ARCHIVES OF AGRONOMY AND SOIL SCIENCE
2025, VOL. 71, NO. 1, 1–19
https://doi.org/10.1080/03650340.2025.2457764

OPEN ACCESS Check for updates

# Village level fertilizer management for increasing nitrogen use efficiency, rice yield and household income

H. M. Al-Amin[a,b], Md. Mizanur Rahman[a], Mohammad Saiful Alam[a], Jo Smith[c], Majharul Islam[a,d], Robert Martin Rees[e], Tapan Kumar Adhya[f], Mark A. Sutton[g], William J. Bealey[g], Md. Giashuddin Miah[a] and Md. Rafiqul Islam[a]

[a]Faculty of Agriculture, Bangabandhu Sheikh Mujibur Rahman Agricultural University, Gazipur, Bangladesh; [b]Soil Science Division, Bangladesh Sugarcrop Research Institute, Ishurdi, Pabna, Bangladesh; [c]School of Biological Science, University of Aberdeen, Aberdeen, UK; [d]Soil Science Division, Bangladesh Institute of Nuclear Agriculture, Mymensingh, Bangladesh; [e]Scotland's Rural College, Edinburgh, UK; [f]School of Biotechnology, Kalinga Institute of Industrial Technology, Bhubaneswar, India; [g]Environmental Physics, UK Centre for Ecology & Hydrology, Midlothian, UK

**ABSTRACT**

Limited soil nitrogen (N) availability constrains crop growth and yield. Low N use efficiency (NUE) coupled with overuse of fertilizer-N result in environmental pollution and huge economic loss. Hence, effects of N management practices on rice grain yield and NUE were studied in two separate experiments in experimental farm and farmer's field. Each of the study was conducted in two consecutive rice seasons of *Boro* (dry season rice) and *Transplanted Aman* (*T. Aman*) (wet season rice) using several N treatments. Results revealed that compared with the recommended dose of N (RDN), urea super granule (USG) and biochar with RDN (BRDN) increased grain yield by 6–18% irrespective of experimental sites and cropping seasons. USG contributed to the highest NUE, while. USG and BRDN increased agronomic efficiency (1.3–2.3 folds), apparent N-recovery (1.3–1.9 folds) efficiency and physiological efficiency (0.9–1.3 folds), compared to RDN. USG appeared to be economically the most viable option, with a benefit-cost ratio (BCR) of 1.5–1.6 over locations and seasons. BRDN showed a lower BCR (1.1–1.2) due to additional expense on biochar. Biochar might contribute towards a carbon-negative economy, and its economic benefits require to be addressed. Supportive government policies are needed for adoption of USG and biochar in agriculture.

**ARTICLE HISTORY**
Received 20 May 2024
Accepted 20 January 2025

**KEYWORDS**
Biochar; deep placement of urea super granule (USG); nitrogen use efficiency (NUE); benefit-cost ratio (BCR)

## Introduction

Over half of the world's population depends on rice as a staple food, especially in the Asia-Pacific region. About 60% of the world's population lives in the Asia-Pacific region (ESCAP 2023). There is approximately 51 million rice-eating people increasing annually in this region (Papademetriou 2000; Asia-Pacific Rice Market 2023). Globally, 513.7 million tons (Mt) of milled rice was produced in 2020–21 (Mohidem et al. 2022), while the demand for milled rice in the world is projected to be about 584 Mt by 2050 (Samal et al. 2022). Shrinking acreage of rice-growing land, erosion of genetic potential of rice varieties, scarcity of irrigation water, declining factor productivity, indiscriminate use of inorganic fertilizers and climate change are all factors that pose major challenges to rice

**CONTACT** Md. Mizanur Rahman mizan@bsmrau.edu.bd Department of Soil Science, Bangabandhu Sheikh Mujibur Rahman Agricultural University, Gazipur 1706, Bangladesh

© 2025 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.
This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. The terms on which this article has been published allow the posting of the Accepted Manuscript in a repository by the author(s) or with their consent.

production (Abdullah et al. 2019). The rice growing area is declining across the globe because of industrialization, urbanization and crop diversification (Hasan et al. 2019). Samal et al. (2022) reported that Asia may lose about 5 million ha (Mha) and Africa gain about 10 Mha of rice land by 2050 (Samal et al. 2021). However, low and declining rice yields are major concerns in Africa. Hence, adoption of best agricultural management technologies might help to increase and sustain rice yields in both the Asian and African continents.

Efficient management of fertilizers, more specifically nitrogen (N), is crucial to rice production. Nitrogen is a key factor controlling food production (Hasnat et al. 2022; Alam et al. 2023). Especially in tropical and subtropical climates, soil N is deficient which seriously limits crop yields (Robertson and Vitousek 2009; Rahman et al. 2022). Due to deficiency of soil N across the world, external supply of N-fertilizer is necessary to meet the increasing demand of food. However, excessive application of N can result in the loss of up to 60–70% of the applied N which can have serious environmental impacts, degrading soils, water and air quality (Good and Beatty 2011; Sutton et al. 2013; Sarkar et al. 2016). During the period from 1980 to 2010, there was a 512% rise in the consumption of chemical fertilizers in China, while cereal grain yields only increased only by 65% (Zhang et al. 2011; Chen et al. 2011; Han et al. 2015). When N fertilizer is applied to rice fields through broadcasting methods, the crop can take up at most 50% of the applied N. Rahman et al. (2024) estimated that nitrogen use efficiency (NUE) rarely surpasses 20–40% of the applied N. Excessive application of N fertilizer also results in low NUE, due to N losses by ammonia volatilization, surface runoff, denitrification and leaching (Rochette et al. 2013; Islam et al. 2024). This results in important environmental concerns, such as eutrophication, soil acidification, nitrate pollution and release of greenhouse gas (GHG) nitrous oxide, contributing to global warming and climate change (UNEP 2014; Alam et al. 2023). Application of biochar and urea deep placement are management methods that can increase NUE and crop yields, while decreasing nitrogen losses (Bach et al. 2016; Islam et al. 2024). Effects of biochar application on rice yields were found variable with different rates. Huang et al. (2019) reported that application of biochar (20 t $ha^{-1}$) initially decreased rice grain yield but increased by 4–10% during fourth to sixth seasons. Huang et al. (2019) found that application of biochar at varying rates increased rice grain yields by 10.7%, while higher rates of biochar over 20 t $ha^{-1}$ contributed more in increasing rice yields. Husan et al. (2014) reported that deep placement of urea super granule (78 kg N $ha^{-1}$) increased rice grain yield by 29% compared to prilled urea (136 kg N $ha^{-1}$) application. Bandaogo et al. (2015) observed about 12% increase in rice grain yield under USG treatment during wet season in Burkina Faso when compared with prilled urea broadcasting.

Recovery efficiencies of N from application 104 kg N $ha^{-1}$ in rice fields in Bangladesh as prilled urea (PU), deep placement of urea super granule (USG) and NPK briquettes were 38, 85 and 76%, respectively (Rea et al. 2019). The USG technique decreases N losses by 40% and increases NUE to 30–40% compared to broadcasting of PU (Gregory et al. 2010; Miah et al. 2016; Huda et al. 2016). Many researchers across the world report that N leaching losses from rice fields vary from 3% to 36% of the applied N (Xinqiang et al. 2014; Shi et al. 2020; Islam et al. 2024). Islam et al. (2024) observed that ammonia ($NH_3$) volatilization in almost all cases exceeded leaching losses; leaching losses of N were only 3% of applied N in the biochar treatment and 4–5% in the USG deep placement, while $NH_3$ volatilization were 8–9% in biochar and 5–6% in USG application. Wang and Wang (2019) stated that $NH_3$ volatilization was between 9% and 60% of the applied N in rice in China. Similarly, Xu et al. (2012) measured volatilization losses as $NH_3$ that were approximately 31% of the applied N in a non-flooded rice-rice cropping system.

Deep placement of USG and application of biochar can also reduce N losses at $N_2O$. Emissions of $N_2O$ were reduced by 61–80% in Boro rice compared with PU broadcasting (Gaihre et al. 2015). However, effects of biochar application on $N_2O$ emissions are inconsistent (Singh et al. 2014; Shaaban et al. 2016). Sanchez-Garcia et al. (2014) observed a 54% increase in $N_2O$ emissions with biochar application compared to fertilizer only treatments, while Tan et al. (2017) reported a reduction in $N_2O$ emission by 37.6%. Such inconsistent findings demand special care and judicial management of biochar for crop production and soil health.

Under such scenarios of N utilization and losses, new strategies to improve N management in rice are necessary for food security and climate change mitigation. This might reduce N losses, while also improving N uptake and increasing crop yields. Many studies on N management and NUE in rice have been conducted in different production environments across the world (Lassaletta et al. 2014; Rahman et al. 2022; Sapkota and Takele 2023). However, effective N management practices that increase rice yield and NUE and are feasible and acceptable to farmers in the context of Bangladesh are yet to be identified. While recent studies have indicated that deep placement of urea super granules (USG) significantly increases NUE, farm level adoption of this technology is low (Gaihre et al. 2018; Rea et al. 2019). Another strategy is to apply biochar with the N fertilizer to better hold the available N in the soil ready for crop uptake (Islam et al. 2018, 2024), but implementation of this approach needs more research.

To be successful, any intervention must consider benefits for farmers and ultimate impacts on the national economy. Hence, the present study comprised of two separate experiments in two different locations in Bangladesh; (1) a highly controlled experimental station trial and (2) a trial on farmer's field. This aimed to investigate the impact on NUE and farm incomes of applying urea fertilizer along with biochar, or applying the N fertilizers by deep placement of USG. We hypothesized that application of the recommended dose of fertiliser with biochar and deep placement of USG would increase yields and improve NUE compared to application of the recommended dose of fertiliser as prilled urea. The on-farm trials were conducted to generate interest amongst farmers in more efficient N fertilizer management and to assess reasons for non-adoption and impacts on farm incomes. The study aims to provide recommendations for practices to improve NUE that are feasible in Bangladesh, the wider Asia-Pacific region and in other rice growing countries of similar agro-climatic conditions.

## Materials and methods

The present study comprised two separate experiments *viz.*, the on-station experiment in 2022 (first study) and the farmer's field experiment in 2023 (second study). Each of the experiments was conducted in two consecutive rice growing seasons of *Boro* - Fallow - *Transplanted Aman* (*T. Aman*) rice cropping pattern. *Boro* rice is grown in the dry season (November to April) with full irrigation, while *T. Aman* rice (July to November) is grown under rainfed condition with supplementary irrigation, if needed. Therefore, altogether, the study was conducted for two consecutive years comprising two *Boro* and two *T. Aman* rice seasons.

### *Site description*

The first experiment (on-station) was conducted at the research field of the Bangabandhu Sheikh Mujibur Rahman Agricultural University (BSMRAU), Gazipur Sadar upazila of Bangladesh (Figure S1). The site is situated at 90.24° E longitude and 24.03° N latitude at an altitude of 10 m above sea level. The area is a part of the Madhupur Tract agro-ecological zone (AEZ). The soil belongs to the Salna series and is categorized as Shallow Red Brown Terrace soil in Bangladesh (Brammer and Brinkman 1977) and Cambisols as per World Reference Base for Soil Resource (Nikodemus et al. 2024). The soil is acidic in nature and is characterized by silty clay loam with kaolinitic clay located within 50 cm of the surface. Total N content was 0.085% which was very low in terms of soil fertility ranking (BARC 2018). The second study was conducted at Tokenagar village under Kapasia upazila of Gazipur, Bangladesh. The village is located at 24°02′and 24°16′ N and 90°30′and 90°42′ E (Figure S2). The study area of the village is under the AEZ of Old Brahmaputra Floodplain (AEZ 9). As per WRB the soil belongs to Cambisols. The soil of the study site is silt loam and slightly acidic in nature. The initial soil characteristics of both the study sites are presented in Table 1.

The cation exchange capacity (CEC) of rice husk biochar was 28.35 cmol kg$^{-1}$. This biochar was used in both the on-station and farmer's field study. Biochar was prepared by pyrolysis

Table 1. The soil physiochemical characteristics at the on-station and farmer's field.

| | Soil depths (0-15 cm) (mean ± SD) | |
|---|---|---|
| | On-station | Farmer's field |
| Soil parameters | Initial | Initial |
| Soil pH | 5.90 ± 0.06 | 6.20 ± 0.08 |
| Organic C (%) | 0.76 ± 0.05 | 1.12 ± 0.11 |
| Total N (%) | 0.085 ± 0.02 | 0.081 ± 0.03 |
| Available P (mg $kg^{-1}$) | 11.90 ± 0.51 | 12.22 ± 0.55 |
| Exchangeable K (meq 100 $g^{-1}$) | 0.21 ± 0.05 | 0.16 ± 0.03 |
| Available S (mg $kg^{-1}$) | 20.30 ± 0.81 | 21.42 ± 0.76 |
| CEC (cmol $kg^{-1}$) | 6.15 ± 0.54 | 7.31 ± 0.62 |
| Bulk density (g $cm^{-3}$) | 1.32 ± 0.03 | 1.25 ± 0.03 |
| Soil texture | Silty clay loam | Silt loam |

of rice husks at a temperature of 450–550°C under oxygen deficient conditions in a pyrolysis kiln (Rahman et al. 2022). Rice husks were sun-dried before pyrolysis. Sun-dried rice husks were placed in the outer chamber of the kiln and then the heat was steadily increased to 550°C and held constant for 4–5 hours (Rahman et al. 2020). The biochar produced was allowed to cool at room temperature and then processed by grinding to make it suitable for field application.

The climate in the study region is humid, wet and subtropical. The mean annual temperature is 25.4°C and the average annual rainfall is 2420 mm, mostly taking place between May and September. Changes in temperature and rainfall during the period of experimentation are given in the supplementary Figures S3 and S4 for the on-station and farmer's field experiments, respectively.

## *Treatments, experimental design and fertilizer applications*

The on-station study comprises seven treatments *viz*., zero N (control), recommended dose of N (RDN as surface broadcast prilled urea), 125% of RDN (RDN125), 75% of RDN (RDN75), cowdung 2 t $ha^{-1}$ + supplemented N as prilled urea (CDSupN), biochar 2 t $ha^{-1}$ + RDN (BRDN), and deep placement of urea supper granules (USG). All the treatments were laid out in a randomized complete block design with four replications each (Table S1). The soil test-based recommended N rates from prilled urea were 186 kg and 102 kg $ha^{-1}$ in *Boro* and *T. Aman* seasons, respectively (BARC 2018), while USG were 95 kg and 75 kg $ha^{-1}$, respectively. Prilled urea (PU) was used in all the N treatments except the USG. Rice husk biochar was used in the BRDN treatment. The experiment started in the *Boro* season in 2022 (15 January – 12 May 2022). Seeds of the rice variety BRRI dhan29 were sown on 22 December 2021 and seedlings were transplanted on 10 February 2022 with three seedlings per hill maintaining a spacing of 20 × 20 cm.

The individual plot size was 30 $m^2$ (7.5 m × 4 m). Partially decomposed cowdung and biochar were applied at a rate of 6 kg $plot^{-1}$ (air dry basis) equal to 2 t $ha^{-1}$ as treatments seven days before the final land preparation and transplanting of seedlings. On the basis of soil test results, the recommended rates of P, K and S, 9, 76 and 12 kg $ha^{-1}$, respectively, for *Boro* rice were broadcasted and mixed with soil on the day of transplanting in all the treatments. Nitrogen in the PU treatments was applied in three equal splits on 15, 35, and 55 DAT (days after transplanting) apart from the control and USG treatments (Table S1). Urea super granules were applied as a single application at 15 DAT of *Boro* rice seedlings and 10 DAT of *T. Aman* seedlings, manually placing them at a soil depth of 7 to 8 cm near the root zone. Urea granules were applied between 4 hills of rice plants in alternate rows once during the crop growth season.

The second season study was in *T. Aman* conducted during 15 August-15 November 2022. Seeds of the experimental rice variety Binadhan-7 were sown on August 20 and seedlings were transplanted on September 15, maintaining three seedlings per hill with a spacing of 20 cm between lines and 15 cm between rows. The soil test-based rates of P, K and S were 6, 52 and 8 kg ha$^{-1}$, respectively. Similar to the *Boro* season, N was applied as PU to treatments in three equal splits on 10, 30, and 50 DAT, respectively (Table S1).

The study at the Farmer's field comprised five treatments: zero N (control), farmer's practice (FP), where prilled urea was used, soil test-based recommended dose of prilled urea (RDN), biochar 2 t ha$^{-1}$ + RDN (BRDN), and deep placement of USG. Among the five treatments, the two best-performing treatments (biochar and deep placement of USG) from the on-station trials were selected for the trial on a farmer's field. Three additional treatments were included; the control using the recommended fertiliser application as prilled urea, a soil-test based fertilizer application as prilled urea, and the farmer's normal practice were considered for the farmer's field study. The number of treatments in the farmer's field study was reduced to simplify the study and help the farmers to better understand the performance of the different treatments. The experiment at the farmer's field was laid out in a randomized complete block design with four replications for each treatment. The size of individual plot was 16 m$^2$ (4 m × 4 m). A 0.5 m irrigation channel separated the blocks from each other, while each plot was separated by a 0.5 m wide levee to prevent horizontal seepage of water and fertilizer between the plots.

Prilled urea (PU) was used in all the N treatments except the USG. Soil samples (from surface 15 cm) were collected before the experiment began and analyzed to determine soil test-based N rates. Soil test-based N rates as PU were 163 kg and 82 kg N ha$^{-1}$ in *Boro* and *T. Aman* rice seasons, respectively (Table S2). In normal farmer-practice, the application rates of PU were 103 kg and 62 kg N ha$^{-1}$. For USG, rates were 104 kg and 69 kg N ha$^{-1}$, respectively. Rice husk biochar was used following the same procedure mentioned in the on-station study.

During the *Boro* season, rice seeds (*cv.* BRRI Dhan29) were broadcasted on 1 December 2022 in the seedbed, and 45-day old seedlings were transplanted on 15 January 2023, with three seedlings per hill at a line-to-line distance of 20 cm, and row-to-row spacing of 15 cm. In the PU treatments, N was applied in three equal splits on 15, 35, and 55 days after transplantation (DAT) (Table S2). For *T. Aman* rice (15 August–15 November 2023) variety Binadhan-17 was sown on July 25, and the 21-day old seedlings were transplanted on August 15, with three seedlings per hill at a line-to-line distance of 20 cm, and row-to-row spacing of 15 cm. The soil test-based rates for P, K, and S were 6 kg, 52 kg, and 8 kg ha$^{-1}$, respectively. In the PU treatments, N was applied in three equal splits on 10, 25, and 40 DAT. Details of N application are provided in the supplementary Table S2.

## Plant sampling and their analysis

Rice plants from three random hills per plot were collected during harvest from all the treatments. Grain and straw samples were separated, and were kept in paper bags and dried in an oven at 75°C until they reached a constant weight. Nitrogen concentration in both grain and straw samples was determined using the Kjeldahl method (Douglas et al. 1980).

## Yield data

At the time of harvesting, fifteen consecutive hills were chosen for assessing the panicle count per hill. From each plot, ten representative hills were gathered to analyse yield components, including spikelets per panicle, filled grain percentage, and 1000-grain weight. Grain and straw yields were calculated from a 4 m$^2$ area situated at the centre of each plot. Biomass (straw and grain) was collected to determine the N uptake by grain and straw. The moisture content of the grain was adjusted to 14%. Biological yield was calculated by adding grain and straw dry weights and harvest index calculated as grain dry weight/biological yield.

## Economic analysis

The economic analysis was done to determine the total cost of production, gross return, net return, and benefit-cost ratio following the guidelines of Ishfaq et al. (2022). For cultivating one hectare of land, the farmer paid \$ 36 to the power tiller owner. The daily wage for each laborer was \$ 4.81. The costs of urea, USG, TSP, MOP, and gypsum were \$ 0.26, \$ 0.34, \$ 0.26, \$ 0.19, and \$ 0.24 kg$^{-1}$, respectively. The price of cowdung was \$ 0.05 kg$^{-1}$ and biochar were \$ 0.19 kg$^{-1}$. The insecticides (Amstar top, Virtako) required for one hectare of land totaled \$ 53. The seed rate of rice was 37.5 kg ha$^{-1}$, and the cost of these seeds was \$ 0.96 kg$^{-1}$. The farmer spent \$ 36 ha$^{-1}$ for each irrigation. Over four months, the farmer had to pay \$ 231 ha$^{-1}$ as land rent to the landowner. The annual bank interest was 10% and farmers took out this loan for the four-month rice production period. The price of rice grain was \$ 0.24 kg$^{-1}$, and the straw was \$ 0.05 kg$^{-1}$. The exchange rate for 1 US dollar (\$) was 104 Bangladeshi Taka (BDT).

To calculate interest for four-month period with a yearly interest rate of 10%, the equation 1 was used.

$$I = \frac{(p \times r \times t)}{100} \tag{1}$$

Where $I$ is the interest over the time period, $p$ is the principal amount (operating capital), $r$ is the annual interest rate and $t$ is the time in years. As the crop season is for ~4 months, the time ($t$) is 4/12 = 0.33 years.

## Determination of nitrogen use efficiency

Three types of NUE were determined (Gweyi-Onyango et al. 2021) using the following equations:

$$\text{Agronomic efficiency of Nuse} : AEN = \frac{(Y_f - Y_u)}{N_a} \tag{2}$$

$$\text{Physiological efficiency of Nuse} : PEN = \frac{(Y_f - Y_u)}{(N_f - N_u)} \tag{3}$$

$$\text{Apparent recovery efficiency of N} : AREN = \frac{(N_f - N_u)}{N_a} \times 100 \tag{4}$$

where, $Y_f$ and $Y_u$ are the grain yield of the fertilized and unfertilized plots, respectively, $N_a$ is the amount of N applied, and $N_f$ and $N_u$ are the amount of N uptake from the fertilized and unfertilized plots, respectively. AEN describes the grain harvested per kilogram of N applied; PEN is a measure of the ability of a plant to produce grain and biomass with N acquired at the whole plant level, while AREN refers to the N uptake in harvested products per unit of N applied and express in percentage.

Increment of rice yield of a particular treatment compared to any treatment was calculated using the equation 5. For example, yield increment of the USG treatment compared to the control treatment at *Boro* season of the on-station study is shown.

$$P_{GY,USG} = \frac{(Y_{USG} - Y_{control})}{Y_{control}} \times 100 \tag{5}$$

where, $P_{GY,\ USG}$ is the percent grain yield increment in the USG treatment over the control. Grain yields of the control and USG treatments of the on-station study were 2.90 t ha$^{-1}$ and 6.13 t ha$^{-1}$, respectively. Using these data in the equation 5, yield increment of the USG treatment over the control was found 111.38%.

### Statistical analysis

Statistix version 10.0 statistical software was used for the statistical analysis of the data. ANOVA and univariate analyses were conducted to assess all parameters, and the separation of treatment means was accomplished through the least significant difference (LSD) method. Various graphs were generated using Microsoft Excel (Office 2007).

## Results

### Nitrogen management influences yield attributes and yields of rice

At the on-station study, nitrogen management practices exhibited significant variations in the yield-attributing characteristics of both *Boro* and *T. Aman* rice (Table 2). In case of *Boro* rice, the BRDN treatment exhibited the highest values in all yield-attributing characters followed by USG. On the other hand, both BRDN and USG treatments showed statistically similar performances in yield contributing characteristics in case of *T. Aman*. The grain, straw and biological yields of rice at the on-station study were significantly ($p < 0.01$) higher in all N fertilizer applied treatments as compared to the control treatment in both *Boro* and *T. Aman* seasons (Table 3). In both of the seasons, BRDN showed the highest grain yield, which was significantly different from the USG, CDSupN and RDN treatments. The BRDN treatment showed the highest grain yields of 6.62 t ha$^{-1}$ in *Boro* and 4.79 t ha$^{-1}$ in *T. Aman season*. The BRDN treatment provided the highest biological yield, which was statistically different from the RDN125, CDSupN, and USG treatments in both the *Boro* and *T. Aman* seasons. The highest biological yields in the BRDN treatment were 13.88 t ha$^{-1}$ and 9.89 t ha$^{-1}$ in *Boro* and *T. Aman* seasons, respectively.

Similar to the on-station experiment, N management options unveiled significant differences in the yield-attributing characteristics of both *Boro* and *T. Aman* rice grown at the farmer's field (Table 4). The USG treatment exhibited the highest values in all yield-attributing characters followed by BRDN (Table 4). In most of the cases USG and BRDN showed statistically equal contributions towards yield attributes in both *Boro* and *T. Aman* seasons in the farmer's field study. Different N management practices at the farmer's field showed significant impact on grain, straw and biological yields of rice. In *Boro* rice (Table 3), the grain yields varied significantly among the different treatments, while the highest yield (6.29 t ha$^{-1}$) was observed in the USG treatment followed by

**Table 2.** Effect of nitrogen management on yield-attributing characters of rice at the on-station experiment of BSMRAU in 2022.

| Treatments | Plant height (cm) | Effective tiller hill$^{-1}$ | Panicle length (cm) | Filled grains panicle$^{-1}$ | 1000-seed weight (g) | Harvest Index |
|---|---|---|---|---|---|---|
| *Boro* | | | | | | |
| Control | 85.55f | 8.67e | 21.37e | 132.00d | 22.90f | 0.43c |
| RDN | 93.78 cd | 15.67c | 24.23c | 166.67b | 23.27d | 0.47a |
| RDN75 | 91.80e | 13.67d | 23.30d | 160.67c | 23.13e | 0.43c |
| RDN125 | 93.20d | 14.67 cd | 23.60d | 163.67bc | 23.27d | 0.42d |
| CDSupN | 94.10c | 17.33b | 24.77b | 173.00a | 23.60b | 0.47b |
| BRDN | 96.32a | 19.67a | 25.53a | 178.00a | 23.80a | 0.48a |
| USG | 95.03b | 18.33b | 25.25ab | 178.00a | 23.43c | 0.47ab |
| LSD (5%) | 0.73 | 0.58 | 0.52 | 5.71 | 0.08 | 0.01 |
| S.E. (±) | 0.33 | 1.27 | 0.24 | 2.62 | 0.04 | 0.01 |
| *T. Aman* | | | | | | |
| Control | 80.33d | 7.33f | 17.23e | 108.33e | 23.07d | 0.46c |
| RDN | 85.33b | 11.67d | 21.30c | 120.33c | 23.73bc | 0.46c |
| RDN75 | 83.00c | 9.33e | 19.40d | 115.67d | 23.43 cd | 0.44d |
| RDN125 | 85.67b | 12.33 cd | 21.30c | 121.67c | 23.90b | 0.44d |
| CDSupN | 85.83b | 13.00bc | 21.93b | 125.67b | 24.77a | 0.47bc |
| BRDN | 88.33a | 13.67ab | 23.10a | 128.00ab | 25.00a | 0.48a |
| USG | 88.83a | 14.33a | 23.50a | 130.33a | 25.10a | 0.47ab |
| LSD (5%) | 1.01 | 1.15 | 0.47 | 3.53 | 0.37 | 0.01 |
| S.E. (±) | 0.47 | 0.53 | 0.22 | 1.62 | 0.17 | 0.01 |

**Table 3.** Effect of different N management practices on grain, straw and biological yields of *boro* and *T. Aman rice* at the on-station in 2022 and farmer's field in 2023.

| | Yield of *Boro rice* (t ha$^{-1}$) | | | Yield of *T. Aman rice* (t ha$^{-1}$) | | |
|---|---|---|---|---|---|---|
| Treatments | Grain | Straw | Biological yield | Grain | Straw | Biological yield |
| On-station 2022: | | | | | | |
| Control | 2.90 g | 3.80f | 6.70 g | 2.31f | 2.76d | 5.07f |
| RDN | 5.76d | 6.51d | 12.37e | 4.07d | 4.87b | 8.94d |
| RDN125 | 5.63e | 7.65a | 13.27b | 3.99d | 5.11a | 9.10 cd |
| RDN75 | 4.56f | 6.01e | 10.56f | 3.10e | 3.95c | 7.05e |
| CDSupN | 5.91c | 6.71c | 12.62d | 4.31c | 4.90b | 9.21c |
| BRDN | 6.62a | 7.26b | 13.88a | 4.79a | 5.10a | 9.89a |
| USG | 6.13b | 6.73c | 12.86c | 4.51b | 4.99ab | 9.50b |
| LSD (5%) | 0.07 | 0.09 | 0.13 | 0.08 | 0.11 | 0.14 |
| S.E. (±) | 0.03 | 0.05 | 0.06 | 0.04 | 0.05 | 0.07 |
| Farmer's field 2023: | | | | | | |
| Control | 3.87e | 4.63d | 8.50d | 2.83e | 3.31d | 6.14e |
| FP | 4.69d | 5.82c | 10.51c | 3.56d | 4.24c | 7.80d |
| RDN | 5.50c | 6.26b | 11.76b | 4.04c | 4.67b | 8.71c |
| BRDN | 6.11b | 6.37ab | 12.48a | 4.36b | 4.75b | 9.11b |
| USG | 6.29a | 6.48a | 12.77a | 4.65a | 4.96a | 9.61a |
| LSD (5%) | 0.17 | 0.17 | 0.31 | 0.23 | 0.17 | 0.31 |
| S.E. (±) | 0.07 | 0.07 | 0.14 | 0.09 | 0.07 | 0.13 |

**Table 4.** Effect of nitrogen management on yield-attributing characters of rice at the farmer's field of Tokenagar, Kapasia in 2023.

| Treatments | Plant height (cm) | Effective tiller hill$^{-1}$ | Panicle length (cm) | Filled grains panicle$^{-1}$ | 1000-seed weight (g) | Harvest Index |
|---|---|---|---|---|---|---|
| *Boro* | | | | | | |
| Control | 96.77c | 11.10d | 20.50b | 162.33b | 22.05b | 0.44d |
| FP | 99.10bc | 13.33 cd | 23.57ab | 165.00b | 22.25b | 0.42e |
| RDN | 99.93bc | 14.70bc | 24.00ab | 173.00ab | 22.48b | 0.46c |
| BRDN | 101.87ab | 16.37ab | 25.47a | 179.00ab | 22.57b | 0.48b |
| USG | 103.93a | 18.13a | 25.67a | 192.00a | 23.27a | 0.49a |
| LSD (5%) | 3.60 | 2.82 | 3.94 | 20.61 | 0.61 | 0.03 |
| S.E. (±) | 1.56 | 1.22 | 1.70 | 8.94 | 0.26 | 0.01 |
| *T. Aman* | | | | | | |
| Control | 83.83b | 8.33d | 19.33c | 122.33e | 21.60e | 0.46 |
| FP | 94.50a | 10.66 cd | 21.00bc | 158.00d | 22.27d | 0.47 |
| RDN | 95.43a | 11.00bc | 22.99ab | 175.00c | 22.55c | 0.47 |
| BRDN | 95.65a | 13.44ab | 23.60ab | 185.00b | 22.73b | 0.48 |
| USG | 96.32a | 13.99a | 23.93a | 195.00a | 22.94a | 0.49 |
| LSD (5%) | 5.41 | 2.50 | 2.72 | 7.27 | 0.18 | NS |
| S.E. (±) | 2.35 | 1.08 | 1.18 | 3.15 | 0.08 | 0.01 |

Control: zero N, FP: prilled urea used as farmer's practice, RDN: recommended dose of N, BRDN: RDN + biochar 2 t ha$^{-1}$ and UDP: urea deep placement as urea supper granules.

BRDN (6.11 t ha$^{-1}$), RDN (5.50 t ha$^{-1}$) and FP (4.69 t ha$^{-1}$). The highest biological yield (12.77 t ha$^{-1}$) was observed in the USG treatment which was statistically similar to the BRDN (12.48 t ha$^{-1}$) treatment. Statistically significant differences were found in other treatments. The order of grain yield in different treatments is USG>BRDN>RDN>FP>Control. In case of *T. Aman* rice (Table 3), significantly higher grain (4.65 t ha$^{-1}$), straw (4.96 t ha$^{-1}$) and biological yields (9.61 t ha$^{-1}$) were recorded in the USG treatment compared to all other treatments except for the straw yield in the BRDN and RDN treatments. Significantly lower grain, straw and biological yields were observed in the control treatment.

On-station study in two consecutive rice seasons confirmed that compared to the control, increment in grain yields in the BRDN and USG treatments were the highest, 128% and 111%, respectively in the *Boro* season and 107% and 95%, respectively in the *T. Aman* season (Table 5). Compared to the RDN, yield increased by 15% and 6% in BRDN and USG treatments, respectively in

**Table 5.** Increase in grain yields of rice under different treatments compared to the control and other treatments at the on-station study at BSMRAU research field in 2022.

| | Increase in yield for *Boro* rice (%) | | | Increase in yield for *T. Aman* rice (%) | | |
|---|---|---|---|---|---|---|
| Treatments | Compared to control | Compared to RDN | Compared to RDN75 | Compared to control | Compared to RDN | Compared to RDN75 |
| Control | – | – | – | – | – | – |
| RDN | 98.56 | – | 26.30 | 76.34 | – | 31.38 |
| RDN125 | 94.01 | −2.30 | 23.40 | 72.64 | −2.07 | 28.62 |
| RDN75 | 57.10 | −20.89 | – | 34.22 | −23.86 | – |
| CDSupN | 103.75 | 2.60 | 29.60 | 86.67 | 5.89 | 39.08 |
| BRDN | 128.11 | 14.86 | 45.09 | 107.34 | 17.62 | 54.48 |
| USG | 111.38 | 6.44 | 34.45 | 95.28 | 10.78 | 45.49 |

the *Boro* season, while in the *T. Aman* season yield increments were 18% and 11%, respectively. Nitrogen application in excess and lower rates reduced crop yield compared to the RDN treatment which is evinced in both *Boro* and *T. Aman* seasons (Table 5).

In the study spread over two seasons at the farmer's field, it was observed that compared to the control, increment in grain yields in the BRDN and USG treatments was the highest, 58% and 63%, respectively in the *Boro* season and 54% and 64%, respectively in the *T. Aman* season (Table 6). Compared with the FP treatment, grain yields were increased by 30% and 34% in the *Boro* season, and 23% and 31% in the *T. Aman* season in the BRDN and USG treatments, respectively. Furthermore, compared to the RDN, yield increased by 11% and 14% in BRDN and USG treatments, respectively in the *Boro* season, while in the *T. Aman* season yield increments were 8% and 15%, respectively.

## *Nitrogen management and its use efficiency in rice cultivation*

At the on-station study, treatments displayed a significant ($p < 0.01$) effect on AEN, PEN and AREN in both *Boro* and *T. Aman* seasons (Table 7). In *Boro* season, the USG treatment showed the significantly highest AEN (28 kg kg$^{-1}$) compared to other treatments. A similar trend was observed in *T. Aman* season where the highest AEN was found in the USG. Likewise, the higher PEN was found in the USG treatment. The highest PEN in *Boro* was 44 kg kg$^{-1}$ and in *T. Aman* season was 43 kg kg$^{-1}$. The highest AREN of 65% was appeared in the USG treatment in *Boro* season followed by BRDN (55%), CDSupN (44%), RDN (36%), RDN125 (29) and RDN75 (28%). In case of *T. Aman*, the highest value of N recovery (AREN) was 61% observed in the BRDN treatment followed by USG, CDSupN, RDN, RDN75 and RDN125.

At the farmer's field study, NUE in both *Boro* and *T. Aman* seasons varied significantly among the different treatments (Table 7). In *Boro* season, the AEN was found to be significantly higher in the USG treatment (21 kg kg$^{-1}$) followed by BRDN (12 kg kg$^{-1}$), RDN (9 kg kg$^{-1}$) and the lowest was in the FP (7 kg kg$^{-1}$) treatment. Significantly higher PEN (38 kg kg$^{-1}$) was recorded in the USG treatment which was statistically similar to the BRDN treatment (35 kg kg$^{-1}$) The AREN followed a similar trend as observed in the case of AEN. The AREN varied significantly among different treatments, while the

**Table 6.** Increase in grain yields of rice under different treatments compared to the control and other treatments at the farmer's field in 2023.

| | Increase in yield for *Boro rice* (%) | | | Increase in yield for *T. Aman* rice (%) | | |
|---|---|---|---|---|---|---|
| Treatments | Compared to control | Compared to FP | Compared to RDN | Compared to control | Compared to FP | Compared to RDN |
| Control | – | – | – | – | – | – |
| FP | 21.19 | – | – | 25.80 | – | – |
| RDN | 42.12 | 17.27 | – | 42.76 | 13.48 | – |
| BRDN | 57.88 | 30.28 | 11.09 | 54.06 | 22.49 | 7.92 |
| USG | 62.53 | 34.12 | 14.36 | 64.31 | 30.62 | 15.09 |

**Table 7.** Effect of different nitrogen management practices on different types of nitrogen use efficiencies at the on-station in 2022 and farmer's field in 2023.

| | *Boro rice* | | | *T. Aman rice* | | |
|---|---|---|---|---|---|---|
| | AEN | PEN | AREN | AEN | PEN | AREN |
| Treatments | (kg kg$^{-1}$) | | (%) | (kg kg$^{-1}$) | | (%) |
| On-station 2022 | | | | | | |
| RDN | 13.68c | 37.84b | 36.25d | 14.02d | 32.72b | 42.82d |
| RDN125 | 10.09d | 34.68c | 29.09e | 10.85e | 32.68b | 33.21e |
| RDN75 | 9.49e | 34.20c | 27.75e | 9.88e | 28.40c | 34.90e |
| CDSupN | 13.91c | 31.43d | 44.30c | 15.64c | 31.00b | 50.47c |
| BRDN | 17.45b | 31.99d | 54.60b | 19.58b | 32.19b | 60.87a |
| USG | 28.34a | 43.64a | 64.98a | 24.43a | 42.83a | 57.02b |
| LSD (5%) | 0.37 | 1.76 | 1.82 | 1.11 | 2.04 | 2.08 |
| S.E. (±) | 0.17 | 0.79 | 0.82 | 0.52 | 0.96 | 0.97 |
| Farmer's field 2023 | | | | | | |
| FP | 7.04d | 29.37b | 23.85d | 8.42c | 41.25 | 20.74d |
| RDN | 8.88c | 30.04b | 29.54c | 10.45bc | 42.13 | 25.01c |
| BRDN | 12.17b | 35.44a | 34.35b | 13.25b | 42.71 | 31.07b |
| USG | 20.57a | 38.41a | 53.60a | 23.35a | 48.27 | 48.72a |
| LSD (5%) | 1.32 | 5.29 | 2.45 | 2.96 | NS | 1.26 |
| S.E. (±) | 0.54 | 2.16 | 1.00 | 1.21 | 3.81 | 3.09 |

AE: agronomic use efficiency, PE: physiological efficiency, ARE: apparent recovery efficiency.

highest (54%) was observed in the USG followed by BRDN (34%), RDN (30%) and the lowest in the FP (24%). Use efficiencies of N under different treatments also significantly changed in case of *T. Aman*. The AEN was found to be significantly higher in the USG treatment (23 kg kg$^{-1}$). Statistically similar AEN was observed in the case of BRDN and RDN treatments, as well as between RDN and FP. The treatments did not show significant effects on PEN of *T. Aman* rice. The treatment effects on the AREN were found significant, with the highest (49%) observed in the USG followed by BRDN (31%), RDN (25%) and the lowest (21%) in the FP.

## Soil carbon enrichment and aggregate formation in the post-harvest paddy soils

The initial soil carbon stock in the on-station study field ranged from 15.15–15.28 t ha$^{-1}$, while it varied from 15.44–15.90 t ha$^{-1}$ after two consecutive rice growing seasons (Figure 1). A significantly higher carbon stock than all other treatments was found in the BRDN treatment. The highest rate of carbon increment from the initial level was found 4.03% in the BRDN followed by the CDSupN

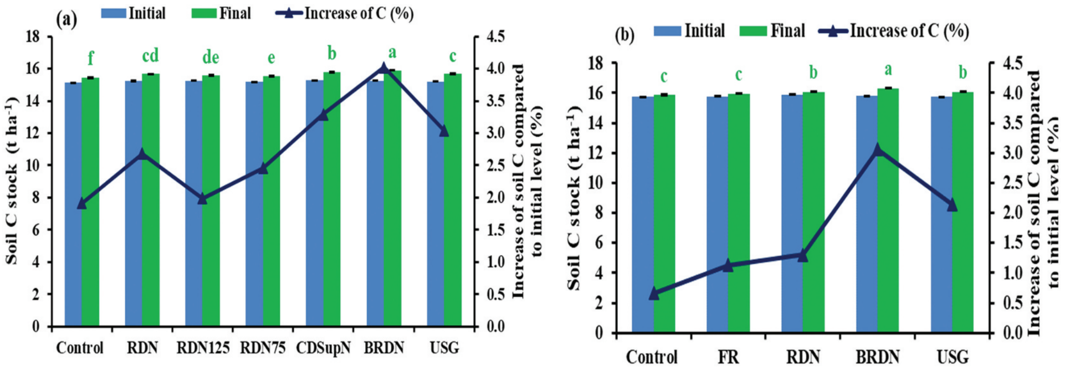

**Figure 1.** Soil C stock and its enrichment compared to the initial level under different treatments: (a) on-station study at BSMRAU, and (b): farmer's field study, Tokenagar, Kapasia, Gazipur, Bangladesh. Different small letters on the bar of the final C stock indicate significant difference among the treatments.

Table 8. Soil aggregates stability at rice harvest both at the on-station and farmer's field study.

| | Water stable soil aggregates (g kg$^{-1}$) of different sized particles | | | | |
|---|---|---|---|---|---|
| | On-station | | | Farmer's field | |
| Treatments | 0.50 mm | 0.25 mm | Treatments | 0.50 mm | 0.25 mm |
| Control | 155.77f | 176.37f | Control | 128.17d | 135.16d |
| RDN | 207.70de | 251.11e | FP | 179.57c | 250.44c |
| RDN125 | 215.93c | 270.49d | RDN | 176.59c | 250.52c |
| RDN75 | 209.82 cd | 294.21c | BRDN | 317.64a | 347.44a |
| CDSupN | 334.23b | 455.33b | USG | 198.62b | 285.25b |
| BRDN | 356.24a | 476.37a | LSD (5%) | 10.50 | 7.64 |
| USG | 201.60e | 253.42e | S.E. (±) | 4.55 | 3.31 |
| LSD (5%) | 7.08 | 11.49 | | | |
| S.E. (±) | 3.25 | 5.27 | | | |

(3.29%). Almost similar patterns of carbon stock in soils were observed at the farmer's field study where BRDN appeared as the most efficient treatment in increasing carbon stock. The BRDN treatment contributed to the highest increment in soil carbon (3.06%) followed by the USG (2.14%) treatment.

Treatments for both the experiments displayed significant effects on soil aggregate stability, while biochar performed the best in the formation of stable aggregates (Table 8). In the on-station experiment, the significantly higher stable aggregates were found in the BRDN treatment than in all other treatments, at 356 g kg$^{-1}$ and 476 g kg$^{-1}$ for 0.50 mm and 0.25 mm sized soil particles, respectively. In case of the farmer's field study, stable aggregates were 318 g kg$^{-1}$ and 347 g kg$^{-1}$ for 0.50 mm and 0.25 mm sized soil particles, respectively.

### *Economic performances of nitrogen management options in rice cultivation*

At both the on-station and farmer's field studies, the total costs of rice production were found the highest in the BRDN treatment followed by the CDSupN treatment (Tables 9 and 10). At the on-station, during *Boro* rice, the highest gross return (\$1940 ha$^{-1}$) was found in the BRDN, while the highest net return (\$605 ha$^{-1}$) and BCR (1.51) were found in the USG (Table 9). Similar results were also observed in case of *T. Aman* with the highest net return of \$480 ha$^{-1}$ and BCR of 1.57 in the USG. In the farmer's field, the total costs of production in the BRDN treatment were \$1583 ha$^{- 1}$ in *Boro* and \$1123 ha$^{-1}$ in *T. Aman*. In *Boro* rice, the gross return (\$2151 ha$^{-1}$), net return (\$933 ha$^{-1}$) and BCR (1.77) were found the highest in the USG treatment (Table 10). Similar results were also observed in case of *T. Aman* rice with the highest net return of \$497 ha$^{-1}$ and BCR of 1.62 in the USG treatment.

## Discussion

### *Nitrogen management influences yield attributes and yields of rice*

The urea super granule (USG) treatment consistently showed higher values in most of the yield-contributing attributes of both *Boro* and *T. Aman* compared to the other treatments. This is applicable for both on-station and farmer's field experiments (Tables 1 and 2). This reveals the superiority of deep placement urea granule in the rootzone for better crop growth and development compared to other treatments. Several researchers reported that rootzone application of N ensures the maximum use of N by the crops and so N losses are substantially reduced (Rochette et al. 2013; Bandaogo et al. 2015; Rea et al. 2019). The combination of biochar and N fertilizer (BRDN) also exhibited superior performance, almost equal to the urea super granule treatment. Biochar is composed of negatively charged particles that can adsorb positively charged ammonium ($NH_4^+$) and limit the nitrification process of $NH_4^+$ to $NO_3^-$. Biochar is capable to inhibit nitrification (Ye et al. 2020; Rahman et al. 2022). At the farmer's field, most of the farmers in the study area are poor and do

**Table 9.** Economic performance of N management options in rice cultivation at the on-station study at BSMRAU research field in 2022.

| | Variable and fixed costs under different treatments (\$ ha$^{-1}$) | | | | | | |
|---|---|---|---|---|---|---|---|
| Items | Control | RDN | RDN75 | RDN125 | CDSupN | BRDN | USG |
| *Boro* | | | | | | | |
| Variable cost: | | | | | | | |
| Power tiller cost | 36 | 36 | 36 | 36 | 36 | 36 | 36 |
| Labour cost | 327 | 332 | 332 | 332 | 337 | 337 | 385 |
| Fertilizer cost | 54 | 159 | 185 | 133 | 237 | 544 | 124 |
| Insecticides | 53 | 53 | 53 | 53 | 53 | 53 | 53 |
| Seed cost | 36 | 36 | 36 | 36 | 36 | 36 | 36 |
| Irrigation charge | 288 | 288 | 288 | 288 | 288 | 288 | 288 |
| Total Variable cost | 795 | 904 | 930 | 878 | 987 | 1294 | 922 |
| Fixed cost: | | | | | | | |
| Interest on operating capital | 35 | 37 | 38 | 51 | 40 | 51 | 40 |
| Land rent | 231 | 231 | 231 | 231 | 231 | 231 | 231 |
| Total Fixed Cost | 265 | 267 | 268 | 281 | 271 | 281 | 271 |
| Total cost of production | 1060 | 1172 | 1199 | 1159 | 1257 | 1575 | 1192 |
| Rice grain | 697 | 1384 | 1353 | 1095 | 1421 | 1590 | 1474 |
| Straw | 183 | 313 | 368 | 289 | 323 | 349 | 323 |
| Gross return | 880 | 1697 | 1720 | 1384 | 1743 | 1940 | 1797 |
| Net return | −180 | 526 | 521 | 225 | 486 | 365 | 605 |
| BCR | 0.83 | 1.45 | 1.43 | 1.19 | 1.39 | 1.23 | 1.51 |
| *T. Aman* | | | | | | | |
| Variable cost: | | | | | | | |
| Power tiller cost | 36 | 36 | 36 | 36 | 36 | 36 | 36 |
| Labour cost | 279 | 284 | 284 | 284 | 288 | 288 | 337 |
| Fertilizer cost | 39 | 96 | 110 | 82 | 177 | 481 | 93 |
| Insecticides | 48 | 48 | 48 | 48 | 48 | 48 | 48 |
| Seed cost | 36 | 36 | 36 | 36 | 36 | 36 | 36 |
| Irrigation charge | 36 | 36 | 36 | 36 | 36 | 36 | 36 |
| Total Variable cost | 474 | 536 | 550 | 522 | 622 | 925 | 586 |
| Fixed cost: | | | | | | | |
| Interest on operating capital | 23 | 25 | 26 | 25 | 28 | 38 | 27 |
| Land rent | 231 | 231 | 231 | 231 | 231 | 231 | 231 |
| Total Fixed Cost | 254 | 256 | 257 | 256 | 259 | 269 | 258 |
| Total cost of production | 728 | 792 | 807 | 777 | 881 | 1194 | 844 |
| Rice grain | 555 | 979 | 958 | 745 | 1036 | 1151 | 1084 |
| Straw | 133 | 234 | 246 | 190 | 236 | 245 | 240 |
| Gross return | 688 | 1213 | 1204 | 935 | 1272 | 1396 | 1324 |
| Net return | −40 | 421 | 397 | 158 | 391 | 202 | 480 |
| BCR | 0.94 | 1.53 | 1.49 | 1.20 | 1.44 | 1.17 | 1.57 |

not have the capacity to buy the required amounts of fertilizers. Therefore, they apply lower rates of fertilizers, resulting in lower yields in the farmer's practice (FP) compared to the recommended dose of nitrogen (RDN).

In the study of two locations during 2022 and 2023, the highest grain and biological yields were recorded in the biochar treatment, except *T. Aman* of the farmer's field where deep placement of urea super granule performed the best (Figure 1). Studies indicated the significant influence of urea super granule deep placement on rice yield and its contributing characteristics (Rea et al. 2019; Alam et al. 2023; Islam et al. 2024). Biochar as a promising soil amendment demonstrated positive impacts on rice yield and soil properties in various studies across the world (Ye et al. 2020; Xin et al. 2022; Islam et al. 2024). On-station study displayed superior performance of deep placement of urea super granule and application of biochar with nitrogen showing varying degrees of enhancement in grain yield of rice compared to the control, recommended nitrogen and other treatments (Table 3). Such findings were further confirmed at the farmer's field that the normal farmer's practice and recommended nitrogen rate exhibited lower performances than that the urea deep placement and biochar treatments (Table 4). In the RDN treatment prilled urea (PU) is broadcasted which might facilitate

**Table 10.** Economic performance of N management options in rice cultivation at the farmer's field in 2023.

| | Variable and fixed costs under different treatments (\$ ha$^{-1}$) | | | | |
|---|---|---|---|---|---|
| Items | Control | FP | RDN | BRDN | USG |
| *Boro* | | | | | |
| Variable cost: | | | | | |
| Power tiller cost | 36 | 36 | 36 | 36 | 36 |
| Labour cost | 337 | 337 | 337 | 341 | 389 |
| Fertilizer cost | 70 | 128 | 162 | 547 | 146 |
| Insecticides | 53 | 53 | 53 | 53 | 53 |
| Seed cost | 36 | 36 | 36 | 36 | 36 |
| Irrigation charge | 288 | 288 | 288 | 288 | 288 |
| Total Variable cost | 820 | 878 | 912 | 1301 | 948 |
| Fixed cost: | | | | | |
| Interest on operating capital | 35 | 37 | 38 | 51 | 39 |
| Land rent | 231 | 231 | 231 | 231 | 231 |
| Total Fixed Cost | 266 | 268 | 269 | 282 | 270 |
| Total cost of production | 1086 | 1146 | 1181 | 1583 | 1218 |
| Rice grain | 930 | 1127 | 1322 | 1469 | 1512 |
| Straw | 223 | 280 | 301 | 306 | 312 |
| Gross return | 1153 | 1407 | 1623 | 1775 | 1824 |
| Net return | 67 | 261 | 442 | 192 | 606 |
| BCR | 1.06 | 1.23 | 1.37 | 1.12 | 1.50 |
| *T. Aman* | | | | | |
| Variable cost: | | | | | |
| Power tiller cost | 36 | 36 | 36 | 36 | 36 |
| Labour cost | 288 | 288 | 288 | 293 | 341 |
| Fertilizer cost | 38 | 73 | 85 | 469 | 89 |
| Insecticides | 48 | 48 | 48 | 48 | 48 |
| Seed cost | 36 | 36 | 36 | 36 | 36 |
| Irrigation charge | 36 | 36 | 36 | 36 | 36 |
| Total Variable cost | 482 | 517 | 529 | 918 | 586 |
| Fixed cost: | | | | | |
| Interest on operating capital | 24 | 25 | 25 | 38 | 27 |
| Land rent | 231 | 231 | 231 | 231 | 231 |
| Total Fixed Cost | 255 | 256 | 256 | 269 | 258 |
| Total cost of production | 737 | 773 | 785 | 1187 | 844 |
| Rice grain | 680 | 856 | 971 | 1048 | 1118 |
| Straw | 159 | 204 | 225 | 228 | 238 |
| Gross return | 839 | 1060 | 1196 | 1276 | 1356 |
| Net return | 102 | 287 | 411 | 89 | 512 |
| BCR | 1.14 | 1.37 | 1.52 | 1.07 | 1.61 |

higher losses of N through denitrification, leaching and volatilization (Yao et al. 2018; Chatterjee et al. 2018). Even though balanced rates of N and other nutrients were applied in the recommended N treatment, lower quantity of nutrients was ultimately used by the crop with the resultant lower yield.

## *Nitrogen management and its use efficiency in rice cultivation*

The N use efficiencies of both *Boro* and *T. Aman* rice showed noteworthy variations due to different N management employed at the on-station and farmer's field experiments. The agronomic and apparent N recovery efficiencies under urea super granule deep placement, biochar and recommended N treatments in all rice growing seasons of both on-station and farmer's field followed the order urea super granule deep placement > biochar > recommended N. Deep placement of urea super granule also contributed to achieve the highest physiological efficiency of N in the on-station, while in case of farmer's field urea super granule and biochar performed equally. Increment of N use efficiencies of both on-station and farmer's field demonstrated greater performance of urea super granule and biochar compared to the control, recommended N rate and farmer's practice and other treatments.

Urea super granule are placed at 7 to 8 cm soil depth near root zone between 4 hills at alternate rows after transplanting of rice. While two to three split applications are needed for broadcasting of prilled urea. Urea super granule releases N slowly and plants can efficiently uptake N which results higher N use efficiencies and crop yields and lower production costs. The application of N fertilizer in the rootzone has been demonstrated to substantially decrease ammonia ($NH_3$) volatilization, lower nitrous oxide ($N_2O$) and nitric oxide (NO) emissions (Rochette et al. 2013), diminish surface run-off, and concurrently enhance crop yields and N use efficiencies (Gaihre et al. 2015). The on-station study also confirmed that extra application of N fertilizer reduces grain yield and N use efficiencies as well. Njinju et al. (2018) suggested balanced supply of fertilizer and avoid excess application of N. The combined application of recommended N and biochar also appeared as one of the desirable and potential options to reduce N losses and increases nitrogen use efficiencies. Because of high surface area and negatively charged particles, biochar is efficient in adsorbing cations like $NH_4^+$ *etc*., and simultaneously biochar has a high cation exchange capacity. Adsorption of $NH_4^+$ by biochar restricts nitrification process and in due course of time $NH_4^+$ released back to soil thorough cation exchange which crops can uptake (Kang et al. 2021). Due to the beneficial interaction between biochar and $NH_4^+$-N, the combination of biochar and N fertilizer exhibited superior performance in terms of N use efficiencies compared to the recommended N alone. Similar results were found by different researchers (Ye et al. 2020; Xin et al. 2022; Islam et al. 2024).

From 1960 to 2018, Bangladesh demonstrated a great improvement in N fertilizer management for crop production with a consequent increase in apparent N recovery to 48% compared to 35% in India and 25% in Pakistan (Bilal and Aziz 2022). Miah et al. (2016) summarized findings from 115 experiments conducted at farmers' fields in Bangladesh which revealed that the urea super granule significantly increased crop yields compared to the broadcasting of prilled urea. Specifically, during the *Aus* and *T. Aman* seasons, the yield increment ranged from 21% to 31%, while in the *Boro* season, it was 11% to 17%. In addition, urea super granule was found to save urea by 33% during *Aus* and *T. Aman* seasons and 35% in the *Boro* season. Similarity and dissimilarity exist among the findings of N use efficiencies in the current study and several other studies. This might occur as the study environments are diverse, soil characteristics and climatic conditions are widely variable, and fertilizer rates and their management are different. Nutrient uptake and crop yields will be variable which might affect N use efficiencies. Gweyi-Onyango et al. (2021) suggested split application of prilled urea for increasing N use efficiencies which is also evinced in our study where prilled urea applied in three equal splits. It has been clearly articulated that adoption of urea super granule and NPK briquettes, and the combined application biochar and N, has increased agronomic and apparent recovery efficiencies of N in rice. The higher recovery of N might be the reason of better soil, crop and fertilizer management.

## *Water stable soil aggregates and carbon contents in the post-harvest soil*

Soil carbon contents after harvesting of rice indicated that biochar contributed in increasing carbon compared to other treatments in both the experiments (Figure 1). Soil carbon is the single most important parameter that governs soil physical, chemical and biological characteristics. The findings on soil aggregates from both the experiments confirmed that smaller sized soil particles are more stable than that of the larger particles (Table 8). The smaller sized soil particles contribute to a higher degree of aggregate stability (Cheng et al. 2023). Soil aggregate stability mainly depends on diverse soil and crop management activities which may disturb and breakdown larger soil aggregates into smaller sized aggregates (John et al. 2005). The percentage of smaller sized soil aggregates is often high in crop land (Simansky et al. 2018). In the formation of microaggregates, soil clay and carbon contribute to the formation of these particles, acting as a glue to bind soil particles. The study soils were silty clay loam and silt loam and moreover carbon content was also increased under biochar treatment. Biochar is a negatively charged colloidal particle that can help to develop well aggregated soils. Therefore, the improved soil structure associated with application of biochar contributes to improving soil health and reducing the impacts of disruptive forces, so reducing soil erosion. A healthy soil can hold more nutrients and increases water retention capacity by reduced loss of soil by erosion and increased charged surfaces.

## *Economic performances of nitrogen management options in rice cultivation*

The different N management practices demonstrated the large financial impacts of N management on *Boro* and *T. Aman* cultivation. The total cost of production was found to be the highest in BRDN in both on-station and farmer's field experiments (Tables 9 and 10). Being a costly input addition of biochar (2 t $ha^{-1}$) with recommended N was the main reason for increased cost of production using biochar. The urea super granule treatment emerged as the most economically viable option, providing the highest gross return, net return, and benefit-cost ratio (BCR). Similar findings were observed by Rea et al. (2019). The biochar plus recommended N exhibited the next highest gross return, but it had a lower net return and BCR, primarily due to the added expense of purchasing biochar. A comprehensive economic analysis shows that the urea super granule stands out as the most favorable choice for achieving optimal economic returns.

However, if environmental benefits of using biochar in agriculture is calculated it would appear as one of the most viable options for long-term agriculture and environmental sustainability. Biochar contains stable carbon that remains in soil hundreds of thousands of years and thus increases carbon sequestration (Gupta et al. 2020; Rahman et al. 2020). The biochar plus recommended N increased soil carbon by 3–4% annually. It is reported that sequestration of 1 kg of carbon in soil reduces approximately 3.67 kg of $CO_2$ from the atmosphere (Rahman et al. 2020; Rajan et al. 2021). Thus, biochar contributes to increase carbon in soils and helps mitigate negative effects of climate change in agriculture and environment (Rahman 2014; Chagas et al. 2022), and ensure a carbon-negative economy (Downie et al. 2012).

## Challenges of adoption of urea super granule and biochar in agriculture and way forward

Use of urea super granule has been identified as a great method of saving 33–35% N (Miah et al. 2016) and increasing 15–20% rice yield (IFDC 2017). But the technology has plenty of barriers that are experiencing over 40 years of engagement since 1980s which yet to be solved for its adoption at farmers level (Sikder and Xiaoying 2014). Urea briquetting is presently done at the village level and such small entrepreneurships are reluctant to produce sufficient amount of urea granules. Lack of large-scale commercial manufacturer of urea super granule seriously inhibits its adoption at the farm level. Secondly, the less availability of farmers' friendly efficient urea super granule applicators acts as an obstruct of the technology implementation (Alam et al. 2023). Conversely, manual application is time consuming which requires more labor and farmers feel backpain as they need to bend down during hand placement of urea super granule (Sikder and Xiaoying 2014). Moreover, negative attitude of fertilizer dealers towards urea super granule discourages farmers to adopt urea super granule. Lack of farmers' awareness about the multiple benefits of urea super granule are also the reasons of low adoption of such an excellent technology.

Biochar is also a proven soil amendment that refurbish degraded soil environment and ensures mitigate global warming and climate change. However, utilization of biochar is not popular because of its higher costs, and lack of understanding about its benefits in agriculture (Rahman et al. 2020). However, small entrepreneurship for wheelbarrow applicator of urea super granule at the local level, and large establishment for motorbike operated urea super granule applicator or combined seedling planter with urea super granule applicator *etc*., are encouraged. Government-owned large industrial setup are suggested for biochar production and supply to the farmers at low price. Favorable government policies and investment from private-public sectors and donor organizations might be helpful to address such challenges. If this is achieved, then biochar in agriculture could become a more economically viable and environmentally sustainable. There are a few non-government organizations like Christian Commission for Development in Bangladesh (CCDB) that are working to manufacture and distribute improved cooking stove to the farming communities. Such stoves are mainly used for cooking using locally available different biomass but as a byproduct it produces biochar. Wider dissemination of such cooking stoves will be helpful for farmers to produce biochar for themselves on-farm, so avoiding extra costs for purchasing biochar. Furthermore, carbon sequestration and soil health improvement through biochar and its environmental benefits in terms of monetary value needs to be evaluated.

## Conclusions

Deep placement of urea super granule showed notable impacts on the yield-attributing traits, grain yields and N use efficiencies in rice followed by biochar with recommended N. Grain yields of both *Boro* and *T. Aman* were significantly increased in BRDN, and urea super granule treatments, compared to the RDN and farmer's practice. The highest agronomic, physiological and recovery efficiencies of N were found in the urea super granule followed by biochar with recommended N treatment in both study sites and both rice seasons. Irrespective of study locations and rice seasons, agronomic and recovery efficiencies of N increased by several folds in the biochar with N and urea super granule treatments with the highest increment in the urea super granule when compared with the recommended N and farmer's practice. Utilization of biochar in rice cultivation was found to be the costliest, because of its higher production price. Long-term environmental economic benefits and soil health improvement need to be highlighted for advocating application of biochar in the crop fields. The urea super granule emerged as the most economically viable option and with the highest net income. However, due to inherent difficulties of urea super granule deep placement and additional labor costs its adoption rate is poor.

## Disclosure statement

No potential conflict of interest was reported by the author(s).

## Funding

We express our gratitude to UK Research and Innovation for supporting this research through the South Asian Nitrogen Hub (SANH) under the Global Challenge Research Fund [Grant Ref. Number NE/S009019/1]. This publication contributes to the 'Towards the International Nitrogen Management Systems (Towards INMS)' project, financially supported by the Global Environment Facility (GEF), the United Nations Environment Program (UNEP), and the International Nitrogen Initiative (INI).

## ORCID

Md. Mizanur Rahman http://orcid.org/0000-0002-2353-6823

## References

Abdullah HM, Muraduzzaman M, Islam I, Miah MG, Rahman MM, Rahman A, Ahmed N, Ahmed Z. 2019. Spatiotemporal dynamics of new land development in Bangladesh coast and its potential uses. Remote Sens Appl Soc Environ. 14:191–199. doi: 10.1016/j.rsase.2019.04.001.

Alam MS, Khanam M, Rahman MM. 2023. Environment-friendly nitrogen management practices in wetland paddy cultivation. Front Sustain Food Syst. 7:1020570. doi: 10.3389/fsufs.2023.1020570.

Asia-Pacific Rice Market. 2023. Asia pacific rice market size & share analysis - growth trends & forecasts (2023-2028). [accessed 2023 Dec 31]. https://www.mordorintelligence.com/industry-reports/asia-pacific-rice-market.

Bach M, Wilske B, Breuer L. 2016. Current economic obstacles to biochar use in agriculture and climate change mitigation. Carbon Manage. 7(3–4):183–190. doi: 10.1080/17583004.2016.1213608.

Bandaogo A, Bidjokazo F, Youl S, Safo E, Abaidoo R, Andrews O. 2015. Effect of fertilizer deep placement with urea supergranule on nitrogen use efficiency of irrigated rice in Sourou Valley (Burkina Faso). Nutr Cycl Agroecosyst. 102 (1):79–89. doi: 10.1007/s10705-014-9653-6.

BARC. 2018. Fertilizer recommendation guide. In: Ahmed S, Jahiruddin M, Razia S, Begum RA, Biswas JC, Rahman ASMM, Ali MM, Islam KMS, Hossain MM, Gani, MN, Hossain GMA, Satter MA, editors, Fertilizer recommendation guide - 2018 Vol. 1215. Dhaka: Bangladesh Agricultural Research Council (BARC), Farmgate.

Bilal HM, Aziz T. 2022. Nitrogen use efficiency in crop production: issues and challenges in South Asia. In: Aziz T, Wakeel A Kiran A, editors. Nitrogen assessment: Pakistan as a case-study. London: Academic Press. pp. 127–148.

Brammer H, Brinkman R. 1977. Surface-water gley soils in Bangladesh: environment, landforms and soil morphology. Geoderma. 17(2):91–109. doi: 10.1016/0016-7061(77)90042-8.

Chagas JK, de Figueiredo CC, Ramos ML. 2022. Biochar increases soil carbon pools: evidence from a global meta-analysis. J Environ Manage. 305:114403. doi: 10.1016/j.jenvman.2021.114403.

Chatterjee D, Mohanty S, Guru PK, Swain CK, Tripathi R, Shahid M, Kumar U, Kumar A, Bhattacharyya P, Gautam P, et al. 2018. Comparative assessment of urea briquette applicators on greenhouse gas emission, nitrogen loss and soil enzymatic activities in tropical lowland rice. Agric Ecosyst Environ. 252:178–190. doi: 10.1016/j.agee.2017.10.013.

Chen XP, Cui ZL, Vitousek PM, Cassman KG, Matson PA, Bai JS, Meng QF, Hou P, Yue SC, Römheld V, et al. 2011. Integrated soil–crop system management for food security. Proc Natl Acad Sci USA. 108(16):6399–6404. doi: 10.1073/pnas.1101419108.

Cheng Y, Xu G, Wang X, Li P, Dang X, Jiang W, Ma T, Wang B, Gu F, Li Z. 2023. Contribution of soil aggregate particle size to organic carbon and the effect of land use on its distribution in a typical small watershed on Loess Plateau, China. Ecol Indic. 155:110988. doi: 10.1016/j.ecolind.2023.110988.

Douglas LA, Riazi A, Smith CJ. 1980. A semi-micro method for determining total nitrogen in soils and plant material containing nitrite and nitrate. Soil Sci Soc Am J. 44(2):431–433. doi: 10.2136/sssaj1980.03615995004400020047x.

Downie A, Munroe P, Cowie A, Van Zwieten L, Lau DM. 2012. Biochar as a geoengineering climate solution: hazard identification and risk management. Crit Rev Environ Sci Technol. 42(3):225–250. doi: 10.1080/10643389.2010.507980.

ESCAP. 2023. United Nations, economic and social commission for Asia and the Pacific Asia-Pacific. Population and development report 2023 (ST/ESCAP/3112).

Gaihre YK, Singh U, Islam SM, Huda A, Islam MR, Sanabria J, Satter MA, Islam MR, Biswas JC, Jahiruddin M, et al. 2018. Nitrous oxide and nitric oxide emissions and nitrogen use efficiency as affected by nitrogen placement in lowland rice fields. Nutr Cycl Agroecosyst. 110(2):277–291. doi: 10.1007/s10705-017-9897-z.

Gaihre YK, Singh U, Islam SM, Huda A, Islam MR, Satter MA, Sanabria J, Islam MR, Shah AL. 2015. Impacts of urea deep placement on nitrous oxide and nitric oxide emissions from rice fields in Bangladesh. Geoderma. 259-260:370–379. doi: 10.1016/j.geoderma.2015.06.001.

Good AG, Beatty PH. 2011. Fertilizing nature: a tragedy of excess in the commons. PLOS Biol. 9(8):e1001124. doi: 10.1371/journal.pbio.1001124.

Gregory DI, Haefele SM, Buresh RJ, Singh U. 2010. Fertilizer use, markets, and management. Rice in the global economy. Strategic research and policy issues for food security 231–263. Los Banos, Philippines: International Rice Research Institute.

Gupta DK, Gupta CK, Dubey R, Fagodiya RK, Sharma G, Noor Mohamed MB, Dev R, Shukla AK. 2020. Role of biochar in carbon sequestration and greenhouse gas mitigation. In: Singh J Singh C, editors. Biochar applications in agriculture and environment management. Springer, Cham; p. 141–165. 10.1007/978-3-030-40997-5_7.

Gweyi-Onyango JP, Ntinyari W, OgollaEgesa A, Mose R, Njinju S, Giweta M, Masso C. 2021. Differences in seasons and rice varieties provide opportunities for improving nitrogen use efficiency and management in irrigated rice in Kenya. Environ Res Lett. 16(7):075003. doi: 10.1088/1748-9326/ac03dd.

Han M, Okamoto M, Beatty PH, Rothstein SJ, Good AG. 2015. The genetics of nitrogen use efficiency in crop plants. Annu Rev Genet. 49:269–289. doi: 10.1146/annurev-genet-112414-055037.

Hasan MA, Muraduzzaman M, Islam I, Miah GU, Rahman MM, Rahman A, Ahmed N, Ahmed Z 2019. Spatiotemporal dynamics of new land development in Bangladesh coast and its potential uses. Remote Sens Appl Soc Environ. 14:191–199. doi:10.1016/j.rsase.2019.04.001.

Hasnat M, Alam MA, Khanam M, Binte BI, Kabir MH, Alam MS, Kamal MZ, Rahman GK, Haque MM, Rahman MM. 2022. Effect of nitrogen fertilizer and biochar on organic matter mineralization and carbon accretion in soil. Sustainability. 14(6):3684. doi: 10.3390/su14063684.

Huang M, Long FAN, Jiang LG, Yang SY, Zou YB, Uphoff N. 2019. Continuous applications of biochar to rice: effects on grain yield and yield attributes. J Integr Agric. 18(3):563–570. doi: 10.1016/S2095-3119(18)61993-8.

Huda A, Gaihre YK, Islam MR, Singh U, Islam MR, Sanabria J, Satter MA, Afroz H, Halder A, Jahiruddin M. 2016. Floodwater ammonium, nitrogen use efficiency and rice yields with fertilizer deep placement and alternate wetting and drying under triple rice cropping systems. Nutr Cycl Agroecosyst. 104(1):53–66. doi: 10.1007/s10705-015-9758-6.

Husan MR, Islam MR, Faried K, Mian MH. 2014. Nitrogen use efficiency and rice yield as influenced by the application of prilled urea and urea super granule with or without organic manure. J Bangladesh Agric Univ. 12(1):37–43. doi: 10.3329/jbau.v12i1.21237.

IFDC. 2017. Rapid introduction and market development for urea deep placement technology for lowland transplanted rice. A reference guide. Muscle Shoals, AL, USA: International Fertilizer Development Center. pp. 135.

Ishfaq M, Akbar N, Zulfiqar U, Ali N, Shah F, Anjum SA, Farooq M. 2022. Economic assessment of water-saving irrigation management techniques and continuous flooded irrigation in different rice production systems. Paddy Water Environ. 20(1):1–14. doi: 10.1007/s10333-021-00871-6.

Islam M, Rahman MM, Alam MS, Rees RM, Rahman GM, Miah MG, Drewer J, Bhatia A, Sutton MA. 2024. Leaching and volatilization of nitrogen in paddy rice under different nitrogen management. Nutr Cycl Agroecosyst. 129(1):1–9. doi: 10.1007/s10705-024-10361-w.

Islam SJ, Mannan MA, Khaliq QA, Rahman MM. 2018. Growth and yield response of maize to rice husk biochar. Aust J Crop Sci. 12(12):1813–1819. doi: 10.21475/ajcs.18.12.12.p944.

John B, Yamashita T, Ludwig B, Flessa H. 2005. Storage of organic carbon in aggregate and density fractions of silty soils under different types of land use. Geoderma. 28(1–2):63–79. doi: 10.1016/j.geoderma.2004.12.013.

Kang SW, Cheong YH, Yun JJ, Park JH, Park JH, Seo DC, Cho JS. 2021. Effect of biochar application on nitrogen use efficiency for sustainable and productive agriculture under different field crops. J Plant Nutri. 44(19):2849–2862. doi: 10.1080/01904167.2021.1921200.

Lassaletta L, Billen G, Grizzetti B, Anglade J, Garnier J. 2014. 50-year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. Environ Res Lett. 9(10):105011. doi: 10.1088/1748-9326/9/10/105011.

Miah MAM, Gaihre YK, Hunter G, Singh U, Hossain SA. 2016. Fertilizer deep placement increases rice production: evidence from farmers' fields in southern Bangladesh. Agron J. 108(2):805–812. doi: 10.2134/agronj2015.0170.

Mohidem NA, Hashim N, Shamsudin R, Che Man H. 2022. Rice for food security: revisiting its production, diversity, rice milling process and nutrient content. Agric. 12(6):741. doi: 10.3390/agriculture12060741.

Nikodemus O, Kārkliņš A, Dirnēna B, Afanasjeva K, Anufrijevs A, Brūmelis G, Kasparinskis R, Krievāns M, Kukuļs I, Lāce B, et al. 2024. Soil cover on complex glacial terrain and challenges for large-scale soil mapping using the world reference base (WRB) classification system. Catena. 245:108305.

Njinju SM, Samejima H, Katsura K, Kikuta M, Gweyi-Onyango JP, Kimani JM, Yamauchi A, Makihara D. 2018. Grain yield responses of lowland rice varieties to increased amount of nitrogen fertilizer under tropical highland conditions in central Kenya. Plant Prod Sci. 21(2):59–70. doi: 10.1080/1343943X.2018.1436000.

Papademetriou MK. 2000. Rice production in the Asia-Pacific region: issues and perspectives. Bridging Rice Yield Gap Asia-Pac. 220:4–25.

Rahman GM, Rahman MM, Alam MS, Kamal MZ, Mashuk HA, Datta R, Meena RS. 2020. Biochar and organic amendments for sustainable soil carbon and soil health. Carbon and nitrogen cycling in soil. In: In: Datta R, Meena R, Pathan S Ceccherini M, editors. Carbon and nitrogen cycling in soil. Singapore: Springer; p. 45–85.

Rahman ML, Rahman MM, Rahman GM, Solaiman AR, Karim MA, Bokhtiar SM, Hossain MB, Meena RS. 2020. Influence of tillage and organic amendments on *terrace soil bio*-physico-chemical properties and carbon sequestration index. Commun Soil Sci Plant Anal. 51(21):2683–2700. doi: 10.1080/00103624.2020.1845355.

Rahman MM. 2014. Carbon and nitrogen dynamics and carbon sequestration in soils under different residue management. The Agriculturists. 12(2):48–55. doi: 10.3329/agric.v12i2.21731.

Rahman MM, Alam MS, Islam MM, Kamal MZ, Rahman GM, Haque MM, Miah MG, Biswas JC. 2022. Potential of legume-based cropping systems for climate change adaptation and mitigation. In: Meena RS, Sihag SK, editors, Advances in legumes for sustainable intensification. London, UK: Academic Press; p. 381–402.

Rahman MM, Al-Amin HM, Alam MS, Smith J, Hillier J, Sutton MA, Adhya TK. 2024. Nitrogen management options: challenges, potentials and prospects. In: Rahman M, Biswas J Meena RS, editors. Climate change and soil-water-plant nexus. Singapore: Springer. doi: 10.1007/978-981-97-6635-2_5.

Rahman MM, Kamal MZ, Ranamukhaarachchi S, Alam MS, Alam MK, Khan MA, Islam MM, Alam MA, Jiban SI, Mamun MA, et al. 2022. Effects of organic amendments on soil aggregate stability, carbon sequestration and energy use efficiency in wetland paddy cultivation. Sustainability. 14(8):4475. doi: 10.3390/su14084475.

Rajan K, Raja P, Dinesh D, Kumar S, Bhatt BP, Surendran U, Karan D, Bhaskar BP. 2021. Quantifying carbon sequestration potential of soils in an agro-ecological region scale. Curr Sci. (00113891).120(8):1334. doi: 10.18520/cs/v120/i8/1334-1341.

Rea RS, Islam MR, Rahman MM, Mix K. 2019. Study of nitrogen use efficiency and yield of rice influenced by deep placement of nitrogen fertilizers. SAARC J Agric. 17(1):93–103. doi: 10.3329/sja.v17i1.42764.

Robertson GP, Vitousek PM. 2009. Nitrogen in agriculture: balancing the cost of an essential resource. Annu Rev Environ Resour. 34:97–125. doi: 10.1146/annurev.environ.032108.105046.

Rochette P, Angers DA, Chantigny MH, Gasser MO, MacDonald JD, Pelster DE, Bertrand N. 2013. Ammonia volatilization and nitrogen retention: how deep to incorporate urea? J Environ Qual. 42:1635–1642. doi: 10.2134/jeq2013.05.0192.

Samal P, Babu SC, Mondal B. 2021. The global rice scenario towards 2050: results for six continents.

Samal P, Babu SC, Mondal B, Mishra SN. 2022. The global rice agriculture towards 2050: an inter-continental perspective. Outlook Agric. 51(2):164–172. doi: 10.1177/00307270221088338.

Sanchez-Garcia M, Roig A, Sánchez-Monedero MA, Cayuela ML. 2014. Biochar increases soil $N_2O$ emissions produced by nitrification-mediated pathways. Front Environ Sci. 2:25. doi: 10.3389/fenvs.2014.00025.

Sapkota TB, Takele R. 2023. Improving nitrogen use efficiency and reducing nitrogen surplus through best fertilizer nitrogen management in cereal production: the case of India and China. Adv Agron. 178:233–294.

Sarkar MU, Rahman MM, Rahman GK, Naher UA, Ahmed MN. 2016. Soil test based inorganic fertilizer and integrated plant nutrition system for rice (oryza sativa L.) cultivation in inceptisols of Bangladesh. The Agriculturist. 14(1):33–42. doi: 10.3329/agric.v14i1.29098.

Shaaban M, Wu Y, Peng QA, Lin S, Mo Y, Wu L, Hu R, Zhou W. 2016. Effects of dicyandiamide and dolomite application on $N_2O$ emission from an acidic soil. Environ Sci Pollut Res. 23(7):6334–6342. doi: 10.1007/s11356-015-5863-y.

Shi X, Hu K, Batchelor WD, Liang H, Wu Y, Wang Q, Fu J, Cui X, Zhou F. 2020. Exploring optimal nitrogen management strategies to mitigate nitrogen losses from paddy soil in the middle reaches of the Yangtze River. Agric Water Manag. 228:105877. doi: 10.1016/j.agwat.2019.105877.

Sikder R, Xiaoying J. 2014. Urea super granule (USG) as key conductor in agricultural productivity development in Bangladesh. Dev Ctry Stud. 4:132–139.

Simansky V, Horak J, Juriga M, Srank D. 2018. Soil structure and soil organic matter in water-stable aggregates under different application rates of biochar. Viet J Earth Sci. 40(2):97–108. doi: 10.15625/0866-7187/40/2/11090.

Singh B, Macdonald LM, Kookana RS, van Zwieten L, Butler G, Joseph S, Weatherley A, Kaudal BB, Regan A, Cattle J, et al. 2014. Opportunities and constraints for biochar technology in Australian agriculture: looking beyond carbon sequestration. Soil Res. 52(8):739–750. doi: 10.1071/SR14112.

Sutton MA, Bleeker A, Howard CM, Erisman JW, Abrol YP, Bekunda M, Datta A, Davidson E, De Vries W, Oenema O, et al. 2013. Our nutrient world. The challenge to produce more food & energy with less pollution. Edinburgh, UK: Centre for Ecology & Hydrology.

Tan Z, Lin CS, Ji X, Rainey TJ. 2017. Returning biochar to fields: a review. Appl Soil Ecol. 116:1–11. doi: 10.1016/j.apsoil.2017.03.017.

UNEP (United Nations Environment Programme). 2014. Excess nitrogen in the environment. UNEP Year Book: Emerging Issues In Our Global Environ. 7–11.

Wang J, Wang S. 2019. Preparation, modification and environmental application of biochar: a review. J Clean Prod. 227:1002–1022. doi: 10.1016/j.jclepro.2019.04.282.

Xin Y, Ping Y, Jue L, Yujie Z, Shuifeng Y, Xiaotao M, Jianqiu C, Haefele SM. 2022. Grain yield, plant nitrogen content and nitrogen use efficiency as affected by controlled-release urea and straw biochar in a rice field. J Plant Nutr. 45 (9):1393–1402. doi: 10.1080/01904167.2021.2014884.

Xinqiang L, Junli Y, Miaomiao H, Hua L, Liang L, Guangming T. 2014. Modeling the fate of fertilizer N in paddy rice systems receiving manure and urea. Geoderma. 228-229:54–61. doi: 10.1016/j.geoderma.2013.09.002.

Xu J, Peng S, Yang S, Wang W. 2012. Ammonia volatilization losses from a rice paddy with different irrigation and nitrogen managements. Agric Water Manag. 104:184–192. doi: 10.1016/j.agwat.2011.12.013.

Yao Y, Zhang M, Tian Y, Zhao M, Zhang B, Zhao M, Zeng K, Yin B. 2018. Urea deep placement for minimizing NH3 loss in an intensive rice cropping system. Field Crops Res. 218:254–266. doi: 10.1016/j.fcr.2017.03.013.

Ye L, Camps-Arbestain M, Shen Q, Lehmann J, Singh B, Sabir M, Condron LM. 2020. Biochar effects on crop yields with and without fertilizer: a meta-analysis of field studies using separate controls. Soil Use Manage. 36(1):2–18. doi: 10.1111/sum.12546.

Zhang F, Cui Z, Fan M, Zhang W, Chen X, Jiang R. 2011. Integrated soil-crop system management: reducing environmental risk while increasing crop productivity and improving nutrient use efficiency in China. J Environ Qual. 40 (4):1051–1057. doi: 10.2134/jeq2010.0292.