REVIEW ARTICLE https://doi.org/10.58297/VZZH6068

Efficient Nitrogen Management Technologies for Sustainable Rice Production

Vijayakumar S[1]*, Lokesh Goud D[2], Hareesh Reddy CH[2], Mahender Kumar R[1] and Sundaram RM[1]

[1]ICAR-Indian Institute of Rice Research, Rajendranagar, Hyderabad, 500030
[2]Amity Institute of Organic Agriculture, Noida, Uttar Pradesh 201313
*Corresponding author's Email: vijayakumar@icar.gov.in, vijitnau@gmail.com

Received: 15th September 2022; Accepted: 18th November 2022

Abstract

The use of nitrogen (N) fertilizers in rice fields as a source of nutrition is the major source of emission of nitrous oxide (N_2O). Two key factors which control the flux of N_2O at the field level are the amount of N supplied and the efficiency at which it is absorbed by plants. To reduce the N_2O emissions, optimum N fertilizer application (in terms of input rate and time of application) and ideal fertilizer selection are crucial. Optimizing N-use efficiency (NUE) is crucial to sustain productivity and profitability. Depending on edaphic and climatic conditions, improved N management can dramatically cut greenhouse gases (GHGs) emissions. Producers must ensure that the kind, rate, and time of N application do not result in substantial losses owing to volatilization, leaching, or denitrification. Adoption of best nitrogen management practices like deep placement of urea, use of nitrification inhibitors, urease inhibitors, and slow-release nitrogen fertilizers will reduce the N loss and increase NUE. The goal of this review is to discuss in detail the various technologies that have been developed and refined to improve NUE and protect the environment.

Keywords: Nitrogen, Nitrification inhibitor, Urease inhibitor, Slow-release fertilizer, Brown manuring, LCC, GreenSeeker, SPAD

Introduction

Fertilizers boost agricultural productivity and encourage crop CO_2 uptake and decrease the need to cultivate new land (deforestation), resulting in fewer GHG emissions as a result of land use change. Nitrogen (N) is the most important element for the overall growth and development of rice plants (Subramanian *et al.,* 2020). The atmospheric N is not readily available to rice plants despite its high abundance in the air (around 79%). The proportion of fertilizer N in the total N input for crop production in India is increasing since the advent of the Green Revolution in the mid-1960s, but NUE has declined from 48 to 35% in 2018. There is a limited opportunity to achieve significant yield gains by applying more fertilizer N. Although optimal fertilizer use on agricultural crops reduces soil erosion, repeated applications of high N fertilizer doses may cause soil acidity, a negative soil health trait (Nayak *et al.,* 2020). Site-specific management strategies based on the principles of synchronizing crop N demand with N supply from all sources, including soil and fertilizer, have the potential to ensure high yields while also preserving soil health (Vijayakumar *et al.,* 2021). Soil organic matter (SOM) is the repository for soil N. Balanced nutrient application and integrated nutrient management using organic manures and mineral fertilizers also contributed to the preservation and improvement of soil health (Nayak *et al.,* 2020). Thus, fertilizer N, when applied in a balanced proportion to other nutrients and in conjunction with organic manures, if available to the farmer, maintains or improves soil health rather than being detrimental (Nayak *et al.,* 2022). The good soil structure improves NUE and reduces N_2O losses. The challenge ahead is to manage N fertilizers in such a way that not only food demands are met continuously, but soil and environment remain healthy to support adequate food production with minimal environmental impact (Gobinath *et al.,* 2021).

N is added to the agricultural lands through inorganic N fertilizer which contains N in three chemical forms *viz*., ammonium (NH_4^+), nitrate (NO_3), and urea (Hakeem *et al*., 2011). Globally, urea is the most preferred form of N in agriculture (Modolo *et al*., 2015). However, once applied to the soil, urea undergoes three microbial-mediated transformations *viz*., hydrolysis, nitrification, and denitrification. Nitrification and denitrification are key processes contributing to N_2O emissions from the soil (Cameron *et al.,* 2013; Guo *et al.,* 2018). In the ammonia oxidation process, N_2O is produced by the chemical decomposition of hydroxylamine (NH_2OH). The loss of externally added N leads to economic and environmental implications. One potential way to mitigate N_2O emissions is to use nitrification and urease inhibitors to slow down the rate of nitrification and reduce the availability of the substrate (NH_4^+) for nitrification. The use of nitrogen fertilizer for crop production has an impact on soil health primarily through changes in organic matter content, microbial life, and acidity. Similarly, the production of N fertilizer also causes environmental pollution through the emission of GHGs. CO_2 emitted during ammonia synthesis and N_2O emitted during the production of nitric acid are the two most important GHG emissions connected with the manufacture of N fertilizers. Increasing NUE is critical for maintaining productivity and profitability. Improved N management, depending on edaphic and climatic conditions, can significantly reduce GHG emissions (Chatterjee *et al.,* 2019).

Farmers must ensure that the type, rate, and timing of N application do not cause significant losses due to volatilization, leaching, or denitrification (Cameron *et al.,* 2013; Vijayakumar *et al.,* 2021a). Good soil structure decreases N_2O losses. Best nitrogen management practices such as deep placement of urea, the use of nitrification inhibitors, urease inhibitors, and slow-release N fertilizers will reduce N loss and increase NUE (Vijayakumar *et al.,* 2021a). Blanket recommendations do not account for the spatiotemporal variability in soil N supply capacity (Subramanian *et al.,* 2020). Variable-rate fertilizer applicators in large fields are used in developed countries to improve synchronization between crop N demand and N supply from various sources (Goud *et al.,* 2022). The goal of this paper is to go over in detail the various technologies that have been developed and refined to improve NUE and protect the environment. The management of fertilizer N has also been discussed in terms of providing adequate amounts of nutrients to crop plants and maintaining soil health.

Nitrification inhibitors

The microbial decomposition of N in soils, manures, and nitrogenous fertilizers produces N_2O, which is often exacerbated when available N exceeds plant requirements, especially in wet conditions. The use of NIs enhances NUE by extending the period of N available to the crop plants which leads to increased N uptake by crop plants due to the matching of soil available N with crop N demand (Huber *et al.,* 1977; Vijayakumar *et al.,* 2021a). Arresting nitrification could be a key strategy to improve N recovery and agronomic NUE in situations where the loss of N is significant. Nitrification inhibitors (NIs) selectively inhibit the microbial enzymes responsible for the conversion of NH_4^+ to NO_3^-. It reduces the risk of loss of N through leaching or denitrification and subsequently increases the NUE (Ruser and Schulz, 2015; Norton and Ouyang, 2019). The ammonia monooxygenase (AMO) is the first enzyme that is involved in the oxidation of NH_4^+ to NO in soils. The inhibition of the AMO by NIs directly decreases the nitrification rate and it reduces the NO concentration which serves as a substrate for denitrification. Hence, the two main pathways of N_2O production in soils are blocked or their source strength is at least decreased. NIs *viz.,* nitrapyrin (2-chloro-6-trichloromethyl pyridine) or N-Serve, AM (2-amino-4-chloro-6 methyl pyrimidine), dicyandiamide (DCD), Ammonium thiosulphate (ATS), Thiosulphoryl triamide (ZPTA), terrazole (etridiazole) and CMP (1-carbamoyle-3-methylpyrazole) slow down the nitrification process in soil and lower N_2O emissions by 10–15 percent (Malla *et al.,* 2005). However, few studies showed even a 30 to 50% reduction in N_2O emission (Sanz-Cobena *et al.,* 2017). The recommended dose of NI is 0.2-0.6 kg ai/ha. A synthetic NI *viz.*, Nitrapyrin reduces nitrate leaching, N_2O emissions, improves NUE, crop yields, and N uptake (Woodward *et al*., 2021). Dicyandiamide (DCD) is another effective NI found more suitable for the temperate region. DCD was found less effective if the temperature is above 20°C because of its rapid decomposition. NIs are effective in inhibiting the emissions of environmentally harmful N compounds from agriculture into the soil, water, and air. The use of NI in paddy soils leads to increased grain yields by 19%, N-recovery efficiency by 30-40%, and reduced N_2O emissions by 73% (Lan *et al*., 2013; Gaihre *et al*., 2020). The NIs *viz*., nitrapyrin and dicyandiamide (DCD) are the most effective inhibitors of nitrification/denitrification for the period of 2-6 and 12-14 weeks, respectively (Delgado and Follett, 2010). Dimethypyrazole phosphate (DMPP) is also effective in increasing soil NH_4^+-N content when combined with urea, organic and inorganic fertilizers and lower soil N_2O emissions in temperate environments (Yang *et al*., 2016). However, there is little evidence of its efficacy in sub-tropical or tropical environments where temperatures and rainfall intensities are typically higher (Rose *et al*., 2017). The application of urease inhibitors and NIs significantly reduced inorganic N leaching (48%), N_2O (44%), and NO emission (24%) (Burzaco *et al*., 2014; Qiao *et al*., 2015; Thapa *et al*., 2016) while increasing crop yield (7.5%) and NUE (12.9%) (Abalos *et al*., 2014). The inhibitor decreased the potential denitrification rate (PDR) at the rice heading stage but had little effect on the denitrifier gene abundance except for nitrapyrin, which decreased the *nirK* gene abundance (Meng *et al*., 2020). The list of NIs which are synthetically made and used in agricultural practices is presented in **Table 1**. Although several synthetic NIs are found very effective in inhibiting nitrification, their uses in agricultural land are limited due to high cost, limited availability, adverse influence on beneficial soil microorganisms, and above all, poor extension and promotional activities. Only a few inhibitors have got approval for commercial marketing. The increase in the cost of fertilization could be counterbalanced by an increment in crop productivity. Also, the potential improvement in crop NUE could minimize the rate of external N fertilizer application by reducing the losses, and thereby lowering fertilization costs (Abalos *et al.*, 2014).

Table 1. Common synthetic nitrification inhibitors

N-Source	Base Compound	N-Process	Common Names	N-Content	Inhibition Duration (weeks)
Nitrapyrin	2-chloro-6-trichloromethylpyridine	Nitrification, denitrification	N-serve, stay-n 2000	12	2-6
DCD	Dicyandiamide	Nitrification	DCD, Ensan	1.6	4-8
DMPP	3,4-dimethypyrazoazole phospate	Nitrification	Entec , Dmpp	12-26	6-8

Source: Havlin *et al*., (2014)

Natural Nitrification Inhibitors (NNIs)

Natural NIs also known as botanical NIs encapsulate control water entry and rate of dissolution by providing a protective cover to the conventional soluble fertilizer which makes N release and availability more synchronized with plant requirements (Abbasi *et al.*, 2011). It also helps in improving soil health by reducing nitrification and N_2O emissions and enhancing crop productivity (Banik *et al.*, 2016). The usage of natural NIs like neem cake improves the N recovery efficiency of applied N in arable soil (Hala *et al*., 2014). The NNI like neem oil can inhibit the nitrification rate up to 20−50% in the soil, which is slightly lower than that of synthetic NIs like DCD (56−80%) (Raza *et al*., 2019). Another potential natural NI is Karanj (*Pongamia pinnata*) seed extract which minimizes N_2O emission from soil (Banik *et al*., 2016). It acts as a highly efficient NI (62−75% reduction in nitrification) as well as an N_2O mitigator (92−96% reduction in N_2O emission)

(Majumdar, 2002). The seed cake and extracts of Mahua contain alkaloids called saponin which slow down the N mineralization through nitrification inhibition. Based on the incubation study conducted on clay loam soil Kumar *et al*., (2015) found that the nitrification inhibitory effect of mahua cake extract persisted only for 20 days. The advantages of NNI are easily available, cheap, and eco-friendly (Upadhyay *et al*., 2011). Some natural NIs obtained from the different plants are enlisted in **Table 2.** The drawbacks of synthetic NIs like high cost, limited availability and adverse effect on beneficial soil microbes are solved through NNI. Therefore, it is necessary to develop and promote plant-based NIs (natural NIs) for augmenting NUE, crop productivity, and for safeguarding the environment.

While discovering a new NNI it is important to look for the following things. (i) *Specificity*: It should block the conversion of ammonium to nitrate, i.e. the activity of *Nitrosomonas*, and be non-toxic to other soil organisms, animals, and humans. (ii) *Persistence:* The material should stay active in the soil for an adequate period. Compounds subject to rapid degradation will not be useful. (iii) *Mobility:* It should move with the fertilizer and nutrient solution. Compounds with too high vapour pressure may move too fast and compounds easily absorbed are probably not very effective (iv) *Economy:* The chemical should be cheap as it is used as an additive to fertilizers (Slangen and Kirchhoff, 1984). In India, 100% of urea produced is neem (*Azadirachta indica*) oil coated. The chemical compound present in neem oil act as a nitrification inhibitor (NI) and also act as a physical barrier thereby slowing down the speed of urea solubility (Reddy and Prasad, 1975).

Table 2. Natural nitrification inhibitors

Common Name	Scientific Name	Alkaloids	Reference
Neem	*Azaridicta Indica*	Azaridictin	Slangen and Kerkhoff (1984)
Karanj	*Pongamia Glabra*	Karanjin, Glabrin, glabrosaponin	Modolo *et al*., (2015)
Mahua	*Madhuca longifolia*	Saponin	Bisht *et al*., (2018)

The ideal conditions where the use of NI is recommended

- Use of NIs may be advantageous in situations where the loss of N due to leaching and denitrification is accompanied by nitrification of fertilizer nitrogen.
- NIs are more effective in light-textured soils so their use may be more effective under these soil conditions as the effectiveness of these compounds decreases fast in heavy-textured soils.
- The application of NIs should be confined to the soil microsites where nitrification occurs rather than treating the entire soil volume so that the concentration of these compounds could be high enough for a reasonable period (Sahrawat and Mukerjee, 1977).

Urease Inhibitors (UIs)

Upon addition of urea to wet soil, it undergoes hydrolysis by the enzyme urease to generate ammonium carbonate, which is more prone to ammonia volatilization loss as carbonate increases the pH in the vicinity (Sahrawat, 1980). Urease enzyme is found both in the soil as well as in plant residues. UIs are chemical compounds that block the activity of the urease enzyme and reduce the rate of hydrolysis of urea to ammonium thereby it reduces the N loss through ammonia volatilization when urea is surface applied (Horta *et al.,* 2016). UIs gradually slow down the hydrolysis of urea for a period of 7 to 14 days by suppressing the activity of urease. The commonly known UIs are N-(n-butyl) thiophosphoric triamide (NBPT), and N-(n-propyl) thiophosphoric triamide (NPPT), PPD/PPDA (phenyl phosphorodiamide), TPT (tiophosphoryl triamide), PT (phosphoric triamide), HQ (hydrquinone). NBPT is sold in the trade name of Agrotain and Limus is new UI that contains two active ingredients (NBPT and NPPT). Among the numerous forms of UI, NBPT has seen the maximum commercial application (Sanz-Cobena *et al.,* 2008; Abalos *et al.,* 2014). UIs can reduce N_2O emissions by up to 80 percent (Sanz-Cobena *et al.,* 2017). UIs, can only be used in conjunction with urea or urea-containing fertilisers (including organic sources). Many factors like soil pH, the texture of soil, and N application rate influence the efficiency of UIs. The hydrolysis of urea is rapid in high soil PH, or soil which is poorly buffered against an increase in pH. Thus, among the soil type, in alkaline soils, the efficiency of UIs is found to be highest. Similarly, in coarse-textured soils and at high N fertilization rates, the efficiency is higher (Abalos *et al.,* 2014). Most of the inhibitors including NBPT are highly effective in neutral soil with a moderate amount of organic matter.

Urea treated with NBPT reduces NH_3 loss by around 53% and yield is gained by 6.0% and varies from 0.8 to 10.2% depending on crop species (Cantarella *et al*., 2018). UIs like NBPT have the potency to reduce ammonia volatilization and nitrite (NO_2) accumulation in the soil by altering the kinetic and thermodynamic behavior of the urease enzyme (Pan *et al.,* 2016). Thiousulfates can be used as UIs to reduce ammonia volatilization from urea or urea ammonium nitrate (UAN) fertilizer. Urea containing Ammonium Thiosulfate (ATS) has been shown to reduce NH_3 volatilization losses up to 11% as compared to UAN (Solan and Anderson, 1995). ATS by itself or in association with urea did not affect the soil microbial biomass pool. On the other hand, a field experiment performed with Canadian clay loam and fine sandy loam soils showed inconsistent results concerning urease inhibition by ATS (Modolo *et al*., 2018). Inhibitor N-(n-propyl) thiophosphoric triamide (NPPT) has shown a similar advantage of reducing ammonia volatilization losses from urea, and application of NBPT+NPPT mixture reduced NH_3 volatilization losses by 6% as compared to NH_3 losses of up to 25% in control (Li *et al*., 2017; Hull, 2018). The application of 12 kg Hydroquinine (HQ) on alluvial soil in conjunction with 120 kg Urea−N ha^{-1}, decreased N_2O emission by 5% in rice and 7% in wheat systems as compared to the crops grown solely in the presence of 120 kg urea N ha^{-1} (Modolo *et al*., 2018). Reduction in N_2O emission on the application of UIs along with urea ranged from 5% with hydroquinone to 31% with thiosulphate in rice. Contrary to the earlier finding, Malla *et al*., (2005) reported the combined application of UI (Hydroquinone and thiosulphate) and urea increased N_2O emission as compared to the application of urea alone. However, the global warming potential (GWP) was lower with the inhibitors (except hydroquinone) as compared to urea alone (Malla *et al*., 2005). In rice, the application of NBPT both in no−till and conventional tillage reduced the ammonia volatilization by delaying the conversion of N to NH_3. However, the magnitude of the effectiveness of inhibitors was associated with soil, season, climate, and cultivation system (Marchesan *et al.,* 2013). Another study conducted at IRRI, Philippines revealed the use of NBPT improve seed germination (from 9.32 to 16.22% for Apo and from 17.76 to 36.81% for Hanyou3) and plant growth and reduced ammonia volatilization (Qi *et al.,* 2012). The properties of various synthetic UIs are presented in **Table 3**.

Table 3. Properties of synthetic urease inhibitors

Source	Common Names	Base Compound	N Process	N Content (%)	Inhibition duration (Weeks)
NBPT	Agrotain, Super U	N−(n−butyl) thiophosphoric triamide	Volatilization	46	2 to 3
Thiousulphate	ATS, CaTS	Ammonium or Calcium thiosulphate	Volatilization, Nitrification	12	2 to 3
NPPT	Limus	N-(n-propyl) thiophosphoric triamide	Volatilization		
Hydroqunine	HQ	Hydroqunine	Volatilization		-

Source: (Havlin *et al*., 2014)

Natural Urease Inhibitors (NUIs)

These inhibitors are naturally found and obtained from plant parts and these chemical compounds block the activity of the enzyme urease thereby reducing the leaching losses. It has the potential to retard the loss of urea from agricultural soil and thus it may be used along with urea for improved utilization of the applied N by plants (Mathialagan *et al*., 2017). The NUIs obtained from various plant parts are presented in **Table 4.** Allicin, a plant derived inhibitor obtained from garlic (*Allium sativum* L.) has shown the potential to inhibit urease activity in the soil (Mathialagan *et al.,* 2017). However, its inhibition is about 75% lower than NBPT at steady state (Matczuk and Siczek, 2021). Tannin, a polyphenolic extract obtained from the bark of *Acacia decurrens* (Green wattle; Fabaceae) or seed coat of *Terminalia chebula* (Inknut; Combretaceae) inhibited both pure urease (urease tablets-BDH) and soil ureases to the same extent that did mercuric chloride and catechol, known urease inhibitors (Modolo *et al*., 2015). Indeed, with urea-polyphenol mixtures, NH_3 volatilization from the soil surface decreased upon soil fertilization. These results highlight the potential of tannin like polyphenols from green wattle and inknut as potent urease inhibitors (Fernando and Roberts 1976). In addition, some natural products such as phenolic compounds (methyl gallate, stilbenoids, and flavonoids) can suppress urease efficiency (Hussain *et al*., 2021).

Table 4. Natural urease inhibitors

Inhibitors	Obtained from	Reference
Allicin	Garlic	Matczuk and Siczek (2021)
Tannin (polyphenolics)	*Acacia decurrens* (Green Wattle)	Modolo *et al*., (2015)
Quercetin	*A. cepa*	Modolo *et al*., (2015)

Slow/Controlled Release Nitrogen Fertilizers

This is a granulated fertilizer that differs from regular fertilizers by releasing nutrients slowly or gradually into the soil. The fertilizer contains a plant nutrient in a form that extends its availability for plant uptake significantly longer than a reference fertilizer such as ammonium nitrate or urea, ammonium phosphate is commonly known as a slow-release fertilizer. Slow-release N fertilizers extend the period of N available to the crop plant by discharging the soluble N (NH_4 and NO_3) over several weeks/months and increase the amount of fertilizer uptake by the plant through synchronizing plant nutrient demand and soil N availability. This type of fertilizer is not readily water-soluble, which means it dissolves more slowly thereby it increases NUE and decreasing nutrient loss.

The demand for N increases gradually from germination to flowering. Usually, young plants have little demand while the demand for N increase from active tillering to the milking stage. The use of slow-release N-fertilizer ensures slow release of N to match crop demand. Slow-release N−fertilizers extend the period of N availability to crop plants as they release the N gradually and steadily in the soil solution thereby it increases NUE and decreasing its losses. The list of slow-release N-fertilizers is presented in **Table 5.** The slow-release N-fertilizers are classified into two categories *viz*., coated and uncoated. These products have been found to improve the recovery of applied N by 33% in cereal grains all over the world, and consequently decrease the external fertilizer applications rate. There are two types of slow-release N-fertilizers available in the market *viz.* coated (induced slow release) and uncoated products (inherently slow release).

Types of slow-release nitrogen fertilizers

Coated slow-release N fertilizers: The coated slow-release N fertilizers contain an external coating consisting of hydrophobic chemicals to provide a physical barrier against water. This type of fertilizer is not readily water-soluble, which means it dissolves more slowly. This promotes the gradual release of urea into the soil solution thereby it minimizes N losses and improves its uptake by crops (Akiyama *et al*., 2010). The release of N is primarily controlled by the external barrier that surrounds the N. Thus, it releases the N rapidly once the barrier is removed.

Examples of coated products are neem-coated urea, sulphur-coated urea, and polymer-coated urea. In neem-coated urea, 0.5 kg of neem oil is used per tonne of urea. Polymer-coated fertilizers are the most recent technology for controlling N release and reducing N losses by leaching, denitrification, and volatilization. Polymer-coated multi-nutrient fertilizers supply all three fertilizer elements (NPK) which are essential for plant growth and development. These polymer-coated fertilizers *viz*; Osmocote, Multicote, and Nutricote gradually release nutrients over extended periods (it can be shorter as three months and longer as eighteen months). Some commonly used coated N-fertilizers are listed in **Table 5**. The coated slow-release N fertilizers are comparatively cheaper than inherently slow-release N fertilizers as the products used for coating are easily available at low cost. In India, 100% urea manufactured is neem-coated urea.

Table 5. Coated N fertilizers

N-source	Base Compound	Common Name	N Content (%)	Inhibition Duration (Weeks)
Neem coated urea	Urea	NCU, NICU (Nimin−coated urea)	46	2-6
Polymer Sulphur-coated urea	Urea	Polyplus, Poly−S	38−42	6−16
Sulfur coated urea	Urea	Enspan, SCU	30−42	4−12
Polymer resin-coated urea	Urea	Polyon, Meister, Escote	38−44	8−14

Source: Havlin *et al*. (2014)

Inherently (uncoated) slow-release N fertilizers: Slow release is the inherent physical characteristic of uncoated products like isobutylidene diurea (IBDU) (31% N), urea form (35% N), and methylene urea (39-40% N) (Varadachari and Goertz, 2010). These are slightly soluble in soil solution, where the N release rate depends on microbial activity and hydrolysis. The inherently slow-release N fertilizers along with their N content and inhibition period are presented in **Table 6.**

Table 6. Slow-release N-fertilizer compounds

N−source	Base Compound	Common Names	N Content (%)	Inhibition Duration (weeks)
Urea Formaldehyde	Urea forms, Methylol urea	Nitamin, Nitroform, Folocorn	35−40	6−10
Isobutylidene Diurea	Isobutylidine urea	IBDU	31	10−16
Triazone	Triazoneƒurea	N−sure	28−33	6−10
Melamine	2,4,6−triamino−1,3,5−triazine	Nitrazine	50−60	6−12
Crotolidene Diurea	Urea Crotonaldehyde	Crotodur, Triabon	34	6−12

Source Havlin *et al*. (2014)

Brown manuring

Generally, brown manuring is the practice of growing *Sesbania spp*. and rice together. When these *dhaincha* plants overtake the rice plants in height at about 25 days of co−culture, a broadleaf herbicide *viz*., 2, 4−D (selective herbicide) is applied to kill *Sesbania* plants, not the rice plants. After 4−5 days of herbicide spraying, *Sesbania* leaves will fall on the ground and form mulch and help in smothering weeds. This is called the knocking down effect. The post-emergence herbicide spray on green manure leaves results in loss of chlorophyll in *Sesbania* leaves appear brown in colour and it is referred to as brown manuring.

Advantages of brown manuring

- Compete with weeds thus reducing their growth.
- Reduce the N requirement of plants as legumes fixed N from the atmosphere through bacteria present in their nodules.
- Prevent the loss of water due to evaporation and thus help in water conservation.
- Reduce the cost of cultivation by reducing the weed control cost and fertilizer N requirement.
- Increase soil organic carbon content and soil fertility.

The differences between green manure and brown manure are given in **Table 7**.

Table 7. Green manures VS Brown manures

Green Manures	Brown Manures
Moisture is necessary for incorporation and decomposition	Moisture is conserved during the practice
The risk of soil surface erosion is after incorporation	The plants are left standing to protect light texture soil from the risk of soil erosion
The microbial population is necessary for decomposition	Chemical desiccation will take place
It is the incorporation of a manure crop by tillage before seed set usually around flowering	It is a no-till version of green manuring, where herbicides are used to kill the manure crop and weeds

Source: Patil *et al*., (2020)

Sesbania is a live cover that offers interference to weeds during the pre-killing period and later as a dead residue mulch (at the post-killing period) offers weed suppression and stimulates rice crop growth by the addition of organic matter and nitrogen release. The knocking down of *Sesbania* by 2,4-D application hastens the decomposition and release of nutrients present in *Sesbania* as compared to *in situ* incorporation. Also, brown manure crops are grown between the lines of rice crops and no free space is available for weeds to germinate and spread as a result a minimum weed population is recorded in brown manuring. *Sesbania* could add C and N into the soil, which facilitates favourable microbial activity (Phukan and Bora, 2012). Other leguminous green manuring crops like sun hemp, cowpea, lentil, etc. are also potential brown manure crops for rice crops. Any pulse crop may be grown for brown manuring. Moreover, *Kharif* pulses which have good foliage and rapid growth are more suitable for this purpose. Nutrient content, Carbon-Nitrogen (C:N) ratio of green manure crops (**Table 8**), and the effect of brown manuring on soil organic carbon and post-harvest available N (**Table 9**) are highlighted below.

Table 8. Nutrient content and C: N ratio of major green manure crops

Crops suitable	Scientific name	Total N	C:N Ratio	Total P	Total K
Sun hemp	*Crotalaria juncea*	3.97	21:1	0.37	4.80
Dhaincha	*Sesbania aculeata*	1.90	44:1	0.34	3.60
Sesbania	*Sesbania speciosa*	2.71	40:1	0.53	2.21

Source: Iliger *et al*. (2017)

Table 9. Effect of brown manuring on soil organic carbon and post-harvest available nitrogen.

Year	Initial OC content of soil (%)	OC content after harvest (%)	% increase in organic carbon	Initial soil available nitrogen content (kg/ha)	Soil available N content after harvest (kg/ha)	% increase in soil available nitrogen
2014	0.54	0.69	0.15	283.0	320.2	13.7
2015	0.58	0.71	0.13	285.38	324.6	13.7
Mean	0.56	0.70	0.14	284.19	322.4	13.4

Source: Samant and Patra (2016). OC - Organic carbon.

More use of organic manures/green manures

The use of solid organic manure reduces the N_2O emission, however, it depends on the type of manure used (Webb *et al.,* 2010). While organic sources such as farmyard manure (FYM), green manure, and crop residues of rice and wheat increased the N_2O emission (Bhatia *et al.,* 2005). The incorporation of organic inputs, such as rice straw and green manure in rice soils promotes CH_4 emission (Van der Gon and Neue, 1995; Vijayakumar *et al.,* 2021). In Mediterranean systems use of solid manures significantly decreased N_2O emissions (23%) (Aguilera *et al.,* 2013) and has the potential to exacerbate long-term C sequestration (Ding *et al.,* 2012). Evidence from past experiments indicates that the technique of slurry application in agricultural soils is a crucial variable in regulating N_2O flux. Based on a meta-analysis study Hou *et al.,* (2015) reported that slurry injection could dramatically increase direct emissions as compared to broadcasting.

Manure, such as FYM, boosts CH_4 flux by providing organic carbon and nitrogen for microbial activities, as well as functioning as an electron source. In comparison to the application of a 100% recommended dose of N through urea, substituting 50% of inorganic N with FYM increased GHG emission by 172 percent (Pathak *et al.,* 2003). Crop residue incorporation/ retention also influences the CH_4 flux by increasing the organic matter availability. The CH_4 flux increased from 100 to 500 kg ha^{-1} yr^{-1} with the increase of rice straw incorporation from 0 to 7 t ha^{-1} (Sanchis *et al.,* 2012). The methane emissions were lowest in the unfertilized plot (28.4 kg ha^{-1}) and highest (41.3 kg ha^{-1}) when the total amount of N was applied by organic sources (Bhatia *et al.,* 2005). However, when compared to FYM, biogas slurry lowered emissions by 2-3 times, indicating that biogas slurry should be favoured over FYM for reducing CH_4 emissions (Debnath *et al.,* 1996). Composting, incorporation of organic manures/ crop residues during the off-season i.e. drained period, and application of fermented manures like biogas slurry instead of unfermented farmyard manure reduce methane emission (Pathak and Wassmann, 2007) thus, promoting aerobic degradation of organic manure which reduces methane emissions.

Leaf colour chart (LCC)

The LCC is used to determine the N fertilizer needs of rice crops by determining the greenness of the rice leaf as it is highly influenced by N content. It is an inexpensive, small size and easy-to-use tool (Bhavana *et al.,* 2020). The use of LCC ensures the precise application of N fertilizer to rice crops. It has four green strips (four to six), with colour ranging from yellow-green to dark green. LCC is a substitute for the chlorophyll meter (SPAD) to estimate rice leaf N status. LCC readings are taken once a week until the first flowering, starting from 14 days after transplanting for transplanted rice and 21 days after seeding for wet direct seeded rice. The topmost fully expanded leaf from each hill is selected and leaf colour is compared by placing the middle part of the leaf on LCC. N top dressing is recommended whenever the green colour of more than 5 out of 10 leaves is found equal to or below the critical value. The critical value is 3 for varieties with light green foliage and 4 for all other varieties and hybrids. If the critical value of the leaf falls below the threshold value, 35 kg N/ha during *kharif/kar/kuruvai/navarai* and 30 kg N/ha during *rabi/samba/thaladi/pishanam* season need to be applied. There is a considerable yield increase under LCC-based N management as N supply matches with the crop demand because of the timely supply of the optimum dose of N-fertilizer. The use of LCC leads to the saving of N fertilizers to the tune of 20 – 40 kg/ha (Sudhalakshmi *et al*., 2008). Although it has many advantages over other N management tools, still it has a few limitations like sunlight influences the readings if the measurements are not taken under the shade; deficiencies are identified after the symptoms are developed, and by this time crop might have been affected by the deficiency; LCC cannot give the exact values like the analysis done in the lab. Readings were taken in the morning (8-10 AM) under the shade of the body to avoid the influence of sunlight. The merits and demerits of LCC are presented below (**Table 10**).

Table 10. Merits and demerits of LCC tool

Merits of LCC	Demerits of LCC
LCC is an uncomplicated and easy-to-use tool for farmers to measure the nitrogen status of the leaf and to identify the instance for N top dressing.	LCC fails to specify minor variations in leaf greenness as the colour shades lie in between two shades.
LCC is cheap and portable thus, making it easy to carry to the field for estimating the N status of the leaf.	The comparative accuracy of LCC is relatively lower than the chlorophyll meter.
It is a non−destructive method and doesn't involve any laboratory analysis.	LCC developed for a particular region may not be appropriate for other regions. Similarly, the same LCC is not suitable for hybrid rice and HYV.
LCC can be better suited to a site-specific nutrient management approach.	LCC was used only to adjust the time of N top dressing not for basal N appliance.
Any specific knowledge or skill is not required for using LCC as it involves only comparing the leaf colour with a standard chart.	Though it does not require any specific skill to use, the user should be careful while taking the reading to avoid errors due to sunlight, time of observation, and selecting leaf for observation.

Source: Bhupenchandra *et al*., (2021).

Integrated Nutrient Management (INM)

INM is the judicious use of all possible nutrient sources to meet the plant nutrient requirement at an optimum level to sustain the desired crop productivity with minimal impact on the environment. In INM, the immediate nutrient requirement of the crop is met through chemical fertilizers. Thus, the rate and time of chemical fertilizer application should synchronize with the real-time need of the crop. The slow and long-term release of nutrients from organic sources helps in meeting the long-term need of the crop. The goal of INM includes (i) Optimization of the benefits from all possible sources of plant nutrients in an integrated manner to achieve a given level of crop production (ii) Maintenance of plant nutrient supplying capacity of soil to ensure sustainable crop productivity (iii) Ensuring higher nutrient use efficiency, minimization of nutrient loss and mitigation of harmful environmental impacts (iv) Minimizing the use of chemical fertilizers thereby reducing the cost of cultivation and enhancing profitability (Vijayakumar *et al.,* 2021a). The INM for different rice production systems is given below (**Table 11**).

Components of INM

Organic manures: Farmyard manure, compost, vermicomposting, biogas slurry, poultry manure, crop residues, and bio wastes like press mud, sugarcane baggages etc.

Green manures & Green leaf manures: Dhaincha (*Sesbania aculeata*), *Sesbania rostrata*, Sunhemp (*Crotalaria juncea*), *Pongamia globra*, *Leucaena leucocephala*, *Azadiracta indica* and all legume pulses except French bean.

Chemical fertilizers: Urea, Ammonium Sulphate, Ammonium Nitrate, Calcium Ammonium Nitrate (CAN), etc.

Table 11. The recommended INM for rice

S.No	Recommendation	Yield	Reference
1	100% recommended dose of N through green manure with 50 percent NPK	62.7 q ha^{-1}	Bhandarin *et al.,* (1992)
2	50% of N through green manure and the remaining 50% through chemical fertilizers	7.3 t ha^{-1}	Sharma and Subehia (2014)
3	Application of soil-based BGA biofertilizer at the rate of 10 kg ha^{-1} along with 90 kg urea	10 percent high yield	Mohanty *et al.,* (2019)

Green seeker

The Green Seeker is a hand-held optical reflectance sensor that uses active radiation from red and near-infrared bands independent of solar conditions. The sensor samples at a very high rate (approximately 1000 measurements per second) and averages measurements between outputs. This device delivers output *viz.,* NDVI, and ratio vegetation index (RVI) directly using the sensor readings at a rate of 10 readings per second with a travel speed of 0.5 m s^{1}. The integrated optical sensing and application system measures nitrogen status in the leaf and provides information on the right time, right place, and right amount of N application in real-time (Song, 2021). The sensor unit has self-contained illumination in both the red (656 nm with about 25 nm full-width half magnitude) and near-infrared (774 with about 25 nm FWHM) bands. Sensor readings (NDVI and RVI) were collected 0.5m above the rice canopy across each plot, except plot borders and the average values were used to represent each plot (Zhang *et al.,* 2017). Sensor readings were collected at five different stages *viz*., tillering, panicle initiation, booting, before heading, and heading stage. The original technology was developed for large farms; however, a small handheld version that costs (approximately Rs. 40,000) a fraction of the original technology is now commercially available (Yao *et al.,* 2012).

Soil Plant Analysis Development (SPAD) Meter

Soil Plant Analysis Development (SPAD) Meter or chlorophyll meter developed by Minolta Company is a simple, portable diagnostic tool that measures the greenness or relative chlorophyll content and is mainly used to identify the crop N status and relative chlorophyll contents (Yuan *et al.,* 2016). The SPAD meter measures the difference between the transmittance of red (650 nm) and infrared (940 nm) light through the leaf, generating a three-digit SPAD value (Uddling *et al.,* 2007). It enables users to measure potential photosynthetic activity quickly and easily, which is closely linked to leaf chlorophyll content, crop nitrogen status, and leaf greenness. SPAD readings indicate the plant N status and the amount of N to be applied. It is a non-destructive method of N status estimation thereby it saves time and money. SPAD readings are greatly influenced by the specific part of the foliage where the measurements are made, as chlorophyll is not evenly distributed along the leaf blade. Several factors such as plant growth stages, cultivars, specific leaf weight, leaf thickness, leaf position on the plant, measurement location on a leaf, environmental stress, and solar radiation could significantly affect chlorophyll meter readings (Yuan *et al.,* 2016). The chlorophyll meter is too costly (around one lakh rupees) which is very high for a small-scale farmer. Leaf area-based N concentration has a unique linear relationship with SPAD values of rice plants at all growth stages (Peng *et al*., 1995). SPAD values for different rice production systems are given below (**Table 12**).

Table 12. Critical SPAD values for different seasons, cropping conditions, and rice varieties

Crop establishment	Varietal group	Panicle density (m^2)	SPAD value	
			Dry season	Wet season
Transplanted rice	Traditional improved local aromatic rice	300-400	30-32	30
	Semi-dwarf indicia varieties	400-500	32-35	35-37
	Hybrid rice	400-500	32-35	35-37
Broadcast sown	All varieties	High -800	29-30	30
		Medium-400 to 500	32	35
Drum seeded	All varieties	High 600-650	32	32
		Medium 400-500	32-35	32-35

Source: Balasubramanian *et al.* (2000)

4R nutrient stewardship-based N application

Any technology which ensures a more precise application of N fertilizer based on soil, plant, and field characteristics will increase the NUE and reduce the N loss. 4R nutrient stewardship-based N application involves applying the right dose, right time, right source, and right place enhances NUE (Vijayakumar *et al.,* 2021). For example, the demand-driven application of N by using a leaf colour chart (LCC) reduced N_2O emission and GWP by about 11% (Bhatia *et al.,* 2010) thereby synchronizing the timing of N application with plant N demand and reducing N losses, including N_2O emissions. It also helps in saving fertilizer costs due to the saving of input N rate (Surjandari and Batte, 2003). Accurate estimation of external N requirements by considering indigenous supply, and target yield will reduce N loss by avoiding the excess N application and subsequent direct and indirect N_2O emissions, while saving energy and lessening other GHG emissions (e.g., associated with manufacturing N fertilizers). The optimized N application might cut N_2O flux by up to 50 percent compared to non-optimized practices in both irrigated and rain-fed Mediterranean agroecosystems (Sanz-Cobena *et al.,* 2017). However, multiple studies have found that direct N_2O emission is non-linear in response to N intake (Philibert *et al.,* 2012; Kim *et al.,* 2013; Shcherbak *et al.,* 2014), and other factors, such as cultural operations, method of fertilizer application, time of application, source of N fertilizer and climate plays a major role in direct N_2O emissions (Aguilera *et al.,* 2013). For rice and wheat, three split applications of N were found more efficient than two split applications. Several findings revealed that choosing the correct fertilizer could help reduce emissions. The use of nitrate (NO_3) based fertilizers significantly lowered the N_2O emissions than ammonium-based fertilizers (Bouwman *et al.,* 2002). N is mostly broadcast applied in India and other Asian countries. The broadcasting of urea and the ammonium-containing fertilizers is often associated with higher volatilization losses and it can be largely reduced by incorporating urea into the soil. This is done in the case of dry direct seeded rice and wheat in IGP regions. The use of seed cum fertilizer drills also enables incorporation of urea into the soil and this method is gaining importance in IGP for sowing zero-till wheat in RWCS.

Time of Application of Nitrogen Fertilizer

For better rice crop growth and development, the perfect time is required for the application of fertilizer. N is required in large amounts for rice plants and the Recommended Dose of Nutrients (RDN) application is advised to broadcast three times (1/3rd is applied before planting, incorporated in dry soil; 1/3rd at the mid-tillering stage and 1/3rd at panicle initiation stage) throughout its growing season. The effect of different times and methods of N application on rice crop is presented in **Table 13**.

Table 13. Time of application of fertilizer for rice crop

S.No	Method	Times of application	Yield	Reference
1	Direct seeded upland rice	3 splits 1/2 at 20 days,1/4th at tillering, 1/4th at panicle initiation	More than expected	Kaur and Kaur (2017)
2	Direct-sown rice under lowland conditions.	4 splits, 17% at 21 days after sowing, 33 at 35 DAS, 33% at panicle initiation and 17% at first flowering	4.18 t ha^{-1}	Thilagavathi and Ramanathan (2005)
3	Direct-sown rice under lowland conditions.	4 splits, 1/6th at 15 DAS,1/3rd at tillering, 1/3rd at panicle initiation, 1/6th at flowering	4.92 t ha^{-1}	Sathiya and Ramesh (2009)
4	Aerobic rice	4 splits – 1/6th at 15 DAYS, 1/3rd at tillering, 1/3rd at PI, 1/6th at flowering recorded higher tillers	2.82 t ha^{-1}	Sathiya and Ramesh (2009)

Deep placement of Urea

Under direct seeded rice (DSR), deep placement of urea reduced N_2O flux by 93% compared to broadcast urea and thereby increased NUE and grain yields (Gaihre *et al.,* 2020). This is most plausible as UDP might have stored much of the nitrogen as NH_4^+ in an anaerobic zone for a long time, where nitrification is less likely due to the lack of O_2. As a result, both nitrification and denitrification emissions of N_2O and NO could be lowered. Furthermore, UDP minimizes N loss through other processes such as NH_3 volatilization and surface runoff (Rochette *et al.*, 2013).

Decision support tool

Many decision support tools are now available for managing nutrient supply in different cropping systems. For example, the Nutrient expert decision support system (DSS) developed by the International Plant Nutrition Institute (IPNI) gives site-specific recommendations (SSNR) for hybrid maize genotypes. DSS was found effective tool under both conservation and conventional production system (Kumar *et al.,* 2014, 2015a, 2015b). DSS provides SSNR even in the absence of soil test values. It needs information that is easily given by the farmer/user. Similarly, for rice RiceXpert developed by ICAR-National Rice Research Institute (NRRI), Cuttack gives N recommendations to standing rice crops by capturing the N status of the plant. The farmer needs to take ten photos of standing rice crops randomly across the field using a smartphone. After uploading captured images, the output i.e. N recommendation immediately delivered to the farmer in terms of urea. Similarly, unmanned aerial vehicle (UAV) mounted sensors capable of detecting N stress in rice plants even before it produces visible visual symptoms (Vijayakumar *et al.*, 2020a). The spectral signature of multi-spectral and hyper-spectral sensors are highly correlated with the N status of the plant. However, at present, the higher cost of the UAV system hinders its application at the field level (Vijayakumar *et al.,* 2021b).

Conclusion

We have reviewed the field-specific N management strategies based on the leaf colour chart, chlorophyll meter (SPAD), and GreenSeeker for the need-based application of N fertilizers in rice. Chlorophyll meters (SPAD), GreenSeeker, and LCC have been standardized for applying N fertilizer to rice crops based on their needs. Farmers are increasingly using a simple and inexpensive LCC to practice field-specific N application in rice, which can increase agronomic efficiency by 5 to 16 kg grain per kg N over the farmers' fertilizer practice. Nutrient decision support tools that are computer, mobile, or web-based can also help manage fertilizer N in rice on a field-by-field basis (Vijayakumar *et al.,* 2022). To achieve higher NUE, farmers in India must significantly improve fertilizer N management by adopting technological innovations and avoiding N applications greater than the crop's need. Adoption of site-specific N management strategies has great potential; however, adoption of technologically advanced N options such as controlled release N fertilizers and nitrification and urease inhibitors will be dependent on the benefit:cost ratio of their use in India.

References

Abalos D, Jeffery S, Sanz-Cobena A, Guardia G and Vallejo A. 2014. Meta-analysis of the effect of urease and nitrification inhibitors on crop productivity and nitrogen use efficiency. *Agriculture, Ecosystems & Environment*, 189: 136-144.

Abbasi MK, Hina M and Tahir MM. 2011. Effect of *Azadirachta indica* (neem), sodium thiosulphate, and calcium chloride on changes in nitrogen transformations and inhibition of nitrification in soil incubated under laboratory conditions. *Chemosphere*, 82: 1629-1635.

Aguilera E, Lassaletta L, Gattinger A, Gimeno BS. 2013. Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: a meta-analysis. *Agriculture, Ecosystems & Environment,* 168: 25–36.

Akiyama H, Yan X and Yagi K. 2010. Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N_2O and NO emissions from agricultural soils: meta-analysis. *Global Change Biology*, 16: 1837-1846.

Balasubramanian V, Morales AC, Cruz RT, Thiyagarajan TM, Nagarajan R, Babu M, Abdulrachman S and Hai LH. 2000. Adaptation of the chlorophyll meter (SPAD) technology for real-time N management in rice: a review. *International Rice Research Notes*, 25: 4-8.

Banik M, Naorem A, Udayana SK and Kumar G. 2016. Efficiency of botanical nitrification inhibitors prepared from neem and karanj plant in suppressing nitrification and N_2O emission. (Progressive Research – An International Journal Print ISSN: 0973-6417, Online ISSN: 2454-6003 Volume 11 (Special-VII): 4912-4915

Bhandari AL, Sood A, Sharma KN and Rana DS. 1992. Integrated nutrient management in a rice-wheat system. *Journal of the Indian Society of Soil Science*, 40: 742-747.

Bhatia A, Pathak H, Jain N, Singh PK and Singh AK. 2005. Global warming potential of manure amended soils under rice-wheat system in the Indo-Gangetic Plains. *Atmospheric Environment,* 39: 6976–6984.

Bhatia A, Sasmal S, Jain N, Pathak H, Kumar R and Singh A. 2010. Mitigating nitrous oxide emission from soil under conventional and no-tillage in wheat using nitrification inhibitors. *Agriculture, Ecosystems & Environment,* 136: 247-253.

Bhatia A, Pathak H, Jain N, Singh PK and Singh AK. 2005. Global warming potential of manure amended soils under rice–wheat system in the Indo-Gangetic plains. *Atmospheric Environment,* 39: 6976-6984.

Bhavana B, Laxminarayana P, Latha AM, Anjaiah T. 2020. Judicious Nitrogen Management using Leaf Colour Chart for Enhancing Growth and Yield of Short Duration Transplanted Rice (*Oryza sativa* L). *International Journal of Current Microbiology and Applied Sciences*, 9: 2850-2856.

Bhupenchandra I, Athokpam HS, Singh NB, Singh LN, Devi SH, Chongtham SK, Singh LK, Sinyorita S, Devi EL, Bhagowati S and Bora SS. 2021. Leaf color chart (LCC): An instant tool for assessing nitrogen content in plant: A review. *The Pharma Innovation Journal,* 10: 1100-1104

Bisht V, Neeraj VK and Dalal N. 2018. Mahua an important Indian species: a review. *Journal of Pharmacognosy and Phytochemistry*, 7: 3414-3418.

Bouwman AF, Boumans LJM and Batjes NH. 2002. Emissions of N_2O and NO from fertilized fields; summary of available measurement data. *Global Biogeochemical Cycles*, 16: 1058–1070.

Burzaco JP, Ciampitti IA and Vyn TJ. 2014. Nitrapyrin impacts on maize yield and nitrogen use efficiency with spring-applied nitrogen: Field studies vs. meta-analysis comparison. *Agronomy Journal*, 106: 753-760.

Cameron KC, Di HJ and Moir JL. 2013. Nitrogen losses from the soil/plant system: a review. *Annals of Applied Biology*, 162: 145-173.

Cantarella H, Otto R, Soares JR and de Brito Silva AG. 2018. Agronomic efficiency of NBPT as a urease inhibitor: A review. *Journal of Advanced Research*, 13: 19-27.

Chatterjee D, Nayak AK, Vijayakumar S, Debnath M, Chatterjee S, Swain CK, Bihari P, Mohanty S, Tripathi R, Shahid M and Kumar A. 2019. Water vapor flux in tropical lowland rice. *Environmental Monitoring and Assessment*, 191: 550.

Debnath G, Jain MC, Kumar Sushil, Sarkar K and Sinha SK. 1996. Methane emission from rice fields amended with biogas slurry and farmyard manure. *Climatic Change*, 33: 97–109.

Delgado JA and Follett RF. 2010. Advances in nitrogen management for water quality. Soil and water conservation society, Ankeny, IA, pp.1-424.

Ding X, Han X, Liang Y, Qiao Y, Li L and Li N. 2012. Changes in soil organic carbon pools after 10 years of continuous manuring combined with chemical fertilizer in a Mollisol in China. *Soil and Tillage Research*, 122: 36–41.

Fernando V and Roberts GR. 1976. The partial inhibition of soil urease by naturally occurring polyphenols. *Plant and Soil*, 44: 81-86.

Gaihre YK, Singh U, Bible WD, Fugice Jr J and Sanabria J. 2020. Mitigating N_2O and NO emissions from direct-seeded rice with nitrification inhibitor and urea deep placement. *Rice Science*, 27: 434-444.

Gobinath R, Manasa V, Surekha K, Vijayakumar S and Bandeppa. 2021. New age nutrient carriers for rice based cropping systems. *Indian Farming*, 71: 12–15.

Goud RB, Tripathi R, Guru PK, Mohanty S, Kumar A, Khanam R, Munda S, Vijayakumar S, Debnath M, Sivashankari M, Kumar K, Mohapatra SD and Nayak AK. 2022. Advanced Techniques for Precision Farming in Rice. Pp 224-247. In Editors P Bhattacharyya, K Chakraborty, K A Molla, Annie Poonam, D Bhaduri, R P Sah, S Paul, P S Hanjagi, Basana-Gowda G, P Swain. Climate Resilient Technologies for Rice based Production Systems in Eastern India. ICAR-National Rice Research Institute, Cuttack-753006, Odisha, India. ISBN 818840902-2.

Guo L, Wang X, Diao T, Ju X, Niu X, Zheng L, Zhang X and Han X. 2018. N_2O emission contributions by different pathways and associated microbial community dynamics in a typical calcareous vegetable soil. *Environmental Pollution*, 242: 2005-2013.

Hakeem KR, Ahmad A, Iqbal M, Gucel S and Ozturk M. 2011. Nitrogen-efficient rice cultivars can reduce nitrate pollution. *Environmental Science and Pollution Research*, 18: 1184-1193.

Hala Y, Jumadi O, Muis A, Hartati H and Inubushi K. 2014. Development of Urea Coated with Neem (*Azadirachta indica*) to Increase Fertilizer Efficiency and Reduce Greenhouse Gases Emission. *Jurnal Teknologi*, 69. https://doi.org/10.11113/jt.v69.3195

Havlin JL Tisdale, Werner L Nelson and James D Beaton. 2014. Soil Fertility and Fertilizers: An Introduction to Nutrient Management. 6th Edition, Prentice Hall, Upper Saddle River, NJ.

Horta LP, Mota YC, Barbosa GM, Braga TC, Marriel IE, Fátima ÂD and Modolo LV. 2016. Urease inhibitors of agricultural interest inspired by structures of plant phenolic aldehydes. *Journal of the Brazilian Chemical Society*, 27:1512-1519.

Hou Y, Velthof GL and Oenema O. 2015. Mitigation of ammonia, nitrous oxide and methane emissions from manure management chains: a meta-analysis and integrated assessment. *Global Change Biology*, 21: 1293–1312.

Huber DM, Warren HL, Nelson DW and Tsai CY. 1977. Nitrification inhibitors—New tools for food production. *Bioscience*, 27: 523-529.

Hull N. 2018. Cover Crop Effects on Urease Inhibitors. Master's Thesis. Auburn University Auburn, Alabama. http://hdl.handle.net/10415/6338.

Hussain A, Jahan N, Jabeen Z, Rehman KU, Rafeeq H, Bilal M and Iqbal H. 2021. Synergistic Effect of Urease and Nitrification Inhibitors in the Reduction of Ammonia Volatilization. *Water, Air, and Soil Pollution*, 232: 1-7.

Iliger MD, Sutar R, Chogatapur SV and Parameshwarareddy R. 2017. Effect of brown manuring on soil properties, weed density, grain yield and economics of different crops. *Advances in Research*, 12: 1-10.

Kaur J and Kaur J. 2017. Appropriate Nitrogen Schedules in Direct Seeded Rice (*Oryza sativa* L.). *International Journal of Bio-resource and Stress Management*, 8: 242-246.

Kim DG, Hernandez-Ramirez G and Giltrap D. 2013. Linear and nonlinear dependency of direct nitrous oxide emissions on fertilizer nitrogen input: a meta-analysis. *Agriculture, Ecosystems & Environment*, 168: 53–65.

Kumar R, Parmar BS, Walia S and Saha S. 2015. Nitrification inhibitors: Classes and its use in nitrification management. In Nutrient Use Efficiency: from Basics to Advances. pp. 103-122. Springer, New Delhi.

Kumar V, AK Singh, SL Jat, CM Parihar, V Pooniya and S Sharma. 2015b. Nutrient uptake and fertilizer use efficiency of maize hybrids under conservation agriculture with nutrient expert based SSNM practices. *Annals of Agriculture Research*, 36: 160-166.

Kumar V, AK Singh, SL Jat, CM Parihar, V Pooniya, B Singh and S Sharma. 2015a. Precision nutrient and conservation agriculture practices for enhancing productivity, profitability, nutrient-use efficiencies and soil nutrient status of maize (*Zea mays*) hybrids. *Indian Journal of Agricultural Sciences*, 85: 926-930.

Kumar V, AK Singh, SL Jat, CM Parihar, V Pooniya, S Sharma and B Singh. 2014. Influence of site-specific nutrient management on growth and yield of maize (*Zea mays*) under conservation tillage. *Indian Journal of Agronomy*, 59: 657-660.

Lan T, Han Y, Roelcke M, Nieder R and Cai Z. 2013. Effects of the nitrification inhibitor dicyandiamide (DCD) on gross N transformation rates and mitigating N2O emission in paddy soils. *Soil Biology and Biochemistry*, 67: 174-182.

Li Q, Cui X, Liu X, Roelcke M, Pasda G, Zerulla W, Wissemeier AH, Chen X, Goulding K and Zhang F. 2017. A new urease-inhibiting formulation decreases ammonia volatilization and improves maize nitrogen utilization in North China Plain. *Scientific Reports*, 7: 1-9.

Majumdar D. 2008. Unexploited botanical nitrification inhibitors prepared from Karanja plant. http://hdl.handle.net/123456789/5647

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: 1410-1417.

Marchesan E, Grohs M, Walter M, Silva LS and Formentini TC. 2013. Agronomic performance of rice to the use of urease inhibitor in two cropping systems. *Revista Ciência Agronômica*, 44: 594-603.

Matczuk D AND Siczek A. 2021. Effectiveness of the use of urease inhibitors in agriculture: a review. *International Agrophysics*, 35: 197–208

Mathialagan R, Mansor N, Al-Khateeb B, Mohamad MH and Shamsuddin MR. 2017. Evaluation of allicin as soil urease inhibitor. *Procedia Engineering*, 184: 449-459.

Meng X, Li Y, Yao H, Wang J, Dai F, Wu Y and Chapman S. 2020. Nitrification and urease inhibitors improve rice nitrogen uptake and prevent denitrification in alkaline paddy soil. *Applied Soil Ecology*, 154: 103665.

Modolo LV, da-Silva CJ, Brandão DS and Chaves IS. 2018. A mini review on what we have learned about urease inhibitors of agricultural interest since mid-2000s. *Journal of Advanced Research*, 13: 29-37.

Modolo LV, de Souza AX, Horta LP, Araujo DP and de Fatima A. 2015. An overview on the potential of natural products as ureases inhibitors: A review. *Journal of Advanced Research*, 6: 35-44.

Mohanty S, Nayak AK, Tripathi R, Shahid M, Panda BB. Vijayakumar S, Mohapatra SD, Priyadarsini S, Saha S, Sarangi DR, Swain CK, Besra B, Nagothu US and Pathak H. 2019. Integrated Nutrient Management for Sustainable Rice Production. Technology Brief No. 2. ICAR-National Rice Research Institute, Cuttack-753006, Odisha

Nayak AK, Chatterjee D, Tripathi R, Shahid M, Vijayakumar S, Satapathy BS, Kumar A, Mohanty S, Bhattacharyya P, Mishra P, Kumar U, Mohapatra SD, Panda BB, Rajak M, Bhaduri D, Munda S, Chakraborty K, Priyadarsani S, Swain CK, Moharana KC, Nayak PK, Kumar GAK, Swain P, Tesfai M, Nagaothu US and Pathak H. 2020. Climate Smart Agricultural Technologies for Rice Production System in Odisha. ICAR-National Rice Research Institute, Cuttack, Odisha, 753006, India. pp 366. ISBN: 81-88409-14-6.

Nayak AK, Rahul Tripathi, Manish Debnath, CK Swain, B Dhal, Vijaykumar S, AD Nayak, S Mohanty, MD Shahid, Anjani Kumar, Manoj Rajak, KC Moharana, D Chatterjee, S Munda, P Guru, Rubina Khanam, B Lal, P Gautam, S Pattanaik, AK Shukla, Nuala Fitton, P Smith and H Pathak. 2022. Carbon and water footprint of rice, wheat and maize crop productions in India, *Pedosphere*, ISSN 1002-0160, https://doi.org/10.1016/j.pedsph.2022.06.045.

Norton J and Ouyang Y. 2019. Controls and adaptive management of nitrification in agricultural soils. *Frontiers in Microbiology*, 10: 1931.

Pan B, Lam SK, Mosier A, Luo Y and Chen D. 2016. Ammonia volatilization from synthetic fertilizers and its mitigation strategies: a global synthesis. *Agriculture, Ecosystems & Environment*, 232: 283-289.

Pathak H, Prasad S, Bhatia A, Singh S, Kumar S, Singh J and Jain MC. 2003. Methane emission from rice-wheat cropping system of India in relation to irrigation, farmyard manure and dicyandiamide application. *Agriculture, Ecosystems & Environment,* 97: 309–316.

Pathak H and Wassmann R. 2007. Introducing greenhouse gas mitigation as a development objective in rice-based agriculture: I. Generation of technical coefficients. *Agricultural Systems*, 94: 807-825.

Patil Chethan ND, Manjunatha SK and Bindu K Ramalingannanavar. 2020. Brown Manuring: A Tool for Integrated Nutrient Management. *Indian Farming*, 7: 701-704.

Peng S, Laza MRC, Garcia FV and Cassman KG. 1995. Chlorophyll meter estimates leaf area-based nitrogen concentration of rice. *Communications in Soil Science and Plant Analysis*, 26: 927-935.

Philibert A, Loyce C and Makowski D. 2012. Assessment of the quality of meta-analysis in agronomy. *Agriculture, Ecosystems & Environment*, 148: 72–82.

Phukan J, Bora P. 2012. Brown manuring. *AgriAllis*, 3 https://agriallis.com/wp-content/uploads/2021/03/BROWN-MANURING.pdf

Qi X, Wu W, Shah F, Peng S, Huang J, Cui K, Liu H and Nie L. 2012. Ammonia volatilization from urea-application influenced germination and early seedling growth of dry direct-seeded rice. *The Scientific World Journal*, 857472.

Qiao C, Liu L, Hu S, Compton JE, Greaver TL and Li Q. 2015. How inhibiting nitrification affects nitrogen cycle and reduces environmental impacts of anthropogenic nitrogen input. *Global Change Biology,* 3: 1249-1257.

Raza S, X Li, N Miao, M Ahmed, Z Liu and J Zhou. 2019. Dicyandiamide increased ammonia volatilization and decreased carbon dioxide emission from calcareous soil during wheat–maize rotation on the Loess Plateau. *Soil Research*, 57: 767-777.

Reddy RNS and Prasad R. 1975. Studies on the mineralization of urea, coated urea, and nitrification inhibitor treated urea in soil. *Journal of Soil Science*, 26: 304-312.

Rochette P, Angers DA, Chantigny MH, Gasser MO, 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.

Rose TJ, Morris SG, Quin P, Kearney LJ, Kimber S and Van Zwieten L. 2017. The nitrification inhibitor DMPP applied to subtropical rice has an inconsistent effect on nitrous oxide emissions. *Soil Research*, 55: 547-552.

Ruser R and Schulz R. 2015. The effect of nitrification inhibitors on the nitrous oxide (N_2O) release from agricultural soils—a review. *Journal of Plant Nutrition and Soil Science,* 178(2): 171-188

Sahrawat KL, Mukerjee SK. 1977. Nitrification inhibitors. *Plant and Soil.* 47: 27-36.

Sahrawat KL. 1980. Control of urea hydrolysis and nitrification in soil by chemicals—prospects and problems. *Plant and Soil*, 57: 335-352.

Samant TK and Patra AK. 2016. Effect of tillage and nutrient-management practices on yield, economics and soil health in rice (*Oryza sativa*)-green gram (*Vigna radiata*) cropping system under rainfed condition of Odisha. *Indian Journal of Agronomy,* 61: 148-153.

Sanchis E, Ferrer M, Torres G, Cambra-López M and Calvet S. 2012. Effect of water and straw management practices on methane emissions from rice fields: a review through a meta-analysis. *Environmental Engineering Science*, 29: 1-12.

Sanz-Cobena A, Lassaletta L, Aguilera E, del Prado A, Garnier J, Billen G, Iglesias A, Sanchez B, Guardia G, Abalos D and Plaza-Bonilla D. 2017. Strategies for greenhouse gas emissions mitigation in Mediterranean agriculture: A review. *Agriculture, Ecosystems & Environment*, 238: 5-24.

Sanz-Cobena A, Misselbrook TH, Arce A, Mingot JI, Diez JA and Vallejo A. 2008. An inhibitor of urease activity effectively reduces ammonia emissions from soil treated with urea under Mediterranean conditions. *Agriculture, Ecosystems & Environment,* 126: 243-249.

Sathiya K and Ramesh T. 2009. Effect of split application of nitrogen on growth and yield of aerobic rice. *Asian Journal of Experimental Sciences*, 23: 303-306.

Sharma U, Subehia SK. 2014. Effect of long-term integrated nutrient management on rice (*Oryza sativa* L.)-wheat (*Triticum aestivum* L.) productivity and soil properties in North-Western Himalaya. *Journal of the Indian Society of Soil Science*, 62: 248-254.

Shcherbak I, Millar N and Robertson GP. 2014. Global metaanalysis of the nonlinear response of soil nitrous oxide (N_2O) emissions to fertilizer nitrogen. *Proceedings of the National Academy of Sciences,* 111: 9199–9204.

Slangen JH and Kerkhoff P. 1984. Nitrification inhibitors in agriculture and horticulture: a literature review. *Fertilizer Research,* 5: 1-76.

Sloan JJ and Anderson WB. 1995. Calcium chloride and ammonium thiosulfate as ammonia volatilization inhibitors for urea fertilizers. *Communications in Soil Science and Plant Analysis,* 26: 2425-47.

Song D, Qiao L, Gao D, Li S, Li M, Sun H and Ma J. 2021. Development of crop chlorophyll detector based on a type of interference filter optical sensor. *Computers and Electronics in Agriculture,* 187: 106260.

Subramanian E, Aathithyan C, Raghavendran VB and Vijayakumar S. 2020. Optimization of nitrogen fertilization for aerobic rice (*Oryza sativa*). *Indian Journal of Agronomy* 65: 180-184.

Sudhalakshmi C, Velu V and Thiyagarajan TM. 2008. Leaf colour chart for nitrogen management in rice–A review. *Agricultural Reviews*, 29: 306-310.

Surjandari I and MT Batte. 2003. Adoption of Variable Rate Technology. Makara, *Teknologi*, December, 120-124.

Thapa R, Chatterjee A, Awale R, McGranahan DA and Daigh A. 2016. Effect of enhanced efficiency fertilizers on nitrous oxide emissions and crop yields: A meta-analysis. *Soil Science Society of America Journal*, 80: 1121-1134.

Thilagavathi T and Ramanathan S. 2005. Nitrogen management for direct wet-seeded rice. *International Rice Research Notes* 30: 44–45.

Uddling J, Gelang-Alfredsson J, Piikki K and Pleijel H. 2007. Evaluating the relationship between leaf chlorophyll concentration and SPAD-502 chlorophyll meter readings. *Photosynthesis Research,* 91: 37-46.

Upadhyay RK, Tewari SK and Patra DD. 2011. Natural nitrification inhibitors for higher nitrogen use efficiency, crop yield, and for curtailing global warming. *Journal of Tropical Agriculture,* 49: 19-24.

Van Der Gon HD and Neue HU. 1995. Influence of organic matter incorporation on the methane emission from a wetland rice field. *Global biogeochemical cycles*, 9: 11-22.

Varadachari C and Goertz HM. 2010. Slow-release and controlled release nitrogen fertilizers. In Singh B (ed.) ING Bulletins on Regional Assessment of Reactive Nitrogen. Bulletin No. 11. Scon-Ing, New Delhi. pp. 1–42.

Vijayakumar S, AK Nayak, Annie Poonam, Aravindan S and Rubina Khanam. 2020a. Unmanned aerial vehicle (UAV) and its application in Indian agriculture: A perspective. *Indian Farming*, 70: 34-37.

Vijayakumar S, Anil Kumar Choudhary, M. Deiveegan, R. Thirumalaikumar and R. Mahender Kumar. 2022. Android Based Mobile Application for Rice Crop Management. *Chronicle of Bioresource Management*, 6: 19-24.

Vijayakumar S, Aravindan S, Saravanane P and Sivashankari M. 2021b. Unmanned aerial vehicles policies evaluation and suggestion to boost its agriculture application in India. *Kerala Karshakan e-journal*, 8: 6-8.

Vijayakumar S, Dinesh Jinger, Saravanane P, Subramanian E and Prabhu Govindasamy May 2021a. Agricultural Waste to Wealth: Way for Sustainable Agriculture Development. *Indian Farming*, 71: 34–36.

Vijayakumar S, Dinesh Kumar, Dinesh Jinger, Bhargavi Bussa and BB Panda. 2021. 4R nutrient stewardship-based potassium management to improve the productivity of dry-direct seeded rice-wheat cropping system. *Indian Farming*, 71: 22-25.

Vijayakumar S, RubinaKhanam, AK Nayak, Aravindan S and Sivashankari M. 2020. Soil Health Card: A critical Review. *Kerala Karshakan e-journal*, 8: 27-29.

Vijayakumar S, SuchismitaPattanaik and Saravanane P. 2021a. Low Carbon technologies for agriculture. *Sabujima*, 29: 94-100.

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 & Environment*, 137: 39-46.

Woodward EE, Edwards TM, Givens CE, Kolpin DW and Hladik ML. 2021. Widespread Use of the Nitrification Inhibitor Nitrapyrin: Assessing Benefits and Costs to Agriculture, Ecosystems, and Environmental Health. *Environmental Science & Technology*, 55: 1345-1353.

Yang M, Fang Y, Sun D and Shi Y. 2016. Efficiency of two nitrification inhibitors (dicyandiamide and 3, 4-dimethypyrazole phosphate) on soil nitrogen transformations and plant productivity: a meta-analysis. *Scientific Reports*, 6: 1-10.

Yao Y, Miao Y, Huang S, Gao L, Ma X, Zhao G, Jiang R, Chen X, Zhang F, Yu K and Gnyp ML. 2012. Active canopy sensor-based precision N management strategy for rice. *Agronomy for Sustainable Development*, 32:925-33.

Yuan Z, Cao Q, Zhang K, Ata-Ul-Karim ST, Tian Y, Zhu Y, Cao W and Liu X. 2016. Optimal leaf positions for SPAD meter measurement in rice. *Frontiers in Plant Science*, 7:719.

Zhang K, Ge X, Liu X, Zhang Z, Liang Y, Tian Y, Cao Q, Cao W, Zhu Y and Liu X. 2017. Evaluation of the chlorophyll meter and GreenSeeker for the assessment of rice nitrogen status. *Advances in Animal Biosciences*, 8: 359-363.