	1.10 ± 0.04 ^{b}	2.10 ± 0.04 ^{b}	1.86 ± 0.01 ^{b}	2.07 ± 0.05 ^{b}	2.65 ± 0.03 ^{b}	2.43 ± 0.08 ^{de}	2.64 ± 0.04 ^{b}	3.36 ± 0.02 ^{d}	3.58 ± 0.04 ^{bc}	3.35 ± 0.02 ^{d}
T_4	0.93 ± 0.03 ^{d}	0.91 ± 0.06 ^{b}	0.89 ± 0.01 ^{d}	1.46 ± 0.03 ^{e}	1.63 ± 0.01 ^{d}	1.48 ± 0.041 ^{d}	2.28 ± 0.02 ^{d}	2.25 ± 0.03 ^{ef}	2.29 ± 0.03 ^{d}	3.11 ± 0.01 ^{e}	3.48 ± 0.04 ^{cd}	3.10 ± 0.01 ^{e}
T_5	1.02 ± 0.02 ^{c}	1.07 ± 0.05 ^{ab}	1.00 ± 0.02 ^{c}	1.98 ± 0.04 ^{cd}	1.73 ± 0.01 ^{c}	1.97 ± 0.04 ^{b}	2.62 ± 0.03 ^{bc}	2.55 ± 0.03 ^{cd}	2.61 ± 0.04 ^{b}	3.53 ± 0.01 ^{c}	3.71 ± 0.06 ^{b}	3.51 ± 0.01 ^{c}
T_6	1.24 ± 0.02 ^{a}	1.24 ± 0.06 ^{a}	1.21 ± 0.03 ^{a}	2.27 ± 0.03 ^{a}	1.96 ± 0.02 ^{a}	2.26 ± 0.033 ^{a}	3.15 ± 0.03 ^{a}	2.94 ± 0.04 ^{a}	3.14 ± 0.03 ^{a}	3.98 ± 0.04 ^{a}	3.91 ± 0.02 ^{a}	3.96 ± 0.02 ^{a}
T_7	1.07 ± 0.01 ^{bc}	1.13 ± 0.08 ^{a}	1.05 ± 0.03 ^{bc}	1.90 ± 0.01 ^{d}	1.84 ± 0.02 ^{b}	1.85 ± 0.02 ^{c}	2.56 ± 0.05 ^{bc}	2.82 ± 0.02 ^{ab}	2.57 ± 0.03 ^{bc}	3.63 ± 0.05 ^{b}	3.70 ± 0.06 ^{b}	3.62 ± 0.03 ^{b}
LS	***	***	***	***	***	***	***	***	***	***	***	***

The mean was calculated from four replicates for each treatment. a, b, c, d, e, etc. indicate significant differences among the treatments. In a column, means having similar letter(s) are statistically similar and those having dissimilar letter(s) differ significantly by LSD at 0.05 levels of probability. T_1 = Zero N/Control N; T_2 = recommended N; T_3 = 125% of recommended N; T_4 = 75% of recommended N; T_5 = cow dung N 2 t ha^{-1} supplemented with prilled urea N; T_6 = deep placement of urea super granule (USG) 165 kg ha^{-1}; T_7 = biochar 4 t ha^{-1} with recommended N as prilled urea; LS = level of significance; *** = 0.1% level of significance; ± = standard error.

Table 7. Effect of N fertilizer management options on panicle length, extrusion length (cm), and weight of 1000 grains (g) of rice (BRRI dhan28).

	Panicle Length (cm)			Extrusion Length (cm)			Weight of 1000 Grains (g)		
	2021	2022	2023	2021	2022	2023	2021	2022	2023
T_1	16.02 ± 0.49 ^{c}	20.67 ± 0.24 ^{d}	22.47 ± 0.57 ^{d}	1.33 ± 0.13 ^{cd}	1.42 ± 0.20 ^{b}	1.35 ± 0.26	21.20 ± 0.33 ^{b}	20.33 ± 0.19 ^{c}	22.32 ± 0.08 ^{c}
T_2	22.71 ± 0.16 ^{ab}	24.75 ± 0.53 ^{a}	24.92 ± 0.28 ^{c}	1.75 ± 0.25 ^{abc}	1.75 ± 0.20 ^{ab}	1.49 ± 0.17	22.43 ± 0.22 ^{a}	21.25 ± 0.18 ^{ab}	22.9 ±ab 0.05 ^{b}
T_3	22.84 ± 0.61 ^{ab}	25.25 ± 0.58 ^{a}	25.75 ± 0.34 ^{bc}	2.16 ± 0.17 ^{a}	1.75 ± 0.08 ^{ab}	1.64 ± 0.03	22.72 ± 0.58 ^{a}	21.15 ± 0.33 ^{ab}	23.15 ± 0.17 ^{a}
T_4	21.97± 0.50 ^{b}	22.59 ± 0.81 ^{c}	25.42 ± 0.25 ^{bc}	1.95 ± 0.26 ^{ab}	1.33 ± 0.12 ^{b}	1.23 ± 0.03	22.36 ± 0.50 ^{a}	20.75 ± 0.16 ^{bc}	23.5 ± 0.12 ^{a}
T_5	21.45 ± 0.42 ^{b}	23.75 ± 0.28 ^{abc}	26.25 ± 0.16 ^{ab}	2.29 ± 0.22 ^{a}	2.17 ± 0.25 ^{a}	1.74 ± 0.09	22.73 ± 0.34 ^{a}	21.00 ± 0.21 ^{abc}	23.25 ± 0.14 ^{a}
T_6	23.95 ± 0.57 ^{a}	24.25 ± 0.28 ^{ab}	26.83 ± 0.22 ^{a}	1.47 ± 0.17 ^{bcd}	1.96 ± 0.31 ^{ab}	1.65 ± 0.12	23.04 ± 0.35 ^{a}	21.65 ± 0.17 ^{a}	23.25 ± 0.04 ^{a}
T_7	22.23 ± 0.36 ^{b}	23.08 ± 0.35 ^{bc}	25.50 ± 0.22 ^{bc}	1.05 ± 0.05 ^{d}	1.63 ± 0.18 ^{ab}	1.62 ± 0.02	22.84 ± 0.06 ^{a}	21.45 ± 0.32 ^{ab}	22.95 ± 0.06 ^{ab}
LS	***	***	***	***	NS	NS	*	**	***

Mean was calculated from four replicates for each treatment. a, b, c, d, e, etc. indicate significant differences among the treatments. In a column, means having similar letter(s) are statistically similar and those having dissimilar letter(s) differ significantly by LSD at 0.05 levels of probability. T_1 = Zero N/Control N; T_2 = recommended N; T_3 = 125% of recommended N; T_4 = 75% of recommended N; T_5 = cow dung N 2 t ha^{-1} supplemented with prilled urea N; T_6 = deep placement of urea super granule (USG) 165 kg ha^{-1}; T_7 = biochar 4 t ha^{-1} with recommended N as prilled urea; LS = level of significance; *** = 0.1% level of significance; ** = 1% level of significance; * = 5% level of significance; NS = not significant; mean ± = standard error.

3.6. Grain Number

The total number of grains per panicle responded to the treatments (Table 8), varying from 90 to 178 during the three years sequential cropping seasons. In 2021, the maximum number of total grains per panicle (171.5) was in the T_6 treatment which was significantly (p = 0.05) greater than that from the rest of the treatments. These results persisted over the next two years (2022 and 2023) where the maximum number of total grains per panicle (178.0 and 170.25) was in the T_6 treatment. It may be due to the slow-release nature of USG that ensures nitrogen availability throughout the critical growth stages of rice plants, resulting in enhanced tillering and panicle development, improved flowering, and fertility which finally improved grain numbers. Next to the T_6 treatment, the T_7, T_3, T_5, and T_2 treatments also provided high total grains per panicle. These responses to different treatments show that USG and biochar provided the best results and can be ranked in the following order: $T_6 > T_7 > T_3 > T_5 > T_2 > T_4 > T_1$ over the whole study period. The minimum number of total grains per panicle (90 to 94) was in the T_1 (Zero N) treatment.

Table 8. Effects of nitrogenous fertilizer management options on total number of grain panicle^{-1}, no. of filled grain panicle^{-1}, and no. of unfilled grain panicle^{-1} of rice (BRRI dhan28).

	Total No. of Grain Panicle^{-1}			No. of Filled Grain Panicle^{-1}			Unfilled Grain Panicle^{-1}		
	2021	**2022**	**2023**	**2021**	**2022**	**2023**	**2021**	**2022**	**2023**
T_1	90.0 ± 1.07 ^{e}	93.50 ± 2.33 ^{d}	90.17 ± 3.61 ^{f}	79.0 ± 0.53 ^{e}	71.25 ± 1.44 ^{d}	78.17 ± 3.06 ^{e}	11.0 ± 0.91 ^{ab}	22.25 ± 1.49 ^{a}	12.0 ± 0.82 ^{a}
T_2	127.50 ± 2.22 ^{c}	163.75 ± 3.52 ^{b}	125.75 ± 0.86 ^{d}	118.50 ± 2.22 ^{d}	152.50 ± 4.01 ^{b}	117.25 ± 0.98 ^{c}	9.0 ± 0.82 ^{bc}	11.25 ± 0.85 ^{bc}	8.50 ± 0.65 ^{b}
T_3	140.50 ± 1.71 ^{b}	174.75 ± 1.60 ^{ab}	137.75 ± 3.61 ^{bc}	131.50 ± 1.32 ^{b}	160.75 ± 1.49 ^{a}	128.50 ± 0.65 ^{b}	9.0 ± 0.71 ^{bc}	14.0 ± 1.08 ^{c}	9.25 ± 0.48 ^{b}
T_4	115.50 ± 1.89 ^{d}	130.25 ± 5.85 ^{c}	113.50 ± 3.01 ^{e}	106.0 ± 0.71 ^{d}	119.25 ± 5.79 ^{c}	105.50 ± 2.22 ^{d}	9.50 ± 1.55 ^{abc}	11.0 ± 0.41 ^{bc}	8.00 ± 0.91 ^{b}
T_5	128.75 ± 1.89 ^{c}	168.25 ± 4.63 ^{ab}	128.08 ± 8.52 ^{cd}	119.25 ± 2.66 ^{c}	157.0 ± 4.02 ^{ab}	119.83 ± 8.13 ^{bc}	9.50 ± 1.32 ^{abc}	11.25 ± 0.85 ^{bc}	8.25 ± 0.48 ^{b}
T_6	171.50 ± 3.59 ^{a}	178.0 ± 2.92 ^{a}	170.25 ± 2.25 ^{a}	165.0 ± 3.49 ^{a}	171.0 ± 3.39 ^{a}	162.50 ± 2.10 ^{a}	6.50 ± 0.29 ^{c}	7.0 ± 1.08 ^{bc}	7.75 ± 0.85 ^{b}
T_7	146.25 ± 3.22 ^{b}	174.0 ± 4.06 ^{ab}	142.42 ± 1.91 ^{b}	135.75 ± 2.81 ^{b}	160.0 ± 3.03 ^{ab}	130.67 ± 1.48 ^{b}	10.50 ± 0.65 ^{a}	14.0 ± 2.42 ^{b}	11.75 ± 0.48 ^{a}
LS	***	***	***	***	***	***	***	***	***

The mean was calculated from four replicates for each treatment. a, b, c, d, e, etc. indicate significant differences among the treatments. In a column, means having similar letter(s) are statistically similar and those having dissimilar letter(s) differ significantly by LSD at 0.05 levels of probability.T_1 = Zero N/Control N; T_2 = recommended N; T_3 = 125% of recommended N; T_4 = 75% of recommended N; T_5 = cow dung N 2 t ha^{-1} supplemented with prilled urea N; T_6 = deep placement of urea super granule (USG)165 kg ha^{-1}; T_7 = biochar 4 t ha^{-1} with recommended N as prilled urea; LS = level of significance; *** = 0.1% level of significance; ± = standard error.

The highest number of filled grains per panicle was recorded (165.0, 171.0, and 162.50, respectively) for the T_6 treatment which was significantly greater (p = 0.05) than that observed in the other treatments (Table 7). The second highest filled grains per panicle (135.75, 159.0, and 130.67, respectively) was in the T_7 treatment (biochar 4 t ha^{-1} with recommended N). The minimum number of unfilled grains per panicle (6.50, 7.0, and 7.75, respectively) was in the T_6 treatment, reflecting the positive effect of USG on the filling of grains. The highest number of unfilled grains per panicle was in the T_1 (Zero N) treatment (11.0, 22.25, and 12.0, respectively).

3.7. Grain Yield (t ha^{-1})

Grain yield responded significantly (p = 0.05) to the different fertilizer management options (Figure 3). The grain yield was in the range of 3.18 to 7.23 t ha^{-1} during the three experimental seasons, where the maximum grain yield in 2021 was 6.99 t ha^{-1} in the T_6 treatment. Grain yields continued to increase in the next two years, at 7.23 and 6.97 t ha^{-1} in the T_6 treatment in 2022 and 2023, respectively. The adequate and consistent N supply from USG might have contributed to better grain formation with more filled grain panicle^{-1} that increased grain yield. The lowest grain yield (3.16–3.19 t ha^{-1}) was in the T_1 treatment (Zero N).

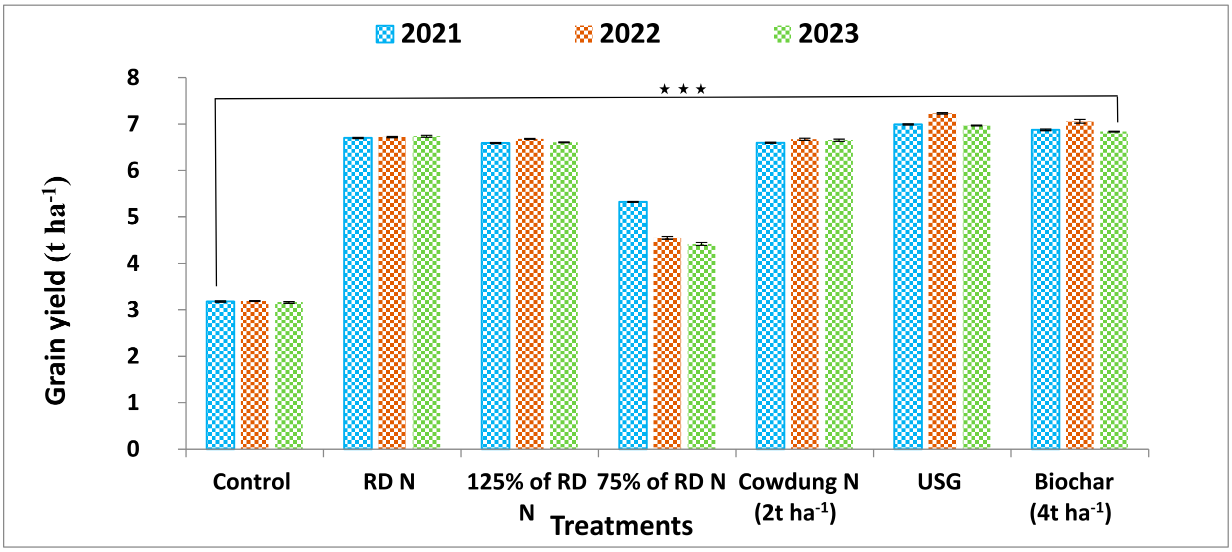

Figure 3. Grain yield (t ha^{-1}) of BRRI dhan28 influenced by the application of nitrogenous fertilizer management options. The mean average of four replications and the capped line represent standard error. Significance difference compared to control at p = 0.05; *** = 0.1% level of significance. RDN = Recommended dose of nitrogen.

3.8. Straw Yield (t ha^{-1})

Straw yield was statistically different for all of the treatments applied in the experiment (Figure 4). The highest straw yield was in the T_3 treatment (recommended dose plus 25% extra N), but the other treatments were similar (T_2, T_6, T_5, and T_4) in the consecutive years. The straw yields in T_3 were 8.78, 8.70, and 8.70 t ha^{-1} in successive cropping years compared to the recommended dose of N (8.69, 8.64, and 8.60 t ha^{-1}). On the other hand, the lowest straw yield (5.65, 5.52, and 5.64 t ha^{-1}) was observed in the T_1 treatment (Zero N) in the respective cropping years.

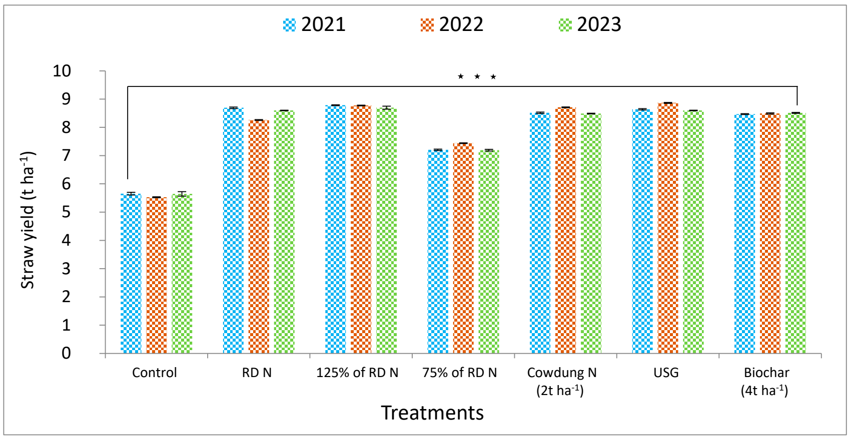

Figure 4. Straw yield (t ha^{-1}) of BRRI dhan28 influenced by the application of nitrogenous fertilizer management options. The mean average of four replications and the capped line represent standard error. Significance difference compared to control at p = 0.05; *** = 0.1% level of significance. RDN = Recommended dose of nitrogen.

3.9. Biological Yield (t ha^{-1})

The total aboveground biomass production or biological yield (Figure 5) was affected significantly (p = 0.05) by the N fertilizer treatment options in the sequential cropping years. The highest biological yields (15.44, 16.09, and 15.45 t ha^{-1}, respectively) were in the T_6 treatment compared to the recommended dose of N (15.39, 14.97, and 15.33 t ha^{-1}) in 2021, 2022, and 2023. The T_7 treatment was closest to the T_6 treatment while the lowest biological yields (8.83, 8.72, and 8.81 t ha^{-1}) were in the T_1 treatment (Zero N) in the three-year experimental period.

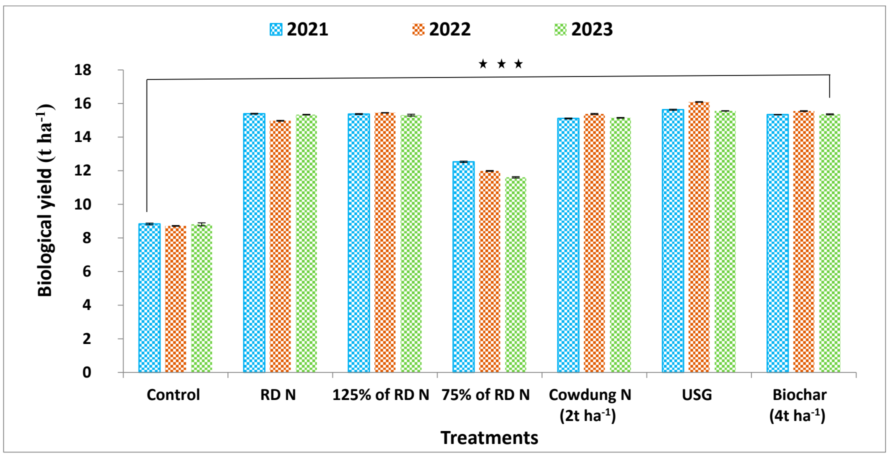

Figure 5. Biological yield (t ha^{-1}) of BRRI dhan28 influenced by the application of nitrogenous fertilizer management options. The mean average of four replications and the capped line represent standard error. Significance difference compared to control at p = 0.05; *** = 0.1% level of significance. RDN = Recommended dose of nitrogen.

3.10. Harvest Index (%)

The harvest index is the ratio of the grain yield to the total biological yield, expressed as a percentage (Figure 6). The highest harvest index (44.72, 44.94%, and 43.71%) was observed in the T_6 treatment (USG) during 2021, 2022, and 2023. The lowest harvest index was observed in T_1 (35.49–36.59%).

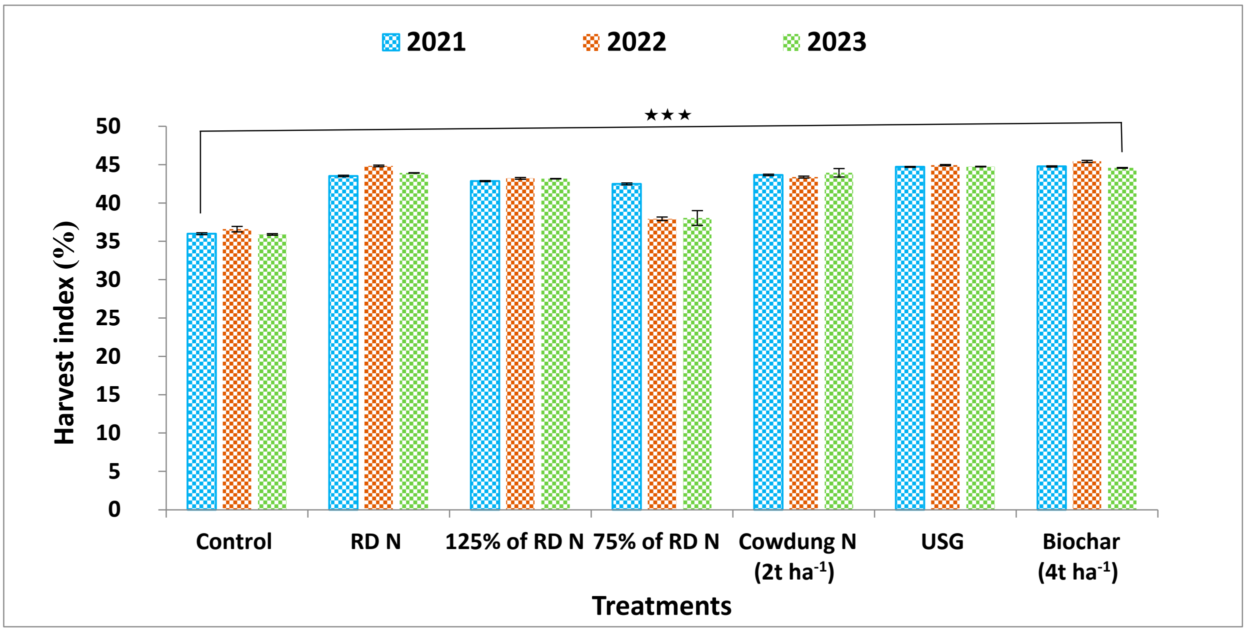

Figure 6. Harvest index (%) of BRRI dhan28 due to the application of nitrogenous fertilizer management options (2021, 2022, and 2023). The mean average of four replications and the capped line represent standard error. Significance difference compared to control at $p = 0.05$; *** = 0.1% level of significance. RDN = Recommended dose of nitrogen.

3.11. Nitrogen Content of Grain and Straw (%)

Grain N content was highest in the T_6 treatment with values of 1.71% in 2021 and 1.72% in 2022 cropping years (Table 9). Next to the T_6 treatment, the T_3 and T_7 treatments also provided high N concentrations of 1.69 and 1.71; 1.60 and 1.71%, respectively, in the respective cropping years. Without N application, the % N concentration of grain was 1.39, 1.30, and 1.22%, respectively, in the T_1 treatment (Zero N) in the three-year experimental period.

Table 9. Effects of nitrogenous fertilizer management options on % N content of grain and straw of rice.

Treatment	% N Content (Grain)			% N Content (Straw)		
	2021	2022	2023	2021	2022	2023
T_1	1.39 ± 0.02^{d}	1.30 ± 0.01^{e}	1.22 ± 0.01	0.98 ± 0.01^{f}	0.97 ± 0.02^{d}	1.04 ± 0.02^{c}
T_2	1.67 ± 0.02^{a}	1.62 ± 0.01^{c}	1.70 ± 0.01	1.15 ± 0.02^{de}	1.04 ± 0.02^{c}	1.16 ± 0.02^{b}
T_3	1.69 ± 0.01^{a}	1.71 ± 0.02^{ab}	1.71 ± 0.4	1.21 ± 0.04^{bc}	1.13 ± 0.01^{ab}	1.35 ± 0.03^{a}
T_4	1.53 ± 0.01^{c}	1.57 ± 0.01^{d}	1.58 ± 0.01	1.11 ± 0.02^{e}	1.05 ± 0.03^{c}	1.16 ± 0.04^{b}
T_5	1.62 ± 0.01^{b}	1.67 ± 0.01^{b}	1.62 ± 0.01	1.17 ± 0.01^{cd}	1.12 ± 0.01^{b}	1.36 ± 0.02^{a}
T_6	1.71 ± 0.01^{a}	1.72 ± 0.01^{a}	1.71 ± 0.4	1.31 ± 0.01^{a}	1.19 ± 0.01^{a}	1.40 ± 0.01^{a}
T_7	1.60 ± 0.02^{b}	1.71 ± 0.01^{ab}	1.69 ± 0.01	1.23 ± 0.01^{b}	1.18 ± 0.01^{ab}	1.37 ± 0.03^{a}
LS	***	***	NS	***	***	***

The mean was calculated from four replicates for each treatment. a, b, c, d, e, etc. indicate significant differences among the treatments. In a column, means having similar letter(s) are statistically similar and those having dissimilar letter(s) differ significantly by LSD at 0.05 levels of probability. T_1 = Zero N/Control N; T_2 = recommended N; T_3 = 125% of recommended N; T_4 = 75% of recommended N; T_5 = cow dung N 2 t ha^{-1} supplemented with prilled urea N; T_6 = deep placement of urea super granule (USG) 165 kg ha^{-1}; T_7 = biochar 4 t ha^{-1} with recommended N as prilled urea; LS = level of significance; *** = 0.1% level of significance; NS = not significant; mean ± = standard error.

Similarly, the highest N content (%) of straw was in the T_6 treatment with values of 1.31, 1.19, and 1.40% during 2021, 2022, and 2023, respectively. In this regard, the closest values were demonstrated by the T_7 treatment. In contrast, the lowest values (0.98, 0.97, and 1.04%, respectively) were in the T_1 treatment (Control N).

3.12. N Uptake by Grain, Straw, and Plant (kg ha^{-1})

N uptake by grain, straw, and plant (kg ha^{-1}) of BRRI dhan28 was significantly (p = 0.05) influenced by the application of treatments (Table 10). The highest N uptake by grain was from T_6, where the values were 115.98, 124.17, and 119.66 kg ha^{-1} in the gradual cropping years. These results were comparatively better than the T_2 treatment (112.06, 108.95, and 114.54 kg ha^{-1}, respectively). Moreover, the T_3, T_7, and T_4 treatments also showed average results, and as usual, the lowest values were recorded in the T_1 treatment (Control N).

Table 10. Effects of nitrogenous fertilizer management options on N uptake by grain, straw, and plant (kg ha^{-1}) of rice (BRRI dhan28).

	N Uptake by Grain(Kg ha^{-1})			N Uptake by Straw (Kg ha^{-1})			N Uptake by Plant (Kg ha^{-1})		
	2021	2022	2023	2021	2022	2023	2021	2022	2023
T_1	44.05 ± 0.75 ^{e}	41.39 ± 0.24 ^{f}	38.61 ± 0.78 ^{f}	55.13 ± 0.58 ^{e}	53.61 ± 1.19 ^{e}	59.11 ± 1.35 ^{e}	99.18 ± 1.17 ^{e}	95.021 ± 1.11 ^{f}	97.72 ± 1.22 ^{g}
T_2	112.06 ± 1.11 ^{b}	108.95 ± 1.35 ^{d}	114.54 ± 0.14 ^{b}	99.53 ± 1.47 ^{c}	85.87 ± 1.01 ^{c}	99.76 ± 1.11 ^{c}	211.59 ± 2.14 ^{bc}	194.83 ± 2.39 ^{d}	214.29 ± 1.08 ^{e}
T_3	111.21 ± 2.45 ^{b}	113.89 ± 0.46 ^{c}	112.49 ± 0.37 ^{c}	106.43 ± 3.26 ^{b}	98.69 ± 1.01 ^{b}	117.91 ± 2.16 ^{ab}	217.64 ± 3.16 ^{b}	212.58 ± 2.28 ^{c}	230.40 ± 2.52 ^{b}
T_4	81.35 ± 1.13 ^{d}	71.42 ± 0.55 ^{e}	69.94 ± 0.84 ^{e}	79.96 ± 1.30 ^{d}	77.74 ± 0.53 ^{d}	84.00 ± 1.58 ^{d}	161.31± 2.98 ^{d}	149.17+ ± 0.98 ^{e}	153.94 ± 1.52 ^{f}
T_5	106.55± 0.67 ^{c}	111.60 ± 0.93 ^{c}	108.35 ± 0.67 ^{d}	99.63 ± 0.96 ^{c}	97.46 ± 0.24 ^{b}	115.68 ± 1.03 ^{b}	206.18 ± 1.12 ^{c}	209.06 ± 1.02 ^{c}	224.03 ± 0.84 ^{d}
T_6	119.18 ± 0.82 ^{a}	124.17 ± 0.75 ^{a}	119.66 ± 0.46 ^{a}	113.39 ± 0.83 ^{a}	104.96 ± 0.96 ^{a}	120.40 ± 0.40 ^{a}	232.57 ± 1.03 ^{a}	229.13 ± 1.02 ^{a}	240.06 ± 0.82 ^{a}
T_7	110.36 ± 0.85 ^{b}	120.45 ± 0.69 ^{b}	116.23 ± 1.76 ^{b}	104.18 ± 1.50 ^{bc}	100.08 ± 0.74 ^{b}	116.83 ± 1.23 ^{ab}	214.54 ± 1.87 ^{b}	220.54 ± 0.82 ^{b}	233.06 ± 1.12 ^{c}
LS	***	***	***	***	***	***	***	***	***

The mean was calculated from four replicates for each treatment. a, b, c, d, e, etc. indicate significant differences among the treatments. In a column, means having similar letter(s) are statistically similar and those having dissimilar letter(s) differ significantly by LSD at 0.05 levels of probability. T_1 = Zero N/Control N; T_2 = recommended N; T_3 = 125% of recommended N; T_4 = 75% of recommended N; T_5 = cow dung N 2 t ha^{-1} supplemented with prilled urea N; T_6 = deep placement of urea super granule (USG) 165 kg ha^{-1}; T_7 = biochar 4 t ha^{-1} with recommended N as prilled urea; LS = level of significance; *** = 0.1% level of significance; mean ± = standard error.

Considering the N uptake by straw, the highest uptake (114.32, 118.78, and 120.40 kg ha^{-1}, respectively) was recorded by the treatment T_6 compared to the recommended N application option (99.53, 85.87, and 99.76 kg ha^{-1}) as well as the other treatments during 2021, 2022, and 2023. Finally, in the case of the N uptake by plants (kg ha^{-1}), the T_6 treatment showed consistently the highest values of 229.30, 128.69, and 240.06 kg ha^{-1} compared to the T_2 treatment (211.59 kg ha^{-1}, 194.83 kg ha^{-1}, and 214.29 kg ha^{-1}, respectively). The T_3 and T_7 treatments also provided good results for increments of N uptake. In contrast, the lowest N uptake by plants (99.33, 95.02, and 104.21 kg ha^{-1}) was in the T_1 treatment (Control N/Zero N) in the three-year experimental period.

3.13. Nitrogen Use Efficiency (NUE)/Partial Factor Productivity (PFP)

Nitrogen use efficiency (NUE) was significantly (p = 0.05) affected by the treatments with the highest NUE in from T_6 (41.83, 43.0, and 41.71, respectively) in the successive cropping years compared to the T_2 treatment (37.22, 37.30, and 37.43, respectively (Figure 7). From the responses to different nitrogenous fertilizer management options, the results can be ranked according to the following order: $T_6 > T_7 > T_2 > T_5 > T_4 > T_3$. The average NUE was 13.05% higher in the T_6 treatment (USG) than the recommended dose of N.

3.14. Agronomic Efficiency of N (AEN %)

The nitrogen fertilizer management options resulted in significant (p = 0.05) variations for the agronomic efficiency of N (AEN %). The highest AEN (23.1, 24.48, and 23.06%, respectively) was for the T_6 treatment (USG) compared to the T_2 treatment (recommended dose of N) where the recorded values were 19.56, 19.58, and 19.85%, respectively, in the consecutive cropping years (Figure 8). The effects of the treatments can be ranked according to the following order: $T_6 > T_7 > T_2 > T_5 > T_3$ and T_4 in respect of % AEN over the respective cropping years. The average AEN was 19.74% higher than the RD of N in the T_6 treatment (USG).

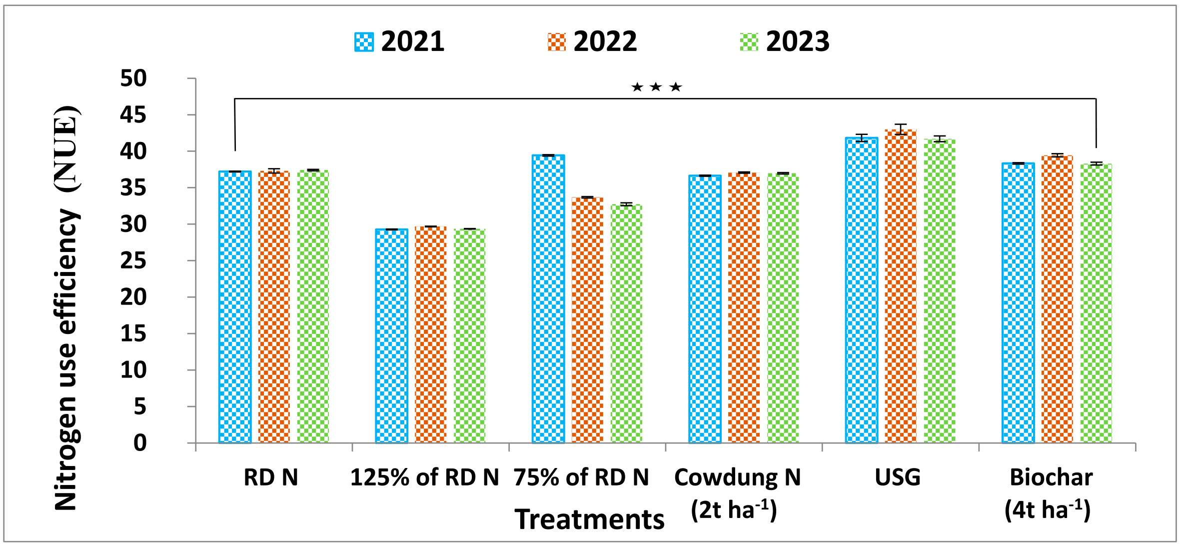

Figure 7. Nitrogen use efficiency (NUE %) of BRRI dhan28 due to the application of nitrogenous fertilizer management options. The mean average of four replications and the capped line represent standard error. Significance difference compared to control at $p = 0.05$; *** = 0.1% level of significance. RDN = Recommended dose of nitrogen.

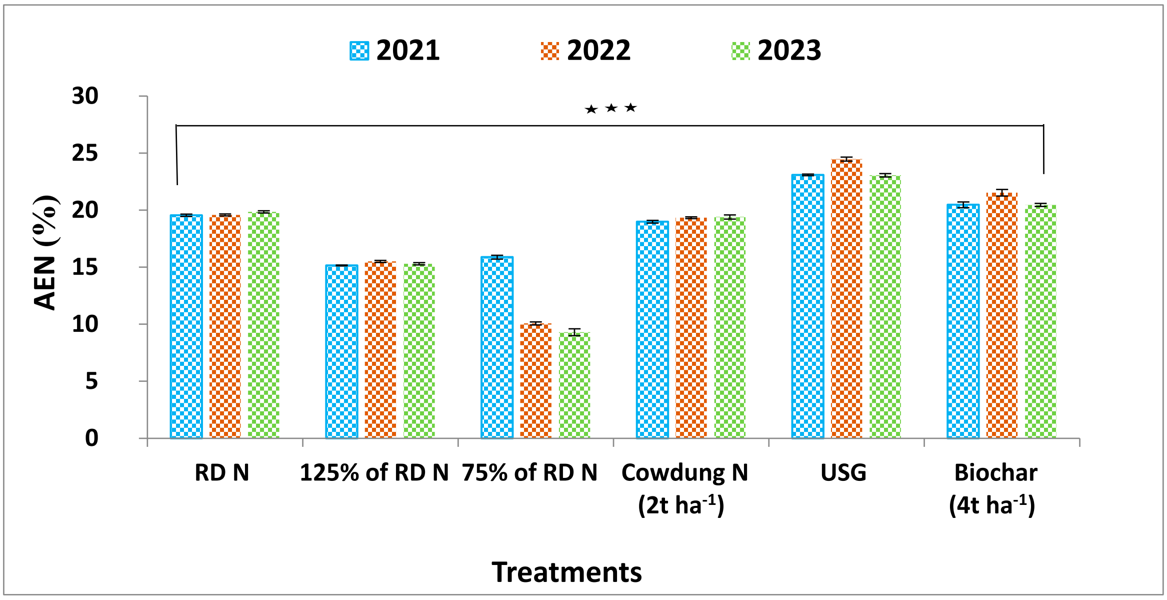

Figure 8. Agronomic efficiency of N (AEN %) of BRRI dhan28 due to the application of nitrogenous fertilizers dozes (2021, 2022, and 2023). The mean average of four replications and the capped line represent standard error. Significance difference compared to control at $p = 0.05$; *** = 0.1% level of significance. RDN = Recommended dose of nitrogen.

3.15. Recovery Efficiency of N (REN %)

The application of the nitrogen fertilizer management options significantly ($p = 0.05$) influenced the recovery efficiency of N (REN) over the serial experimental years (Figure 9). The highest REN (0.73, 0.75, and 0.73%, respectively) was by the T_6 treatment compared to T_2 (0.62, 0.60, and 0.64%, respectively) in the sequential cropping years. The average REN by the T_6 treatment (USG) was 18.87% higher than the RD (T_2).

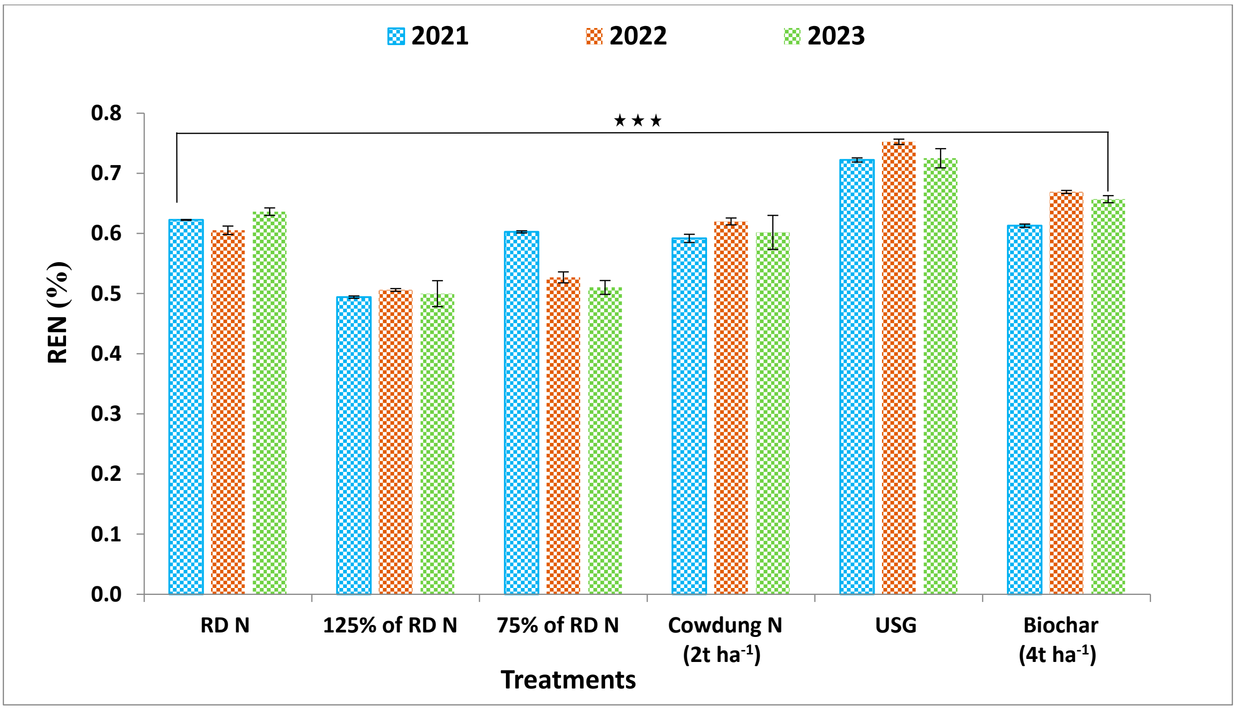

Figure 9. Recovery efficiency of N (REN %) of BRRI dhan28 due to the application of nitrogenous fertilizer management options (2021, 2022, and 2023). The mean average of four replications and the capped line represent standard error. Significance difference compared to control at p = 0.05; *** = 0.1% level of significance. RDN = Recommended dose of nitrogen.

3.16. Dry Matter Yield (Kg ha^{-1}) and Grain N Uptake

There was a statistically positive relationship between the DM yield and total N application. The highest DM yield was in the USG treatment (Figure 10) as it provided a more continuous supply of N through the growing period of the rice plant. N promotes rapid plant growth and improves grain yield and quality.

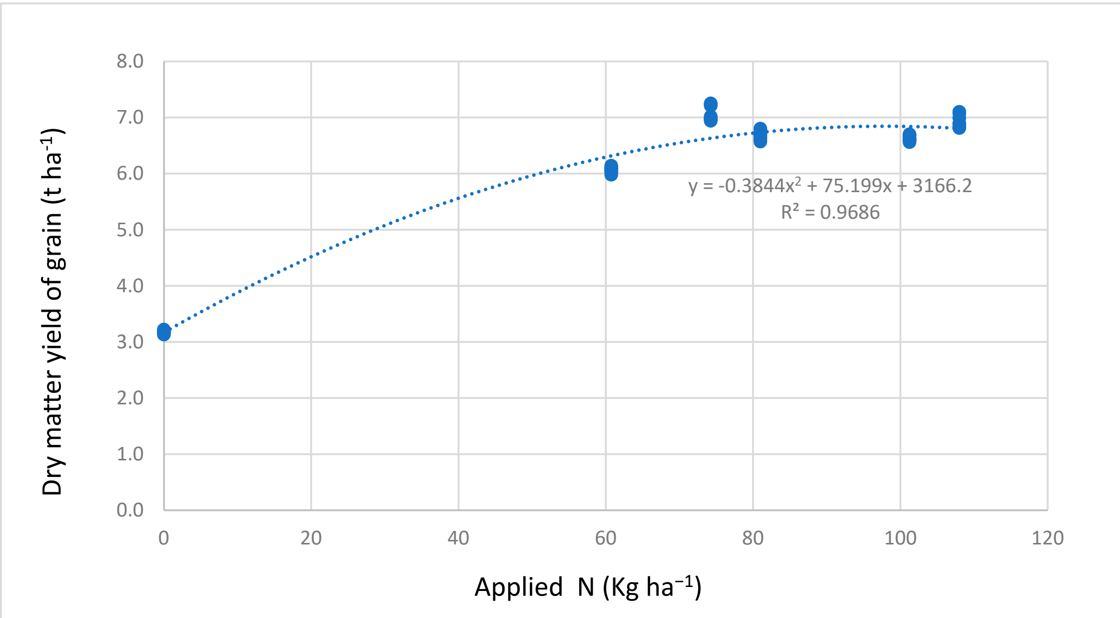

Figure 10. Effects of grain N uptake (Kg ha^{-1}) of rice in response to applied N.

3.17. Benefit–Cost Ratio (BCR)

A profitability indicator benefit–cost ratio analysis was used to determine the viability of cash flows generated from a project. The benefit–cost ratio (BCR) of rice cultivation responded significantly to N fertilizer application options in the three consecutive years (Figure 11). The highest BCR values (2.56, 2.64, and 2.55) were from the T_6 treatment. Next to the T_6 treatment, the fertilization option T_2 also had a high BCR (2.42, 2.41, and 2.43, respectively) in the sequential cropping years. But, the T_7 treatment (Biochar) had low BCR values (2.11, 2.15, and 2.10, respectively) reflecting the high cost of biochar.

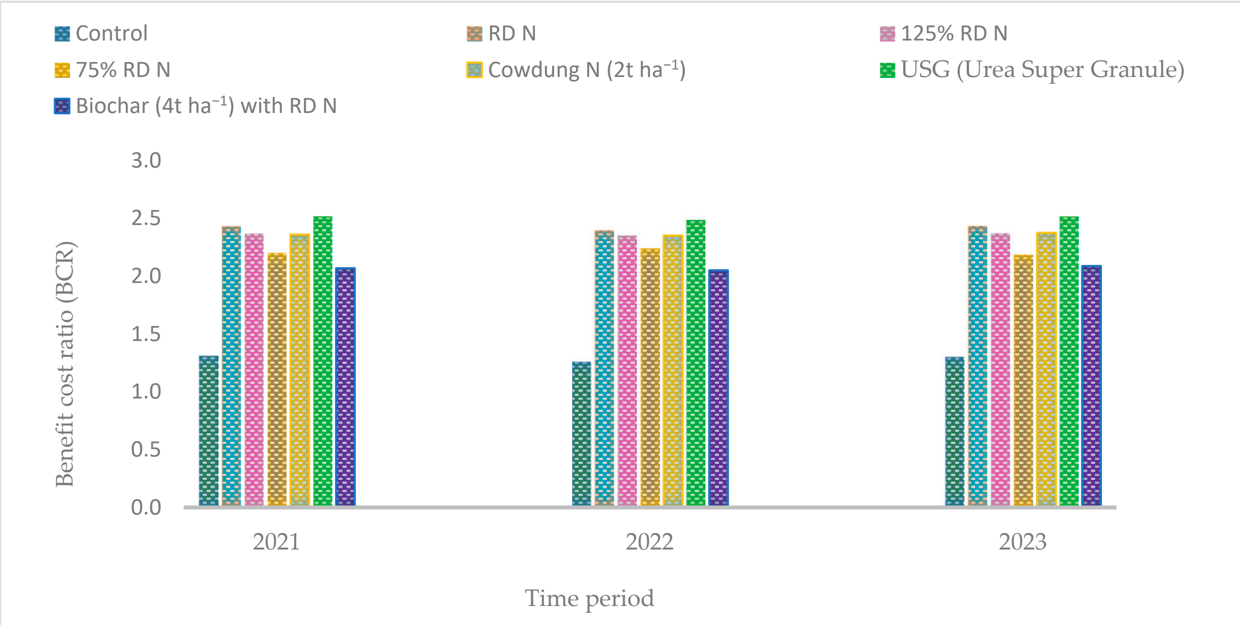

Figure 11. Benefit–cost ratio of BRRI dhan28 due to effects of nitrogenous fertilizer management options (2021, 2022, and 2023). RDN = Recommended dose of nitrogen.

4. Discussion

The application of the optimum amount of N can enhance crop growth and yield while reducing N loss and increasing N use efficiency. Although the applications of large amounts of N fertilizers can lead to increased crop yields, this practice is often associated with significant economic costs and adverse environmental impacts [42,43]. Excessive N application in crop production is common in Bangladesh. Reduction in N applications to the optimal rate is an efficient strategy to mitigate environmental risk [44]. Compared to the conventional application method, reducing N input significantly decreases reactive nitrogen losses in terms of leaching and gaseous emissions [45]. Appropriate N management approaches based on the conventional fertilizer application rate would not reduce yield but maintain yield to some extent as well as increasing the nitrogen use efficiency. Our study has demonstrated that improved nitrogen use efficiency (NUE) under different management practices can be achieved without a loss of yield and while reducing total N inputs. The deep placement of USG (slow-release N) and biochar (urease inhibitor) with the recommended dose of N fertilizer significantly influenced plant growth, yield, and NUE. The application of USG significantly increased plant height. It might be that the continuous supply of N from USG over the entire life cycle of the plant contributed to various physiological processes including the cell division and cell elongation of the plant which contributed to the observed increases in plant growth. Our findings are in line with the results reported by Singh and Singh [46], and Chopra and Chopra [47]. The results are also consistent with the findings of Alam [48]. Biochar also has beneficial effects on regulating plant growth by enhancing soil nutrient retention and uptake efficiency as reported by Ghorbani and Amirahmadi [49]. Tiller density is an important attribute that influences the yield of rice. The USG treatment significantly increased the number of tillers per hill. The application of USG resulted in more vigorous growth and produced more effective tillers compared to the recommended dose of N fertilizer. An adequate N supply from USG probably led to an increased number of productive tillers. This result is supported by the findings of Adhikari et al. [50] and Das [51]. On the other hand, Schnier et al. [52] reported that N supply controlled the tiller production of rice plants unless other factors such as spacing or light became limiting factors. The highest leaf chlorophyll content (SPAD value) of rice was from the USG treatment. The improving effects of slow-release N fertilizer (USG) on the chlorophyll content and vegetative growth of rice plants might be attributed to its role in regulating the release of N to synchronize with plants' demand [53]. In addition, the role of N in plants is that it increases the growth and development of all living tissue and is also an important constituent of chlorophyll [54]. The accumulation of dry matter (DM) was highest in the USG treatment compared to the recommended dose of N fertilizer. The finding is also in line with the opinion of Rao et al. [55] who mentioned that USG was most effective in increasing DM compared with the split applications of urea. From three years of sequential cropping seasons, the highest panicle length was recorded from USG treatment. These results are also consistent with the findings of other researchers [56,57] who found that the application of USG significantly increased panicle length. Moreover, this result is in line with another study [58] which found that the application of USG significantly increased the panicle length in rice plants compared to conventional urea application methods. This improvement is attributed to the slow-release nature of USG, which provides a more consistent supply of nitrogen to the plants, leading to better growth and development of the panicle structure. The weight of 1000 grains was highest in the treatment with USG, probably because of the increased photosynthesis and chlorophyll content in the leaves and finally dry matter accumulation in the plant which was possible due to the supply of N from USG in response to plant requirements [59]. Our results indicated that the overall dry matter production was associated with higher levels of grain yield. The increase in weight of 1000 grains of rice was also reported by Ashrafuzzaman et al. [60] in response to improved N management. The positive effects of USG as a source of N on the grain yield of rice have been observed by other researchers [61]. It might be due to the fact that an adequate supply of N from USG contributed to grain formation which probably increased the number of grains per panicle. This finding was also supported by the results reported by Rama et al. [62] and Kapre et al. [63], who observed significantly higher filled grains per panicle with the application of USG over a split application of urea. The grain yield of rice responded significantly to the USG treatment compared to the recommended dose of N. The yield analysis showed a greater yield in response to N fertilizer which was attributed largely to the number of effective tillers per hill and increased in the USG treatment compared to the RD treatment. The higher yield of rice grain in the biochar treatments might have been associated with higher soil nutrient retention, higher cation exchange capacity, and better soil fertility. It may be due to improving porosity that enhances its ability to retain water and nutrients, a large surface area that allows more space for nutrient adsorption and microbial colonization, and surface functional groups that improve cation exchange capacity, facilitating nutrient retention [64,65]. USG deep placement (8–10 cm depth) may have the capacity to slow the release of N which helps in the continuous supply of N over the entire life cycle of the plant that contributes to various physiological processes that ultimately lead to better growth, development, and yield of rice.

Improved grain and straw yields may have resulted from an adequate N nutrient supply which could be attributed to better synchrony between the supply and crop demand for N in the USG and biochar treatments, thereby contributing to superior crop growth and development [66,67]. The biological yield was also significantly influenced by the USG application and recorded the highest result compared to the recommended PU. Most of the treatments gave more or less similar results for harvest index except the T_1 treatment (Zero N).

However, throughout the cropping period, USG and biochar performed consistently better for the harvest index. Similar results were observed at the highest harvest index from the report of Huang et al. [68] and Rahman et al. [69]. Soil amendment with biochar and USG could decrease total nitrogen leaching (TNL) compared to that without amendments. Therefore, the appropriate management practices can effectively reduce the TNL and ultimately contribute to better growth and yield of rice and finally the harvest index. Higher grain yields in the fertilizer treatments were associated with a higher harvest index. The USG treatment consistently showed the highest N uptake by grain and straw throughout the cropping seasons. These results were comparatively better than the recommended PU. All the NUE indices (NUE, AEN, and REN) were significantly higher in the USG and biochar treatments with few exceptions. Many studies have demonstrated that the application of controlled release N significantly increases the grain yield of rice and NUE in comparison with the application of traditional prilled urea [70,71]. During the study period, the highest agronomic efficiency of N was observed in the USG treatment. Biochar at 4 t ha^{-1} with recommended N (T_7) also showed statistically similar results with respect to % AEN over the recommended N in the successive cropping years. However, this study was unable to assess the longer-term (>3 year) impacts of biochar. This should be a priority for future studies given the longevity of biochar in soils. The performance of USG as a slow-release N fertilizer is highly beneficial for wetland rice cultivation for synchronous N management leading to the reduction in volatilization leaching and other N losses. AEN is usually higher at low N rates than at higher N rates [67,72]. Our observation is consistent with those findings.

The highest recovery efficiency of N was in the USG treatment. The recovery efficiency of N was higher in USG than in the traditional application of prilled urea (PU) in a study reported by Hossain et al. [73]. This might be because the deep placement of USG increases the N use efficiency of the urea N over an extended period of time [74]. Biochar improves soil structure by increasing soil porosity and water retention, which is particularly beneficial in paddy fields where maintaining optimal moisture levels is critical for rice growth. It helps retain nutrients like nitrogen (N), phosphorus (P), and potassium (K) by reducing leaching [75].

Due to the application of various N management practices, the grain N uptake responded significantly. A higher grain yield and grain N uptake were recorded for the USG treatment compared to the other treatments. Higher levels of partial factor productivity (PFP) indicate a higher amount of nutrient input, while lower levels indicate a productivity-limiting deficit. In our study, N partial factor productivity (PFP) varied with treatment. The highest partial factor productivity was in the T_6 treatment (USG). This finding was supported by Chen et al. [71]. They observed that compared to the application of urea, controlled release urea increased the partial factor productivity. The highest benefit–cost ratio of rice was also recorded from the T_6 treatment (USG). Biochar with the recommended dose of prilled urea also showed good results in terms of growth, yield, and N use efficiency, but the extra cost of the biochar reduced the cost–benefit ratio. The findings suggest that the deep placement of urea super granules is the best option for improving the yield of rice while also improving N use efficiency.

5. Conclusions

These results clearly demonstrate that the application of different N fertilizer management options had a significant influence on the growth, yield, and N use efficiency of the BRRI dhan28 rice variety. The plant height, chlorophyll content, dry matter accumulation per plant (g), tiller density, filled grain per panicle, 1000-grain weight, grain yield, biological yield, and harvest index were increased with the urea super granule (USG) treatment at the same N rate as prilled urea applied in conventional management practices. The same treatment successfully increased all the indices of N use efficiency in wetland rice cultivation. Moreover, the USG treatment showed the highest benefit–cost ratio (BCR). In summary, the USG treatment would be the best option for higher yield production as well as improved NUE of BRRI dhan28 in wetland rice cultivation under the calcareous dark gray soils of Bangladesh.

Author Contributions: M.K.: writing—original draft, visualization, investigation, formal analysis, and data curation. R.M.R.: conceptualization, methodology, formal analysis, and review and editing. M.T.I.: investigation, data curation, and formal analysis. J.D.: conceptualization, methodology, and editing. M.S.: conceptualization and methodology. A.B.: conceptualization, methodology, and editing. W.J.B.: conceptualization, methodology, and editing. M.M.H.: writing—original draft, review and editing, supervision, investigation, methodology, validation, and data curation. All authors have read and agreed to the published version of the manuscript.

Funding: The study was carried out under the financial assistance of "UKRI-GCRF-South Asian Nitrogen Hub" in collaboration with the Department of Agronomy and Agricultural Extension, University of Rajshahi.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Bangladesh Rice Knowledge Bank-BRKB. Bangladesh Rice Research Institute (BRRI) Gazipur, Bangladesh. 2022. Available online: http://www.knowledgebank-brri.org/riceinban.php (accessed on 10 April 2023).
2. Bhuiya, N.I. Integrated Nutrient Management for Sustainable Rice Based Cropping System. In Proceedings of the Workshop on Experiences with Modem Rice Cultivation; BARC, Farmgate, Dhaka, Bangladesh, August 1991; p. 94.
3. Lawal, M.I.; Lawal, A.B. Influence of N rate and placement method on growth and yield of rice at Kadawa, Nigeria. *Crop Res. Hisar.* **2002**, *23*, 403–411.
4. Zhu, Z.L.; Chen, D.L. Nitrogen fertilizer use in China–Contributions to food production, impacts on the environment, and best management strategies. *Nutr. Cycl. Agroecosyst.* **2002**, *63*, 117–127. [CrossRef]
5. Raun, W.R.; Johnson, G.V. Improving nitrogen use efficiency for cereal production. *Agron. J.* **1999**, *91*, 357–363. [CrossRef]
6. Chivenge, P.; Sharma, S.; Bunquin, M.A.; Hellin, J. Improving nitrogen use efficiency—A key for sustainable rice production systems. Front. Sustain. *Food Syst.* **2021**, *5*, 737412.
7. Omara, P.; Aula, L.; Oyebiyi, F.; Raun, W.R. World cereal nitrogen use efficiency trends: Review and current knowledge. *Agrosyst. Geosci. Environ.* **2019**, *2*, 1–8. [CrossRef]
8. Guo, J.H.; Liu, X.J.; Zhang, Y.; Shen, J.L.; Han, W.X.; Zhang, W.F.; Christie, P.; Goulding, K.W.T.; Vitousek, P.M.; Zhang, F.S. Significant acidification in major Chinese croplands. *Science* **2010**, *327*, 1008–1010. [CrossRef]
9. Amirahmadi, E.; Moudry, J.; Konvalina, P.; Hortenhuber, S.J.; Ghorbani, M.; Neugschwandtner, R.W.; Jiang, Z.; Krexner, T.; Kopecky, M. Environmental Life Cycle Assessment in Organic and Conventional Rice Farming Systems: Using a Cradle to Farm Gate Approach. *Sustainability.* **2022**, *14*, 15870. [CrossRef]
10. Le, C.; Zha, Y.; Li, Y.; Sun, D.; Lu, H.; Yin, B. Eutrophication of lake waters in China: Cost, causes, and control. *Environ. Manag.* **2010**, *45*, 662–668. [CrossRef]
11. Xu, X.; Nie, L.; Buresh, R.J.; Huang, J.; Cui, K.; Xu, B.; Gong, W.; Peng, S. Emissions of N_2O and NH_3, and nitrogen leaching from direct-seeded and transplanted rice production systems in South China. *Agric. Water Manag.* **2013**, *116*, 37–44. [CrossRef]
12. Vitousek, P.M.; Aber, J.D.; Howarth, R.W.; Likens, G.E.; Matson, P.A.; Schindler, D.W.; Schlesinger, W.H.; Tilman, D. Human alteration of the global nitrogen cycle: Sources and consequences. *Ecol. Appl.* **1997**, *7*, 737–750. [CrossRef]
13. Erisman, J.W.; Sutton, M.A.; Galloway, J.N.; Billen, G.; Bleeker, A.; Pearce, H. Consequences of human modification of the global nitrogen cycle. *Philos. Trans. R. Soc. B Biol. Sci.* **2013**, *368*, 20130116. [CrossRef] [PubMed]
14. Galloway, J.N.; Aber, J.D.; Paul, E.A.; Galloway, J.H. Transformation of the nitrogen cycle: Recent trends, questions, and potential solutions. *Science.* **2008**, *320*, 889–892. [CrossRef] [PubMed]
15. Islam, M.R.; Bhuiyan, N.I.; Miah, M.A.M. Nitrogen management in wetland rice soils: The Bangladesh perspective. *Nutr. Cycl. Agroecosyst.* **1995**, *42*, 127–134. [CrossRef]
16. Jat, R.K.; Singh, R.G.; Singh, S.S. Precision Nitrogen Management in Rice-Wheat Systems for Enhanced NUE and Sustainability. *Agron. J.* **2021**, *113*, 2194–2204.
17. Zhang, H.; Liu, X.; Zhang, L.; Chen, Y.; He, X. Precision nitrogen management in rice production using a site-specific nitrogen management system. *Field Crops Res.* **2015**, *183*, 188–199. [CrossRef]
18. Ketterings, Q.M.; Van Es, H.M.; McCarty, G.W. Fertilizer best management practices to improve nitrogen use efficiency. *J. Environ. Qual.* **2007**, *36*, 1162–1170.
19. Ali, A.; Rahman, M.M. Integrated nutrient management practices enhance nitrogen use efficiency in rice. *Sustainability.* **2019**, *11*, 3400. [CrossRef]

20. Ladha, J.K.; Reddy, C.K.; Padre, A.T.; van Kessel, C. Role of Nitrogen Fertilization in Sustaining Organic Matter in Lowland Rice Soils. *Soil Sci. Soc. Am. J.* **2011**, *75*, 198–211.
21. Hossain, S.M.A.; Islam, M.S. *Fertilizer Management in Bangladesh. Advances in Agronomic Research in Bangladesh*; Society Agronomy: Gazipur, Bangladesh, 1986; p. 4854.
22. Yang, Y.C.; Zhang, M.; Li, Y.C.; Fan, X.H.; Geng, Y.Q. Controlled Release Urea Improved Nitrogen Use Efficiency, Activities of Leaf Enzymes, and Rice Yield. *Soil Sci. Soc. Am. J.* **2012**, *76*, 2307–2317. [CrossRef]
23. Lyu, X.; Wang, J.; Guo, J.; Meng, S.; Wu, J.; Zhang, J.; Zhang, X.; Zhang, C. Controlled-release nitrogen fertilizer decreases ammonia volatilization in summer maize fields. *Environ. Pollut.* **2021**, *268*, 116422. [CrossRef]
24. Islam, M.; Rahman, M.M.; Alam, M.S.; Rees, R.M.; Rahman, G.M.; Miah, M.G.; Drewer, J.; Bhatia, A.; Sutton, M.A. Leaching and volatilization of nitrogen in paddy rice under different nitrogen management. *Nutr. Cycl. Agroecosyst.* **2024**, *129*, 135–151. [CrossRef]
25. Chao, X.; Wu, L.H.; Ju, X.T.; Zhang, F.S. Role of nitrification inhibitor DMPP (3,4-dimethylpyrazole phosphate) in NO_3—N accumulation in greengrocery (*Brassica campestris* L. ssp chinensis) and vegetable soil. *J. Environ. Sci.* **2005**, *17*, 81–83.
26. Zhong, X.; Peng, S.; Zhi, Y. Effect of combining organic and inorganic fertilizers on nitrogen use efficiency and yield in rice cultivation. *Nutr. Cycl. Agroecosystems.* **2017**, *107*, 175–187.
27. Wang, J.; Xiong, Z.; Kuzyakov, Y. Biochar stability in soil: Meta-analysis of decomposition and priming effects. *GCB Bioenergy.* **2016**, *8*, 512–523. [CrossRef]
28. Rahman, G.M.; Rahman, M.M.; Alam, M.S.; Kamal, M.Z.; Mashuk, H.A.; Datta, R.; Meena, R.S. Biochar and organic amendments for sustainable soil carbon and soil health. In *Carbon and Nitrogen Cycling in Soil*; Springer: Singapore, 2020; pp. 45–85.
29. Gupta, K.; Kumar, R.; Baruah, K.K.; Hazarika, S.; Karmakar, S.; Bordoloi, N. Greenhouse gas emission from rice fields: A review from Indian context. *Environ. Sci. Pollut. Res.* **2021**, *28*, 30551–30572.
30. Gao, S.; Hoffman-Krull, K.; Bidwell, A.L.; DeLuca, T.H. Locally produced wood biochar increases nutrient retention and availability in agricultural soils of the San Juan Islands, USA. *Agric. Ecosyst. Environ.* **2016**, *233*, 43–54. [CrossRef]
31. Zhang, D.; Zhang, G.; Wang, Y.; Zeng, Y. Effects of biochar application on the yield and nutrient uptake of rice (*Oryza sativa* L.) in a sandy soil. *Field Crops Res.* **2016**, *186*, 152–160. [CrossRef]
32. Cheng, C.H.; Liu, X.Y.; Wang, H.J. The impact of biochar application on soil fertility. *Appl. Soil Ecol.* **2008**, *39*, 278–285. [CrossRef]
33. Ding, J.; Zhang, R.; Liu, Y.; Chen, F. Effects of biochar application on soil nutrients and microbial communities in rice cultivation. *Soil Biol. Biochem.* **2016**, *103*, 18–29. [CrossRef]
34. Anon. *Agro-Ecological Regions of Bangladesh*; Bangladesh Agricultural Research Council (BARC): Dhaka, Bangladesh, 1988.
35. BRRI (Bangladesh Rice Research Institute). *Organic Matter Management. Annual Report for 1993–1994*; BRRI: Gazipur, Bangladesh, 1994.
36. Bangladesh Meteorological Department. Available online: https://www.bmd.gov.bd/ (accessed on 19 November 2023).
37. BRRI (Bangladesh Rice Research Institute). *Annual Report 2014–2015*; BRRI: Gazipur, Bangladesh, 2016; p. 1701.
38. Jackson, M.L. *Soil Chemical Analysis*; Prentice Hall of India Pvt. Ltd.: New Delhi, India, 1973.
39. Moll, R.H.; Kamprath, E.J.; Jackson, W.A. Analysis and interpretation of factors which contribute to efficiency of nitrogen utilization. *Agron. J.* **1982**, *74*, 562–564. [CrossRef]
40. Ortiz-Monasterio, J.I.; Sayre, K.D.; Rajaram, S.; McMahon, M. Genetic progress in wheat yield and nitrogen use efficiency under four nitrogen rates. *Crop Sci.* **1997**, *37*, 898–904. [CrossRef]
41. Guarda, G.; Padovan, S.; Delogu, G. Grain yield, nitrogen-use efficiency and baking quality of old and modern Italian bread-wheat cultivars grown at different nitrogen levels. *Eur. J. Agron.* **2004**, *21*, 181–192. [CrossRef]
42. Robertson, G.P.; Vitousek, P.M. Nitrogen in agriculture: Balancing the cost of an essential resource. *Annu. Rev. Environ. Resour.* **2009**, *34*, 97–125. [CrossRef]
43. Ju, X.T.; Xing, G.X.; Chen, X.P.; Zhang, S.L.; Zhang, L.J.; Liu, X.J.; Cui, Z.L.; Yin, B.; Christie, P.; Zhu, Z.L.; et al. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. *Proc. Natl. Acad. Sci. USA* **2009**, *106*, 3041–3046. [CrossRef] [PubMed]
44. Zhao, H.; Li, X.; Jiang, Y. Response of Nitrogen Losses to Excessive Nitrogen Fertilizer Application in Intensive Greenhouse Vegetable Production. *Sustainability* **2019**, *11*, 1513. [CrossRef]
45. Nayak, D.; Saetnan, E.; Cheng, K.; Wang, W.; Koslowski, F.; Cheng, Y.F.; Zhu, W.Y.; Wang, J.K.; Liu, J.-X.; Moran, D.; et al. Management opportunities to mitigate greenhouse gas emissions from Chinese agriculture. *Agric. Ecosyst. Environ.* **2015**, *209*, 108–124. [CrossRef]
46. Singh, G.; Singh, O.P.; Yadav, R.A.; Singh, R.S.; Singh, B.B. Effect of sources and levels of nitrogen on grain yield, yield attributes, N uptake, recovery and response by rice in deep water conditions (100 cm). *Crop Res.* **1993**, *6*, 213–216.
47. Chopra, N.K.; Chopra, N. Seed yield and quality of 'pusa 44'rice (*Oryza sativa*) as influenced by nitrogen fertilizer and row spacing. *Indian J. Agric. Sci.* **2004**, *74*, 144–146.
48. Alam, B.M.R. Effect of Different Level of Urea Super Granules on the Growth and Yield of Three Varieties of Boro Rice. Master's Thesis, Department of Agronomy, Bangladesh Agriculture University, Mymensingh, Bangladesh, 2002; p. 119.
49. Ghorbani, M.; Amirahmadi, E. Biochar and soil contributions to crop lodging and yield performance—A meta-analysis. *Plant Physiol. Biochem.* **2024**, *215*, 109053. [CrossRef]
50. Adhikari, J.; Sarkar, A.R.; Uddin, M.R.; Sarker, U.K.; Hossen, K.; Rosemila, U. Effect of nitrogen fertilizer and weed management on the yield of transplant aman rice. *J. Bangladesh Agric. Univ.* **2018**, *16*, 12–16. [CrossRef]

51. Das, K.P.B. Effect of PM and Nitrogenous Fertilizer on the Growth and Yield of Boro Rice cv. BRRI dhan45. Master's Thesis, Department of Agronomy, Bangladesh Agricultrual University, Mymensingh, Bangladesh, 2011.
52. Schnier, H.F.; Dingkuhn, M.; De Datta, S.K.; Mengel, K.; Faronilo, J.E. Nitrogen fertilization of direct seeded flooded vs. transplanted rice: I. nitrogen uptake, photosynthesis, growth and yield. *Crop Sci.* **1990**, *30*, 1276–1284.
53. Mondal, M.M.A.; Puteh, A.B.; Malek, M.A.; Ismail, M.R.; Rafii, M.Y.; Latif, M.A. Seed yield in relation to growth and developmental aspects of mungbean. *Sci. World J.* **2012**, *2012*, 425168. [CrossRef] [PubMed]
54. El-Naggar, I.M.; El-Adah, M.; El-Sobany El-Tawil, A.Y. Yield and yield components of sur flower and some physical and chemical properties of different used soils as affected by organic and mineral fertilization. *J. Agric. Mansoura Univ.* **2002**, *27*, 7909–7925.
55. Rao, C.M.; Ramaish, N.V.; Reddy, S.N.; Reddy, G.V. Effect of urea and urea super granules on dry matter accumulation yield and nutrient uptake in rice (*Oryza sativa*). *J. Res.* **1986**, *14*, 23–33.
56. Rahman, M.S.; Islam, M.R.; Rahman, M.M.; Hossain, M.I. Effect of cowdung, poultry manure and Urea-N on the yield and nutrient uptake of BRRI dhan29. *Bangladesh J. Res. Publ.* **2011**, *2*, 552–558.
57. Sader, N.A.; Shamusuddin, A.M.; Khan, N.H. Yield and yield component of wetland rice under various sources and levels of nitrogen. *Philippine J. Crop Sci.* **1991**, *13*, 155–158.
58. Djaman, K.; Mel, V.C.; Ametonou, F.Y.; El-Namaky, R.; Diallo, M.D.; Koudahe, K. Effect of Nitrogen Fertilizer Dose and Application Timing on Yield and Nitrogen Use Efficiency of Irrigated Hybrid Rice under Semi-Arid Conditions. *J. Agric. Sci. Food Res.* **2018**, *9*, 223.
59. Mikkelesen, R.L.; Williams, H.M.; Behel, A.D. Nitrogen leaching and plant uptake from controlled release fertilizaers. *Fert. Res.* **1994**, *37*, 43–50. [CrossRef]
60. Ashrafuzzaman, M.; Islam, M.R.; Ismail, M.R.; Shahidullah, S.M.; Hanif, M.M. Evaluation of six aromatic rice varieties for yield and yield contributing characters. *Int. J. Agric. Biol.* **2009**, *11*, 616–620.
61. Jeng, T.L.; Tseng, T.H.; Wang, C.S.; Chen, C.L.; Sung, J.M. Yield and grain uniformity in contrasting rice genotypes suitable for different growth environments. *Field Crops Res.* **2006**, *99*, 59–66. [CrossRef]
62. Rama, S.; Reddy, G.; Reddy, K. Effect of levels and source of nitrogen on rice. *Indian J. Agron.* **1989**, *34*, 364–366.
63. Kapre, M.M.; Bisen, C.R.; Johar, M.S. Effect of slow released N fertilizers on rice under low land conditions crop Res. (hisar). *Crop Res.* **1996**, *11*, 17–23.
64. Kammann, C.; Ratering, S.; Eckhard, C.; Müller, C. Biochar as a soil amendment: A review on its impact on nutrient retention and soil properties. *J. Plant Nutr. Soil Sci.* **2015**, *178*, 564–579.
65. Mukherjee, A.; Lal, R. Biochar impacts on soil physical properties and greenhouse gas emissions. *Agronomy* **2013**, *3*, 313–339. [CrossRef]
66. Zheng, Y.; Han, X.; Li, Y.; Liu, S.; Ji, J.; Tong, Y. Effects of mixed controlled release nitrogen fertilizer with rice straw biochar on rice yield and nitrogen balance in northeast China. *Sci. Rep.* **2020**, *10*, 15612. [CrossRef]
67. Riste, D.; da Silva, M.P.; Ryan, C.A.; Cross, A.W.; Corcoles, A.D.; Smolin, J.A.; Gambetta, J.M.; Chow, J.M.; Johnson, B.R. Demonstration of quantum advantage in machine learning. *NPJ Quantum Inf.* **2017**, *3*, 16. [CrossRef]
68. Huang, M.; Fan, L.; Jiang, L.; Yang, S.; Zou, Y.; Uphoff, N. Continuous applications of biochar to rice: Effects on grain yield and yield attributes. *J. Integr. Agric.* **2019**, *18*, 563–570. [CrossRef]
69. Rahman, M.M.; Samanta, S.C.; Rashid, M.H.; Abuyusuf, M.; Hassan, M.Z.; Sukhi, K.F.N. Urea Super Granule and NPK Briquette on Growth and Yield of Different Varieties of Aus Rice in Tidal Ecosystem. *Asian J. Crop Sci.* **2016**, *8*, 1–12. [CrossRef]
70. Li, P.; Lu, J.; Wang, Y.; Wang, S.; Hussain, S.; Ren, T.; Cong, R.; Li, X. Nitrogen losses, use efficiency, and productivity of early rice under controlled-release urea. *Agric. Ecosyst. Environ.* **2018**, *251*, 78–87. [CrossRef]
71. Chen, Z.; Wang, Q.; Ma, J.; Zou, P.; Jiang, L. Impact of controlled-release urea on rice yield, nitrogen use efficiency and soil fertility in a single rice cropping system. *Sci. Rep.* **2020**, *10*, 10432. [CrossRef]
72. Yasuhiro, T.; Tovohery, R.; Astuko, T.; Kazuki, S. Challenges and opportunities for improving N use efficiency for rice production in Sub-Saharan Africa. *Plant Prod. Sci.* **2019**, *22*, 4.
73. Hossain, A.T.M.S.; Rahman, F.; Saha, P.K. Performance of Prilled Urea and Urea Super Granule by Applicators on Yield and Nitrogen Use Efficiency in Boro Rice. *Bangladesh Rice J.* **2018**, *22*, 63–69. [CrossRef]
74. IFDC. Fertilizer Deep Placement. IFDC Solutions. International Fertilizer Development Center (IFDC). 2013, p. 6. Available online: http://issuu.com/ifdcinfo/docs/fdp_8pg_final_web?e= (accessed on 18 November 2024).
75. Kapoor, V.; Singh, U.; Patil, S.K.; Magre, H.; Shrivastava, L.K.; Mishra, V.N.; Das, R.O.; Samadhiya, V.K.; Sanabria, J.; Diamond, R. Rice growth, grain yield and floodwater nutrient dynamics as affected by nutrient placement method and rate. *Agron. J.* **2008**, *100*, 526–536. [CrossRef]