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Research Paper

Effect of neem-coated urea and application methods on nitrogen uptake and use efficiency of rice (*Oryza sativa*) in the coastal rainfed lowlands

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ABSTRACT

An experiment was conducted during 2014 and 2015 at Canning Town, West Bengal, to study the influence of neem-coated urea and its application methods on nitrogen uptake and use-efficiency of 'Amal-Mana' rice (*Oryza sativa* L.).The experiment was laid out in in randomized block design, consisting of 10 treatments, viz., T_1, application of 50% N as prilled urea at transplanting and rest N as 6 foliar sprays from active tillering to flowering; T_2, 50% N as neem-coated urea at transplanting and rest N as 6 foliar sprays from active tillering to flowering; T_3, 50% N as prilled urea 1 week after transplanting (WAT) and rest N as 6 foliar sprays from active tillering to flowering; T_4, 50% N as neem-coated urea 1 WAT and rest N as 6 foliar sprays from active tillering to flowering; T_5, 50% N as prilled urea at transplanting, 25% N as prilled urea at active tillering and rest N as 3 foliar sprays from panicle initiation (PI) to flowering; T_6, 50% N as neem-coated urea at transplanting, 25% N as prilled urea at active tillering and rest N as 3 foliar sprays from PI to flowering; T_7, 50% N as prilled urea 1 WAT, 25% N as prilled urea at active tillering and rest N as 3 foliar sprays from PI to flowering; T_8, 50% N as neem-coated urea 1 WAT, 25% N as prilled urea at active tillering and rest N as 3 foliar sprays from PI to flowering; T_9, 50% N at transplanting, 25% N at active tillering and rest N at PI all as prilled urea; T_{10}, 50% N as neem-coated urea 1 WAT, 25% N as prilled urea at active tillering and rest N as soil application at booting stage. Rice variety 'Amal-Mana' with a common fertilizer dose of 75, 20 and 10 kg N, P_2O_5 K_2O/ha was used. Use of neem-coated urea with 50% applied 1 WAT, and 25% each at active tillering and flowering, resulted in 40 more grains/panicle than current practice (T_9). Nitrogen supplied through neem-coated urea resulted in higher (0.6 and 0.7) normalized difference vegetation index, net photosynthesis (>15 mmol/m^2/s), and nitrate reductase activity than current N-management practices. Internal efficiency (IE_N, 76–82 kg grain/kg N uptake) and partial factor productivity (PFP_N, 72–87 kg grain/kg N applied) of N increased significantly with improved management strategy. Grain yield increased from 3.4 t/ha (existing recommendations) to 4.6 t/ha using 50% N as neem-coated urea 1 WAT, with similar results when the remaining N was applied to the soil or through foliar application.

Key words: Flooding, NDVI, Neem-coated urea, Nitrate Reductase, Nitrogen-use efficiency

Rice is predominantly grown during the wet season in the coastal region of India, as this is the source of livelihood for majority of the people of this region. In these areas, natural calamities like floods, cyclones, and drought are frequent and often result in partial or even complete crop failures leading to low and unstable productivity (Haefele *et al*., 2016). Water stagnation (30–50 cm of standing water for most of the season) and flash floods (complete submergence for up to 2 weeks during the vegetative stage) are common either within the same season or in successive seasons. Deficiency of major nutrients and toxicity of micronutrients under such conditions further aggravate the crop conditions and result in low yields. However, replacement of farmers' conventional varieties with improved varieties that can withstand prevailing abiotic stresses, together with proper agronomic practices and use of soil amendments can enhance rice yield in these coastal areas (Sarangi and Maji, 2017).

Soils in coastal tropics are mostly low to medium in N (Sarangi *et al*., 2012) and recovery of applied N fertilizer in flooded rice fields is low due to losses through leaching, volatilization and denitrification (Kiran *et al*., 2010). Low N recovery not only results in low crop yields but also has adverse environmental consequences. *Sundarbans* in West Bengal (The Ganges delta) represent typical coastal low-

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lands, with more than 4 weeks of water stagnation during the wet season due to heavy rain (>1,800 mm per annum), resulting in low-use efficiency of applied N fertilizers.

Nitrogen is conventionally applied by farmers directly to the soil at various stages, starting from the nursery, then before transplanting and at panicle-initiation stage in different splits. Foliar application through spraying of standing crop is also being practiced, which speeds its uptake and enhances N-use efficiency by reducing losses through leaching and run-off. The foliar application also has less adverse impacts on the environment by minimizing nitrate (NO_3) contamination of groundwater. However, the use of foliar sprays could not gain popularity in India, and only 1% of N fertilizer is applied through this method, compared with 14% worldwide (Bhadraray and Singh, 2016). Foliar application is likely to be more adopted in coastal areas where stagnant floods are common, and soil application is difficult or not possible.

The use of neem-coated urea (NCU) prolongs N availability for crop growth, thereby minimizes losses and improves nitrogen-use efficiency (Suganya *et al*., 2009). Recent policy changes in India had made it mandatory to manufacture only NCU, a significant shift from previous regulation that mandates only 35% of the total production to be neem coated. Besides saving energy and labour, coating of urea inhibits the diversion of subsidized urea for non-agricultural purposes. Use of slow-release NCU and a combination of basal and foliar application methods suitable for soil and flood conditions will have positive effects on grain yield while reducing fertilizer use (Jat *et al*., 2011). An appropriate use of NCU in coastal lowland areas could result in higher yields while minimizing N losses. Further, net return and benefit: cost ratio (BCR) arising from the use of this integrated approach need to be thoroughly assessed in farmers' fields before any recommendations could be made in these highly impoverished areas. The objective of this study is to develop efficient fertilizer-management package for coastal areas predominantly affected by stagnant floods. We hypothesize that slow-release N fertilizer sources like NCU if applied at the appropriate time using proper methods integrating soil and foliar application, will further increase and stabilize yield, enhance productivity and profits in flood-prone rainfed lowlands.

MATERIALS AND METHODS

The field experiment was conducted during the wet seasons (June–November) of 2014 and 2015 at the ICAR-Central Soil Salinity Research Institute (CSSRI), Regional Research Station (RRS), Canning Town in West Bengal to evaluate a range of N application methods and timings using an improved rice variety ('Amal Mana'). The soil of the station is a silty clay with 40–43% clay, 10% sand and 47–50% silt. The *p*H of the top soil was 6.8, with an average bulk density of 1.49 g cm^3 and an organic carbon concentration of 0.48%. The experimental area had a history of rice-rice cropping for the 3 years preceding the trials. The site is within the tropical monsoon climate with annual rainfall of 1,802 mm, solar radiation of 13 MJ/m^2/day, and mean temperature of 26.6°C. The weather data (rainfall, maximum and minimum temperatures) during the experimental period (2014–15) are presented in Fig. 1. Rainfall received from June to November was 1,045.7 and 1,676.5 mm during 2014 and 2015, respectively, with long-term average (1966–2016) of 1,521.0 mm during the corresponding period. The higher rainfall in 2015 was mainly due to unusually high rain in July 2015 (834.4 mm), compared with 51-year average rainfall for this month (371 mm). Consequently, field water depth was higher during the initial growth period in the second year compared to the first (Fig. 1c). Maximum temperature varied from 29 to 34°C and minimum temperature from 18 to 27°C. Both maximum and minimum temperatures declined towards the end of the season.

The rice variety 'Amal-Mana', tolerant of stagnant flooding, with yield advantage of 0.5–1.0 t/ha than local varieties (Sarangi *et al*. 2016) was used to assess the effectiveness, method, and time of application of NCU in flood-prone areas. The N application methods involved various combinations of prilled urea (PU), NCU, and foliar urea sprays. The specifications of NCU used in the study are: (*i*) moisture per cent by weight, maximum 1.0, (*ii*) total nitrogen per cent by weight, minimum 46.0, (*iii*) Biuret, per cent by weight, maximum 1.5, (*iv*) benzene soluble content, per cent by weight, minimum 0.035, (*v*) particle size: not less than 90% of the material shall pass through 2.8 mm IS sieve and not less than 80% by weight shall be retained on 1 mm IS sieve. Ten treatments viz. T_1, application of 50% N as PU at transplanting and rest N as 6 foliar sprays from active tillering to flowering; T_2, 50% N as NCU at transplanting and rest N as 6 foliar sprays from active tillering to flowering; T_3, 50% N as prilled urea 1 week after transplanting (WAT) and rest N as 6 foliar sprays from active tillering to flowering; T_4, 50% N as NCU 1 WAT and rest N as 6 foliar sprays from active tillering to flowering; T_5, 50% N as prilled urea at transplanting, 25% N as prilled urea at active tillering and rest N as 3 foliar sprays from panicle initiation to flowering; T_6, 50% N as NCU at transplanting, 25% N as prilled urea at active tillering and rest N as 3 foliar sprays from panicle initiation to flowering; T_7, 50% N as prilled urea 1 WAT, 25% N as prilled urea at active tillering and rest N as 3 foliar sprays from panicle initiation to flowering; T_8, 50% N as NCU at 1 WAT, 25% N as prilled urea at active tillering and rest N as 3 foliar sprays from PI to flowering; T_9, 50% N at transplanting, 25% N at active tillering and rest N at PI all as prilled urea; T_{10}, 50% N as NCU at 1 WAT, 25% N as prilled urea at active tillering and rest N as at booting stage, were evaluated in a randomized block design with 3 replications. A common fertilizer dose of 75, 20 and 10 kg N, P_2O_5 and K_2O/ha was applied in all treatments. Foliar spray was done with 1% PU solution (w/v), as per treatments.

Pre-germinated seeds (25 g dry seeds/m²) were sown in the nursery on 15 June, and 40-day-old seedlings were transplanted on 25 July in both the years at a spacing of 15 cm row-to-row and 15 cm hill to hill with 2–3 seedlings/hill. Fertilizers @ 5, 3 and 1.5 kg N,P_2O_5 and K_2O were applied per 1,000 m² for nursery establishment. The N was applied in 3 splits, 50% at the time of nursery bed preparation, and the remaining in 2 equal splits at 15 days and 30 days after sowing (Sarangi *et al*., 2015). Recommended package of practices for control of insect-pests and diseases were followed uniformly for all the treatments. Field water depth was measured daily using meter sticks installed in each plot; mean field water depth was calculated at the end of the season for each treatment from daily data. Plant height (cm) was measured from the stem-base to the tip of the longest leaf or panicle, whatever is longer. Twelve hills from each plot were randomly sampled for determining plant height and the number of panicles/hill. From each plot (31.96 m²), plants were harvested, sun-dried and threshed, and straw and grains were separately weighed. Grain weight was adjusted to 14% moisture content. Ten panicles from each plot were hand-threshed to record the total number of spikelets/panicle. Filled (grains) and unfilled spikelets (chaffs) were separated, and spikelet fertility was calculated. After thoroughly sun-drying the grains, 1,000-grain weight was recorded for each treatment. Grain and straw samples from each treatment were collected, oven-dried at 70°C for 3–4 days until constant weight, grounded to pass through a 0.5-mm sieve and used for tissue N analysis following micro-Kjeldahl method (Yoshida *et al*., 1976). Uptake of N in grain and straw at harvesting was calculated using the following equations:

$$\text{Grain N uptake (kg/ha)} = \left[\frac{[\text{Grain N content (\%)} \times \text{Grain yield (kg/ha)}]}{100}\right]$$

$$\text{Straw N uptake (kg/ha)} = \left[\frac{[\text{Straw N content (\%)} \times \text{Straw yield (kg/ha)}]}{100}\right]$$

Nitrogen-use efficiencies (NUE) like internal (physiological) efficiency (IE_N) (Dobermann and Fairhurst, 2000) and partial factor productivity (PFP_N) (Ladha *et al*., 2005) of different N-management practices were calculated using the following equations.

Internal efficiency (IE_N; kg grain/kg N uptake) =

$$\left[\frac{\text{Grain yield (kg/ha)]}}{\text{Total above ground N uptake (kg/ha)}}\right]$$

Partial factor productivity (PFP_N; kg grain/kg N applied)

$$= \left[\frac{GY + N}{FN}\right]$$

where GY_{+N} is the grain yield (kg/ha), and FN is the amount of N fertilizer applied (kg/ha).

In-vivo assay of nitrate reductase (NR) activity (µg NO_2^- produced per hr per g fresh weight) was determined based on the procedure of Jowarski (1971) using the 3rd leaf from the top at booting and the flowering stages. About 250 mg fresh leaf samples were chopped and suspended in screw cap vials containing 4.5 ml medium comprising 2 ml 0.2 M phosphate buffer (*p*H 7.5), 0.5 ml of 0.02 M KNO_3 and 2 ml of 5% propanol. The vials were capped and kept in the dark at 30°C for 2 hr. Nitrate released into the medium was determined by treating 0.4 ml aliquot with 0.3 ml each of sulphanilamide and N-(1-naphthyl) ethylene diamine di hydrochloride (NEDH). After 20 minutes, the solution was diluted with distilled water to 5 ml volume, and the absorbance was measured at 540 nm using a double-beam spectrophotometer (UV-VIS Double Beam Spectrophotometer, 177, SI No. 558, Systronics, Ahmedabad, India).

Normalized difference vegetation index (NDVI) values of crop canopy were recorded with Trimble® Green Seeker® handheld crop-sensing system at a weekly interval, beginning from 2 weeks after transplanting (WAT) to 16 WAT. Net photosynthesis rate (Pn; m mol/m²/s) was measured weekly, by a CI-340 Ultra-Light Portable Photosynthesis System (CID BioScience Inc., 4901 NW Camas Meadows Drive, Camas, WA 98607, USA) and was calculated using the equation: $Pn = W' (C_o - C_i)$; where W = Mass flow rate per unit leaf area (mol/m²/s) and C_o (C_i) = outlet (inlet) CO_2 concentrations (mmol/mol). The Pn was measured on the 3rd leaf from the top, at 1100 – 1200 h on bright sunny days with photosynthetically active radiation of 900–950 mmol/m²/s. The mean of two measurements taken from each plot was used for analysis.

Statistical analysis of experimental data was done using STAR (Statistical Tool for Agricultural Research) version 2.0.1 software, developed by the International Rice Research Institute. Pair-wise mean comparison of treatments was done using Critical Difference (CD) at $p<0.05$ level of significance (Gomez and Gomez, 1984). Since the interaction between treatments and year of study (2014 and 2015) for all measured parameters was not significant, the pooled data across the 2 years are presented.

RESULTS AND DISCUSSION

Growth parameters, yield attributes, grain and straw yields

Plant height (range 150–163 cm, mean 156 cm) did not vary with different N sources, method and time of application. Among yield attributes, significant treatment differences were observed for the panicle density, spikelets/ panicle and per cent spikelet fertility (Table 1). Spikelet fertility under treatment T_8 (application of 50% N as neem-coated urea 1 week after transplanting, 25% N as prilled urea at active tillering and rest N as 3 foliar sprays from panicle initiation to flowering) was 90% and significantly higher than that recorded under all the other treatments except T_{10} (50% N as neem-coated urea 1 week after transplanting, 25% N as prilled urea at active tillering and rest N as soil application at booting stage). The number of spikelets/panicle was significantly higher under T_8 than those of T_1, T_3 and T_9 treatment. The panicle density was the highest (184 panicles/m^2) under T_8 and the lowest (167 panicles/m^2) in T_1 treatment. The grain weight did not vary with treatments. Grain yield recorded under treatment T_8 was significantly higher than those of all the other treatments except T_{10}. Straw yield of T_8 was also significantly higher than those of T_7 and T_3 treatments. The increase in grain yield with neem-cake-coated urea (NCU) was owing to better growth with prolonged N availability (Singh *et al*., 2019). Neem coating helps in retarding the activity and growth of the bacteria responsible for denitrification, prevents the loss of urea, and reduces the effects of large number of pests (Lokanadhan *et al*., 2012). Studies by Bazaya *et al*. (2009) revealed an increase in yield of 7% and 16% when NCU was used, compared to prilled urea + *Mentha* spent (distillation waste of *Mentha arvensis* herb with nitrification inhibitory properties) and prilled urea, respectively.

Normalized difference vegetation index, photosynthetic rate and nitrate-reductase activity

Normalized difference vegetation index (NDVI) of all treatments was similar during the first 6 WAT (Fig. 2). At later stages, NDVI was significantly higher for treatments with NCU applied at 2 or more stages as under treatments T_8 (50% N at 1 WAT through NCU + top dressing of 25% N through NCU at active tillering+ 25% N through foliar

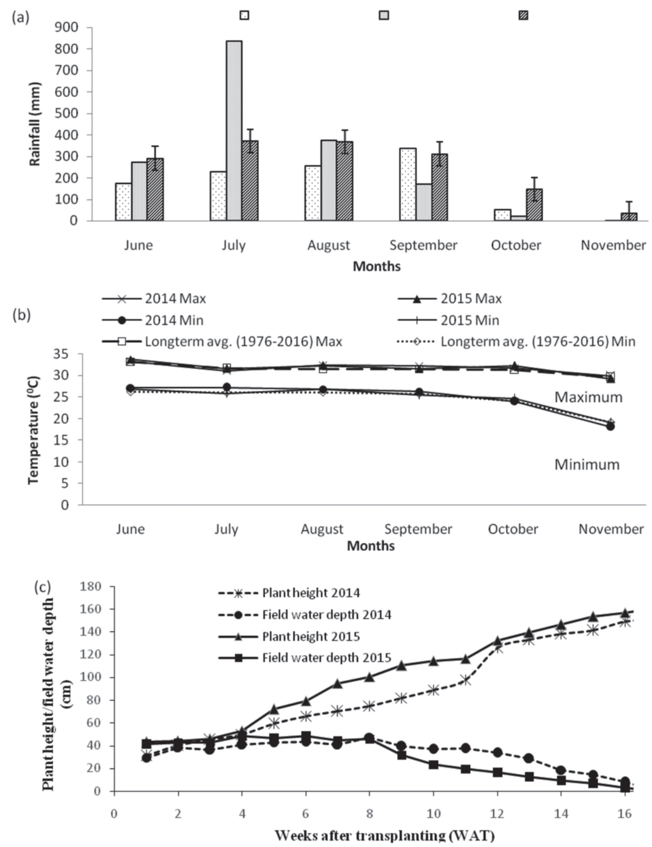

Fig. 1.(a) Monthly total rainfall, (b) average maximum (max) and minimum (min) temperatures for 2014, 2015 and long-term averages recorded at the research farm, Canning Town, West Bengal, India and (c) field water depth and plant height during the wet seasons of 2014 and 2015.

Table 1. Growth, yield attributes and yield of ('Amal-Mana') rice as influenced by nitrogen management practices in rainfed lowland during the wet seasons of 2014 and 2015 (pooled data of 2 years)

Treatment	Plant height (cm)	Panicles/m^2	Spikelet/ panicle	Spikelet fertility (%)	1,000-grain wt. (g)	Grain yield (t/ha)	Straw yield (t/ha)
T_1	155.4	167	102	81.0	28.0	3.1	4.3
T_2	158.6	172	109	83.2	28.1	3.9	5.8
T_3	154.0	169	107	83.3	28.2	3.4	4.8
T_4	156.0	180	134	83.1	28.0	5.0	6.2
T_5	156.3	176	105	85.0	28.1	3.5	4.8
T_6	150.0	177	120	85.2	28.1	4.3	5.1
T_7	151.2	182	125	85.1	28.1	5.4	5.5
T_8	156.2	184	145	90.2	28.3	6.5	6.8
T_9	159.1	171	105	85.0	28.2	3.4	4.6
T_{10}	163.2	179	131	87.5	28.2	5.6	6.4
SEm±	3.7	0.7	3.9	0.9	0.1	0.2	0.4
CD (P=0.05)	NS	2.1	11.7	2.7	NS	0.6	1.2

Details of treatments are given under Materials and Methods
NS, non-significant

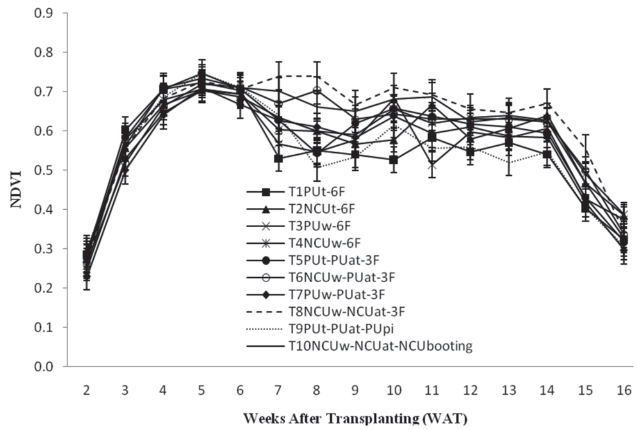

Fig. 2. Normalized difference vegetation index (NDVI) values (pooled data of 2 years) of Amal-Mana rice canopy under different treatments of N fertilizer source, method and time of application. Measurements were taken at weekly interval beginning from 2 weeks after transplanting (WAT) to 16 WAT.

application) and T_{10} (50% N at 1 WAT, 25% at active tillering and 25% at booting). Net photosynthesis rates (Pn) were also significantly higher under T_8 and T_{10} treatments (> 15 mmol/m^2/s) compared with the values in other treatments (Fig. 3). The effects of sources, methods and time of nitrogen application on plant height were not significant because of equal availability of N in all treatments during the period from seedling to maximum tillering (MT), through the 6th WAT, as evident from the NDVI values, which started showing variation from 7 WAT through the reproductive stage, indicating that application of NCU prolonged N availability through the reproductive stage. The NDVI dropped from 0.7 at 6 WAT to about 0.5–0.6 at 7 WAT when PU was used, whereas, it either remained the same or increased in case of NCU (Fig. 2). The NDVI value increases with the increase in leaf greenness and green leaf area (Jat *et al*., 2011).

Nitrate reductase (NR) activity was higher at flowering than during booting stage in all treatments. Variations between treatments were significant at both stages with the highest activity (11.6 µg NO_2/hr/g fresh weight) under T_8, followed by T_6 (Fig. 4), where NCU constitute 75% of the applied N. Prolonged availability of N through NCU during reproductive stage as evident from NR activity in the 3rd leaf increased panicle length and grains per panicles. NR activity during flowering was 11.6 µg NO_2^- produced/hr/g fresh weight in the treatment with 50% N at 1 WAT through NCU + top dressing of 25% N through NCU at AT + 25% N through the foliar application (T_8), but lower, 7.7 µg NO_2/hr per g fresh weight when only PU was used, with 50% of it applied to soil and 50% as a foliar spray (T_1). Kumar and Shivay (2009) reported that, plants supplied with neem bitter-coated urea (NBCU) and Pusa neem golden urea (PNGU) resulted in greater leaf area and accumulated more dry matter at later stages of crop growth. However, plants supplied with PU performed better during the initial 1 month after transplanting than those supplied with NBCU and PNGU. They also observed longer panicles with NBCU and PNGU and attributed that to variation in solubility of N sources. The N absorbed by the plant from tillering to panicle initiation might have increased the number of productive tillers, and that absorbed during panicle initiation to flowering might have increased the number of filled spikelets/panicle. Coated fertilizers provide a slow but steady supply of N over a longer period,

Table 2. Nitrogen concentration, uptake and use efficiencies of rice ('Amal-Mana') as affected by N-fertilizer source, method and time of application (pooled data of 2 years)

Treatment	Grain N (%)	Straw N (%)	Grain N uptake (kg/ha)	Straw N uptake (kg/ha)	IE_N (kg grain/kg N uptake)	PFP_N(kg grain/kg N applied)
T_1	1.03	0.33	31.9	24.6	54.9	41.3
T_2	1.04	0.32	35.4	25.9	63.6	52.0
T_3	1.01	0.34	34.5	23.2	58.9	45.3
T_4	1.08	0.33	37.8	24.5	80.3	66.7
T_5	1.04	0.41	36.0	27.9	54.8	46.7
T_6	1.12	0.41	40.9	29.1	61.4	57.3
T_7	1.05	0.41	38.4	27.7	81.7	72.0
T_8	1.11	0.39	51.0	34.5	76.0	86.7
T_9	1.08	0.37	35.8	26.9	54.2	45.3
T_{10}	1.07	0.40	43.4	32.8	73.5	74.7
SEm±	0.04	0.04	2.5	4.1	2.0	2.9
CD (P=0.05)	ns^c	ns	7.5	ns	6.0	8.8

Details of treatments are given under Materials and Methods
IE_N, Internal efficiency; PFP_N, partial factor productivity; ns, non-significant

whereas for PU, N availability is fast but for a shorter period. Sustained supply of N was also reflected as higher photosynthesis rate during reproductive phase (Fig. 3). Better availability of N during reproductive stage ensures higher leaf chlorophyll concentration with consequent increase in net photosynthesis. Sufficient N supply during grain-filling and ripening is essential to maintain photosynthesis and increase protein content in the grain (Dobermann and Fairhurst, 2000). This data showed that switching from PU to NCU will prolong N availability later in the season and enhance photosynthesis during grain filling.

The NR activity was higher when NCU was used, indicating that rice plants in lowland ecosystem can use the NO_3^- form of N effectively. Rice plants absorb NO_3^- formed by nitrification in the rhizosphere, and this could reach one-third of the total N (NH_4^+ and NO_3^-) absorbed by rice plants. Most of the nitrogen absorbed as NH_4^+-N is incorporated into organic compounds in the roots, whereas NO_3^- –N is more mobile in the xylem, and is also stored in the vacuoles of different plant parts. NO_3-N may also contribute to maintaining cation-anion balance and osmoregulation (Duan *et al*., 2006).

Nitrogen concentration in grains and straw, and nitrogen uptake and use efficiencies

Nitrogen concentration in grain and straw varied from 1.01 to 1.12% and 0.32 to 0.41%, respectively (Table 2), though the differences between treatments were not significant. The highest grain N uptake (51 kg/ha) was recorded in T_8, with 75% N applied as NCU to the soil and 25% as a foliar spray with PU. Replacing the source of N by NCU also resulted in higher N uptake. The lowest grain and straw N uptake were recorded in the treatments where PU

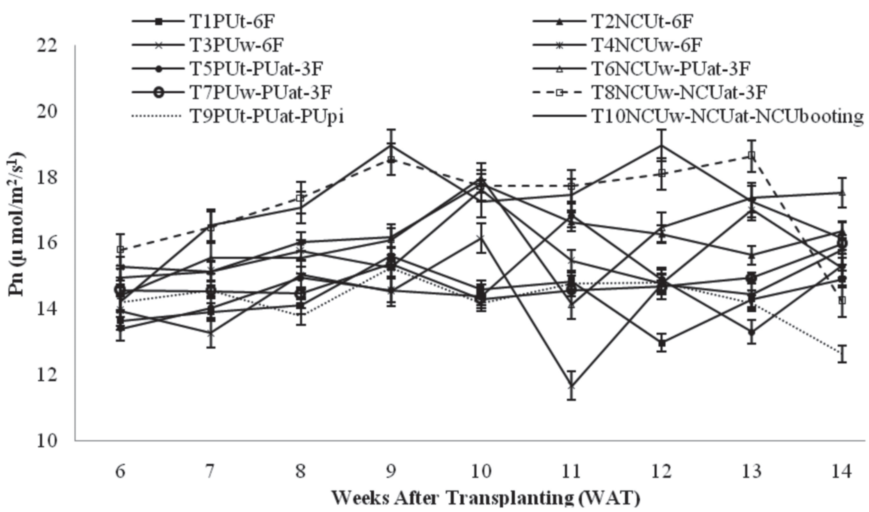

Fig. 3. Net photosynthesis rate (Pn; mmol/m²/s) measured (pooled data of 2 years) at reproductive stages (6–14 WAT) under different treatments of N fertilizer source, method and time of application

Table 3. Economics of N fertilizer source, method and time of application in rainfed lowland rice (pooled data of 2 years)

Treatment	Cost of production (× 10³₹/ha)	Gross returns (× 10³₹/ha)	Net returns (× 10³₹/ha)	Benefit: cost ratio
T_1	40.5	53.4	12.9	1.3
T_2	40.1	54.3	14.2	1.4
T_3	40.5	50.2	9.7	1.2
T_4	40.2	52.0	11.8	1.3
T_5	40.4	51.1	10.7	1.3
T_6	39.9	54.5	14.6	1.4
T_7	40.4	51.8	11.4	1.3
T_8	40.0	68.4	28.4	1.7
T_9	40.2	54.7	14.5	1.4
T_{10}	39.6	63.9	24.3	1.6
SEm±	–	4.2	4.2	0.11
CD (P=0.05)	–	12.6	12.5	0.33

Details of treatments are given under Materials and Methods
NS, non-significant

was used e.g. T_1 (half as basal and half as foliar spray); and T_3 (half at 1 WAT and half foliar spray). The current practice of application of PU (T_9) in 3 splits (50% basal, 25% at active tillering and 25% at PI) resulted in grain N uptake of 35.8 kg N/ha, which was 21 and 42% lower than treatments where all N was broadcast using NCU (50% N at 1 WAT, 25% at active tillering and 25% at booting; T_{10}) and where 50% N applied at 1 WAT through NCU + top-dressing of 25% N through NCU at active tillering + 25% N through foliar application; T_8). In the lowland rice ecosystems, the nitrogen-use efficiency (NUE) is approximately 30%, whereas in upland rice, NUE would be in the range of 40–60% (Nayak *et al*., 2016). Nitrogen-use efficiencies were computed as internal efficiency (IE_N) and partial factor productivity (PFP_N). Variation in IE_N (range of 54.2–81.7 kg grain/kg N uptake) was significant with the lowest value under treatment T_9 and the highest under T_7, which was at par with T_8 treatment. Replacing PU as source of N by NCU resulted in an additional 17 kg of grain yield/kg applied N owing to increase in PFP_N (Table 2). The PFP_N was lower for PU than for NCU irrespective of the method and time of application (50 versus 67 kg grain yield/kg applied N). The lowest PFP_N (41.3 kg grain/kg applied N) was observed when the N was applied as sole PU, with 50% basal and 50% as afoliar spray (T_1). This index was, however, highest (86.7 kg grain/kg applied N) when 50% of NCU was applied 1 WAT, 25% applied to soil at active tillering and the remaining 25% applied as foliar spray using PU at reproductive stage (T_8). The PFP_N increased by about 35% when the source of N was changed from PU to

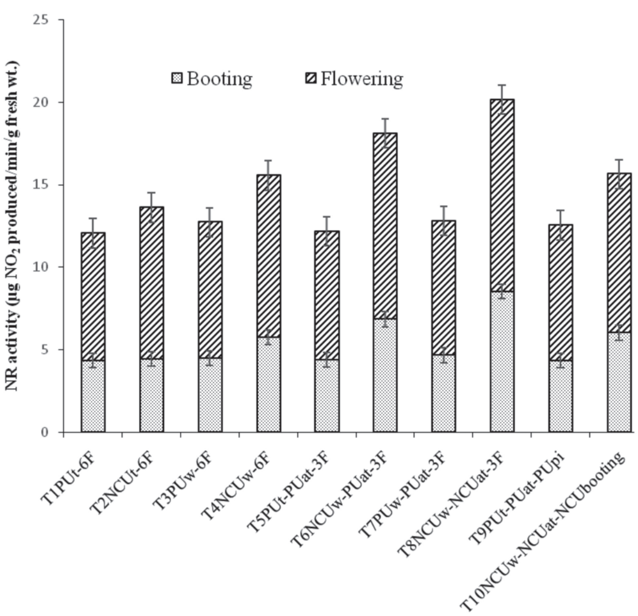

Fig. 4. Nitrate reductase (NR) activity (µg NO_2^-/hr/g fresh weight) using the 3rd leaf from the top; at booting and flowering stages under different treatments (pooled data of 2 years) of N fertilizer source, method and time of application

NCU (Table 2). Kumar *et al*. (2012) reported that coating of urea with nitrification-inhibitors could substantially increase NUE, depending on the type of inhibitors used. The lowest was recorded with *Palmarosa* oil-coated urea (14.4%) and the highest with *Citronella* oil-coated urea (145.5%), which translated into increased grain yield of 4.4% and 44.2% respectively. Neem-cake/neem oil emulsion as a natural nitrification-inhibitor enhanced the NUE by 20–25% (Upadhyay *et al*., 2011). In our experiment, PFP_N varied between 41.3 and 86.7 kg grain/kg applied N. The highest value obtained was owing to the optimized N management with 50% of N dose applied as NCU at 1 WAT, 25% of N dose at active tillering and rest 25% applied as foliar spray from panicle initiation to flowering of the crop. Probably, this management was closer with the requirements of the rice variety 'Amal-Mana'. Higher N application to tall genotypes may decrease grain yield due to lodging, causing a drastic decline in NUE, with the additional consequence of increased N loss to the environment, polluting soil and water resources. Zhao *et al*. (2010) observed the highest PFP_N (61.3 kg grain/kg N applied) in a *japonica* rice variety ('Bing 98110') with the lowest dose of N (80 kg/ha). The PFP_N decreased (37.9 kg grain/kg N applied) with increasing dose to 160 kg/ha and drastically declined to 23.9 kg grain/kg N when N dose was further increased to 240 kg/ha.

Economics

The cost of production was significantly lower when NCU was used, partially because of its availability over an extended period and likely the low incidences of pest infestation under this treatment. With the use of PU, farmers have to spray more frequently for control of stem-borers, leaf folders and other sucking pests. As a result, the cost of cultivation was increased under these treatments. Gross returns, net returns, and benefit: cost ratio (BCR) were higher with the use of NCU. However, there was no variation with the method of application. When 75% NCU was applied to soil and 25% as foliar using PU (T_8), the net returns were ₹28,399/ha, being at par (₹24,349/ha) with sole NCU applied to the soil (T_{10}). The benefit: cost ratio for these 2 treatments were 1.7 and 1.6, respectively, with a range of 1.3–1.4 for other treatments (Table 3). Increase in the benefit: cost ratio of rice-based systems to the tune of 1.9 to 2.0 was achieved through application of farmyard manure and green-manuring of *Sesbania cannabina;* however, the effects due to the application of organic sources of N was noticed from 5th year onwards (Patra *et al*., 2017).

Using slow-release N fertilizer sources such as neem-coated urea as well as efficient application methods can improve N-use efficiency in coastal areas, as in the *Sundarbans* of West Bengal, where rice faces frequent sub-