frontiers | Frontiers in Sustainable Food Systems

TYPE Review
PUBLISHED 06 March 2023
DOI 10.3389/fsufs.2023.1020570

OPEN ACCESS

EDITED BY
Dibyendu Chatterjee,
National Rice Research Institute (ICAR), India

REVIEWED BY
Surajit Mondal,
ICAR-Research Complex for Eastern Region, India
Sangita Mohanty,
Indian Council of Agricultural Research (ICAR), India

*CORRESPONDENCE
Md. Mizanur Rahman
✉ mizan@bsmrau.edu.bd

†These authors have contributed equally to this work

SPECIALTY SECTION
This article was submitted to Climate-Smart Food Systems, a section of the journal Frontiers in Sustainable Food Systems

RECEIVED 16 August 2022
ACCEPTED 08 February 2023
PUBLISHED 06 March 2023

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

Environment-friendly nitrogen management practices in wetland paddy cultivation

Mohammad Saiful Alam†, Mariam Khanam† and Md. Mizanur Rahman*†

Department of Soil Science, Bangabandhu Sheikh Mujibur Rahman Agricultural University, Gazipur, Bangladesh

A large amount of nitrogen (N) fertilizer is required for paddy cultivation, but nitrogen use efficiency (NUE) in paddy farming 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 a great challenge to increase NUE and sustain rice production to meet the food demand of the growing population. This review attempted to find out promising N management practices that might increase NUE while reducing the trade-off between rice production and environmental pollution. We collected and collated information on N management practices and associated barriers. A set of existing soil, crop, and fertilizer management strategies can be suggested for increasing NUE, which, however, might not be capable to halve N waste by 2030 as stated in the "Colombo Declaration" by the United Nations Environment Program. Therefore, more efficient N management tools are yet to be developed through research and extension. Awareness-raising campaign among farmers is a must against their misunderstanding that higher N fertilizer provides higher yields. The findings might help policymakers to formulate suitable policies regarding eco-friendly N management strategies for wetland paddy cultivation and ensure better utilization of costly N fertilizer.

KEYWORDS
reactive nitrogen, environmental pollution, use efficiency, smartphones, urea deep placement

1. Introduction

Rice is one of the vital cereal crops used as a staple food for more than half of the world's population (Fageria et al., 2003; Muthayya et al., 2014). It is crucial to increase rice production across the world to feed the growing population. To manage the situation, it has been estimated that the annual yield of rice must be increased by at least 1% (Normile, 2010). It is a great challenge to ensure food security by increasing rice yield from the land that is decreasing continuously (Jiang et al., 2016). During the last few decades, the use of nitrogen (N) fertilizers in rice production has increased tremendously. Heffer et al. (2017) reported that ~16% of the global N fertilizer is applied in rice production. The rate of N for rice cultivation in different countries varies, e.g., 65 kg N ha^{-1} in Nepal (Baral et al., 2019) and 300 kg N ha^{-1} in China (Liu et al., 2016), but the increment of rice yield is not linearly interrelated with the increased application rate of N fertilizers. Nitrogen use efficiency (NUE) in rice cultivation is only 20–50% (Chivenge et al., 2021), while the average value for grain production is less than 40% (Omara et al., 2019). It indicates ~60–80% 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. (Clark and Tilman, 2008; Guo et al., 2010; Le et al., 2010; Rahman et al., 2022a,b). Therefore, it is crucial to improve NUE for minimizing adverse environmental issues through better N management practices for sustainable rice production. In this connection, some efficient N management approaches have been endorsed throughout the world for ensuring optimum N application and better NUE. Leaf color chart, chlorophyll meter reading, controlled release N fertilizer, root zone fertilization, site-specific N management, planting N smart rice varieties, integrated use of organic and inorganic fertilizers, nitrification inhibitors, deep placement of urea, alternate wetting and drying (AWD) irrigation practices, application of N fixing blue-green algae and *Azolla*, application of N saving plant growth-promoting microorganisms, etc., have been used in different countries for increasing NUE and rice productivity. The AWD is mainly a water-saving technology, which, however, has been found positive to increase NUE (Djaman et al., 2018; Zhang et al., 2021).

However, the adoption of some emerging N management practices by farmers is a great challenge, e.g., lack of technical know-hows for using a leaf color chart and chlorophyll meter, high-cost involvement with a urease inhibitor and controlled release fertilizer, extra labor requirements for urea deep placement (UDP), and unavailability of biochar and nitrification inhibitors at farmers' level. To overcome this scenario, farmer-friendly fertilizer management approaches must be developed. Necessary steps should be taken by policymakers to make such technologies available at the farmers' level through greater extension efforts. The stakeholders should have easy access to the available resources regarding better N management practices. It was hypothesized that the existing N management tools might not be effective enough in increasing NUE while upscaling of available tools and innovation of new tools are needed. This review identified a set of available N management practices across the globe. Through a rigorous discussion of their availability and applicability in farmers' fields, and performance in terms of their efficiency, some best tools have been identified for improving NUE in wetland rice for sustainable production with minimal environmental hazards. Deliberate application of recommended N management tools in rice cultivation might increase NUE and reduce the loss of N, and ultimately contributes to climate change mitigation which ensures environmental sustainability.

2. Sources of N in rice-ecosystem

Nitrogen is the most abundant element in the atmosphere while dry air contains 78% of N_2 by volume. Though the amount of N in the atmosphere is huge but is practically unavailable for plants with the exception of legumes. Atmospheric dinitrogen is added to the rice ecosystem through the natural N fixation during lightning, thunderstorm, 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*, *Azotobacter*), and associative nitrogen fixers such as *Azolla* (Panda et al., 2019).

Organic matter is one of the important sources of soil N. The addition of organic manures from both animal and plant sources such as dung and urine of the animals, farm yard manure, green manure, bone meal, fish meal, guano, and mustard oil cake could be a good source of soil N. Crop residues from both legumes and non-legumes also contain N, but residues of the leguminous plants such as common bean (*Phaseolus vulgaris*), pea (*Pisum sativum*), soybean (*Glycine max*), chickpea (*Cicer arietinum*), groundnut (*Arachis hypogaea*), *Lathyrus* (*Lathyrus sativus*), mung bean (*Vigna radiata*), lentil (*Lens culinaris*), Pigeonpea (*Cajanus cajan*), lupins (*Lupinus*), clover (*Trifolium*), black gram (*Vigna mungo*), alfalfa (*Medicago sativa*), etc., have higher N content than residues of non-leguminous plants. The higher N content in legumes is due to their unique characteristics of N-fixing ability from the atmosphere (Stagnari et al., 2017; Islam et al., 2019; Rahman G. K. M. M. et al., 2020).

Nitrogen is considered the most limiting plant nutrient. All of the natural sources of N as well as N from the organic sources do not provide sufficient N for the satisfactory yield of rice. Therefore, the application of N element in the form of fertilizer is a common practice in rice-growing countries of the world. A number of N fertilizers are used as a source of N throughout the world where urea $[CO(NH_2)_2]$ is the major N fertilizer. Sources and losses of N in the rice ecosystem are presented in Figure 1. Nitrogen input for paddy fields may vary from one place to another, depending on management practices, climatic conditions, soil types, etc. In the middle of the Kanto Plain of Japan, Katayanagi et al. (2013) reported that N input in rice fields from fertilizer, precipitation, and biological fixation was 79.5, 8.8, and 43.0 kg N ha^{-1}, respectively. Furthermore, in Northern Japan, Takakai et al. (2017) demonstrated that amounts of N inputs from fertilizer, irrigation, precipitation, and biological fixation were 70.0, 3.0, 16.3, and 20.0 kg N ha^{-1}, respectively.

3. Rate of N use in rice culture throughout the world

The application of N fertilizers has increased several folds in many rice-growing countries of the world. For instance, in India, N fertilizer consumption in agriculture has increased from 0.44 kg ha^{-1} in 1951–1952 to 86.2 kg ha^{-1} in 2013–2014, which is ∼195 times increment in 62 years (FAI, 2015). The rate of N fertilizer consumption for rice cultivation in Bangladesh in 2006 was 104 kg ha^{-1} (Shah et al., 2008) and increased to 130 kg ha^{-1} in 2021 (Islam et al., 2022), which indicated ∼25% higher N requirement in rice in the last 15 years. The application rate of N in China for rice cultivation was 145 kg ha^{-1} in 1997 which increased to 300 kg ha^{-1} in 2006 (Liu et al., 2016). Interestingly, the N application rate was as high as 360 kg ha^{-1} in the Taihu Lake region of China (Zhao et al., 2012). The rate of N for irrigated rice in Nepal ranged from 54 kg ha^{-1} to 78 kg ha^{-1} with an average value of 65 kg ha^{-1} (Baral et al., 2019), while in Egypt, the average N application rate is as much as 270 kg ha^{-1} (Chivenge et al., 2021). The increasing trend of N fertilizer use for rice cultivation is very common in many parts of the world. Chivenge et al. (2021) reported that the rate of N fertilizer for rice cultivation from 2006 to 2014 has increased in India, Pakistan, the Philippines, Thailand, Brazil, Mexico, and Egypt. However, it is noteworthy that available data on the application rate of fertilizer

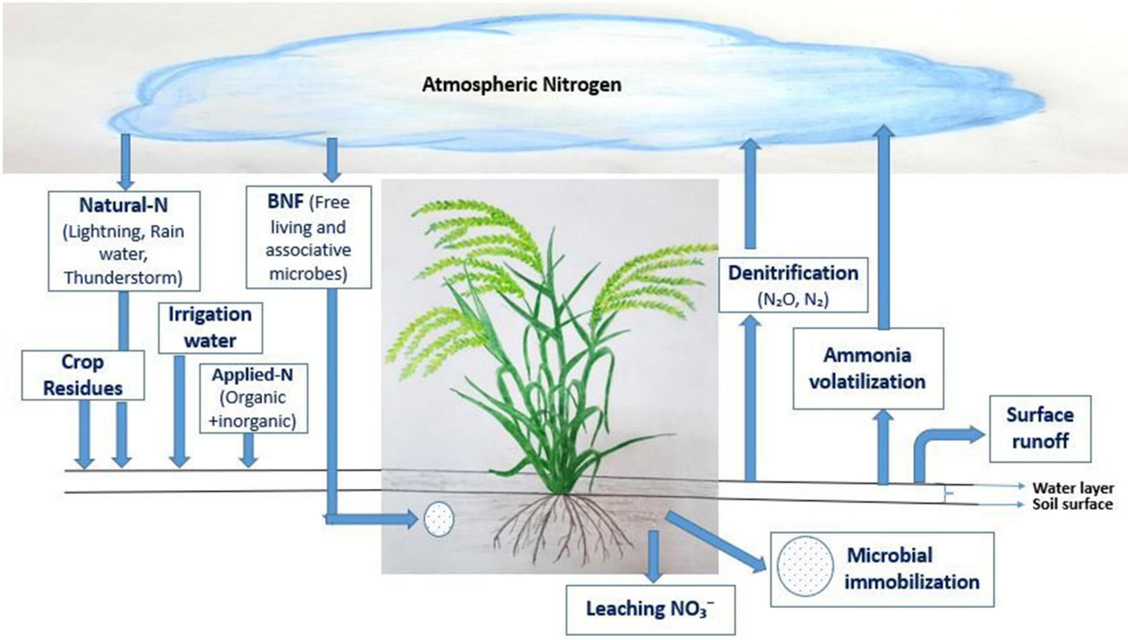

FIGURE 1
Sources and losses of nitrogen (N) in wetland rice ecosystem.

for crop production in different countries are often contradictory and unreliable (Chivenge et al., 2021). Asia is the largest contributor to the world's rice production where more than 90% of the crop is produced. Under Asian circumstances, rice is typically grown by smallholder farmers. In addition to the lack of awareness of the rice growers for balanced fertilization, higher subsidies on agricultural inputs and lower N fertilizer prices at the farmers' level led to the increased N inputs in agriculture in excess of crop requirements (Zhang et al., 2000; Ladha et al., 2005). Data regarding the N use rate for rice cultivation are presented in Table 1, indicating a huge variation among different countries. This variation might be due to different factors including price and availability of N fertilizers, climatic conditions, culture, soil types, rice varieties, yield goal, rice growing seasons, socioeconomic condition of the farmers, credit access, extension efforts, farmers' awareness, and government policy. Fertilizer adoption is also affected by the characteristics of the farmers and farm, such as age, education, gender, farming experience, and farm resources (Nkamleu and Adesina, 2000; Chianu and Tsujii, 2004).

4. Fate of applied nitrogen in wetland rice

Excess N does not necessarily increase the grain yield of rice due to its diminishing returns (Tilman et al., 2011). It has been estimated that N recovery in wetland condition seldom exceeds 30–40% (De Datta, 1995), while it is 25–30% for irrigated rice in Bangladesh (Rahman et al., 2022a). However, N utilization by the rice plant depends on a number of factors including rice genotype, soil characteristics, climatic conditions, management practices, and plant population. Most of the applied N in rice fields (60–70%) is lost in various forms of reactive N (Nr) species such as nitrate (NO_3^-), ammonia (NH_3), nitric oxide (NO), nitrous oxide (N_2O), and nitrogen dioxide (NO_2) by different processes (Panda et al., 2019). Nitrogen loss from rice soil is associated with various processes, which are presented in Figure 1. Nitrogen loss pollutes the groundwater, aquatic environments, and the atmosphere, acidifies the cultivable lands, and exerts negative effects on human and animal health. Moreover, the loss of costly fertilizers from the rice ecosystem enhances the cost of rice production.

Gaseous emission from rice fields in the form of NH_3, N_2O, and NO due to volatilization and denitrification causes serious environmental problems (Azam et al., 2002; Reeves et al., 2002). Nitrous oxide is a potent greenhouse gas that contributes to global warming and the depletion of the stratospheric ozone layer (Ravishankara et al., 2009). It has been estimated that the global warming potential of N_2O is ~298 times higher than that of CO_2 on a 100 years time scale (Myhre et al., 2013). Assuming the dynamic role of N_2O in stratospheric chemistry, it is considered one of the vital forces regulating regional and global climate change (IPCC, 2013). Nitric oxide is responsible for the creation of ozone in the troposphere that adversely affects animal health, crop production, and terrestrial and aquatic ecosystems. Acid deposition is also related to NO, as it is a precursor to nitric acid. Deposition of NH_3 and nitric acid in natural ecosystems might cause acidification, alterations in species diversity, and eutrophication (Vitousek et al., 1997; Reeves et al., 2002).

Leaching loss of N as NO_3^- causes groundwater pollution, which may result in serious health and ecological consequences. The application of higher amounts of N in soil could cause more NO_3^- leaching, resulting in a reduction of the NUE. Research

TABLE 1 Nitrogen application rate for rice cultivation throughout the world.

Sl. No.	Country/ region	N application rate (kg ha^{-1})	References
1	China	200–300	Liu et al., 2016; Chen et al., 2020
2	India	110	Chivenge et al., 2021
3	Indonesia	200–250	Widowati et al., 2011
4	Egypt	270	Chivenge et al., 2021
5	Bangladesh	120–130	Islam et al., 2022
6	South Korea	103	Lee et al., 2011
7	Philippines	78–85	PhilRice, 2017
8	Thailand	49–83	Hussain et al., 2022
9	Nepal	54–78	Baral et al., 2019
10	Pakistan	170	Chivenge et al., 2021
11	USA	170	Chivenge et al., 2021
12	Nigeria	60–80	Kamai et al., 2020
13	Vietnam	105	Chivenge et al., 2021
14	Malaysia	120	Bakar et al., 2021
15	Brazil	78	Chivenge et al., 2021
16	Mexico	175	Chivenge et al., 2021
17	Japan	60	Moritsuka, 2019
18	EU	70	Chivenge et al., 2021
19	Myanmar	33–100	Thar et al., 2021
20	World	110	Ladha et al., 2016

findings confirmed the presence of NO_3^- ions in the ground water and surface water throughout the world (Iqbal et al., 2013) at levels above the maximum permissible limit (MCL) suggested by the World Health Organization (2004). Excess amounts of NO_3^- in food and drinking water may cause health problems in humans including methemoglobinemia in infants, thyroid problems, acute respiratory infection, colon cancer, and birth defects (Bibi et al., 2016). The aquatic environment may seriously affect by the presence of excess amounts of NO_3^- ions. This Nr species may contribute to a decrease in the pH levels of the water bodies and create algal blooms in the aquatic ecosystem due to eutrophication (Bibi et al., 2016).

Nitrogen loss from paddy fields differs greatly due to differences in soil types, precipitation patterns, crop growth stages, management strategies, particularly fertilizer, irrigation management practices, etc. (Liang et al., 2013; Yang et al., 2013; Das and Adhya, 2014; Zhang et al., 2018). Data presented in Table 2 disclose that ammonia volatilization and leaching are the major pathways of N loss from the paddy field. Qi et al. (2020) showed that continuous flooding irrigation and local common N fertilization practice (180 kg N/ha) in the Jianghan Plain of China resulted in 19.38 kg N loss due to leaching. Yang et al. (2013) reported that under traditional flooding, irrigation along with farmers' fertilization practice management (324.6 kg N/ha) displayed 68.2–71.7 kg/ha N loss as NH_3 volatilization. Loss of N in the form of N_2O emission varies greatly due to manure application, fertilizer rate, and irrigation management practices (Table 2).

5. Eco-friendly nitrogen management practices

Globally, more than half of the N fertilizer is applied to three major cereal crops *viz.*, wheat (*Triticum aestivum)* 18%, maize (*Zea mays)* 17%, and rice (*Oryza sativa)* 16% (Heffer et al., 2017). In addition, NUE at the global level is estimated to be <40% (Omara et al., 2019), confirming that a major portion of applied N (60%) remains unused (Dobermann, 2000; Ladha et al., 2005). Therefore, it is very crucial to improve NUE in rice-based agro-ecosystems (GRiSP, 2013). Though it is a great challenge to ensure efficient fertilizer management under a smallholder farming system, various N management approaches have so far been advocated to ensure higher NUE in rice cultivation (Figure 2).

5.1. Soil test-based fertilization

Soil test-based (STB) fertilization ensures a higher NUE. The STB approach is an important component of the 4R strategy for nutrient management, i.e., 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., 2020). It has been recognized that sustainable N management in the soil largely depends on soil analysis (Nair, 2018). This approach offers a number of economic, agronomic, and environmental benefits. The STB approach ensures appropriate doses of fertilizers, optimizes production cost, enhances yield and quality of crops, and reduces nutrient loss to water and the atmosphere to a greater extent. The STB fertilization program can be linked with the cropping system-based soil health card (SHC) program for the farmers. The SHC remains viable for 3–5 years and then again soil from the farmers' field needs to be analyzed, and a new SHC is issued. Planned utilization of SHC might increase NUE.

Singh et al. (2021) reported that STB fertilizer application in rice enhances productivity and profitability, as well as NUE. In their experiment, they showed that STB fertilization produced a higher grain yield of rice (4.2 t ha^{-1}) as compared with the standard recommended fertilizer dose (3.75 t ha^{-1}) and farmer's practice (FP) (3.18 t ha^{-1}). Similarly, NUE in STB was found higher than that of FP treatment. Agronomic efficiency (AE) in STB was 9.1, while the value was 6.1 in FP. The apparent recovery efficiency of N (AREN) and the reciprocal internal use efficiency of N (RIUEN) were also higher in STB than that of the FP treatment. In the STB treatment, the AREN and RIUEN values were 23.5 and 13.77, respectively, whereas the values were 19.1 and 12.83, respectively, for the FP treatment.

It has been reported that basal application of a full dose of N fertilizer enhances N losses to a greater extent through volatilization resulting in a lower NUE (Blandino et al.,

TABLE 2 Amount of nitrogen losses (kg/ha) from paddy field.

Nature of N loss	Amount (kg/ha)	Management practice	References
Runoff (NH_4^+-N)	2.7	Continuous flooding irrigation and local common N fertilization practice	Qi et al., 2020
Runoff (NO_3^--N)	1.16	Continuous flooding irrigation and local common N fertilization practice	Qi et al., 2020
Runoff (dissolved organic N (DON)	2.21	Continuous flooding irrigation and local common N fertilization practice	Qi et al., 2020
Leaching (NH_4^+-N + NO_3^--N + DON)	19.38	Continuous flooding irrigation and local common N fertilization practice	Qi et al., 2020
NH_3 Volatilization (NH_3-N)	68.2–71.7	Flooding irrigation + farmers' fertilization practice management (FFP)	Yang et al., 2013
N_2O emission	2.86–3.27	Traditional flooding irrigation + N application rate 300 kg/ha	Zhang et al., 2018
N_2O emission	2.49–2.69	Traditional flooding irrigation + N application rate 240 kg/ha	Zhang et al., 2018
N_2O emission	0.76	Urea (120 kg N/ha)	Das and Adhya, 2014
N_2O emission	0.67	Compost (30 kg N/ha) + Urea (90 kg N/ha)	Das and Adhya, 2014

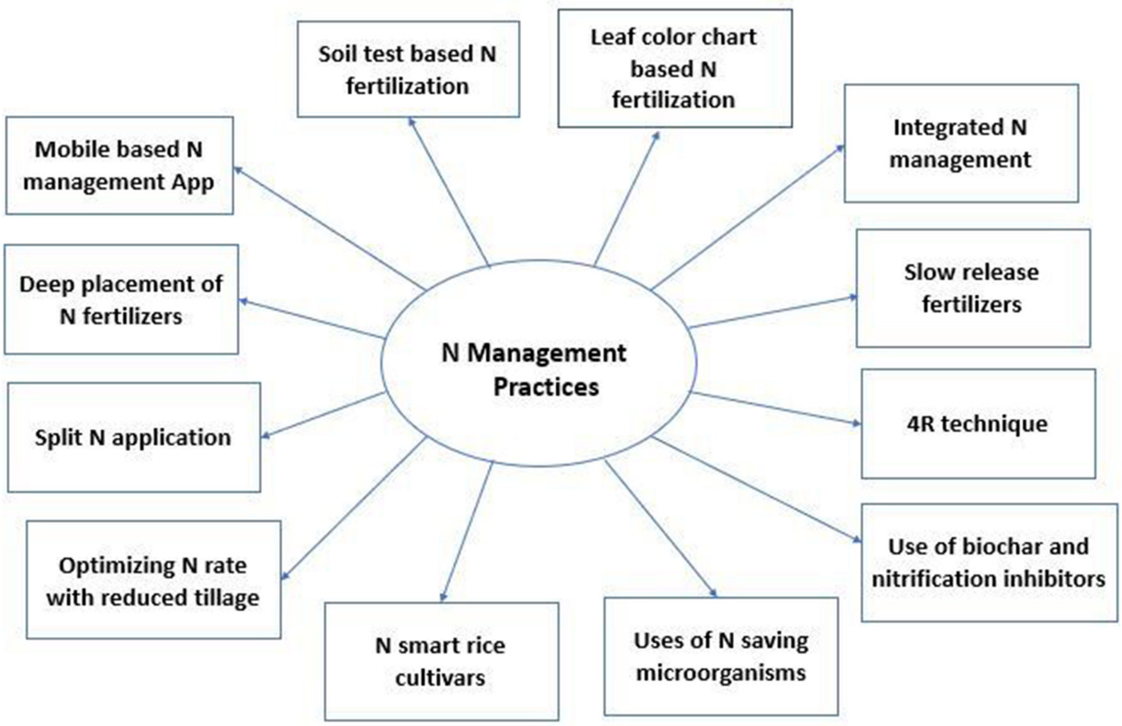

FIGURE 2
Nitrogen management practices for wetland rice.

2015). On the contrary, split application of N fertilizer ensures the availability of the nutrient based on the crops' demand during the whole growing season. Research findings indicate that three splits of N application are effective for achieving higher yield and better NUE in rice. Kaushal et al. (2010) reported that three splits of N fertilizer at planting, tillering, and panicle initiation stages ensure higher benefits for getting a higher grain yield from the modern rice varieties.

5.2. Site-specific nitrogen management

Most of the fertilizer management approaches 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 nitrogen management (SSNM) technique was introduced to enhance NUE in wetland rice (Dobermann et al., 2002). The SSNM approach considers several factors while calculating the proper N requirement for the crop.

The factors include nutrient demand of a crop, desirable yield goal, climatic conditions (temperature and solar radiation), N supply from soil, irrigation water, mineralization of crop residues, and other organic materials (Peng et al., 2010; Panda et al., 2019). Quantification of the availability of indigenous N source for a specific site is very important, which commonly differ from one site to another (Panda et al., 2019). Therefore, the N recommendation would vary from site to site. Field experimentation considering SSNM-based N fertilization in wetland rice grown in some parts of South Asia showed 30–40% higher NUE (Dobermann et al., 2002). Sarkar et al. (2017) reported that the SSNM approach in India increased rice yield by 12% and profitability by 14%. Peng et al. (2010) observed a 61% higher agronomic efficiency of nitrogen in rice cultivation in China under the SSNM method compared with farmers' practice. The SSNM method is an efficient method of optimizing fertilizer rates, and thus, the approach can reduce greenhouse gas emissions by up to 50% (Richards et al., 2015). In the rice-based cropping systems of Indo-Gangetic Plains, Singh et al. (2015) found an increased nitrogen harvest index of 6.1–18.1 under the SSNM method compared with the farmers' practice. The results presented in Table 3 indicated that SSNM could increase NUE from 31% to 40% when compared with farmers' N practices, in addition to the 5% increase in rice grain yield. Peng et al. (2010) further confirmed a 32% reduction of N fertilizer in the SSNM technique compared with farmers' practice. Under Indian conditions, Mishra et al. (2006) appraised the performance of the SSNM approach and confirmed the increase of rice grain yield from 6.22 to 6.80 Mg ha^{-1} when compared with farmers' fertilizer practice (FFP). Their findings further revealed that SSNM could save ∼41 kg N ha^{-1} in rice.

5.3. Leaf color chart and chlorophyll meter-based N management

The leaf color of a crop is closely related to the N concentration of the leaf (Wang et al., 2014). Farmers normally like to keep the dark green color of their crop's leaf, 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 International Rice Research Institute (IRRI) in collaboration with the Philippine Rice Research Institute introduced an LCC to ensure the appropriate time of N application in the rice field (Bhat et al., 2017). The leaf color of a standing rice crop is compared with the color of the LCC strip. By observing the greenness of rice leaves, farmers can understand when to apply N fertilizer to their fields (Bhat et al., 2017).

The LCC-based N fertilization in rice significantly increases NUE as well as reduces the application of N fertilizers without compromising the grain yield (Table 3). Singh et al. (2002) reported that the LCC-based N management approach could save 10–30 kg N ha^{-1} without any significant loss of rice grain yield as compared with the fixed-time N application approach. 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^{-1}) at LCC ≤4 decreased CH_4 emission by 11% and N_2O emission by 16% as compared with 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 with 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. Nitrogen is applied to the rice field at a specific rate only when the leaf N content (measured as SPAD value) is lower than the critical limit (Singh et al., 2010). The method allows less N application to achieve the targeted yield of rice. Ghosh et al. (2020) conducted a field experiment in two consecutive wet seasons of 2010 and 2011 in the eastern part of India to optimize SPAD values for achieving better NUE under the rice–wheat cropping pattern. They confirmed that chlorophyll meter SPAD-based N management practices increase 58.5% agronomic N use efficiency (AE_N) and 32.2% N recovery efficiency (RE_N) over the fixed time N management (FTNM) practice. The higher NUE (AE_N and RE_N) under chlorophyll meter SPAD-based N management approach might be accredited to the crop's need-based availability of N. The application of N fertilizer based on SPAD value could save a substantial amount of N (33.3%) in rice cultivation than that of the conventional N management without hampering the grain yield (Ghosh et al., 2020). Therefore, chlorophyll meter-based N management practice in wetland rice culture is promising for better NUE.

5.4. Controlled-release N fertilizer

The recent development of the controlled-release urea (CRU) application technology can ensure higher crop yields and NUE because CRU reduces N loss through various processes including surface run off, NH_3 volatilization, leaching, and N_2O emission (Ji et al., 2013; Chalk et al., 2015; Ke et al., 2017; Li et al., 2017). Controlled-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 (Guertal, 2009; Wang et al., 2018; Chen et al., 2020; Sireesha et al., 2020; Sun et al., 2020). The function of controlled-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 of time as compared with normal fertilizers (Kaplan et al., 2013; Azeem et al., 2014).

Data presented in Table 3 reveal that the application of CRU in rice fields dramatically increased the NUE than that of the conventional urea without compromising the grain yield. Li et al. (2017) observed a noticeable increment of apparent N recovery and rice grain yield by 3–17% and 6–18%, respectively, when compared with the application of the same dose of conventional urea. Tian et al. (2021) reported that the application of 80% controlled-release N fertilizer (CRNF) in rice provided higher AREN and grain yield as compared with the full dose of urea fertilizer in China. They further showed that CRNF decreased the cumulative NH_3 volatilization for early- and late-season rice by 20–43% and

TABLE 3 Nitrogen use efficiency (NUE) under different management practices.

Sl. No.	Management practice	NUE related benefits	Other benefits	Country	References
01.	Deep Placement of N fertilizer	a. Root Zone Fertilization (RZF) significantly enhanced rice NUE according to the difference method (1.8 times higher on average) and by the ^{15}N labeled method (3.0 times higher on average) as compared to the Farmer Fertilizer Practice (FFP)	Rice yield and total N accumulation of RZF increased by 4.3 ± 44.9% and 12.7 ± 111.2% compared to FFP, respectively. RZF reduced fertilizer N loss by 56.3 ± 81.9% compared to FFP.	China	Liu et al., 2016
		b. Urea super granule (USG) at 78 kg N ha-^{1} produced a higher NUE of 28.88%, while prilled urea at 130 kg N ha-^{1} showed 17.55% NUE.	Yield of rice under 78 kg N ha-^{1} as USG (5.44 t ha^{-1}) is comparable with the yield (5.54 t ha^{-1}) obtained from 130 kg N ha-^{1} as prilled urea	Bangladesh	Shaha et al., 2018
02.	Site-specific N management (SSNM)	SSNM could enhance NUE from 31 to 40% when compared with farmers' N practices	SSNM increased grain yield by 5% compared with farmers' N practices	China/Asian sites	Peng et al., 2010
03.	Controlled release urea (CRU)	a. Compared to the application of conventional urea, application of CRU (resin-coated and polyurethane-coated urea) increased N agronomic efficiency (NAE) and N partial factor productivity (NPFP) by 17.4–52.6% and 23.4–29.8% at Lincheng site, and 15.0–84.1% and 23.2–33.4% at Xintang town sites, respectively.	The N rate in the CRU treatment was reduced by 20% as compared to traditional urea without affecting the grain yield of rice.	China	Chen et al., 2020
		b. Neem-coated urea (NCU) increases NUE as compared to the traditional prilled urea. NUE in 125% NCU (3 split) was 33.01 % followed by 100% NCU (3 split) 32.59%, 75% NCU (3 split) 29.41% and 100% prilled urea 20.68%.	Grain yield of rice was increased 14% in 100 % NCU (3 split) when compared with 100% prilled urea (3 split)	India	Sireesha et al., 2020
04.	Leaf color chart (LCC) based N management	Average partial factor productivity of N for nine rice genotypes in LCC was 102 and in farmer's practice the value was only 62.	19–37 kg N /ha could be saved over different rice genotypes from LCC-used plots than that of the farmers practice without scarifying the grain yield.	Bangladesh	Haque et al., 2003
05	Chlorophyll meter-based N management	SPAD value-based N management increased the agronomic N use efficiency by 58.5% and AREN by 32.2% in rice as compared to the conventional one fixed time nitrogen management (FTNM).	N management through chlorophyll meter (based on SPAD value) could save 33.3% N in rice as compared to the traditional N management.	India	Ghosh et al., 2020
06	Nitrification inhibitors	Use of 2-chloro-6-(trichloromethyl)-pyridine (CP) as nitrification inhibitor significantly ($p < 0.05$) increased NUE in rice by 16 and 29% in 2012 and 2013, respectively when 180 kg N ha^{-1} was applied	Application of 180 kg N ha^{-1} + CP increased grain yield of rice by 10% in 2012 and 17% in 2013 when compared with 180 kg N ha^{-1} alone, and attained the same yield as 240 kg N ha^{-1}	China	Sun et al., 2015
07	Crop rotation with legumes	AREN for rice ranged from 13.3 to 32.5% under pulse-legume crop rotation, while the value ranged from 9.8 to 16.3% in corn-rice rotation and 13.3–25.5% in fallow-rice rotation system.	13–23% higher grain yield of rice was obtained from winged bean -rice rotation system as compared to fallow-rice rotation with 8 g N m^{-2}.	Malaysia	Rahman et al., 2014
08	Azolla	As compared to the farmers' nitrogen (FN) treatment, 15% N reduction from FN + Azolla cover (RN15A) and 30% N reduction from FN + Azolla cover (RN30A) considerably increased apparent AREN by 46.5 and 39.1%, respectively in rice cultivation.	RN15A and RN30A reduced yield-scaled volatilization by 52.3 and 64.3% than for FN. rice yield for RN30A was comparable to the FN, while a higher grain yield was attained from RN15A as compared to FN.	China	Yang et al., 2021
09	Cyanobacteria	The average NUE of conventional full application of urea (N10C0) was 34.7%, whereas the value for cyanobacteria + 50% urea of the conventional rate (N5C5) was 47.7%, which was 37.5% higher as compared to N10C0.	Total dissolved nitrogen leaching was reduced by 37.2 % in N5C5 as compared to N10C0 treatment.	China	Song et al., 2021

TABLE 4 Reduction of N loss under different management practices.

Sl. No.	Management practice	Reduction of N loss	References
01.	Controlled release N fertilizer (CRNF)	As compared to the application of conventional urea, CRNF could reduce the cumulative NH_3 volatilization for early and late season rice by 20–43% and 20–32%, respectively.	Tian et al., 2021
02.	Legume-based cropping system	Run-off loss of N was decreased by 30–60% in rice-vetch and rice-bean cropping systems when comparing with rice-wheat rotation.	Yu et al., 2014
03.	AWD irrigation	Surface run-off was decreased by 19–57% in AWD practice as compared to the CF.	Ye et al., 2013
04.	Tillage practices	N_2O emission was reduced by 3–6% in RT than the ZT	Kar et al., 2021
05	Starch-coated urea (SCU) and neem-coated urea (NCU)	12–21% reduction of N_2O emission in SCU and NCU treatment as compared to conventional urea.	Bordoloi et al., 2020
06	Integrated nutrient management (INM)	Urea+ organic manure treatment reduced N_2O emission by 11–24% than that of the urea treatment.	Mohanty et al., 2020
07	Reduction of N application	25% reduction of N application resulted in 6% reduction of N_2O emission without reducing grain yield of rice.	Bordoloi et al., 2019
08	Urea deep placement (UDP)	As compared to the broadcasting method, UDP reduced 8–46% N_2O emission.	Datta et al., 2017
09	Nitrification inhibitors	Urea+DCD reduced 9-42% N_2O emission as compared to urea alone	Majumdar et al., 2001
10	Biochar	Application of biochar in the rice field reduced NO_3^- -N leaching by 30–39% and NH_3 volatilization loss by 12–18%.	Chen X. et al., 2021
11	Azolla	Urea+Azolla reduced N_2O emission by 27.13% as compared to the recommended dose of N.	Malyan et al., 2019
12	Rice cultivars	Rice variety IR 64 was found to reduce 34% N_2O emission.	Gorh and Baruah, 2019

20–32%, respectively, as compared with the conventional urea (Table 4).

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% of NCU increased NUE (32.59 %) when compared with 100% of prilled urea (20.68 %). In addition to NUE, the grain yield of lowland rice was increased by 14% in 100% NCU in comparison with 100% prilled urea. Conducting research with eco-friendly NCU in wetland transplanted rice cultivation, Shivay et al. (2001) showed that NCU increased NUE and rice grain yield.

Sulfur-coated and polymer-coated urea are very promising controlled-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 yields by 55–68% and N absorption by up to 39.4% (Khan et al., 2015), and doubled N recovery over prilled urea (Xin et al., 2017). Li et al. (2018) noticed a reduction of 8–58% N surface runoff and 23–62% in ammonia volatilization for polyurethane-coated urea and degradable polymer-coated urea compared with uncoated urea. They further reported a 3–34% increase in NUE and a 3–55% increase in N uptake by rice plants for controlled-release urea compared with uncoated urea.

5.5. Reducing N loss with conservation tillage

Conservation tillage, e.g., minimum tillage (MT) and no-till (NT), ensures crop residue incorporation into the soil and is found effective in soil and water conservation (Jordán et al., 2010; Rahman et al., 2017). Nitrogen dynamics in the soil are greatly influenced by tillage systems (Bibi et al., 2016). Conventional tillage (CT) induces aerobic condition, which enhances the decomposition of crop residues and other organic materials 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 an important role in improving NUE and decreasing N loss to the environment. The effectiveness of conservation tillage depends on many factors *viz*., geographical regions, climatic conditions, soil types, and cropping systems (Wang et al., 2015). 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 favor of it (Xiao et al., 2007; Nayak et al., 2013; Qin et al., 2022). For example, Qin et al. (2022) in China found that the average NUE under ridge tillage (RT) was 31% which was 14% and 11% higher as compared with the CT and flooded paddy field (FPF), respectively. As ridges are formed above the water surface, this may contribute to reducing the loss of N. Therefore, the NUE is attributed to the RT system.

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). The reduction of CH_4 emission from the rice field under reduced tillage is well-reported by several researchers (Harada et al., 2007; Ahmad et al., 2009), but contrasting effects of reduced tillage on N_2O emission from rice fields have also been documented. The less N_2O emission was observed from NT rice fields than that of CT (Liang et al., 2007; Xiao et al., 2007). In contrast, some researchers confirmed that N_2O emission could be increased from rice fields under the NT system as compared with the CT practice (Nyamadzawo et al., 2013; Zhang et al., 2013). The contrasting findings regarding N_2O emission under the same tillage practice might be due to the duration of the NT system, management practices, soil types, and the climatic condition of the experimental site (Liang et al., 2016). Bordoloi et al. (2019) optimized the N rate with tillage practices to find out their effect on NUE, N_2O emission, and grain yield under the summer rice ecosystem. From their findings, they confirmed that a 25% reduction of N fertilizers in both RT and CT resulted in higher NUE and reduced N_2O emission without affecting the rice yield.

5.6. Use of nitrification inhibitors and biochar

Nitrification inhibitors (NI) are widely used throughout the world to enhance NUE in various crops including rice. The application of NI 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 (CP), 3,4-dimethylpyrazole phosphate (DMPP), and [methyl 3-(4-hydroxyphenyl) propionate (MHPP)] have gained significant consideration in recent years (Razzak et al., 2012; Guo et al., 2013; 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. Different NIs ensure a continuous and uninterrupted supply of N for crops. The application of NIs enhances N content in rice grains, straw, and post-harvest soil. Sun et al. (2015) evaluated the influence of NI *viz*., 2-chloro-6-(trichloromethyl)-pyridine (CP) on NUE, rice grain yield, and N losses in China and found that NI in combination with 180 kg N ha^{-1} significantly increased NUE by 16–29% as compared with the sole application of 180 kg N ha^{-1}. They further showed that CP+ 180 kg N ha^{-1} and 240 kg N ha^{-1} treatments were performed equally to produce rice yield. Thus, the application of NI saved 60 kg N ha^{-1} from rice cultivation (Table 3). NIs have so far been well-recognized to reduce N_2O emissions from the rice fields due to their positive effects on lowering the availability of substrate (NO_3^-) for denitrification (Malla et al., 2005; Datta and Adhya, 2014; Sun et al., 2015). Malla et al. (2005) reported a 4–34% reduction of N_2O emissions from the rice fields of New Delhi, India, with the use of NIs.

Biochar, a kind of carbon-rich organic material produced from any organic biomass through pyrolysis, *i.e.*, under limited oxygen and high temperature (400–550°C), is found to be efficient for enhancing NUE (Rahman G. K. M. M. 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 has the capacity to 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 recommendation on the rates of biochar application to crop fields is not available. However, with proper nutrient and other crop management, the use of biochar (5–50 t ha^{-1}) was found positive in terms of soil health improvement and crop productivity (Major, 2010). The application of rice straw biochar (22.5 t ha^{-1}) in combination with urea fertilizer increased rice yield by 11.3–14.4% as compared with the sole application of urea (Dong et al., 2015). Chen X. et al. (2021) found 15.53% and 24.43% higher rice yield with the application of 20 t ha^{-1} and 40 t ha^{-1} biochar, respectively, as compared with the non-biochar applied rice fields. The higher yield of rice grain in the biochar-added fields might be associated with higher soil nutrient retention ability, higher cation exchange capacity, and better soil fertility (Gao et al., 2016; Zhang et al., 2019; Zheng et al., 2020). A number of previous studies indicated that biochar application could reduce the N_2O emissions from rice fields (Wang et al., 2011; Yang et al., 2020). Liu et al. (2014) observed that the application of biochar (4% w/w) reduced N_2O fluxes by 36–52% compared with the control (without biochar) treatment. Reduced N_2O emission with biochar application is interlinked with the inhibition of nitrification as well as denitrification (Gupta et al., 2021). The application of biochar in soil is also reported to enhance microbial immobilization of N which may decrease N loss through different processes including N_2O emission (DeLuca et al., 2006). The results presented in Table 4 showed that the application of biochar could reduce NO_3^--N leaching by 30–39% and NH_3 volatilization loss by 12–18% from the rice field.

5.7. 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 cost, and minimizes energy consumption in agriculture (Dwivedi et al., 2016; Panda et al., 2019; Afrad et al., 2021, 2022a,b). The partial factor productivity of applied N (PFPN) in rice ranged from 26 to 52 kg grain kg^{-1} N for recommended dose (RD) of NPK, whereas the value increased to 33–77 kg grain kg^{-1} N for 75% of RD + 25% N from FYM (Dwivedi et al., 2016). This management further reduces 25% N application in the subsequent dry season of rice. AREN of applied N in rice is also positively influenced by the INM practice. Singh et al. (2012) found 61.7% AREN under the NPK+FYM treatment, which is much higher as compared with the NPK treatment alone (44.4%). 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 t ha^{-1} over the sole application of NPK (Panda et al., 2019). Lakshmi et al. (2012) found that the application of 75% RD along with 2.5 t ha^{-1} vermicompost provided a higher NUE and grain yield of rice when compared with 100% sole RD. It is noteworthy that INM practice ensured higher NUE and rice grain yield in the second year of the experiment as compared with the first-year experiment which might be attributed due to the continuous supply of N from the organic part of the INM practice as well as residual effects (Lakshmi et al., 2012). 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.

5.8. Inclusion of legumes in the cropping system

The inclusion of legume crops in any cropping system ensures the reduction of synthetic fertilizer, water, and associated energy use and improves soil fertility (Rahman et al., 2022c). Legumes could fix atmospheric inert N_2, making association with the symbiotic bacteria, *Rhizobium*. The research findings indicate that BNF through legume–*Rhizobium* symbiosis could fix a substantial amount of N. For example, alfalfa (*Medicago sativa* L.), cowpea (*Vigna unguiculata*), and groundnut (*Arachis hypogaea*) could fix 465, 201, and 101 kg N ha^{-1}, respectively (Dakora et al., 1987; 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., 2022c). In addition to other nutrients in the soil, the decomposition of legume residues and root nodules provides a considerable amount of N, thereby lessening the N requirement for the next crop (Pikul et al., 2008). The addition of legume crops either as green manuring crops or grain legumes in rotation with cereals conserves soil fertility and improves soil structure and moisture-holding capacity (Kumar and Goh, 1999; Goh et al., 2001; Russell et al., 2006). Therefore, the inclusion of legumes in the rice-based cropping system could play a vital role in better rice production with less N application. Rahman et al. (2014) reported a variable range of AREN, e.g., 19.6–29.5%, 19.6–29.4%, 20–28.8%, and 13.3–32.5% in bush bean-rice, long bean-rice, mung bean-rice, and winged bean-rice crop rotation, respectively, whereas the values were 9.8–16.3% and 13.3–25.5% for corn-rice and fallow-rice crop rotation, respectively. The inclusion of legume crops in the rice-based cropping systems might play effective roles 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 cropping systems increased the grain yield of rice by 5 and 10% in 2010 and 2011, respectively, as compared with the rice–wheat rotation system. Legume-based cropping systems increased 9.7–20.5% of N content in rice residues and decreased run-off loss of N by 30–60% when compared with rice–wheat rotation (Table 4). 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., 2022c). Thus, the inclusion of legumes in the rice-based cropping system brings tremendous benefits in terms of NUE, grain yield, soil fertility status, and environmental protection.

5.9. Deep placement of N fertilizer

Deep placement of N fertilizers is an effective and eco-friendly technique to enhance NUE. It also increases rice grain yield under minimum environmental consequences. The application of urea fertilizer in the form of urea super granule (USG) or NPK briquette in the rice field is a popular and successful practice in south Asian countries, especially in Bangladesh. Root zone application of N fertilizer is being practiced in some rice-producing countries, particularly in China. Deep placement of N fertilizer 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 (Kapoor et al., 2008; Gaihre et al., 2015). Previous studies conducted in the 90s showed that deep placement of N fertilizers, particularly the USG increased NUE (31.7%) when compared with the traditional application method of prilled urea (Jaiswal and Singh, 2001). A very recent study conducted by Chen Y. et al. (2021) confirmed that the application of N fertilizer at both 12 and 8 cm depth considerably increased the rice yield by 81.84 and 72.91%, respectively, as compared with the 0 cm depth of N application. They further showed that AREN and AEN were 129.45 and 165.42 % higher, respectively, at 12 cm application depth as compared with the 0 cm application depth. Similar findings were also reported by some other researchers (Table 3). Liu et al. (2015) observed that deep placement of N fertilizer in 10 cm soil remarkably increased NUE and rice grain yield due to reduced average floodwater NH_4^+-N concentration compared with the conventional broadcasting application of N fertilizer. In terms of N losses, recent studies reported that deep placement of urea in the rice field could suppress 91% NH_3 volatilization loss (Yao et al., 2018) and 8–46% N_2O emission as compared with surface broadcasting (Table 4).

Under the deep placement or root zone application of N fertilizer, N is applied into the anaerobic layer of puddled soil which restricts the volatilization loss of N as NH_3 (Hoque et al., 2016). Reduced N loss coupled with better NUE from deep placement of nitrogenous fertilizers might enhance the higher grain yield of wetland rice. To popularize this effective method of N fertilizer application, it is a prerequisite to overcome some constraints regarding the application of USG in developing countries such as Bangladesh. The hand placement method of USG requires more labor and cost, which is also time-consuming and tedious work and sometimes causes back pain (Hoque et al., 2016). Therefore, farmers are reluctant to adopt the method as compared with the traditional broadcasting method of urea application. To attain full benefits in terms of grain yield and environmental protection from USG application, efforts should be taken to develop a low-cost, efficient, and farmer-friendly USG applicator to place the fertilizer at an appropriate depth.

5.10. Improved manure management

Manures of both plant and animal sources bear great potential to enhance crop production and sustain soil fertility (Adekiya et al., 2019; Akhtar et al., 2019; Khanam et al., 2022; Salma et al., 2022). Manure reduces the use of inorganic fertilizers in crop production and lessens the detrimental effects on air, water, and soil environment (Iqbal et al., 2020). 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 (Rahman et al., 2015; Barua et al., 2018; Iqbal et al., 2020; Rahman M. M. et al., 2020; Ali et al., 2021; Hasnat et al., 2022). Manure application to the soil following the conventional method is a vital source of atmospheric NH_3 (Webb and Misselbrook, 2004). Therefore, improved manure management is crucial to maximizing the utilization of manure N by crops with minimum environmental hazards. Manure management should be started from the collection and storage period. For ensuring better manure quality, it is important to keep the stable floor clean and to keep a lid on the manure tray which will reduce N loss from the manure as gaseous compounds, particularly as 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 (Huther, 1988; Webb et al., 2010). The conventional method of manure application on soil surface may favor the entry of manure into the waterbodies through surface run-off (Uusi-Kamppa and Heinonen-Tanski, 2001). 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 plowing (Webb et al., 2010). In the case of the 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.

5.11. 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 (Midya et al., 2021; 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 emission, and enhance N recovery without affecting the grain yield of rice (Liu et al., 2013; Lampayan et al., 2015; Gupta et al., 2021). AWD practice could save 38% of irrigation water without hampering the grain yield of rice (Lampayan et al., 2015). Islam et al. (2016) confirmed a 16% increase in rice yield under AWD irrigation over conventional continuous standing water (CSW) irrigation. Many researchers confirmed higher root biomass and N recovery in AWD systems than that in CSW conditions (Dong et al., 2012; Liu et al., 2013; Ye et al., 2013). Compared with CSW water management practice, AWD improves AEN, partial factor productivity of N (PFPN), and AREN by 6.1, 5.7, and 5.1% in 2010 and 8.9%, 6.9, and 6.1% in 2011, respectively (Ye et al., 2013). Moreover, surface run-off in AWD practice decreased by 57.9% in 2010 and 19.1% in 2011 as compared with the CSW. 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 with traditional flooding in the rice field (Towprayoon et al., 2005; Hadi et al., 2010; 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 with traditional irrigation management.

5.12. Android-based N management apps

The smartphone is one of the miracle inventions of science which is an integral part of daily life. Recently, the smartphone has gained popularity as a tool in agriculture farming (Pongnumkul et al., 2015). At present, the number of smartphone users in the world exceeds 6.56 billion, and it is projected that by the next 5 years, the number of users will be increased to 7.69 billion (Statista, 2022). 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. The number of internet users in the world was only 0.41 billion in 2000, but it increased to 4.3 billion in 2016 (Roser et al., 2015). Smartphones with internet facilities can be used to document soil nutrients, calculate fertilizer and water requirements for crops, forecast weather and 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 demanding.

5.13. 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 fixation and production of plant growth-enhancing phytohormones. Therefore, the utilization of plant growth-promoting bacteria would reduce the use of costly and energy involving 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

TABLE 5 Reduction of inorganic nitrogen in rice cultivation through biological approaches.

Approach	Benefits	Experimental site	References
Azolla	a. Culture of *Azolla* in rice field could reduce 50–100 kg N ha^{-1} (15–30% of the farmers' N rate) having no significant decrease of grain yield.	China	Yang et al., 2021
	b. Application of *Azolla* in rice field along with 75% of recommended N provided same amount of yield with the recommended 120 kg N ha^{-1}.	India	Malyan et al., 2019
Plant-growth promoting microorganisms	a. Application of a microbial consortium (a *Pseudomonas*, two bacilli and a soil yeast) significantly enhanced NUE by rice, saving 43 kg N ha^{-1} with an additional rice yield of 270 kg ha^{-1}.	Vietnam	Cong et al., 2009
	b. About 50% reduction of NPK fertilizers could be attained with the application of both *Pseudomonas aeruginosa* and *Burkholderia* sp. without hampering the growth and yield of rice.	Bangladesh	Khan et al., 2017
	c. Inoculation of bacterial isolates AG15 (*Burkholderia* sp.), AC32 (*Herbaspirillum* sp.), UR51 (*Azospirillum* sp.) and CA21 (*Pseudacidovorax* sp.) with half of the N fertilizer showed similar growth of rice plants to those that received 100% N fertilizer without inoculation.	Brazil	de Souza et al., 2013
	d. When compared with 100% N fertilizer, combination of three bacterial isolates (*Bacillus aryabhattai, Burkholderia ambifaria*, and *Sphingobium yanoikuyae*) along with 25–50% N in rice culture produced comparable yield of rice.	Taiwan	Kobua et al., 2021
	e. Inoculation of *Rhizobium* in rice cultivation could save one third of the recommended dose of N fertilizer without sacrificing the grain yield.	Egypt	Elekhtyar et al., 2015
	f. Inoculation of rice plant with *Azospirillum* and *Azotobacter* could save 20 kg N ha^{-1} with extra grin yield of 1.34 t ha^{-1} and 1.24 t ha^{-1}, respectively.	Bangladesh	Sattar et al., 2008
BGA/cyanobacteria	a. Rice yield increased significantly due to the inoculation of cyanobacterial isolates along with 30 kg N ha^{-1} as compared to 40 kg N ha^{-1} without BGA isolate, demonstrating 25% saving of N fertilizer.	Bangladesh	Sattar et al., 2008
	b. Nitrogen fixing cyanobacteria could replace half of the conventional rate of urea fertilizer demonstrating no significant reduction of rice grain yield.	China	Song et al., 2021

significantly. Such bacteria possess unique characteristics which enhance crop yield as well as lessen the usage of agrochemicals 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 to reducing nitrogenous fertilizers in rice fields (Dobbelaere et al., 2003). Plant-associated effective microorganisms enhance the ability of the plants to use N fertilizer efficiently and reduce the loss of Nr to the environment. The application of plant growth-promoting microorganisms in combination with inorganic N fertilizer would reduce the requirement for N fertilizers without reducing the growth and yield of rice (Table 5). The utilization of suitable and efficient bacterial strains with a reduced dose of N fertilizer may produce higher grain yields of rice. Khan et al. (2017) reported that the utilization of *Burkholderia* sp. (isolate BRRh-4) and *Pseudomonas aeruginosa* (isolate BRRh-5) with a 50% reduced dose of recommended NPK fertilizers could increase the grain yield of rice by 5 and 17%, respectively, compared with 100% recommended dose of NPK fertilizers. Research findings suggested that the application of a single strain of microorganism or a combination of two or more microorganisms as consortia in rice culture would be beneficial in terms of N fertilizer saving and yield increment of rice (Table 5). Therefore, it is urgent to make rice farmers aware about the benefits of this eco-friendly approach so that the farmers can integrate the utilization of PGPB with the conventional rice cultivation method for the sustainability of the production system and the environment.

5.14. *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 for achieving increased NUE, reducing N loss, and maintaining grain yield in an intensively fertilized rice cultivation system (Deng et al., 2012; Qiao et al., 2012; 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 (Malyan et al., 2019; Yang et al., 2021). It has been reported that the application of *Azolla* in the rice field along with urea fertilizer could reduce N_2O emission by 27.13% more than that of the RD of N (Table 4). Findings presented in Table 5 reveal that *Azolla* application in rice fields could replace 15–30% of N from the RD or farmers' applied N having comparable or higher rice yield. 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.

5.15. Cyanobacteria/blue-green algae

Cyanobacteria (blue-green algae) are prokaryotic and photosynthetic microorganisms having the ability to fix atmospheric inert N_2 utilizing the energy from sunlight (Stewart, 1980). Nitrogen-fixing cyanobacteria mostly belong to the orders Nostocales and Stigonematales under the genera of *Anabaena*, *Anabaenopsis*, *Nostoc*, *Calothrix*, *Aulosira*, *Scytonema*, *Chlorogloea*, *Tolypothrix*, *Cylindrospermum*, *Fischerella*, and *Stigonema* (Subba Rao, 2018). A wetland rice ecosystem is ideal for the survival and multiplication of cyanobacteria but does not interfere with the growth of the plant. Cyanobacteria provide multiple benefits such as increased NUE, reduced nitrate leaching and urea application, and increased soil organic carbon and post-harvest soil N. Using half of the RD of urea along with N fixing cyanobacteria ∼38% higher NUE can be obtained without reducing rice yields as compared with 100% urea application (Song et al., 2021). Furthermore, Sattar et al. (2008) demonstrated that cyanobacterial inoculation in the rice field along with N fertilizer could save 25% N fertilizer for wetland rice cultivation, in addition to the significant increment of grain yield. The benefits of cyanobacterial inoculation in rice cultivation largely depend on soil types. It was reported that cyanobacteria could reduce 25–35% of N fertilizers required for rice production in saline, acid, and red soils (Hashem, 2001). In addition to the N-fixing ability of cyanobacteria, they also release growth-enhancing substances such as vitamins, hormones (Gibberellins, Auxin), and amino acids which might help to ensure better growth and yield of wetland rice (Rodríguez et al., 2006).

6. Nitrogen smart rice cultivars—Genetical approach to enhance N use efficiency

Selection and cultivation of N smart rice genotypes ensure higher NUE and agricultural sustainability. Such rice cultivars can absorb and utilize applied and native N more efficiently. Nitrogen absorption, uptake, and utilization among the wetland rice genotypes vary greatly and thereby differ in yield response to added N (Fageria and Baligar, 2003, 2005; Choudhury et al., 2013). Duan et al. (2007) conducted an experiment in China and found that the NUE of Nanguang and Elio rice cultivars were high and low, respectively. Agronomic efficiency (AE) in terms of kg rice grain kg^{-1} N applied of two rice varieties *viz.*, BRRI dhan29 and BRRI dhan22 in Bangladesh were 19.17 and 15.0, respectively (Choudhury et al., 2013). Choudhury et al. (2013) also confirmed that tall-statured rice varieties could utilize more soil N as compared with short-statured varieties. It has also been opined that the NUE of a plant is greatly controlled by genotypic factors (Mahmud et al., 2021). Genetic variability of rice cultivars leads to differences in N uptake, assimilation, and ultimately NUE. As the genetic traits are controlled by specific genes, it is highly important to screen responsible genes for higher NUE.

7. Barriers and way forward

Nitrogen is useful for our lives, but the use of higher rates of N for food production is of great concern across the world. Researchers developed and identified a number of good practices and technologies for increasing NUE and reducing its losses. The reluctant attitude toward adopting '4R' nutrient stewardship (fertilizer from the right source with the right rate at the right time in the right place) may reduce NUE. However, socioeconomic, technological, infrastructural, and farmers' behavioral and policy constraints exist in different countries to achieve the full benefits of N management practices.

Many farmers are not willing to get their soil analyzed before growing crops. In many Asian and African countries, government organizations provide SHC to farmers, but they do not use the SHC, even though it is effective to increase NUE and reduce fertilizer requirements of crops. In Bangladesh, UDP is a very good technology for increasing NUE and environmental sustainability. In addition, because of the unavailability of a suitable applicator and extra labor requirements for UDP, farmers are not willing to use such technology. Balanced fertilization through STB, SSNM, and INM techniques needs yield goal and N demand of a crop, N supply from soil and other sources, rates of mineralization of organic materials, etc. Farmers face difficulties in obtaining such information while calculating the N requirements. Therefore, most of the farmers do not feel comfortable applying STB, SSNM, and INM approaches to nutrient management. The adoption of LCC for N management in rice is low because of the behavioral constraints of farmers. The lack of knowledge of leaf color charts and chlorophyll meters also restricts farmers to apply such good technologies. Poor knowledge and ignorance of farmers always restrict the adoption of different efficient N management strategies such as crop rotation, BNF, nitrification inhibition, etc. Moreover, because of the high costs of involvement with a urease inhibitor and a controlled-release fertilizer, and the unavailability of biochar and nitrification inhibitors, farmers hardly use these approaches. The main barrier to the optimization of N rates with reduced tillage is the mindset of farmers related to traditional tillage. Reduced tillage may increase the abundance of disease and pest and weed infestation in crops. The unavailability of suitable seeding and planting equipment also acts as a barrier to reducing tillage adoption.

Lack of information, limited access to resources including credit facilities, negative attitude of farmers toward new technologies, and traditional mindset seriously impede the adoption of best N management practices. Farmers' motivation through training, education, social campaign, etc., is suggested to change their mindset in adopting the efficient N management options. The establishment of small industries for manufacturing urea applicators, seeding and planting equipment, and better solution of pest control measures may help in removing the barriers. Local entrepreneurship should be promoted to produce biochar so that farmers can buy it and apply it to their crop fields. A suitable policy formulation is a must to remove all barriers so that farmers can easily and comfortably implement N management practices to increase NUE. Beyond the existing approaches, scientists should invent more efficient N guidance tools such as development of N smart crop varieties, android best N management apps, etc., to halve N waste by 2030 as stated in the "Colombo Declaration" by the United Nations Environment Program.

6. Conclusion

From this comprehensive review, it is revealed that the improvement of NUE in wetland rice is challenging. Some existing best N management practices are identified through a rigorous discussion and interpretation of results, bridging the rice production and environmental benefits, and addressing the fertilizer policy issues more specifically subsidies. To attain efficient N management in the rice ecosystem, fertilizers should be applied in the rice field in such a way that will ensure maximum utilization of natural and applied N with minimum loss to the environment. Setting the priority and finding out some eco-friendly and advanced N management options are the utmost tasks of global scientists in order to upswing NUE to 60–80% from the present level of 30–40%. Until now, no single measure could bring a magical upsurge in NUE in rice cultivation. The best adoption of the existing N management practices may increase NUE to a certain extent, which, however, may not be efficient to reduce N loss considerably. However, a combination of location-specific and locally available promising technologies *viz.*, urea deep placement, coated urea, inclusion of legumes in the cropping systems, alternate wetting and drying for irrigation, and biological nitrogen fixation 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.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Funding

This article is a contribution of the Toward the International Nitrogen Management Systems (Toward INMS) project funded by the Global Environment Facility (GEF)/United Nations Environment Program (UNEP) and the GCRF South Asian Nitrogen Hub (SANH) funded through the Global Challenge Research Fund (Grant Ref. Number NE/S009019/1) of UKRI as coordinated by the UK Centre for Ecology and Hydrology (UKCEH). The article also represents a contribution from the work of the Krishi Gobeshona Foundation (KGF), CRP II (2nd phase), Dhaka 1215, Bangladesh.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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