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Research Article

Slow release nitrogen fertilizers-an ideal approach for reducing nitrogen losses and improving crop yields

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Abstract

About one-fourth to one-third of the applied fertilizer nitrogen is lost as ammonium and nitrous oxide gases to the atmosphere or as nitrates to the surface or ground waters, creating a number of environmental and health problems. With the global nitrogen consumption of about 102 million tonnes (mt) in 2009, the loss of applied nitrogen could range from 25 to 34 mt amounting to 12.5 to 17 billion US dollars; the N loss estimates for India could be 3-4 mt valued at 1.5-2.0 billion US dollars. The estimates for 2050 are at 27.5 to 36.6 billion US dollars globally and 3.25 to 4.35 billion US dollars for India. This is a colossal loss of natural resources, energy and money and must be reduced if not completely avoided. Controlled release fertilizer (CRF), slow release fertilizer (SRF) and fertilizers amended with nitrification/urease inhibitors referred to as 'bio-amended fertilizers offer a way to increase productivity and reduce nitrogen losses. International funding similar to that for carbon bonds must come forward to help the utilization of such N fertilizers for use in South, Southeast and East Asia, the region that consumes about 60% of World's total N fertilizer consumption and where the largest portion of the world's below poverty line people reside. This paper mainly reviewed the different types of slow release fertilizers commonly available, their global consumption, effect on crop growth and nitrogen losses.

Keywords: Nitrogen losses; Yield increase; Slow release nitrogen fertilizers

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Introduction

The demand for plant nutrients will increase continuously with increase in population [1], [2] and by 2020, about 70% of food grain production will be dependent on fertilizers. The global population is expected to rise by 2.3 billion by 2020 and double by 2050 [2]. If food and meat consumption continued to rise in the same pattern, then the demand for grain and nutrients is expected to triple [2]. As the nutrient load per unit area is increasing steadily due to decrease in the amount of land used for food production [2], the efficiency is decreasing continuously. This calls for a more intensive and efficient food production than ever before. Among different nutrients, the steady decrease in efficiency of nitrogen use efficiency is of serious concern. Nitrogen is considered to be the yield limiting nutrient and as such is the most widely applied plant nutrient [3]. Of the 170 Tg N reaching the world's cropland annually, the anthropogenic inputs of N in fertilizers, irrigation water, seeds, etc. constitute about 85% [4]. However, the global agricultural output of N is only 23 Tg N annually [1], [3], indicating the poor efficiency of N utilization for food production. Globally apparent nitrogen recovery in cereals is 40-50 per cent [5], [6] and it is lowest in rice [7, 3]. Nutrient recovery from N fertilizers varies with crop species [8], [9], soil properties and environmental conditions [10], [11], management practices [12] and nutrient source [11].

Introduction of dwarf high yielding and nutrient responsive varieties coupled with expansion of irrigation facilities and increased use of chemical fertilizers and other agro-chemicals have led to spectacular increases in crop productivity, particularly of rice and wheat. About 50% of the increase in food grain production been attributed to fertilizer use and more than 30-40% increase is due to nitrogen fertilizers alone. Of late, the partial factor productivity of fertilizers has been declining as evident from stagnant food grain production despite increased fertilizer use in the country. The causes of low nitrogen use efficiency (NUE) include losses due to volatilization as ammonia [13], leaching [14], [4], denitrification in flood condition, run-off, fixation as non-exchangeable NH_4^+ and immobilization by soil microbes. The unrecovered nitrogen constitutes a potential contributor to ground water contamination [14],

[4], eutrophication [15], [16], acid rain [17] and global warming [18]. The excessive and injudicious use of N fertilizers affect the quality of crops, human and animal health, and cause lodging in cereals, which may affect crop yield and quality. In surface water, presence of high N results in growth of algae and other planktonic growth and affect the water quality and usage. Incidences of stomach cancer in humans [19] and Methamoglobinemia (blue baby syndrome) in infants [20], [21], [6] and in ruminants [15], [22] due to intake of water contaminated with nitrates and hypoxia leading to fish mortality in estuaries and gulfs have been reported. Nitrosamines produced from nitrates are reported to be carcinogenic. These concerns are continuously drawing the attention of agricultural scientists for efficient nitrogen use and arresting declining response to fertilizers [23], [24]. Due to rising health and environmental concerns, standards for nitrate concentration in potable water have been set at 10 mg-N litre^{-1} in the US [25] and 50 mg-NO_3 litre^{-1} by the EEC [26]. It is therefore imperative to reduce these nitrogen losses from nitrogen fertilizers. Slow release nitrogen fertilizers (SRNF) offer a solution to this problem by releasing small amounts of nitrogen coinciding with the crop need and increasing the efficiency of nitrogen by minimizing its losses. But, unfortunately, the total use of slow and controlled release fertilizers (SRFs and CRFs) is much smaller than the total amount of fertilizers used globally. The estimated use of CRFs/SRFs was about 560,000 tons worldwide in 1996-97and about double this amount of processed organic products [27]. Although the use of SRFs/CRFs has doubled over the last decade, the percentage share is only 0.15% of the total use of nutrients [27]. The major proportion of these fertilizers is used in non-agricultural markets (e.g., for lawn care, golf courses, landscaping), with yearly increase in demand by about 5%. The consumption of SRFs/CRFs in agriculture hardly exceeds 10% of the total amount of SRFs/CRFs in use, but the demand is increasing sharply at an annual rate of about 10% [27]. The highest production and consumption of CRFs/SRFs is in the USA, Canada, Japan and Europe [27].

Available options

By 2050, the world population is likely to be 9.0 billion and this will call for a 50 per cent increase in cereal production [28]. Further, a large share of this increase in population will be in South, Southeast and East Asia (SSEEA), where rice and wheat are the staple food. Since the availability of agricultural land per person in SSEEA is already too short and will decline further, most of the increase in cereal production has therefore to come from increasing the crop yield. About 30-40 per cent increase in cereal production is attributed to fertilizer nitrogen [29]. Nitrogen fertilizer consumption in this region is likely to increase considerably and with this the concomitant losses of N_2O to atmosphere and nitrate to ground water and estuaries. Assuming that one-fourth (25%) to one-third (33%) of applied fertilizer nitrogen is lost as ammonia and nitrous oxide to the atmosphere and as nitrates to the surface and ground waters, about 25.5 to 34 million tonnes (mt) of fertilizer N was lost in 2009 (**Table 1**) and if the fertilizer materials and their management continues to be the same in future, as much as 55 to 73.3 mt may be lost by 2050. The N loss estimates for India could be 3-4 mt in 2009 and 6.5-8.7 mt in 2050. Taking current urea prices @ US 500$ /t, the financial loss in 2009 works out to 1.5-2.0 billion US$ and 3.25 to 4.35 billion US$ in 2050 for India and 12.75 to 17 billion US$ in 2009 and 27.5 to 36.6 billion US$ in 2050 globally. This is a colossal loss of natural resources, energy and money and must be checked as early as possible. Slow release fertilizers (SRF) offer one way of doing it [3, 30].

Table 1 Nitrogen fertilizer consumption and expected losses (million tonnes)

Consumption/loss	2009	2050
Global		
Consumption	102	220*
Loss @ 25 %	25.5	55.0
Loss @ 33.3 %	34.0	73.3
India		
Consumption	12	26**
Loss @ 25 %	3.0	6.5
Loss @ 33.3 %	4.0	8.7

*As predicted by [81]
**Calculated in the same ratio as global

There are two options at the moment: (a) To increase the use of conventional N fertilizer with apparent nitrogen recovery efficiency (AREn) of 30-40 per cent or (b) To produce N fertilizers with higher AREn of 50-80 per cent (**Table 2**). As regards the second option, the available literature suggests this can be partly achieved by blending the conventional N fertilizer with nitrification inhibitors [27], urease inhibitors [31] and urea super granules/briquettes

[32], [33]. The real solution, however, lies in developing slow/controlled release nitrogen fertilizers (SRNF) that can release N as per need of the crop. As regards transplanted rice the crop uptake of N is about 1 to 1.5 kg N/ha/day which can be met through the use of slow release fertilizers.

Table 2 Apparent recovery (AREn) of urea and slow-release nitrogen fertilizers applied to rice

Fertilizer	Method of application	AREn (%)	Reference
Urea	i. Single application at transplanting	28.6	[73]
	ii. Split application	34.0	
IBDU	Single application at transplanting	51.1	[73]
Urea or Am. Sulphate	Broadcast	22-23	[75]
PCU-100	Broadcast	48-62	[82]
PCU-100	Single application in a nursery box	79	[56]

Slow release nitrogen fertilizers (SRNF)

Application of slow release nitrogen fertilizers or controlled release fertilizers (CRF) is a new approach for minimizing non-point contamination in agriculture. The goal in developing SRNF is having N release rated to the requirement of growing crop, thereby reducing the loss of applied fertilizer N and increasing the nitrogen use efficiency (NUE). The increase in nutrient use efficiency (NUE) and reduction in environmental problems through nutrient supply control mainly depends on two factors: matching supply of nutrient with plant demand and maintaining nutrient availability. The nutrient availability in the soil-plant system is influenced by the complex interactions existing between plant roots and soil micro-organisms and the chemical reactions and pathways involved in the process of nutrient loss. Most of the transformations of nutrients from one phase to another depend on concentration, indicating that the supply of nutrient that exceeds the ability of plant uptake will induce processes intending to decrease the concentration of nutrient in the soil. These processes include transformations induced by physical processes (e.g., leaching, runoff, and volatilization), chemical reactions (e.g., exchange, fixation, precipitation, and hydrolysis) and microbes (e.g., nitrification, denitrification, and immobilization). The extent to which these processes remove the nutrients from soil solution influence the NUE and the environment. The surplus supply of nutrients should thus be reduced both temporally and spatially through improved management practices. Appropriate type of fertilizer in the right amount and at right time should be applied as the total nutrient requirement, peak period of nutrient demand and preferred chemical forms crop and variety specific. Generally the time pattern of macro-nutrient uptake is sigmoidal [34], [35], [36], [37] for the seasonal crops as well as for the perennials or trees when a shift from dormant to biologically active phases occurs. Therefore, following a sigmoidal pattern of nutrient uptake and synchronizing nutrient supply with plant demand will led to optimal nutrition for plant growth and reduction in losses by the processes competing with nutrient uptake [38], [5], [39], [40]. The advantages associated with controlling/optimizing nutrient supply are further discussed in respect of three important aspects.

Economic Aspects

- Potential for Reducing Nutrient Losses: The nutrient losses via different processes may be considered “irreversible” from a practical view point, at least for a short range. Such processes are often the main factors for poor N recovery [12], [41], varying from 30-40% in poorly managed practices such as paddy rice [7], [42] to 70% in better managed ones. Several researchers have suggested the use of CRF/SRFs or nitrification inhibitors to reduce such losses [43], [5], [44], [45], [27].
- Reducing cost of Fertilizer Applications: Slow release/controlled release fertilizers reduce the spreading costs through single application of fertilizers for the entire season. Moreover, SRFs/CRFs reduce the labour demand for top dressing as in paddy [45]. The additional application cost may also be saved through addition of bio-amendments, such as nitrification inhibitors [12], [5], [27].

Physiological Aspects

Several agronomic advantages related to the improvement of plant growth conditions are associated with the use of SRF/CRFs, apart from the direct savings.

- Reduction of Stress: Due to fast nutrient supply from conventional soluble fertilizers, the root zone gets saturated with high concentration of soluble salts [39], [27]. This sometimes induces physiological drought and causes specific injuries at different growth stages [46]. Oppositely, the use of SRFs/CRFs improves germination, crop growth and quality together with reduced disease infestation, leaf burns and stem breakage [43], [5], [47], [27].

- Supply of preferred nutrient forms: A great deal of attention is being paid now towards the question of the preferred form of plant nutrients, particularly in respect of ammonium or nitrate nutrition. Numerous publications have reported a significant increase in grain yield or protein content due to mixed ammonium-nitrate nutrition, in comparison to sole application of ammonium or nitrate [48], [49], [39]. Such results were obtained in experiments where reasonable control over the ratio of ammonium/nitrate in soil could be maintained. [50] and [51] suggested that by using nitrification inhibitors, fertigation or high local concentrations of ammonium, enhanced ammonium nutrition can be achieved. According to [47], CRFs containing higher proportions of NH_4 resulted in higher yield of millets and led to increased accumulation of proteinaceous material in plants.

Environmental Aspects

Any nutrient application method that improves NUE and synchronizes nutrient supply with plant demand has the potential to reduce losses to the environment [38], [5], [9], [3], [37]. As SRFs/CRFs display a lag in release, the supply is matched by the plant uptake and thereby reducing the potential contamination of the environment.

Classification of controlled/slow release fertilizers

There are broadly two groups of SRNFs: (i) those having inherently low solubility and (ii) coated conventional fertilizers. The first group is formed by reacting urea with an aldehyde, which leads to the formation of an adduct, that has low solubility and includes urea form (UF), isobutylidene diurea (IBDU), crotylidene diurea (CDU), oxamide, guanylurea, difurfurlidene triueid, glyculuril, triazines, N-enriched coal and metal ammonium phosphates [52], of which UF, IBDU and CDU are the most important and have been tested and are being used as SRNFs.

The second group includes sulphur coated urea (SCU), polymer coated urea (PCU), neem coated urea (NCU) and N/NP/NPK fertilizers coated with inert materials such as resins, waxes, paraffin, gums, tars, gypsum, ground rock phosphate etc. of which SCU, PCU and NCU are the most important and have been widely tested and are being used as SRNF. The two terms, namely, controlled release and slow release are generally used synonymously. However, [53] suggested that the term controlled release fertilizers (CRF) may be reserved for those fertilizer, for which rate, pattern and duration of release are well known and controllable, while the term 'slow release fertilizers' (SRF) may be used for those fertilizers, where the release of nitrogen is slowed down, but the rate, pattern and duration of release are not well defined and controlled. [27] provides details on SRNF being manufactured, marketed and used in USA, Western Europe and Japan (**Table 3**).

Table 3 Consumption ('000 tonnes) of slow/controlled release nitrogen fertilizers in 1995-96 [27]

Slow release fertilizer	USA	Western Europe	Japan	Total	% of total SRNF
UF	190	30	5	225	40
SCU/SCU+P	100	2	6	108	19
PCU/PCU NPK's 45	20	72	137	24	-
IBDU/CDU	14	35	33	82	15
Others	7	-	3	10	2
Total	356	87	119	562	100

Fertilizers with inherent low solubility

Urea-formaldehyde (UF)

Urea-formaldehyde (UF) contains about 38 per cent N and its release depends upon microbial decomposition which in turn depends on several soil properties, such as, microbial population, organic matter content, moisture and temperature. The solubility depends on U:F ratio (ranging from 1.2 to 1.9), particle size and soil pH. It has three fractions as:- Fraction I: [cold water (25^0C) soluble]: contains residual urea, methylene diurea, dimethylene triurea and some other soluble products. Fraction II: [hot water (100^0C) soluble urea]: Methylene ureas of intermediate chain lengths. Fraction III: [Insoluble in cold and hot water]: Methylene ureas of longer chains. An availability index (AI) is generally used for UF's, which is defined as:-

$$AI = \frac{100[\% \text{ cold water insoluble N (CWIN)} - \% \text{ hot water insoluble N}}{\% \text{ CWIN}}$$

The Association of American Plant Food and Control Officials (1) has set a standard of AI of 40% as minimum and at least 60% of its N as CWIN (cold water insoluble N). The nitrogen in UF is released firstly by dissolution and then by decomposition, gradually in 3 to 4 months. Its major consumption is in USA, where it is used on turfs and in strawberries, vegetables, citrus and other fruit crops [27].

Isobutylidene diurea (IBDU)

The N content in IBDU is about 32%. As a contrast to UF, where condensation of urea and formaldehyde results in the formation of a number of polymer oligomers of different chain lengths, the reaction of urea with isobutylidene (a liquid) results in a single oligomer. [54] standards require a minimum of 30 per cent N, of which 90 per cent is cold water insoluble (CWIN) (prior to grinding). The rate of release of N from IBDU depends on chemical composition and is governed by particle size, soil moisture, temperature and pH.

In Japan, experiments with rice revealed that IBDU resulted in 12-25% higher grain yield as compared to ammonium sulphate and urea [55]. [56] observed that the release of N from IBDU was much more rapid in acid than in alkaline soils. In a field experiment at New Delhi, IBDU produced 6.6 per cent more rough rice as compared to split application of urea; the increase over a single application of urea was 11.2 per cent [57]. The advantage of IBDU over urea was much more under alternate wetting and drying moisture regime, where the N losses are more and at 150 kg N /ha as IBDU produced 26 per cent more rough rice than a single application of urea., the increase was 11 per cent when IBDU was compared to split application of urea [58]. IBDU is generally marketed as blends with conventional N fertilizers and its use is still restricted to specialty agriculture.

Crotylidene diurea (CDU)

CDU contains about 32.5 per cent N and is made by acid catalyzed reaction of urea with acetaldehyde. As with IBDU, particle size determines rate of release of N from it; the larger the particle size, the slower is the release. N from CDU is released by hydrolytic as well as microbial processes. It is again a specialty agriculture fertilizer.

Modified or coated fertilizers

Sulphur coated urea (SCU)

SCU contains 30-40%. It was initially developed by Tennessee Valley Authority (TVA) in 1961. Preheated urea granules were sprayed with molten sulphur (10-20% by weight) in a rotating drum. The pores and cracks in the coating are then are sealed by adding a wax like polymeric sealant (2-3% by weight). Finally a conditioner is added (2-3% by weight) to give a free flowing and dust free product. Nitrogen release in SCU is affected by coating thickness and quality and depends upon the rate of microbial and hydrolytic degradation. In a laboratory study at New Delhi, release of N from SCU was higher under field capacity moisture regime than under continuous flooding or alternate wetting and drying [59]. As a contrast, the release of N from IBDU was higher under continuous flooding.

In field experiments under All India Coordinated Rice improvement Project of ICAR, SCU gave 1.8 t/ha more rough rice than urea applied in a single dressing during *rabi* (dry) season, results were not so encouraging during *kharief* (wet) season (AICRIP, 1970). However, during *kharief* season at New Delhi, SCU gave 0.7 to 1.7 t/ha more rough rice than urea [60]. Further under reduced flooded conditions as in rice, part of S may be converted to ferrous sulphide and may prevent the urea particles to come in contact with urease and thus reducing its availability. This would explain, why in some experiments SCU did not perform well [61]. SCU has a great advantage of supplying S and could be very useful in India, where nearly 50 per cent of its soils are deficient in S [62]. A disadvantage with SCU is that it floats when broadcasted on standing water and gets washed when applied on sloping lands.

Polymer coated urea (PCU)

PCU contain 40-44% N depending upon the amount and thickness of coating. Thus with regard to N content, PCU is better than SCU or urea aldehyde condensates, which contain only 30-38% N. Much more research has been done on PCU than any other coated fertilizer [45], [63], [64].

Polymer coatings on urea are semi-permeable or impermeable membranes with tiny pores. As compared to SCU, IDBU, FU, CDU and NCU, where soil properties control the release of N, the release of N from PCU is primarily dependent on temperature and permeability of the polymer used for coating [45]. PCU can be made to release N during 70 to 400 days as per requirement of the crop. Most polymers used are photo-degradable but some may persist in soil for a long period.

PCU is used in rice culture in Japan and it is reported that same yield can be obtained with lesser amounts of PCU than urea [65]. In zero-till farming systems, a single dose of PCU can reduce rice production cost by 30-50% [66], [67], [37]. However, in a field experiment PCU (3 or 6 per cent coating) gave similar yield of rice as urea, but significantly higher N uptake than urea; the AREn being 55.9% with PCU as compared to 35% with urea [68]. In a laboratory study PCU gave lesser ammonia volatilization losses as compared to urea [69].

Neem coated urea (NCU)

Neem (*Azadirachta indica* Juss) coated urea was developed at the Indian Agricultural Research Institute (IARI), New Delhi. It started with a field experiment on rice, where urea treated with an acetone extract of Neem kernels increased grain yield over urea and even performed better than SCU [61]. It was followed by the development of Neem cake (left after extraction of oil) coated urea (NCCU, generally referred to as NCU). Neem cake was used to save the oil, because those were the days of energy crisis. Neem cake (15-20 per cent by weight of urea) was coated on urea in a rotating drum using a coaltar:kerosene (1:2) solution as a sticker. Superiority of NCCU over urea was reported not only in rice but several other crops [70]. Nitrification inhibiting properties of neem cake have been reported [71], [72]. However, due to the requirements of large amounts of neem cake, this technique could not be accepted by the fertilizer industry. A plant producing 1000 t/day NCCCU would have requirement of 150-200 t neem cake/day.

Since nitrification inhibitors in neem are lipid associates, a neem oil micro-emulsion technique was later developed [73], [67]. This technique needed only 0.5 kg neem oil/t of urea. Results with this modified neem coated urea (NCU) were quite encouraging and in a large number of on-farm trials in the states of Haryana, UP, Punjab and Delhi, NCU gave 8-11% more rice grain than urea [74]. This technique or its modification is now being used to manufacture NCU in India and at present is being sold to the farmers at the same price as urea due to a small subsidy by the Government of India. NCU is free flowing and caking on storage is much less than in urea.

NCU should not be looked upon as a slow release or nitrification inhibitor blended fertilizer only but also as a ‘soil health fertilizer’ because neem products can control a large number of plant pathogens including insects, nematodes and disease causing bacteria and fungi [75]. Also most Asian farmers broadcasting urea in rice fields by hands suffer from irritation, but this does not happen with NCU.

SRNFs and nitrification inhibitors

A large number of chemicals have been reported to have nitrification inhibiting property but only four have been commercially produced and widely tested. These are: N-serve or nitrapyrin (2-chloro-6 trichloromethyl pyridine) in USA, AM (2 amino-4-chloro-6 methyl pyrimidine) and ST (sulphathiazole) in Japan and DCD (dicyandiamide) in Germany. Of these, N-serve is being commercially marketed in USA for crop production. It is well established that use of these materials along with urea retards the formation of nitrate and thereby reduces the loss of N through leaching and denitrification. Exhaustive reviews of such studies have indicated that 10-20% increase in NUE compared with PU can be obtained in most crops and cropping systems [66]. It has also been shown that 30-40% of the N needs of the crop can be cut down by the application of these materials. These results have led the Government of India to include NCU in the fertilizer (Control) Order. The use of ammonium N sources with the nitrification inhibitor 3, 4-dimethylpyrazole phosphate (DMPP) shows promise to increase NUE and PUE. Compacting phosphogypsum (PG), diammonium phosphate (DAP), $ZnSO_4$ and KCL separately with urea slowed down urea hydrolysis and reduced NH_3 volatilization loss [76].

SRNF’s and crop growth

Several studies since early 1970’s indicated superiority of neem coated urea (NCU) over prilled urea (PU) in increasing the grain yield of rice under irrigated conditions [78]. Application of NCU and pusa neem golden urea (PGNU) also increased apparent N recovery of rice compared with PU. Coating of PU with PGNU imparts anti-caking as well as anti-dusting properties to PU and also increases its agronomic efficiency (crop response to applied fertilizers). However, coating of urea with lac, coaltar, *lisa* (resin) and wax has met with limited success compared with uncoated PU. The IARI’s urea coating technology employing neem oil emulsion needing 0.5-1.0 kg neem oil per tonne urea was found superior to prilled urea [78]. The neem coated urea of National Fertilizers Limited recorded better shelf-life, slow dissolution as well as nitrification inhibition property. With marginal additional cost for coating, the product showed increased NUE in Punjab, Uttar Pradesh and Himachal Pradesh [77].

Sulphur coated urea (SCU) has shown better performance in lowland rice than other materials due to N release for a longer period, synchronizing with important stages of crop growth [78].

Table 4 Increase in crop yield due to application of controlled release fertilizers

Crop	Fertilizer	Yield increase (%)	Reference
Rice	^{15}N-labelled CRF*	26	[83]
Wheat	FMP-coated urea	9-15	[83,84]
	CRU	2-6	[85]
	ESR	56	[86]
	Agrotain	17	-
Maize	Polymer coated CRF	36-47	[83]
	Attapulgite-coated fertilizers	15-18	[87]
Tomato	CRU	29	[88,89]
Canola	ESN	4-105	[86]
	Agrotain U	58	-
Onion	Osmocote	2-25	[90]

*CRF, controlled release fertilisers; FMP, fused magnesium phosphate; N, nitrogen; CRU, controlled release urea; ESN, environmentally smart nitrogen (polymer-coated urea).

Table 5 Recently reported effects of nitrification and urease inhibitor fertilizers on crop yield, nitrate leaching, ammonia volatilization and direct nitrous oxide (N_2O) emissions*

Technology	Range or mean effect of technology vs conventional source (%)				Reference
	Increase in crop yield	Reduction in nitrate leaching	Reduction in ammonia volatilization	Reduction in direct N_2O emission	
Nitrification	0-13				[91]
inhibitor	-6 to 3			24	[92]
Urease	7				[93]
inhibitor	3	17			[94]
	<2				[95]
	-5.5 to -1.2			63	[96]
				19-100	[97]
				37-44	[98]
	5-14	48	-20	44	[99]
	-3 to -7				[100]
	4.5				[101]
	-5 to 1			0-60	[102]
	0	0		17-56	[103]
			-3 to -65	8-57	[104]
	3				[105]
			-38		[106]
	-1.6 to 8			32-83	[107]
	7			38	[108]
				-43 to 66	[109]
	-5.5 to 7.8			0	[110]
	0			0-36	[111]
			68		[112]
	5				[113]
			25-100		[114]
	-17 to -5		23-70		[115]
				0-5	[116]
	-4 to 6				[117]
	10				[101]
			54		[106]
	<2		0-36		[108]
				-400 to 6	[109]
Urease	3				[113]
inhibitor	3			18	[118]

plus	-11	-28		25-42	[119]
nitrification	0-5			37-46	[116]
inhibitor	9				[111]
	0			30-34	[108]
	-2			17	[120]
Polymer-	0-34				[121]
coated urea	12-30			-28 to 14	[122]
	-1 to 20		62-91		[123]
	12-22				[124]
	7				[93]
	7				[125]
	-7	34			[126]
	-3 to 13				[127]
	-10	-41		20	[118]
		0			[122
				14-42	[116]
	-6 to 5			26	[119]
	3-6			29-45	[128]
	-27 to -10				[100]
	10-59				[129]
			68		[106]
	0			70	[107]
	0			19	[108]
	-3.5 to 3.9			0	[110]
				-50 to -31	[111]

*Negative values indicate decreased yield or increased N loss relative to reference conventional sources

Since leaching and denitrification losses occur only after the nitrates are formed, efforts have been made to retain applied fertilizer in ammonical form with the help of a group of chemicals known as nitrification inhibitors. The use of nitrification inhibitors might contribute to increased NUE or apparent N recovery efficiency. Maintenance of more NH_4^+ available in the soil might also increase P absorption, and therefore increase P use efficiency (PUE) [79].

Yield and nitrogen loss response to efficiency fertilizers

Number of agronomic studies has revealed that CRFs are superior to conventional fertilizers. **Table 4** summarizes increased yield of cereal crops, oil seeds and vegetables when CRFs are applied. [75] conducted experiments at IARI, New Delhi, and reported that among different sources of Nitrogen, NCU and PNGU produced significantly higher grain yield than PU. Similarly [80] reported significantly higher grain yield when NCU was applied either at planting or at planting and panicle initiation compared to application of PU at planting. This was due to delayed conversion of ammonical form to nitrite form, thereby improving and prolonging the continuous availability of N to the rice crop. The N uptake by rice grain was significantly higher due to use of slow release N fertilizers over prilled urea either basal or split [80].

The recovery of fertilizer nitrogen was in order of NCU followed by LGU, MRPU and PU respectively. Maximum recovery of applied nitrogen was with basal and split application of NCU respectively. Thus NCU applied at planting or at planting and panicle initiation stage was best suited in rice ecosystem which meets the N demand of the rice plant slowly over a long period of time and thereby reducing the ground water contaminations. Application of NCU in rice resulted in more grain yield of succeeding wheat than PU because of greater availability of N after rice harvest. Further NCU, MRPU and LGU had similar carry-over effect on the yield of wheat. However, effect of NCU was significant over basal application of prilled urea only [80].

Table 5 lists recent data on the effects of nitrification inhibitor, urease inhibitor and polymer coated urea on yield, nitrate leaching, ammonia volatilization and direct nitrous oxide (N_2O) emissions. A yield increase of 0-59 % has been reported, while as nitrate leaching, ammonia volatilization and N_2O emissions ranged from -41 to 48 %, -65 to 91 % and -400 to 100 % respectively (Table 5)

Conclusions

CRF/SRF provide a N release pattern that is more likely to match the crop growth and N demand and therefore these fertilizers are likely to give higher yield and nitrogen use efficiency. In general, CRF/SRF are reported to increase crop yield by 5-40% and in many cases the increase in yield pays well for the increased cost of fertilizer, which may be 2-3% over urea. Of late, the partial factor productivity of fertilizers has been declining as evident from stagnant food grain production despite increased fertilizer use in the country. The causes of low nitrogen use efficiency (NUE) include losses due to volatilization as ammonia, leaching, denitrification in flood condition, run-off, fixation as non-exchangeable NH_4^+ and immobilization by soil microbes. The unrecovered nitrogen constitutes a potential contributor to ground water contamination, acid rain and global warming. Slow release nitrogen fertilizers offer a solution to this problem by releasing small amounts of nitrogen coinciding with the crop need and increasing the efficiency of nitrogen by minimizing its losses. SRNF reduce the cost of fertilizer application, causes reduction in stress and specific toxicity and reduces environmental pollution. However there is a need for better understanding of nutrient release from such fertilizers and development of advanced technologies for production of cost effective SRNF/CRNF.

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