International Journal of Farm Sciences **15(1):** 16-24, 2025; **doi: 10.5958/2250-0499.2025.00004.7**
Winner of SADHNA Best Paper Award 2025
Review

Eco-friendly nitrogen management practices for rice cultivation: a review

VINOD KUMAR*, **DK SINGH, T PANDIARAJ and VIMLESH KUMAR**

College of Agriculture, Acharya Narendra Deva University of Agriculture and Technology Kotwa, Azamgarh 276001 Uttar Pradesh, India
*Email for corresponding: atulyavinod@gmail.com

 Received: 27.07.2024/Accepted: 06.09.2024

ABSTRACT

Rice (*Oryza sativa* L) is one of the most important stable food crops for human beings. One of the alternatives to feed the ever-increasing population is exploiting the production potential of high-yielding rice varieties through nutrient and agronomic management. A large amount of nitrogen (N) fertilizer is required for rice cultivation, but nitrogen use efficiency (NUE) in rice cultivation is low (20-40%). Much of the unutilized N potentially degrades the quality of soil, water and air and disintegrates the functions of different ecosystems. It is the task to increase NUE and sustain rice production to meet the demand of the ever-increasing world population. This review attempts to find out promising N management practices that might improve NUE while reducing the trade-off between rice production and environmental pollution. The information on N management practices and associated barriers was collected and collated. More efficient N management tools are yet to be developed through research and extension. Awareness-raising campaign among the farming community is a must against their misunderstanding that higher N fertilizer provides higher yields. The conclusion might help policymakers to formulate suitable policies regarding eco-friendly N management strategies for rice cultivation and ensure better utilization of costly N fertilizer.

Keywords: Rice; nitrogen; nitrogen use efficiency; sustainable agriculture

INTRODUCTION

Rice (*Oryza sativa* L) is one of the most important stable food crops in the world. Currently, the world population is increasing at an alarming rate but there is no scope to increase the net cultivable land for crop production. It is a great challenge to ensure food security by increasing rice yield from the land that is decreasing continuously (Jiang et al 2016).

Nitrogen (N) is an integral part of amino acids, proteins, nucleic acids and chlorophyll in plants and is usually the most yield-limiting nutrient in rice production except in soils containing high organic matter content, which can supply enough N during the crop season. During the last few decades, the use of N fertilizers in rice production has increased tremendously. The rate of N for rice cultivation in different countries varies, but the increment of rice yield is not linearly inter-related with the increased application rate of N fertilizers. Nitrogen use efficiency (NUE) in rice cultivation is only 20-50 per cent (Chivenge et al 2021), while the average value for grain production is less than 40 per cent (Omara et al 2019). It indicates that about 60-80 per cent of the applied N remains surplus in the crop fields. Surplus N contributes to greenhouse gas (GHG) emissions (N_2O, NO, NO_2 etc), biodiversity loss, soil acidity development, groundwater pollution, surface water eutrophication etc (Rahman et al 2022a). Therefore, it is crucial to improve NUE to minimize adverse environmental issues through better N management practices for sustainable rice production.

Intensive rice cultivation and future rice demands will require knowledge-intensive strategies for the efficient use of all inputs, including fertilizer nutrients. As irrigated and rainfed lowland rice systems account for about 80 per cent of the worldwide harvested rice area and 92 per cent of total rice production (Dobermann and Fairhurst 2000), the discussions in this review article focuses on the deliberate application of recommended N management tools in rice cultivation that might increase NUE and reduce the loss of N and ultimately contribute to climate change mitigation which ensures environmental sustainability.

Sources of N in rice ecosystem

Nitrogen is the most abundant element in the atmosphere while dry air contains 78 per cent of N_2 by volume. Though the amount of N in the atmosphere is huge but is practically unavailable for plants except legumes. Atmospheric di-nitrogen (N_2) is added to the rice ecosystem through the natural N_2 fixation during lightning, thunderstorms and rainfall (Panda et al 2019). Biological nitrogen fixation (BNF) is considered another important process of N addition in rice soil from the atmosphere by autotrophs (blue-green algae), heterotrophs (*Azospirillum* and *Azotobacter*) and associative N_2-fixers such as *Azolla* (Panda et al 2019).

Eco-friendly N management practices

Globally, more than half of the N fertilizer is applied to three major cereal crops viz wheat (18%), maize (17%) and rice (16%) (Heffer et al 2017). In addition, NUE at the global level is estimated to be <40 per cent (Omara et al 2019), confirming that a major portion of applied N (60%) remains unused (Dobermann 2000).

Soil test-based N application

Soil test-based (STB) N application ensures a higher NUE. The STB practice is an important component of the 4R strategy for nutrient management viz right source, right rate, right time and right place. The 4R technique increases fertilizer efficiency, minimizes nutrient losses and reduces environmental hazards (Wang et al 2016).

The STB fertilization programme can be linked with the cropping system-based soil health card (SHC) programme for the farmers. The SHC remains viable for 3-5 years and again soil from the farmers' fields needs to be analyzed and a new SHC is issued. Planned utilization of SHC might increase NUE. Singh et al (2021) reported that STB N application produced a higher grain yield of rice (4.2 tonnes/ha) as compared to the standard recommended fertilizer dose (3.75 tonnes/ha) and farmers' practice (3.18 tonnes/ha).

Site-specific N management

Most of the fertilizer management practices do not consider field-specific variations of available soil N status. Therefore, there is a chance of excess application of N fertilizer, which may result in low NUE. The site-specific nutrient management (SSNM) practice considers several factors while calculating the proper N requirement for the crop. Quantification of the availability of indigenous N sources for a specific site is very important, which commonly differs from one site to another (Panda et al 2019). Sarkar et al (2017) reported that the SSNM practice in India increased rice yield by 12 per cent and profitability by 14 per cent. The SSNM method is an efficient method of optimizing fertilizer rates and, thus the practice can reduce GHG emissions by up to 50 per cent (Richards et al 2015).

Leaf colour chart and chlorophyll meter-based N management

The leaf colour of a crop is closely related to the N content of the leaf. Farmers normally like to keep the dark green colour of their crop's leaves, which often leads to applying higher doses of N fertilizers in the rice field. Such practices augment the loss of fertilizers and diminish NUE. The leaf colour of a standing rice crop is compared with the colour of the leaf colour chart (LCC) strip. Singh et al (2002) reported that the LCC-based N management practice could save 10-30 kg N per ha without any significant loss of rice grain yield as compared to the fixed-time N application practice. The rate of N fertilizer is reduced when the LCC is used for urea application. Therefore, N_2O, NO and CH_4 emissions must be reduced. Bhatia et al (2012) confirmed that the application of N (120 kg/ha) at LCC $\leq$4 decreased CH_4 emission by 11 per cent and N_2O emission by 16 per cent as compared to the conventional split application of urea in rice.

Chlorophyll meter-based N management is another successful approach that can ensure real-time N application based on the demand of rice crop as compared to the fixed-time split N application. The spectral properties of leaves are used in the soil plant analysis development (SPAD) meter to determine the chlorophyll content of the leaves by measuring light transmittance. The method allows less N application to achieve the targeted yield of rice. Ghosh et al (2020) conducted a field experiment to optimize SPAD values for achieving better NUE under the rice-wheat cropping system. They confirmed that chlorophyll meter SPAD-based N management practices increased 58.5 per cent agronomic NUE and 32.2 per cent N recovery efficiency over the fixed-time N management practice.

Slow-release N fertilizer

The development of the slow-release urea (SRU) application technology can ensure higher crop yields and NUE because SRU reduces N loss through various processes including surface runoff, NH_3 volatilization, leaching and N_2O emission (Li et al 2017). Slow-release N fertilizers are mainly coated with different types of natural or synthetic products such as resin, paraffin, polychlorovinyl, polyurethane, sulfur, polylactic acid, natural rubber and neem (Sun et al 2020). The function of slow-release fertilizers is to release the specific nutrient element slowly so that the target plants can absorb and utilize the nutrient element for a longer period as compared to the normal fertilizers (Azeem et al 2014).

Neem-coated urea (NCU) is very popular in India and is garnering continuous attention from scientific communities across the world (Ramappa et al 2022). Sireesha et al (2020) reported that 100 per cent of NCU increased NUE (32.59%) when compared with 100 per cent of prilled urea (20.68%). In addition to NUE, the grain yield of lowland rice was increased by 14 per cent in 100 per cent NCU in comparison to 100 per cent prilled urea.

Sulfur-coated and polymer-coated urea are very promising slow-release fertilizers in rice cultivation for enhancing grain yield and NUE as well as reducing N loss from the rice field. Sulfur-coated urea could reduce N loss and enhance use efficiency (Shivay et al 2016). It has been reported that urea coated with sulfur increased rice dry matter yield by 55-68 per cent and N absorption by up to 39.4 per cent (Khan et al 2015). Li et al (2018) noticed a reduction of 8-58 per cent in N surface runoff and 23-62 per cent in ammonia volatilization for polyurethane-coated urea and degradable polymer-coated urea compared to uncoated urea.

Reducing N loss with conservation tillage

Conservation tillage, eg minimum tillage and zero-till, ensures crop residue incorporation into the soil and is found effective in soil and water conservation (Rahman et al 2017). Conventional tillage (CT) induces aerobic conditions which enhance the decomposition of organic matter in the soil. The process of residue decomposition supplies readily available N that increases the probability of N loss to the soil, water and atmosphere (Dinnes et al 2002). Under this scenario, conservation tillage practices might play a vital role in improving NUE and decreasing N loss to the environment. Even though contradiction exists on the efficacy of conservation tillage on increasing NUE, reducing GHG emissions and increasing crop yields, a good number of studies advocated in favour of it (Qin et al 2022). They confirmed that the average NUE under ridge tillage was 31 per cent which was 14 and 11 per cent higher as compared to the CT and flooded rice fields respectively.

Soil tillage profoundly influences the physical, chemical and biological properties of soil. Therefore, tillage must contribute to either increasing or decreasing the GHG emissions from the rice-based agro-ecosystem (Gupta et al 2021). Reducing soil disturbance with reduced tillage could lessen GHG emissions from rice ecosystems (Nayak et al 2013). There is reduction of CH_4 emission from the rice field under reduced tillage (Ahmad et al 2009), but contrasting effects of reduced tillage on N_2O emission from rice fields have also been documented. There was a trade-off between CH_4 and N_2O production in paddy fields, with CT plots showing lower N_2O flux than NT as reported by Gangopadhyay et al (2023).

Application of nitrification inhibitors and biochar

Nitrification inhibitors (NIs) are widely used throughout the world to enhance NUE in various crops including rice. The application of NIs in the soil suppresses the nitrification process. It helps to delay the production of NO^{-3} from NH^{+4}. Such inhibitors reduce the availability of NO^{-3} and restrict the denitrification process in flooded soil (Guo et al 2013). Use of synthetic and natural NIs such as dicyandiamide (DCD), 2-chloro-6-(trichloromethyl)-pyridine, 3,4-dimethyl pyrazole phosphate (DMPP) and methyl 3-(4-hydroxyphenyl) propionate (MHPP) have gained significant consideration (Sun et al 2015). Razzak et al (2012) found that both natural (MHPP produced from the root exudates of sorghum) and synthetic (DMPP) NIs enhanced the yield-contributing characteristics, yield and the harvest index of transplanted rice. The application of NIs enhances N content in rice grains, straw and post-harvest soil. Malla et al (2005) reported a 4-34 per cent reduction of N_2O emissions from the rice fields of New Delhi with the use of NIs.

Biochar, a kind of carbon-rich organic material produced from any organic biomass through pyrolysis, ie under limited oxygen and high temperature (400-550°C), is found to be efficient for enhancing NUE

(Rahman et al 2020). It possesses the characteristics of NI by inhibiting the nitrification process in soil (Gupta et al 2021). Biochar is negatively charged and can fix cations including NH^{+4} and limit the nitrification process. The characteristics of biochar vary widely because of its production process and the nature and types of biomass from which biochar is produced. Therefore, general recommendations on the rates of biochar application to crop fields are not available. However, the application of rice straw biochar (22.5 tonnes/ha) in combination with urea fertilizer increased rice yield by 11.3-14.4 per cent as compared to the sole application of urea (Dong et al 2015).

Integrated nitrogen management

Integrated nutrient management (INM) is considered an attractive and holistic approach to nutrient management. In INM, nutrients are supplied from all possible sources of inorganic fertilizers, organic manures and biofertilizers for crop production (Dwivedi et al 2016). INM maintains soil fertility, enhances crop yield and quality, reduces nutrient losses from the soil, improves NUE, curtails production costs and minimizes energy consumption in agriculture (Panda et al 2019). The partial factor productivity of applied N (PFPN) in rice ranged from 26 to 52 kg grain per kg N for the recommended dose (RD) of NPK, whereas, the value increased to 33-77 kg grain per kg N for 75 per cent of RD + 25 per cent N from FYM (Dwivedi et al 2016). This management further reduced 25 per cent N application in the subsequent dry season of rice. The results obtained from a long-term experiment in India showed that the combined application of NPK fertilizers and FYM significantly increased the grain yield of rice by 0.4-0.7 tonnes per ha over the sole application of NPK (Panda et al 2019). Lakshmi et al (2012) found that the application of 75 per cent RD along with 2.5 tonnes per ha vermicompost provided a higher NUE and grain yield of rice as compared to 100 per cent sole RD. In the INM system, the organic component enhances the microbial activity in the soil, which performs a significant role in nutrient mobilization and leads to higher nutrient availability for crops ensuring higher crop yield and better NUE.

Inclusion of legumes in the crop rotation

The inclusion of legume crops in any crop rotation ensures the reduction of synthetic fertilizer, water and associated energy use and improves soil fertility (Rahman et al 2022b). Legumes could fix atmospheric-N_2, making association with the symbiotic bacteria, *Rhizobium*. The research findings indicate that biological nitrogen fixation (BNF) through legume-*Rhizobium* symbiosis could fix a substantial amount of N. For example, alfalfa, cowpea and groundnut could fix 465, 201 and 101 kg N per ha respectively (Anglade et al 2015). BNF is not only beneficial for standing crops but also reduces the N requirement for the subsequent non-leguminous crops (Rahman et al 2022b). Therefore, the inclusion of legumes in the rice-based crop rotation could play a vital role in better rice production with less N application. The inclusion of legume crops in the rice-based crop rotation might play an effective role in increasing rice yield and N content in rice and decreasing N loss from the soil (Yu et al 2014). They further reported that rice-vetch and rice-bean crop rotation increased the grain yield of rice by 5 and 10 per cent in 2010 and 2011 respectively, as compared to the rice-wheat rotation system. Legume crops substantially reduce N_2O and CO_2 emissions by lessening N fertilizer use, sequestering more carbon and reducing the burning of fossil fuels for agricultural practices including irrigation and tillage (Rahman et al 2022b).

Deep placement of N fertilizers

Deep placement of N fertilizers is an effective and eco-friendly technique to enhance NUE. Deep placement of N fertilizers significantly decreases volatilization loss, as NH_3 reduces N_2O and NO emissions by regulating nitrification and denitrification processes (Rochette et al 2013). The technology also reduces surface run-off and increases NUE and grain yield (Gaihre et al 2015). Previous studies conducted in the 90s showed that deep placement of N fertilizers, particularly the use of urea super granule (USG) increased NUE (31.7%) as compared to the traditional application method of prilled urea (Jaiswal and Singh 2001). A recent study confirmed that the application of N fertilizers at both 12 and 8 cm depths considerably increased the rice yield by 81.84 and 72.91 per cent respectively, as compared to the 0 cm depth of N application (Chen et al 2021). Under the deep placement or root zone application of N fertilizers, N is applied into the anaerobic layer of puddled soil which restricts the volatilization loss of N as NH_3 (Hoque et al 2016).

Improved manure management

Manures of both plant and animal flesh and dead tissue sources bear great potential to enhance crop production and sustain soil fertility (Salma et al 2022). The application of manures in the crop field substantially increases carbon sequestration and improves soil properties including soil structure and enzymatic activity and augments microbial diversity and functions (Hasnat et al 2022). To ensure better manure quality, it is important to keep the stable floor clean and to keep a lid on the manure tray which reduces N loss from the manure as gaseous compounds, particularly NH_3. Volatilization loss of N as NH_3 may be decreased by reducing exposure of manures to the atmosphere and by maximizing contact with land (Sommer and Hutchings 2001). The conventional method of surface broadcasting of manure and spreading slurry is rapid and inexpensive but mostly uneven (Webb et al 2010). Manure management may be improved by spreading the manure uniformly in the soil through efficient methods including trailing shoes, trailing hoses, slot injectors and rapid incorporation of slurry and solid manures through ploughing (Webb et al 2010). In case of unavailability of such improved instruments, it is better to collect and apply the solid and liquid parts separately. The liquid will pass through the soil (infiltrates) easily allowing less release of NH_3. For the solid portion, it is better to cover the manure with the soil as early as possible to minimize the volatilization loss.

Irrigation management

Water management plays a key role in regulating soil redox potential, which influences nutrient mobility and its availability in soil and nutrient uptake by the crops (Zhu et al 2022). Alternate wetting and drying (AWD), mid-season drainage, controlled irrigation and intermittent irrigation are adopted to increase water use efficiency, minimize GHG emissions and enhance N recovery without affecting the grain yield of rice (Gupta et al 2021). AWD practice could save 38 per cent of irrigation water without hampering the grain yield of rice (Lampayan et al 2015).

Water-saving irrigation management practice is an eco-friendly and climate-smart technology that reduces GHGs, especially CH_4 and N_2O from rice fields. Improved water management practices reduce N_2O emissions compared to traditional flooding in the rice field (Feng et al 2013). Better NUE in water-saving management practices might be associated with the fact that these practices ensure sufficient oxygen supply to the rice root to enhance the mineralization of soil organic matter and reduce N immobilization, which makes the nutrients more available for plants' uptake (Dong et al 2012). Water-saving techniques reduce surface run-off and gaseous loss (N_2O) and ensure better NUE in wetland rice as compared to traditional irrigation management.

Android-based N management apps

Recently, the smartphone has gained popularity as a tool in agriculture farming (Pongnumkul et al 2015). Smartphones are equipped with different sensors and can execute various activities as a promising tool in farming systems when connected to the internet. The internet is another fast growing technology. Smartphones with internet facilities can be used to document soil nutrients, calculate fertilizer and water requirements of crops, forecast weather, market prices of agricultural products etc. The unprecedented progress in Android-based mobile technology and high-speed internet connectivity across the world might open a new avenue for the optimization of N fertilizer in crop production. Many free N fertilizer management apps are available across the world. Some apps are user-friendly and provide quantitative N guidance, but most of them are generalized and do not use farmers' field data such as soil nutrients, yield goals etc while calculating N requirements. Therefore, smartphone-based suitable, efficient and solely N guidance tools are still in demand.

Nitrogen saving plant growth-promoting bacteria

Bacteria associated with the plants may play a positive role in the growth, development and yield of crops using a wide range of mechanisms including N_2 fixation and production of plant growth-enhancing phytohormones. Therefore, the utilization of plant growth-promoting bacteria would reduce the use of costly and energy-involved inorganic fertilizers in agriculture. During the last few years, the use of efficient plant growth-promoting bacterial strains as eco-friendly inoculants in agriculture has been increasing significantly. Such bacteria possess unique characteristics that enhance crop yield as well as lessen the usage of agro-chemicals including inorganic fertilizers (Borriss 2011). It has been reported that *Rhizobium* and *Azospirillum* demonstrate plant growth-promoting characteristics with the synthesis of plant hormones such as auxins, gibberellins, cytokinins, and ethylene. Such growth hormones contribute in reducing nitrogenous fertilizers in rice fields (Dobbelaere et al 2003). Khan et al (2017) reported that the utilization of *Burkholderia* sp and *Pseudomonas aeruginosa* with a 50 per cent reduced dose of recommended NPK fertilizers could increase the grain yield of rice by 5 and 17 per cent respectively, compared to 100 per cent recommended dose of NPK fertilizers.

Azolla

Making a symbiotic association with *Anabaena azollae* (a type of cyanobacteria), the free-floating water fern *Azolla* can fix a significant amount of atmospheric N_2. Therefore, the application of *Azolla* in the rice field could reduce a considerable amount of N fertilizer. It has been advocated to reduce the use of N fertilizer in rice culture to achieve increased NUE, reduce N loss and maintain grain yield in an intensively fertilized rice cultivation system (Guo et al 2019). Research findings demonstrated that the application of *Azolla* in combination with N fertilizer could replace a significant portion of recommended N fertilizer without sacrificing the grain yield of rice (Yang et al 2021). Combined application of *Azolla* and synthetic N fertilizer increases NUE and reduces NH_3 volatilization from the rice field. Therefore, the utilization of *Azolla* in wetland rice fields might be a sustainable approach to increase NUE and reduce environmental threats.

Cyanobacteria/blue-green algae (BGA)

Cyanobacteria are prokaryotic and photosynthetic microorganisms that can fix atmospheric N_2 utilizing the energy from sunlight (Stewart 1980). Cyanobacteria provide multiple benefits such as increased NUE, reduced nitrate leaching, urea application, increased soil organic carbon and post-harvest soil N. Using half of the RD of urea along with N_2-fixing BG, about 38 per cent higher NUE can be obtained without reducing rice yields as compared to 100 per cent urea application (Song et al 2021).

CONCLUSION

The review reveals that the improvement of nitrogen use efficiency (NUE) in rice is challenging. To attain efficient N management in the rice ecosystem, fertilizers should be applied in the rice field in such a way that would ensure maximum consumption of natural and applied N with minimum loss to the environment. Setting the priority and finding some eco-friendly and advanced N management options, are the utmost tasks of global scientists to upswing NUE to 60-80 per cent from the present level of 30-40 per cent. Until now, no single measure could bring a magical upsurge in NUE in rice cultivation. However, a combination of site-specific and locally available promising practices viz deep placement, coated urea, inclusion of legumes in the crop rotation, alternate wetting and drying for irrigation and biological nitrogen fixation (BNF) could achieve a satisfactory level of NUE. The development of an android-based N management app in rice cultivation could be a breakthrough in this venture.

REFERENCES

Ahmad S, Li C, Dai G, Zhan M, Wang J, Pan S and Cao C 2009. Greenhouse gas emission from direct seeding paddy field under different rice tillage systems in central China. Soil and Tillage Research **106(1):** 54-61.

Anglade J, Billen G and Garnier J 2015. Relationships for estimating N_2 fixation in legumes: incidence for N balance of legume-based cropping systems in Europe. Ecosphere **6(3):** 1-24.

Azeem B, KuShaari K, Man ZB, Basit A and Thanh TH 2014. Review on materials and methods to produce controlled release coated urea fertilizer. Journal of Control Release **181:** 11-21.

Bhatia A, Pathak H, Jain N, Singh PK and Tomer R 2012. Greenhouse gas mitigation in rice-wheat system with leaf color chart-based urea application. Environmental Monitoring and Assessment **184(5):** 3095-3107.

Borriss R 2011. Use of plant-associated *Bacillus* strains as biofertilizers and biocontrol agents in agriculture. In: Bacteria in agrobiology: plant growth responses (DK Maheshwari, Ed), Springer, Berlin, Heidelberg, pp 41-76.

Chen X, Yang S, Ding J, Jiang Z and Sun X 2021. Effects of biochar addition on rice growth and yield under water-saving irrigation. Water **13(2):** 209; doi: 10.3390/w13020209.

Chivenge P, Sharma S, Bunquin MA and Hellin J 2021. Improving nitrogen use efficiency – a key for sustainable rice production systems. Frontiers in Sustainable Food Systems **5:** 737412; doi: 10.3389/fsufs.2021.737412.

Dinnes DL, Karlen DL, Jaynes DB, Kaspar TC, Hatfield JL, Colvin TS and Cambardella CA 2002. Nitrogen management strategies to reduce nitrate leaching in tile-drained mid-western soils. Agronomy Journal **94(1):** 153-171.

Dobbelaere S, Vanderleyden J and Okon Y 2003. Plant growth-promoting effects of diazotrophs in the rhizosphere. Critical Reviews in Plant Sciences **22(2):** 107-149.

Dobermann A 2000. Future intensification of irrigated rice systems. In: Redesigning rice photosynthesis to increase yield (JE Sheehy, PL Mitchell and B Hardy, Eds), Proceedings of the Workshop on the Quest to Reduce Hunger: Redesigning Rice Photosynthesis, 30 November – 3 December 1999, Los Baños, Philippines, pp 229-247.

Dobermann A and Fairhurst T 2000. Rice: nutrient disorders and nutrient management. Handbook Series, Potash and Phosphate Institute (PPI), Potash and Phosphate Institute of Canada (PPIC), International Rice Research Institute, Philippines.

Dong D, Feng Q, Mcgrouther K, Yang M, Wang H and Wu W 2015. Effects of biochar amendment on rice growth and nitrogen retention in a waterlogged paddy field. Journal of Soils and Sediments **15(1):** 153-162.

Dong NM, Brandt KK, Sørensen J, Hung NN, Van Hach C, Tan PS and Dalsgaard T 2012. Effects of alternating wetting and drying versus continuous flooding on fertilizer nitrogen fate in rice fields in the Mekong delta, Vietnam. Soil Biology and Biochemistry **47:** 166-174.

Dwivedi BS, Singh VK, Meena MC, Dey A and Datta SP 2016. Integrated nutrient management for enhancing nitrogen use efficiency. Indian Journal of Fertilizers **12(4):** 62-71.

Feng J, Chen C, Zhang Y, Song Z, Deng A, Zheng C and Zhang W 2013. Impacts of cropping practices on yield-scaled greenhouse gas emissions from rice fields in China: a meta-analysis. Agriculture, Ecosystems and Environment **164:** 220-228.

Gaihre YK, Singh U, Islam SMM, Huda A, Islam MR, Satter MA, Sanabriya J, Islam MR and 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.

Gangopadhyay S, Chowdhuri I, Das N, Pal SC and Mandal S 2023. The effects of no-tillage and conventional tillage on greenhouse gas emissions from paddy fields with various rice varieties. Soil and Tillage Research **232:** 105772; doi: https://doi.org/10.1016/j.still.2023.105772.

Ghosh M, Swain DK, Jha MK, Tewari VK and Bohra A 2020. Optimizing chlorophyll meter (SPAD) reading to allow efficient nitrogen use in rice and wheat under rice-wheat cropping system in eastern India. Plant Production Science **23(3):** 270-285.

Guo J, Chai Y, Li L, Gao L, Xie K, Ling N and Guo S 2019. The potential and related mechanisms of increasing rice yield by reducing chemical nitrogen application in Jiangsu province. Scientia Agricultura Sinica **52:** 849-859.

Guo YJ, Di HJ, Cameron KC, Li B, Podolyan A, Moir JL, Monaghan RM, Smith LC, O'Callaghan M, Bowatte S, Waugh D and He J-Z 2013. Effect of 7-year application of a nitrification inhibitor, dicyandiamide (DCD), on soil microbial biomass, protease and deaminase activities and the abundance of bacteria and archaea in pasture soils. Journal of Soils and Sediments **13:** 753-759.

Gupta K, Kumar R, Baruah KK, Hazarika S, Karmakar S and Bordoloi N 2021. Greenhouse gas emission from rice fields: a review from Indian context. Environmental Science Pollution Research **28(24):** 30551-30572.

Hasnat M, Alam MA, Khanam M, Binte BI, Kabir MH, Alam MS, Kamal MZU, Rahman GKMM, Haque MM and 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.

Heffer P, Gruère A and Roberts T 2017. Assessment of fertilizer use by crop at the global level. International Fertilizer Association (IFA) and International Plant Nutrition Institute (IPNI), 20p.

Hoque MA, Karim MR, Miah MS, Rahman MA and Rahman MM 2016. Field performance of BARI urea super granule applicator. Bangladesh Journal of Agricultural Research **41(1):** 103-113.

Jaiswal VP and Singh GR 2001. Performance of urea super granule and pilled urea under different planting methods in irrigated rice (*Oryza sativa*). Indian Journal of Agricultural Sciences **71(3):** 187-189.

Jiang P, Xie XB, Huang M, Zhou XF, Zhang R, Chen JN, Wu D, Xia B, Xiong H, Xu F and Zou Y 2016. Potential yield increase of hybrid rice at five locations in southern China. Rice **9:** 11; doi: 10.1186/s12284-016-0085-6.

Khan AZ, Ali B, Afzal M, Wahab S, Khalil SK, Amin N, Ping Q, Qiaojing T and Zhou W 2015. Effects of sulfur and urease coated controlled release urea on dry matter yield, N uptake and grain quality of rice. Journal of Animal and Plant Sciences **25(3):** 679-685.

Khan MA, Haque E, Paul NC, Khaleque A, Al-Garni SMS, Rahman M and Islam T 2017. Enhancement of growth and grain yield of rice in nutrient deficient soils by rice probiotic bacteria. Rice Science **24(5):** 264-273.

Lakshmi CSR, Rao PC, Sreelatha T, Madahvi M, Padmaja G, Rao PV and Sireesha A 2012. Nitrogen use efficiency and production efficiency of rice under rice-pulse cropping system with integrated nutrient management. Journal of Rice Research **5(1-2):** 42-49.

Lampayan RM, Rejesus RM, Singleton GR and Bouman BA 2015. Adoption and economics of alternate wetting and drying water management for irrigated lowland rice. Field Crops Research **170:** 95-108.

Li P, Lu J, Hou W, Pan Y, Wang Y, Khan MR, Ren T, Cong R and Li X 2017. Reducing nitrogen losses through ammonia volatilization and surface runoff to improve apparent nitrogen recovery of double cropping of late rice using controlled release urea. Environmental Science and Pollution Research **24(Supplement 2):** 11722-11733.

Li P, Lu J, Wang Y, Wang S, Hussain S, Ren T, Cong R and Li X 2018. Nitrogen losses, use efficiency and productivity of early rice under controlled-release urea. Agriculture, Ecosystems and Environment **251:** 78-87.

Malla G, Bhatia A, Pathak H, Prasad S, Jain N and Singh J 2005. Mitigating nitrous oxide and methane emissions from soil in rice-wheat system of the Indo-Gangetic plain with nitrification and urease inhibitors. Chemosphere **58(2):** 141-147.

Nayak D, Cheng K, Wang W, Koslowski F, Yan X, Guo M, Newbold J, Moran D, Cardenas L, Pan J and Smith P 2013. Technical options to reduce greenhouse gas emissions from croplands and grasslands in China. Policy Brief Number 9, UK-China Sustainable Agriculture Innovation Network.

Omara P, Aula L, Oyebiyi F and Raun WR 2019. World cereal nitrogen use efficiency trends: review and current knowledge. Agrosystems, Geosciences and Environment **2(1):** 1-8.

Panda D, Nayak AK and Mohanty S 2019. Nitrogen management in rice. Oryza **56(Special):** 125-135.

Pongnumkul S, Chaovalit P and Surasvadi N 2015. Applications of smartphone-based sensors in agriculture: a systematic review of research. Journal of Sensors **2015:** doi: 10.1155/2015/195308.

Qin C, Wright AL, Ma L, He X, Xie D and Jiang X 2022. Improving nitrogen-use efficiency by using ridge tillage in rice paddy soils. Soil Use and Management **38(1):** 528-536.

Rahman GKMM, Rahman MM, Alam MS, Kamal MZ, Mashuk HA, Datta R and Meena RS 2020. Biochar and organic amendments for sustainable soil carbon and soil health. In: Carbon and nitrogen cycling in soil (Datta R, Meena RS, Pathan SI and MT Ceccherini, Eds), Springer, Singapore, pp 45-85.

Rahman MM, Alam MS, Islam MM, Kamal MZU, Rahman GKMM, Haque M, Miah MG and Biswas JC 2022b. Potential of legume-based cropping systems for climate change adaptation and mitigation. In: Advances in legumes for sustainable intensification (RS Meena and S Kumar, Eds), Academic Press, pp 381-402.

Rahman MM, Biswas JC, Maniruzzaman M, Choudhury AK and Ahmed F 2017. Effect of tillage practices and rice straw management on soil environment and carbon dioxide emission. Agriculturists **15(1):** 127-142.

Rahman MM, Biswas JC, Sutton MA, Drewer J and Adhya TK 2022a. Assessment of reactive nitrogen flows in Bangladesh's agriculture sector. Sustainability **14(1):** 272; doi: 10.3390/su14010272.

Ramappa KB, Jadhav V and Manjunatha AV 2022. A benchmark study on economic impact of neem coated urea on Indian agriculture. Scientific Reports **12:** 9082; doi: 10.1038/s41598-022-12708-1.

Razzak MA, Hossain AKMZ, Rahman MM, Debsharma SK and Roy C 2012. Effect of nitrification inhibitors on yield and yield attributes of T Aman rice varieties. Planter **88(1041):** 865-873.

Richards MB, Butterbach-Bahl K, Jat ML, Lipinski B, Ortiz-Monasterio I and Sapkota T 2015. Site-specific nutrient management: implementation guidance for policymakers and investors. Climate-Smart Agriculture Practice Brief, Copenhagen, CGIAR Research Programme on Climate Change, Agriculture and Food Security (CCAFS), Denmark.

Rochette P, Angers DA, Chantigny MH, Gasser M-O, MacDonald JD, Pelster DE and Bertrand N 2013. Ammonia volatilization and nitrogen retention: how deep to incorporate urea? Journal of Environmental Quality **42:** 1635-1642.

Salma U, Alam MS, Khanam M, Solaiman ARM, Zakaria M, Rahman GKMM and Rahman MM 2022. Effect of organic manures and mineral fertilizers on soil properties and yield of sweet pepper (*Capsicum annuum* L). Asian Journal of Soil Science and Plant Nutrition **8(2):** 32-43.

Sarkar D, Meena VS, Haldar A and Rakshit A 2017. Site-specific nutrient management (SSNM): a unique approach towards maintaining soil health. In: Adaptive soil management: from theory to practices (A Rakshit, PC Abhilash, HB Singh and S Ghosh, Eds), Springer Verlag, Singapore, pp 69-88.

Shivay YS, Pooniya V, Prasad R, Pal M and Bansal R 2016. Sulphur-coated urea as a source of sulphur and an enhanced efficiency of nitrogen fertilizer for spring wheat. Cereal Research Communications **44(3):** 513-523.

Singh B, Singh Y, Ladha JK, Bronson KF, Balasubramanian V, Singh J and Khind CS 2002. Chlorophyll meter- and leaf colour chart-based nitrogen management for rice and wheat in northwestern India. Agronomy Journal **94(4):** 821-829.

Singh VK, Gautam P, Nanda G, Dhaliwal SS, Pramanick B, Meena SS, Alsanie WF, Gaber A, Sayed S and Hossain A 2021. Soil test-based fertilizer application improves productivity, profitability and nutrient use efficiency of rice (*Oryza sativa* L) under direct seeded condition. Agronomy **11(9):** 1756; doi: 10.3390/agronomy 11091756.

Sireesha A, Krishna JR and Satyanarayana PV 2020. Effect of neem coated urea on nitrogen uptake, nitrogen use efficiency and yield of rice under low land ecosystem of Godavari delta of Andhra Pradesh, India. International Journal of Current Microbiology and Applied Sciences **9(8):** 2086-2091.

Sommer SG and Hutchings NJ 2001. Ammonia emission from field applied manure and its reduction. European Journal of Agronomy **15(1):** 1-15.

Song X, Zhang J, Peng C and Li D 2021. Replacing nitrogen fertilizer with nitrogen-fixing cyanobacteria reduced nitrogen leaching in red soil paddy fields. Agriculture, Ecosystems and Environment **312:** 107320; doi: 10.1016/j.agee.2021.107320.

Stewart WD 1980. Some aspects of structure and function in N_2-fixing cyanobacteria. Annual Review of Microbiology **34:** 497-536.

Sun H, Zhang H, Powlson D, Min J and Shi W 2015. Rice production, nitrous oxide emission and ammonia volatilization as impacted by the nitrification inhibitor 2-chloro-6-(trichloromethyl)-pyridine. Field Crops Research **173:** doi: 10.1016/j.fcr.2014.12.012.

Sun H, Zhou S, Zhang J, Zhang X and Wang C 2020. Effects of controlled-release fertilizer on rice grain yield, nitrogen use efficiency and greenhouse gas emissions in a paddy field with straw incorporation. Field Crops Research **253:** 107814; doi: 10.1016/j.fcr.2020.107814.

Wang Q, Liu G, Morgan KT and Li Y 2016. Implementing the four Rs (4Rs) in nutrient stewardship for tomato production: HS1269, 10/2015. EDIS **2016(1):** doi: 10.32473/edis-hs1269-2015.

Webb J, Pain B, Bittman S and Morgan J 2010. The impacts of manure application methods on emissions of ammonia, nitrous oxide and on crop response – a review. Agriculture, Ecosystems and Environment **137(1-2):** 39-46.

Yang G, Ji H, Liu H, Feng Y, Zhang Y, Chen L and Guo Z 2021. Nitrogen fertilizer reduction in combination with *Azolla* cover for reducing ammonia volatilization and improving nitrogen use efficiency of rice. PeerJ **9:** e11077; doi: 10.7717/peerj.11077.

Yu Y, Xue L and Yang L 2014. Winter legumes in rice crop rotations reduces nitrogen loss and improves rice yield and soil nitrogen supply. Agronomy for Sustainable Development **34(3):** 633-640.

Zhu H, Zhang T, Zhang C, He X, Shi A, Tan W, Yi Z and Wang X 2022. Optimizing irrigation and nitrogen management to increase yield and nitrogen recovery efficiency in double-cropping rice. Agronomy **12(5):** 1190; doi: 10.3390/agronomy12051190.