Field Crops Research 154 (2013) 246–254

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Review

Enhanced efficiency nitrogen fertilizers for rice systems: Meta-analysis of yield and nitrogen uptake

Bruce A. Linquist[a,*], Lijun Liu[b], Chris van Kessel[a], Kees Jan van Groenigen[c,d]

[a] *Department of Plant Sciences, University of California, Davis, CA 95616, USA*
[b] *Department of Agronomy, College of Agriculture, Yangzhou University, Yangzhou 225009, China*
[c] *Department of Biological Sciences and The Ecosystem Science and Society Center, Northern Arizona University, Flagstaff, AZ 86011, USA*
[d] *Department of Botany, School of Natural Sciences, Trinity College Dublin, Dublin 2, Ireland*

ARTICLE INFO

Article history:
Received 13 June 2013
Received in revised form 20 August 2013
Accepted 25 August 2013

Keywords:
EENF
Nitrogen use efficiency
Nitrification inhibitor
Urease inhibitor
Coated urea
Rice

ABSTRACT

Nitrogen is deficient in most soils and is applied in the greatest quantities of all nutrients. Given its high potential for loss, efficient fertilizer N management has both economic and environmental consequences. Enhanced efficiency nitrogen fertilizers (EENF) have been developed to decrease N losses and improve N use efficiency. However, studies evaluating the effectiveness of EENF products in rice systems show mixed results. The objective of this meta-analysis was to quantify the benefits of EENF (i.e. nitrification and urease inhibitors, neem, and slow release fertilizers) in terms of yield and N uptake and to determine under what conditions EENF are most effective. The analysis included 32 field studies (178 observations) for the effects of EENF on crop yield and 14 studies (82 observations) on N uptake. Overall, the use of EENF led to a 5.7% (95% CI = 3.9–7.7%) increase in yield and an 8.0% (95% CI = 5.2–10.7%) increase in N uptake. Soil pH (pH of dry soil) had a significant impact on EENF effectiveness. In acidic soils ($\text{pH} \leq 6.0$) the application of EENF did not significantly affect yield or N uptake; however the yield response to EENF increased to 10.2% (95% CI = 5.3–16.6%) in alkaline soils ($\text{pH} \geq 8.0$). There was no difference among the classes of EENF when separated by their mode of action (i.e. urease inhibitors, nitrification inhibitors or slow release). When EENF products were analyzed separately, NBPT [N-(n-butyl) phosphoric triamide] and neem proved effective in increasing yield, while PPD (phenyl phosphorodiamidate) and DCD (dicyandiamide) were not effective. The EENF effectiveness was not dependent on N rate, method of first N application (incorporated, surface applied, or applied into water), timing of first N application in relation to a permanent flood being established, and how water was managed during the season (permanent flood vs. intermittent wet and dry). Overall, this meta-analysis suggests that certain EENF products can increase yield and N uptake but the average increase is modest.

Contents

1. Introduction 247
2. Materials and methods 247
    2.1. Data 247
    2.2. Data analysis 248
3. Results and discussion 248
    3.1. Overall effect 248
    3.2. Effect of soil pH 248
    3.3. Mode of action 248
    3.4. EENF product 250
    3.5. Water and nitrogen management 250
    3.6. Study limitations 251

---

* Corresponding author. Tel.: +1 530 752 3125; fax: +1 530 752 4361.
E-mail address: balinquist@ucdavis.edu (B.A. Linquist).

0378-4290/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.fcr.2013.08.014

4. Conclusions 252
References 252

1. Introduction

Of all the nutrients required by crops, N is the one most often deficient in soils, applied in the greatest quantities, and has the greatest potential for losses. The N use efficiency of agricultural systems therefore, has both economic and environmental consequences (Chien et al., 2009). In rice systems, based on global estimates, fertilizer N recovery by the crop averages 46% (Ladha et al., 2005). The major pathways of N loss in rice systems are from NH_3 volatilization and nitrification–denitrification (Buresh et al., 2008). Leaching is not normally considered to be a major N loss pathway in rice as many rice soils have limited permeability and soils often remain flooded; however leaching can occur during aerobic phases of rice-upland crop rotations (Zhu et al., 2000).

Ammonia volatilization occurs naturally in both flooded and non-flooded soils. In non-flooded soils, NH_3 volatilization is of primary concern when urea fertilizer is used, because this is readily hydrolyzed by urease enzymes to NH_3 and CO_2 resulting in an increase in soil pH and NH_4^+ around the fertilizer granule (Francis et al., 2008). Non-flooded periods are of concern in rice systems where fertilizer is applied before flooding such as in dry-seeded, delayed flooded systems commonly practiced in the southern USA (Street and Bollich, 2003). Ammonia volatilization losses in such systems amount to 24 to 32% of applied fertilizer N with the magnitude of loss depending in part on the period of time between fertilizer application and flooding (Norman et al., 2009; Griggs et al., 2007). In flooded systems, high ammoniacal N originating from hydrolyzed urea or NH_4 fertilizers can accumulate in floodwater; this, coupled with elevated pH of flood water during daylight hours (due to photosynthetic activity by aquatic biomass) and increased temperatures provides conditions that are favorable for NH_3 volatilization (Fillery and Vlek, 1986; Mikkelsen et al., 1978; Vlek and Stumpe, 1978). In these systems, N losses attributed to NH_3 volatilization range from 20 to 56% of applied fertilizer N (Mikkelsen et al., 1978; Fillery and De Datta, 1986; Fillery et al., 1984; De Datta et al., 1989).

In rice systems, N fertilizers are typically NH_4^+-based or urea which is rapidly converted into NH_4^+. Nitrification of this fertilizer and subsequent denitrification can lead to fertilizer N losses. Nitrification is the biological conversion of NH_4^+ to NO_3^- and requires free O_2, while denitrification is the reduction of NO_3^- in the absence of O_2 to nitrogen gas (N_2). Both nitrification and denitrification processes can also produce nitrous oxide (N_2O) (Klemedtsson et al., 1988). Losses via denitrification can occur when an aerobic period is followed by an anaerobic period such as in a drying and wetting cycle (Bacon et al., 1986) or in intermittent wet and dry (IWD) rice systems (Belder et al., 2004). Also, flooded rice fields are unique as there are adjoining aerobic zones where nitrification can occur and anaerobic zones where denitrification occurs. The transport of substrates between aerobic and anaerobic zones couples nitrification with denitrification (Buresh et al., 2008; Reddy and Patrick, 1986). Losses due to denitrification are difficult to determine directly. Buresh et al. (2008) estimated that denitrification losses represented <10% of urea fertilizer N losses from rice fields. However, denitrification losses are affected by soil type and N fertilizer management, and other studies have estimated denitrification losses in the 12–33% range (Buresh et al., 1993a; Aulakh et al., 2001).

Enhanced efficiency nitrogen fertilizers (EENF) are formulated to reduce N losses to the environment. While there are many EENF products available, they are generally formulated to prevent NH_3 volatilization and nitrification–denitrification losses from taking place by inhibiting urease activity, inhibiting nitrification, or by controlling the release of N into the soil:water matrix and allowing better synchrony between N supply and crop demand. Urea supergranules are another EENF that limit both NH_3 volatilization and nitrification–denitrification losses in rice systems (Savant and Stangel, 1998). However, supergranules are not included in this review, because their benefit is largely attributed to deep placement of fertilizer while the other EENF products involve an additive to the fertilizer. In addition to increasing N use efficiency and reducing N losses, some EENF products (i.e. DCD and calcium carbide) reduce both CH_4 and N_2O emissions from rice systems (Linquist et al., 2012) and are being proposed as options to mitigate greenhouse-gas emissions from rice systems (Akiyama et al., 2010; Wassmann and Pathak, 2007; Majumdar, 2003).

Because the effects of EENF in rice systems have shown mixed results, a better understanding is needed to determine when EENF are effective and if so, whether the use of EENF is cost-effective. Indeed, economic considerations have been one of the main factors limiting the adoption of EENF (Cassman et al., 1998; Chien et al., 2009). While many factors control the economic viability of EENF, two main factors to be considered are their effects on yield and N use efficiency, by which the overall N rate could be decreased. The main objectives of this meta-analysis were therefore (1) to quantitatively summarize the effects of different EENF on rice yields and N uptake in flooded rice systems, and (2) to determine under what conditions EENF are the most effective.

2. Materials and methods

2.1. Data

Data were extracted from the literature where the effect of EENF on rice yield or plant N uptake was compared in side-by-side field experiments to an identical fertilizer without EENF (control) in a rice system. An exhaustive literature survey of peer-reviewed publications was carried out using ISI-Web of Science for articles published before December 2012. We only included studies in which the control fertilizer N treatment was applied at the same time, with the same number of split applications and in the same way as the EENF treatment. We did not include studies where, for example, an EENF treatment that was applied in a single basal dose to a control where the fertilizer N was split into multiple doses.

To evaluate the effect of management practices and soil characteristics we categorized studies according to soil pH, EENF mode of action, fertilizer N rate, timing of first N application, method of first fertilizer N application, and growing season water management. For soil pH we divided the soils into 3 classes: $\leq$6, 6–8 and $\geq$8 based on the air dry soil pH (upon flooding, soils become more neutral with time (Ponnamperuma, 1972)). The EENF modes of action were urease inhibitor (UI), nitrification inhibitor (NI), and slow release (SR). Slow release fertilizers include those products formed by the condensation products urea and urea aldehydes (such as IBDU – isobutylidene diurea) and coated or encapsulated fertilizers such as sulfur-coated urea and polymer-coated urea (Chien et al., 2009).

Fertilizer N management was evaluated in a number of ways. Fertilizer N rate was divided into 3 classes: $\leq$60 kg N ha^{-1}, 60–120 kg N ha^{-1} and $\geq$120 kg N ha^{-1}. To evaluate the timing of first N application the studies were divided up into classes based on when the first N application was applied in relationship to when a permanent flood was applied. For this comparison we did not include studies or treatments where intermittent wet and dry (IWD) was used because a permanent flood was not established in these systems. We divided the data into two classes: (1) N applied at flooding in which the fertilizer-N was applied less than 4 days before a permanent flood was established or it was applied into flood water; (2) pre-flood in which the fertilizer-N was applied more than 4 days before a permanent flood was established. The N applied at flooding is typical of most rice production systems including transplanted and water seeded rice systems, while pre-flood N applications are common in dry seeded systems either because farmers want to apply N at planting (with fields being flooded up to a month later) or because large rice fields can take up to 10 days to fully flood. Three methods of N-fertilizer application were identified based on how the first N application was applied: N applied before flooding and incorporated into the soil (or applied in bands below soil surface); N applied to the soil surface and not incorporated; and N applied directly into the flood water.

To examine the effects of growing season water management we divided the data set into two classes: (1) permanent flood and (2) IWD, in which a permanent flood was never established and there were periods during the crop cycle in which the soil achieved an aerobic state. IWD is commonly used as a water savings practice in Asia (Belder et al., 2004) but similar conditions can also occur in rainfed systems due to rainfall fluctuations.

2.2. Data analysis

For each study, all comparisons between control fertilizer N treatments and EENF treatments for rice yield and plant N uptake were included as separate data points ("observations"). As such, multifactorial studies (i.e. studies in which EENF additions were combined with other treatments in a factorial design) and studies in which multiple types of EENF were compared could contribute more than one observation to the dataset.

For rice yield and plant N uptake, we used the natural log (ln$R$) of the response ratio as our effect size (Hedges et al., 1999):

$$\ln R = \ln\left(\frac{V_E}{V_C}\right) \qquad (1)$$

where V is the mean value of rice yield or plant N uptake for the EENF (E) treatment or the control fertilizer N treatment (C). Studies were weighted by replication:

$$w_i = n \qquad (2)$$

where w_i is the weight for the ith observation and n is the number of field replicates (i.e. plots per treatment combination). By favoring field experiments that were well replicated, our weighting approach assigns more weight to more precise effect size estimates. Mean effect sizes were estimated as:

$$\overline{\ln R} = \frac{\sum(\ln R_i \times w_i)}{\sum(w_i)} \qquad (3)$$

where lnR_i is the effect size for rice yield or plant N uptake from the ith observation, and w_i as before. We used METAWIN 2.1 to generate mean effect sizes and 95% bootstrapped CIs (4999 iterations) (Rosenberg et al., 2000). To ease interpretation, the results for the analyses on ln$R$ were back-transformed and reported as percentage change with EENF application relative to the control treatment ($[R-1]\times 100$). Treatment effects were considered significant if the 95% CI did not overlap with zero. Similarly, treatment effects of categories of studies were considered significantly different if their 95% CI did not overlap. P-values for differences between categories of studies were calculated using resampling techniques incorporated in MetaWin 2.1.

3. Results and discussion

We identified 32 studies (Table 1) with a total of 178 observations for the effect of EENF on crop yield. Of these, 14 studies (82 observations) also reported N uptake. Studies were conducted from as early as1968 and were from Asia (China, India, Thailand and Philippines), the Americas (USA and Nicaragua), Australia, and Europe (Spain). Rice establishment practices included transplanted and direct seeded systems. In all studies urea was used as the primary N source (and served as the control treatment) with the exception of the Patrick et al. (1968) study where ammonium sulfate and 15-15-15 was used and the Ghosh et al. (2003) study where both urea and ammonium sulfate were used. In 15 of the studies N was applied as a split application and in all of these cases, with the exception of two studies (Fillery et al., 1986; Phongpan and Byrnes, 1990), the EENF was applied in basal and topdress applications.

3.1. Overall effect

On average, the use of EENF led to a 5.7% (95% CI = 3.9–7.7%) increase in yield and an 8.0% (95% CI = 5.2–10.7%) increase in N uptake (Fig. 1). The yield increase found here and attributed to EENF is similar to findings from a meta-analysis showing that the EENF, Pyridine [2-chloro-6-(trichloromethyl)-pyridine], increased US maize yields on average by 7.0% (Wolt, 2004).

3.2. Effect of soil pH

Soil pH had a significant effect on the magnitude of yield response to EENF products. In acidic soils (soil pH $\leq$ 6.0) there was no significant yield or N uptake response to the application of EENF products (Fig. 1). With increasing soil pH the yield response became significant. In neutral soils (pH 6.0–8.0) yields increased by 5.7% (95% CI = 3.7–7.9%) and in alkaline soils (pH $\geq$ 8.0) by 10.2% (95% CI = 5.3–16.6%). This trend was also observed with crop N uptake; in acidic soils there was not a significant response to EENF application while in neutral to alkaline soils crop N uptake increased significantly by 8.2 and 9.9%, respectively (Fig. 1).

Both NH_3 volatilization and nitrification are affected by pH. In particular, NH_3 losses following the addition of either urea or NH_4^+ salts increases with increasing soil pH (Francis et al., 2008). Similarly, nitrification rates are favored by neutral to slightly alkaline soils (Norton, 2008). Given that both N loss mechanisms are favored in higher pH soils, both UI and NI could potentially be beneficial in these soils. However, there is concern when using NI products that they retain NH_4^+ in the soil for a longer time period which in turn may lead to an increase in NH_3 losses (Kim et al., 2012). A separate analysis of our data indicates that in the 6–8 soil pH range (data too limited for separate analysis of soil above pH 8) both UI (5.9%–95% CI = 2.9–9.4%) and NI (9.6%–95% CI = 3.5–16.9%) increase yields (data not shown). Since NI are effective it is not possible to determine from our analysis if they lead to increased NH_3 volatilization; however NI do appear to reduce the net N losses that may be attributed to both nitrification–denitrification and NH_3 volatilization in this range of soil pH. It is possible that NI may be less effective in higher pH soils, where the risk of NH_3 volatilization is greater (Francis et al., 2008).

3.3. Mode of action

The EENF were classified as urease inhibitors (UI), nitrification inhibitors (NI), and slow release (SR) of which there were 65, 41, and 27 observations, respectively (Table 2). Evaluation of the EENF based on their mode of action showed no significant difference among the products either in terms of yield or N uptake (Fig. 2). Both UI and NI had similar benefit (5.6%, on average). The use of

Table 1
Summary of studies included in analysis indicating research location, EENF products evaluated and the soil pH of the research site.

Study reference	Country	EENF[a]	Soil pH
Adhya et al. (2000)	India	DCD, neem	6.2
Banerjee et al. (2002)	India	DCD	8.1
Buresh et al. (1988a)	Philippines	NBPT, PPD	6.0
Cai et al. (1989)	Australia	NBPT, PPD	8.2
Carreres et al. (2003)	Spain	IBDU, SCU, PCU	7.5
Chaiwanakupt et al. (1996)	Thailand	CaC_2, NBPT, PPD (comb.)[b]	5.1
Dillon et al. (2012)	USA	NBPT, DCD (comb.)	7.2
Fillery et al. (1986)	Philippine	PPD	6.7
Franzen et al. (2011)	USA	Nutrisphere	7.3
Freney et al. (1995)	Thailand	CHPT, NBPT, PA (comb.)	5.1
Ghosh et al. (2003)	India	DCD	7.6
Humphreys et al. (1992)	Australia	DCD, IBDU, PPD, SCU	2 site average
Kumar et al. (2010)	India	Neem	8.2
Kumar et al. (2011)	India	Neem	8.2
Li et al. (2009)	China	DCD, hydroquinone (comb.)	6.9
Majumdar (2005)	India	DCD, neem	7.9
Malla et al. (2005)	India	CaC_2, DCD, hydroquinone, neem, thiosulfate	8.0
Norman et al. (1989)	USA	DCD	6.2
Norman et al. (2009)	USA	NBPT	7.3
Pasda et al. (2001)	India	DMPP	na[c]
Patrick et al. (1968)	USA	Pyridine, pyrimidine	2 sites (na, 6.1)
Phongpan and Byrnes (1990)	Thailand	NBPT	5.4
Phongpan et al. (1995)	Thailand	NBPT, PPD (comb.)	5.1
Pohlan and Tercero (1994)	Nicaragua	CMP	6.0
Prasad and Prasad (1980)	India	Neem	7.7
Rath et al. (1999)	India	Neem	6.4
Satrusajang et al. (1991)	Thailand	PPD	5.0
Singh et al. (1990)	India	Neem	7.6
Slaton et al. (2009)	USA	PCU	8.3
Snitwongse et al. (1988)	Thailand	PPD	4.1
Thomas and Prasad (1987)	India	Neem, Pyridine	7.7
Wilson et al. (1990)	USA	DCD	na

[a] See Table 2 for explanation of EENF product.
[b] Comb.: indicates a study in which at least one of the treatments combined EENF products.
[c] Data not available.

NI can increase NH_3 volatilization due to increased retention time of NH_4^+ in the soil (Kim et al., 2012; Soares et al., 2012), suggesting that it may be beneficial to combine UI and NI. However, in the limited number of studies that evaluated the combined use of UI and NI (see Table 1), the treatment effects on yield and N uptake were similar as to when applied separately or combined (Fig. 2).

The SR class of products was the only class that did not result in a significant increase in either yield or N uptake; however the number of studies for SR was low. The high variation observed for SR suggests that there are conditions where its use should be avoided and conditions where it may benefit rice yields. The SR products in this analysis were only evaluated in three studies – all in drill seeded rice systems (Slaton et al., 2009; Carreres et al., 2003; Humphreys et al., 1992). The objective of these studies was to identify fertilizers that could be applied at planting and that would not be subject to high NH_3 volatilization losses or nitrification before the fields were permanently flooded which occurred between one and 15 days after fertilizer application. In the Humphreys et al. (1992) study SR was applied one to four days before flooding and they reported relatively small benefits from SR (1.6 to 6.5% increase in yields). In the other two studies (Slaton et al., 2009; Carreres et al., 2003) where the fertilizer was applied 12–15 days before the fields were flooded the SR fertilizers increased rice yields by up to 14–76%. These yield increases, attributed to EENF, were all observed in high pH soils. Slaton et al. (2009) evaluated EENF across several soil types and reported that the greatest benefits of EENF in terms of

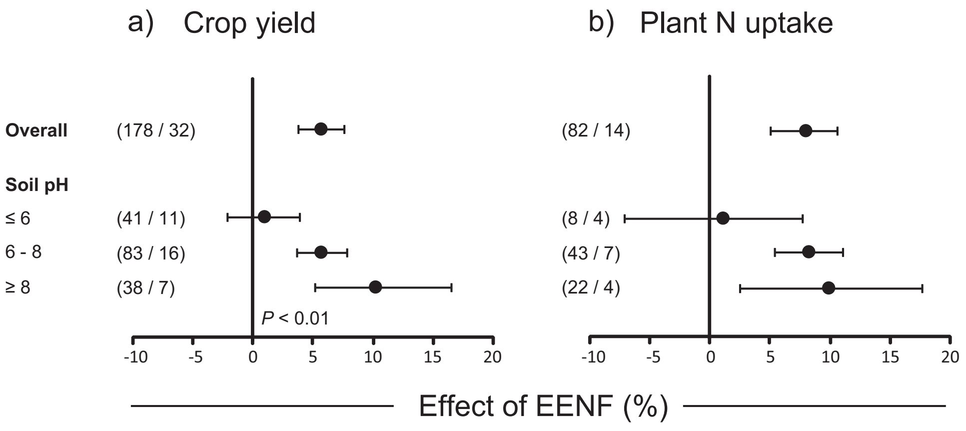

Fig. 1. The overall benefit of EENF on rice yield and plant N uptake, and the influence of soil pH on the benefit of EENF. In the brackets the first number indicates the number of observations and the second the number of studies used for the analysis.

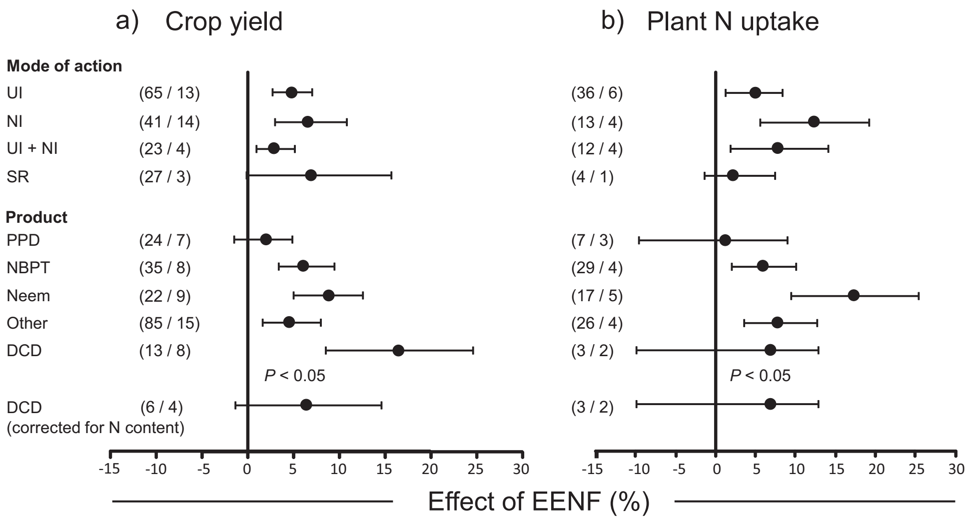

Fig. 2. The influence of EENF mode of action [urease inhibitor (UI), nitrification inhibitor (NI), combined (UI + NI) and slow release (SR)] and specific EENF products (see Table 2 for details) on crop yield and N uptake. A subset of the DCD observations which specifically accounted for the N content of DCD in their total N rate was subjected to a separate analysis. In the brackets the first number indicates the number of observations and the second the number of studies used for the analysis.

increasing yields were in high pH soils. In fact, in low pH soils (pH 5.7) they found that EENF resulted in lower yields. Also, in both of these studies some SR products performed better than others. For example, Slaton et al. (2009) found when evaluating two polymer-coated urea (PCU) products that PCU-38 outperformed PCU-43. This highlights the importance of not only having suitable environmental conditions but also selecting an appropriate EENF in order to maximize the benefits of EENF.

3.4. EENF product

In our data set, four EENF products were tested across an adequate number of studies to evaluate their individual effects on yield: PPD (phenyl phosphorodiamidate), NBPT [N-(*n*-butyl) phosphoric triamide], DCD (dicyandiamide) and neem. Products derived from the seeds of the neem tree (*Azadirachta melia*) (nimin, neem cake, neem oil) can be combined with urea (i.e. as a coating) and have been shown to inhibit nitrification (Reddy and Prasad, 1975; Vyas et al., 1991).

Table 2
List of EENF products evaluated in the meta-analysis.

EENF	EENF material	Mode of action[a]
CaC_2	Calcium carbide	NI
CMP	l-Carbamoyl-3(5)-methyl-pyrazole	NI
DCD	Dicyandiamide	NI
DMPP	3,4-Dimethylpyrazole phosphate	NI
Neem	Neem cake, neem coated urea, neem oil, nimin	NI
Nutrisphere	Co-polymer of maleic and itaconic acid	NI
PA	Phenyl acetylene	NI
Pyridine (N-serve)	2-Chloro-6-(trichloromethyl) pyridine	NI
Pyrimidine	2-Amino-4-chloro-6 methyl pyrimidine	NI
Thiosulfate	Thiosulfate	NI
CHPT	Cyclohexylphosphorictriamide-phorictiamide	UI
Hydroquinone	Hydroquinone	UI
NBPT	N-(*n*-butyl) phosphoric triamide	UI
PPD	Phenyl phosphorodiamidate	UI
IBDU	Isobutylidene diurea	SR
PCU	Polymer-coated urea	SR
SCU	Sulfur-coated urea	SR

[a] NI – nitrification inhibitor, UI – urease inhibitors, SR – slow release.

DCD resulted in the largest overall increase in yields of 16.5% (95% CI = 8.6–24.8%) (Fig. 2). DCD contains 67% N and in most studies, DCD was applied at a rate that supplied 10 to 15% of the total N rate. However, not all studies included DCD-N as part of the total N budget. Therefore, some of the benefit reported here for DCD may be because more N was applied using DCD and could confound a nitrification inhibition effect. A separate analysis of studies where DCD-N was accounted for as part of the N rate (Banerjee et al., 2002; Ghosh et al., 2003; Malla et al., 2005; Majumdar, 2005) shows that the benefit of DCD decreased to 6.4% and its effect on yield became non-significant (95% CI = −1.3 to 14.7%) (Fig. 2). Several studies (Norman et al., 1989; Wilson et al., 1990; Humphreys et al., 1992) evaluated ^{15}N uptake with and without DCD and in some cases DCD increased N uptake efficiency (Norman et al., 1989; Wilson et al., 1990) whereas in other studies DCD had no effect (Humphreys et al., 1992). Therefore, the benefits of DCD are smaller (and perhaps not significant) than the data would first suggest. One potential cause for the limited effectiveness of DCD in rice systems is that DCD degrades with increasing temperature, and in soils at 25 °C the half-life of DCD is reduced to 20 days (Kelliher et al., 2008). Rice is typically grown in the tropics or warmer temperate regions and it is possible that high DCD degradation rates render DCD less effective.

Neem products and NBPT both showed a positive and similar benefit (Fig. 2). PPD was the only product that did not significantly increase yields. Our results support the findings of Byrnes (1988) who, based on a greenhouse study, reported that NBPT was more effective than PPD at retarding urea hydrolysis and reducing NH_4^+ concentration in the flood water. Buresh et al. (1988b) also showed that NBPT was more effective in reducing the vapor pressure of ammonia (pNH_3) in flood water than PPD. In our analysis, the effect of EENF on N uptake did not always show the same results as it did for yield – most likely due to the low number of observations available for the analysis.

3.5. Water and nitrogen management

We hypothesized that at higher N rates the yield response to EENF would be less pronounced because N rates may be above optimal and therefore yields may not respond positively to EENF applications. However, we found no difference in response among the different N rates. It may be that yields were still responsive to increasing N in the upper rate class that we identified (>120 kg N ha^{-1}). Most of the studies in this upper class had N fertilizer input of less than 168 kg N ha^{-1} which is not considered to be excessive in high yielding environments (e.g. Linquist et al., 2009). Two studies had N fertilizer inputs in excess of 200 kg N ha^{-1} (Li et al., 2009; Wilson et al., 1990). In both cases there was an increase in yield with the use of DCD. Some of the benefits of DCD in these high N fertilizer rate studies can be attributed to an increase in N applied because of the N present in DCD (see earlier discussion). Whereas the additional N in DCD was not taken into consideration by Wilson et al. (1990), it remains unclear if this extra N was considered in the other study (Li et al., 2009). Also, both studies applied N in conditions where high N losses may be expected: intermittent wet and dry (Li et al., 2009) or applied 28 days before flooding the field (Wilson et al., 1990). Furthermore, increasing N inputs also generally increases NH_3 volatilization losses (Hargrove, 1988); thus even at high N input rates, especially using urea (Francis et al., 2008), it may be possible to obtain a benefit of adding EENF.

Nitrogen placement also influences potential N losses. Generally, incorporation of N into the soil minimizes N losses (Linquist et al., 2009; Mikkelsen and Finfrock, 1957) while broadcasting N-fertilizer onto soil or into floodwater can increase N losses – particularly NH_3 volatilization losses (De Datta et al., 1989; Mikkelsen et al., 1978). For example, Mikkelsen et al. (1978) reported that incorporating N fertilizer at 10–12 cm depth reduced NH_3 volatilization losses to just 1% compared to losses of 20% when N fertilizer was surface applied. Three methods of applying the first N application were evaluated: (1) incorporated into soil before flooding (soil may have been dry or saturated when N was applied and incorporated), (2) broadcast onto soil before flooding, and (3) broadcast into floodwater. Another practice that is common in Asia is to broadcast N into floodwater and then incorporate it just before transplanting; however, in none of the studies in this database was N managed in this way. Due to high N losses often associated with broadcast N applications (either onto soil or into water), a greater benefit of EENF products was expected when N was applied this way. However, no differences between application methods in terms of either yield or N uptake were found (Fig. 3). One possible explanation may be that many of the studies that reported incorporating the N into the soil did not report at what depth the fertilizer was applied. Often N was initially broadcast onto the soil and then lightly harrowed or raked in. It is possible that a significant amount of fertilizer N remained at or near the surface. Second, in some studies classified here as "incorporated", the basal N application was incorporated but subsequent split applications were broadcasted into the water (i.e. Satrusajang et al., 1991). Therefore, in both these instances, a portion of the N applied would still be subjected to relatively high losses and therefore do not serve as a good control to test the effectiveness of EENF.

Nitrogen dynamics and potential N losses in rice systems are driven in large part by how water is managed in relationship to N. Both major N loss pathways (nitrification–denitrification and NH_3 volatilization) are directly affected by water management. To evaluate the effect of the timing of first N application in relationship to when a permanent flood was established we divided the database into two classes: preflood (where N was applied more than 4 days before a permanent flood and where N was applied at flood) and at flooding (where N was applied less than 4 days before a permanent flood or applied directly into flood water). Pre-flood applications of N fertilizer can lead to nitrification–denitrification losses (Norman et al., 2003) or high NH_3 volatilization losses especially when urea is applied to the soil surface (Norman et al., 2009; Mikkelsen et al., 1978). When N is applied at flooding (a common practice in transplanted and water seeded systems), nitrification–denitrification losses may be reduced, but NH_3 volatilization losses can be significant when urea is applied directly into the water (Fillery and Vlek, 1986). Comparing these two classes shows that EENF benefits were similar under both conditions (Fig. 3). The high variability of EENF effects in the pre-flood class suggests there are conditions under which EENF products may be more effective. Looking more closely at the pre-flood studies, relatively high benefits of EENF (14 to 76% increase in yield) were reported in three studies for at least some of the treatments and/or sites (Carreres et al., 2003; Norman et al., 2009; Slaton et al., 2009). The EENF were beneficial in soils with a pH higher than 7.3, with a long period (10–15 d) between N application and flooding, and when either polymer coated products or NBPT (a UI) was used. Within this set of studies the largest benefits were found when the N was surface applied (Norman et al., 2009; Slaton et al., 2009). All of these conditions (soil pH, long period before flooding, and surface applications) favor high N losses via both NH_3 volatilization and nitrification–denitrification as discussed earlier and are likely to benefit from the use of EENF.

The effect of water management was also evaluated by comparing how water was managed during the growing season by dividing the dataset into two classes: permanent flood and intermittent wet and dry (IWD). In IWD systems N losses via nitrification–denitrification pathway can be high due to the aerobic/anaerobic cycles (Liu et al., 2010; Bacon et al., 1986). Despite the greater potential for nitrification–dentirification losses using IWD, there was not a significant difference between these two classes of water management, in fact on average the EENF benefit was lower in IWD (3.3%) than in permanent flood (5.9%) systems (Fig. 3). This suggests that N use efficiency in IWD systems can be equal to or better than permanent flood systems as has been shown by others (Ye et al., 2013) and that the use of EENF does not necessarily result in increased efficiency.

3.6. Study limitations

We evaluated 18 different EENF products (Table 2) some of which may be effective whereas others were not. Efforts were made to analyze separately those products that were evaluated in a large number of studies. In general we found little difference between these products relative to others with the exception of PPD and DCD which was shown not to be effective in rice systems (Fig. 2).

We examined the primary management factors which are likely to have the greatest impact on N use efficiency, i.e. N rate, water management and application method. Among these categories, no effect of varying management practices on the benefit of EENF products was found (Fig. 3). However, the absence of a significant effect on N use efficiency should not be interpreted to suggest that these management practices are not important. It is possible that the data base was too limited to examine these data more rigorously by examining possible interactions between management and other important factors such as EENF mode of action or soil pH. Certainly the high variability found in some of the analyses suggests that under certain conditions the use of EENF has promise.

We only examined the benefit of EENF when the EENF treatment was applied in a similar manner as the N fertilizer in the control treatment. In some studies, the N fertilizer in the control was applied in such a way that it would enhance N losses. Nitrogen use efficiency can be increased by changing how and when the fertilizer N is applied; for example by incorporating N fertilizer (Linquist et al., 2009; Savant and Stangel, 1998) or by better synchronizing N supply with crop demand through split N applications (Cassman et al., 1998; Linquist and Sengxua, 2003). A valid question that deserves further analysis is whether EENF can improve yields and N uptake relative to when N fertilizer is applied according to best management practices. Unfortunately, there were too few published studies to conduct such an analysis.

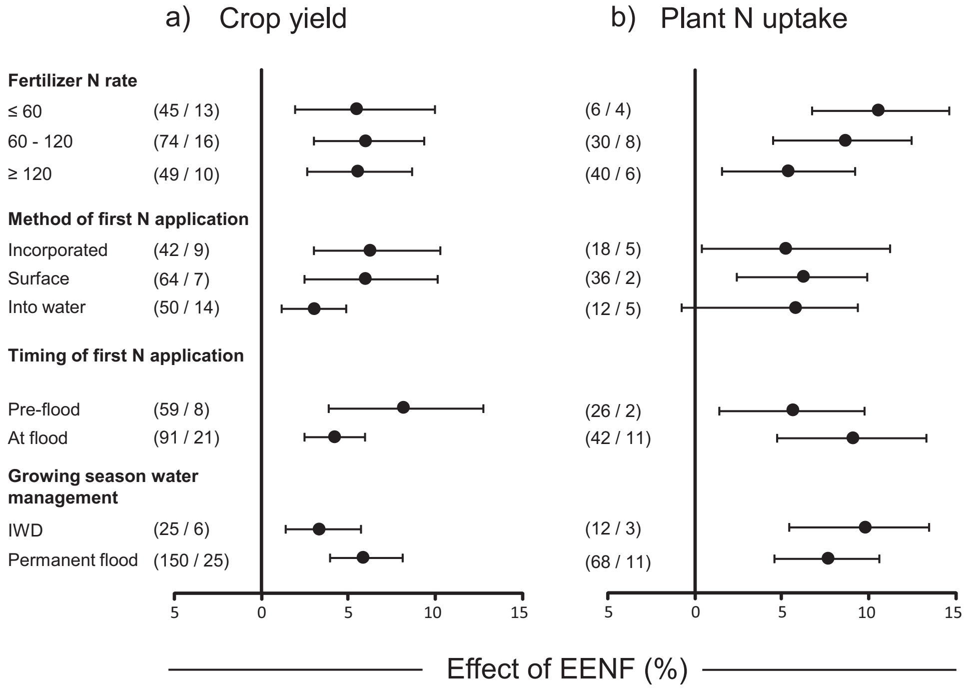

Fig. 3. The combined influence of EENF and crop management practice on crop yield and N uptake. For "Timing of first N application" the following classes were analyzed: "preflood" where N was applied more than 4 days before a permanent flood was established, and "at flood" where N was applied less than 4 d before a flood was established. For "growing season water management" a permanent flood and intermittent wet and dry (IWD) was evaluated. Method of first N application refers to the first N application in cases where split applications were used. In the brackets the first number indicates the number of observations and the second the number of studies used for the analysis.

4. Conclusions

There is potential for increasing yields and improving N use efficiency with certain EENF products. Buresh and Baanante (1993b) suggested that, based on an economic analysis, EENF are cost effective in environments with a high N fertilizer response, high price of conventional urea, and high N losses that could be prevented by the use of EENF. The cost of urea and other N fertilizers has been increasing. For example, between 2000 and 2012 the cost of urea increased by 177% (USDA, 2013). On average, the benefits of EENF are modest – increasing yield and N uptake in rice production by about 5.7 and 8.0%, respectively. Such increases may not be cost effective given the higher costs of EENF. However, when some EENF products are used under certain conditions EENF products can substantially increase yields. We found that the benefits from EENF increase as soil pH increases. The greatest benefits from EENF were in alkaline soils; however soil alkalinity is not common in most rice production regions (FAO, 2013). EENF has potential benefit when N-fertilizers are applied to the soil well in advance of when the field is flooded – such as in delayed-flood systems common in the southern USA, where fertilizer N may be applied well in advance of a permanent flood due to the long period of time it can take to flood large fields or the desire to apply N at planting. While we evaluated a number of EENF products with different modes of action, we were not able to detect large differences in yield responses and plant N uptake among EENF. When products are evaluated individually PPD, and possibly DCD, were not effective in increasing yield or plant N uptake. Other factors such as water management and N application method had little effect on the effect of EENF. However, our data set may have been too limited to determine in detail under what conditions EENF becomes effective. Importantly, similar increases in N use efficiency and yields as we report here for EENF may also be obtained by improving other N management practices such as timing or N placement.

References

Adhya, T.K., Bharati, K., Mohanty, S.R., Ramakrishnan, B., Rao, V.R., Sethunathan, N., Wassmann, R., 2000. Methane emission from rice fields at Cuttack, India. Nutr. Cycl. Agroecosyst. 58, 95–105.

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

Aulakh, M.S., Khera, T.S., Doran, J.W., Bronson, K.F., 2001. Denitrification, N_2O and CO_2 fluxes in rice-wheat cropping system as affected by crop residues, fertilizer N and legume green manure. Biol. Fertil. Soils 34, 375–389.

Bacon, P.E., McGarity, J.W., Hoult, E.H., Alter, D., 1986. Soil mineral nitrogen concentration within cycles of flood irrigation: effect of rice stubble and fertilization management. Soil Biol. Biochem. 18, 173–178.

Banerjee, B., Pathak, H., Aggarwal, P.K., 2002. Effects of dicyandiamide, farmyard manure and irrigation on crop yields and ammonia volatilization from an alluvial soil under a rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.) cropping system. Biol. Fertil. Soils 36, 207–214.

Belder, P., Bouman, B.A.M., Cabangon, R., Guoan, L., Quilang, E.J.P., Yuanhua, L., Spiertz, J.H.J., Tuong, T.P., 2004. Effect of water-saving irrigation on rice yield and water use in typical lowland conditions in Asia. Agric. Water Manage. 65, 193–210.

Buresh, R.J., Baanante, C.A., 1993b. Potential economic benefits of modifications to urea that increase yield through reduction in nitrogen losses. Agron. J. 85, 947–954.

Buresh, R.J., Castillo, E.G., De Datta, S.K., 1993a. Nitrogen losses in puddled soils as affected by timing of water deficit and nitrogen fertilization. Plant Soil 157, 197–206.

Buresh, R.J., De Datta, S.K., Padilla, J.L., Samson, M.I., 1988a. Field evaluation of two urease inhibitors with transplanted lowland rice. Agron. J. 80, 763–768.

Buresh, R.J., De Datta, S.K., Padilla, J.L., Samson, M.I., 1988b. Effect of 2 urease inhibitors on floodwater ammonia following urea application to lowland rice. Agron. J. 80, 763–768.

Buresh, R.J., Reddy, K.R., van Kessel, C., 2008. Nitrogen transformations in submerged soils. In: Schepers, J.S., Raun, W.R. (Eds.), Nitrogen in Agricultural Systems. Agronomy monograph 49. American Society of Agronomy, Madison, WI, USA, pp. 401–436.

Byrnes, B.H., 1988. The degradation of the urease inhibitor phenyl phosphorodiamidate in soil systems and the performance of N-(n-butyl) thiophosphoric triamide in flooded rice culture. Technical University of Munich, Weihenstephan, Germany (Ph.D. thesis).

Cai, G.X., Freney, J.R., Muihead, W.A., Simpson, J.R., Chen, D.L., Tretitt, A.C.F., 1989. The evaluation of urease inhibitors to improve the efficiency of urea as an N-source for flooded rice. Soil Biol. Biochem. 21, 137–145.

Carreres, R., Sendra, J., Ballesteros, R., Valiente, E.F., Quesada, A., Carrasco, D., Leganés, F., de la Cuadra, J.G., 2003. Assessment of slow release fertilizers and nitrification inhibitors in flooded rice. Biol. Fertil. Soils 39, 80–87.

Cassman, K.G., Peng, S., Olk, D.C., Ladha, J.K., Reichardt, W., Dobermann, A., Singh, U., 1998. Opportunities for increased nitrogen-use efficiency from improved resource management in irrigated rice systems. Field Crops Res. 56, 7–39.

Chaiwanakupt, P., Freney, J.R., Keerthisinghe, D.G., Phongpan, S., Blakeley, R.L., 1996. Use of urease, algal inhibitors, and nitrification inhibitors to reduce nitrogen loss and increase the grain yield of flooded rice (*Oryza sativa* L.). Biol. Fertil. Soils 22, 89–95.

Chien, S.H., Prochnow, L.I., Cantarella, H., 2009. Recent developments of fertilizer production and use to improve nutrient use efficiency and minimize environmental impacts. Adv. Agron. 102, 267–322.

De Datta, S.K., Trevitt, A.C.F., Freney, J.R., Obcemea, W.N., Real, J.G., Simpson, J.R., 1989. Measuring nitrogen losses from lowland rice using bulk aerodynamic and nitogen-15 balance methods. Soil Sci. Soc. Am. J. 53, 1275–1281.

Dillon, K.A., Walker, T.W., Harrell, D.L., Krutz, L.J., Varco, J.J., Koger, C.H., Cox, M.S., 2012. Nitrogen sources and timing effects on nitrogen loss and uptake in delayed flood rice. Agron. J. 104, 466–472.

FAO (Food and Agriculture Organization), 2013. World topsoil pH map, http://www.fao.org/nr/land/sols/en/ (checked 13.08.13).

Fillery, I.R.P., De Datta, S.K., Craswell, E.T., 1986. Effect of phenyl phosphorodiamidate on the fate of urea applied to wetland rice fields. Fertil. Res. 9, 251–263.

Fillery, I.R.P., De Datta, S.K., 1986. Ammonia volatilization from nitrogen sources applied to rice fields: I. Methodology, ammonia fluxes, and nitrogen-15 loss. Soil Sci. Soc. Am. J. 50, 80–86.

Fillery, I.R.P., Simpson, J.R., De Datta, S.K., 1984. Influence of field environment and fertilizer management on ammonia loss from flooded rice. Soil Sci. Soc. Am. J. 48, 914–920.

Fillery, I.R.P., Vlek, P.L.G., 1986. Reappraisal of the significance of ammonia volatilization as an N loss mechanism in flooded rice fields. Fertil. Res. 9, 79–98.

Francis, D.D., Vigil, M.F., Moiser, A.R., 2008. Gaseous losses of nitrogen other than through denitrification. In: Schepers, J.S., Raun, W.R. (Eds.), Nitrogen in Agricultural Systems. Agronomy monograph 49. American Society of Agronomy, Madison, WI, USA, pp. 255–279.

Franzen, D., Goos, R.J., Norman, R.J., Walker, T.W., Roberts, T.L., Slaton, N.A., Endres, G., Ashley, R., Staricka, J., Lukach, J., 2011. Field and laboratory studies comparing nutrisphere-nitrogen urea with urea in North Dakota, Arkansas, and Mississippi. J. Plant Nutr. 34, 1198–1222.

Freney, J.R., Keerthisinghe, D.G., Phongpan, S., Chaiwanakupt, R., Harrington, K.J., 1995. Effect of urease, nitrification and algal inhibitors on ammonia loss and grain yield of flooded rice in Thailand. Fertil. Res. 40, 225–233.

Ghosh, S., Majumdar, D., Jain, M.C., 2003. Methane and nitrous oxide emissions from an irrigated rice of North India. Chemosphere 51, 181–195.

Griggs, B.R., Norman, R.J., Wilson Jr., C.E., Slaton, N.A., 2007. Ammonia volatilization and nitrogen uptake for conventional and conservation tilled dry-seeded, delayed-flooded rice. Soil Sci. Soc. Am. J. 71, 745–751.

Hargrove, W.L., 1988. Evaluation of ammonia volatilization in the field. J. Prod. Agric. 1, 104–111.

Hedges, L.V., Gurevitch, J., Curtis, P.S., 1999. The meta-analysis of response ratios in experimental ecology. Ecology 80, 1150–1156.

Humphreys, E., Chalk, P.M., Muirhead, W.A., White, R.J.G., 1992. Nitrogen fertilization of dry-seeded rice in south-east Australia. Fertil. Res. 31, 221–234.

Kelliher, F.M., Clough, T.J., Clark, H., Rys, G., Sedcole, J.R., 2008. The temperature dependence of dicyandiamide (DCD) degradation in soils: a data synthesis. Soil Biol. Biochem. 40, 1878–1882.

Kim, D.G., Saggar, S., Roudier, P., 2012. The effect of nitrification inhibitors on soil ammonia emissions in nitrogen managed soils: a meta-analysis. Nutr. Cycl. Agroecosyst. 93, 51–64.

Klemedtsson, I., Svensson, B.H., Rosswall, T., 1988. Relationships between soil moisture content and nitrous oxide production during nitrification and denitrification. Biol. Fertil. Soils 6, 106–111.

Kumar, D., Devakumar, C., Kumar, R., Das, A., Panneerselvam, P., Shivay, Y.S., 2010. Effect of neem-oil coated prilled urea with varying thickness of neem-oil coating and nitrogen rates on productivity and nitrogen-use efficiency of lowland irrigated rice under Indo-Gangetic plains. J. Plant Nutr. 33, 1939–1959.

Kumar, D., Devakumar, C., Kumar, R., Panneerselvam, P., Das, A., Shivay, Y.S., 2011. Relative efficiency of prilled urea coated with major neem (*Azadirachta indica* A. Juss) oil components in lowland irrigated rice of the Indo-Gangetic plains. Arch. Agron. Soil Sci. 57, 61–74.

Ladha, J.K., Pathak, H., Krupnik, T.J.J., Six, J., van Kessel, C., 2005. Efficiency of fertilizer nitrogen in cereal production: retrospects and prospects. Adv. Agron. 87, 85–156.

Li, X., Zhang, X., Xu, H., Cai, Z., Yagi, K., 2009. Methane and nitrous oxide emissions from rice paddy soil as influenced by timing of application of hydroquinone and dicyandiamide. Nutr. Cycl. Agroecosyst 85, 31–40.

Linquist, B.A., Sengxua, P., 2003. Efficient and flexible management of nitrogen for rainfed lowland rice. Nutr. Cycl. Agroecosyst. 67, 107–115.

Linquist, B.A., Hill, J.E., Mutters, R.G., Greer, C.A., Hartley, C., Ruark, M.D., van Kessel, C., 2009. Assessing the necessity of surface applied pre-plant nitrogen fertilizer in rice systems. Agron. J. 101, 906–915.

Linquist, B.A., Adviento-Borbe, M.A., Pittelkow, C.M., van Kessel, C., van Groenigen, K.J., 2012. Fertilizer management practices and greenhouse gas emissions from rice systems: a quantitative review and analysis. Field Crops Res. 135, 10–21.

Liu, S., Qin, Y., Zou, J., Liu, Q., 2010. Effects of water regime during rice-growing season on annual direct N_2O emission in a paddy rice-winter wheat rotation system in southeast China. Sci. Total Environ. 408, 906–913.

Majumdar, D., 2003. Methane and nitrous oxide emission from irrigated rice fields: proposed mitigation strategies. Curr. Sci. India 84, 1317–1326.

Majumdar, D., 2005. Crop yield and soil nitrogen dynamics in an intermittently flooded rice field affected by nitrification inhibitors. Arch. Agron. Soil Sci. 5, 645–653.

Malla, G., Bhatia, A., Pathak, H., Prasad, S., Jain, N., 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, 141–147.

Mikkelsen, D.S., Finfrock, D.C., 1957. Availability of ammoniacal nitrogen to lowland rice as influenced by fertilizer placement. Agron. J. 49, 296–300.

Mikkelsen, D.S., De Datta, S.K., Obcemea, W.N., 1978. Ammonia volatilization losses from flooded rice soils. Soil Sci. Soc. Am. J. 42, 725–730.

Norman, R.J., Eilson, C.E., Slaton, N.A., 2003. Soil fertilization and mineral nutrition in U.S. mechanized rice culture. In: Smith, C.W., Dilday, R.H. (Eds.), Rice: Origin, History, Technology, and Production. John Wiley & Sons, Inc., New Jersey, pp. 331–412.

Norman, R.J., Wells, B.R., Moldenhauer, K.A.K., 1989. Effect of application method and dicyandiamide on urea-nitrogen-15 recovery in rice. Soil Sci. Soc. Am. J. 53, 1269–1274.

Norman, R.J., Wilson Jr., C.E., Slaton, N.A., Griggs, B.R., Bushong, J.T., Gbur, E.E., 2009. Nitrogen fertilizer sources and timing before flooding dry-seeded, delayed-flood rice. Soil Sci. Soc. Am. J. 73, 2184–2190.

Norton, J.M., 2008. Nitrification in agricultural soils. In: Schepers, J.S., Raun, W.R. (Eds.), Nitrogen in Agricultural Systems. Agronomy monograph 49. American Society of Agronomy, Madison, WI, USA, pp. 173–199.

Pasda, G., Hähndel, R., Zerulla, W., 2001. Effect of fertilizers with the new nitrification inhibitor DMPP (3,4-dimethylpyrazole phosphate) on yield and quality of agricultural and horticultural crops. Biol. Fertil. Soils 34, 85–97.

Patrick Jr., W.M.H., Peterson, F.J., Turner, F.T., 1968. Nitrification inhibitors for lowland rice. Soil Sci. 105, 103–105.

Phongpan, S., Byrnes, B.H., 1990. The effect of urease inhibitor N-(n-butyl) thiophosphoric triamide on the efficiency of urea application in a flooded rice field trial in Thailand. Fertil. Res. 25, 145–151.

Phongpan, S., Freney, J.R., Keerthisinghe, D.G., Chaiwanakupt, R., 1995. Use of phenylphosphorodiamidate and N-(n-butyl)thiophosphorictriamide to reduce ammonia loss and increase grain yield following application of urea to flooded rice. Fertil. Res. 41, 59–66.

Pohlan, J.F.I., Tercero, F.I., 1994. Inhibition of weed competition effects by the mixture of reduced nitrogen and nitrification inhibitor CMP in flooded rice (*Oryza sativa* L.), variety Altamira-2. In: 5th EWSR Mediterranean Symposium Weed control in Sustainable Agriculture in the Mediterranean area, Perugia, pp. 277–284.

Ponnamperuma, F.N., 1972. The chemistry of submerged soils. Adv. Agron. 24, 29–97.

Prasad, M., Prasad, R., 1980. Yield and nitrogen uptake by rice as affected by variety, method of planting and new nitrogen fertilizers. Fertil. Res. 1, 207–213.

Rath, A.K., Swain, B., Ramakrishnan, B., Panda, D., Adhya, T.K., Rao, V.R., Sethunathan, N., 1999. Influence of fertilizer management and water regime on methane emission from rice fields. Agr. Ecosyst. Environ. 76, 99–107.

Reddy, K.R., Patrick Jr., W.H., 1986. Denitrification losses in flooded rice fields. Fertil. Res. 9, 99–116.

Reddy, R.N.S., Prasad, R., 1975. Studies on mineralization of urea, coated urea and nitrification inhibitor treated urea in soil. J. Soil Sci. 26, 305–312.

Rosenberg, M.S., Adams, D.C., Gurevitch, J., 2000. MetaWin, Statistical Software for Meta-Analsysis, Version 2. Sinauer Associates, Inc., Sunderland.

Satrusajang, A., Snitwongse, P., Buresh, R.J., Friesen, D.K., 1991. Nitrogen-15 and sulfur-35 balances for fertilizers applied to transplanted rainfed lowland rice. Fertil. Res. 28, 55–65.

Savant, N.K., Stangel, P.J., 1998. Urea briquettes containing diammonium phosphate: a potential NP fertilizer for transplanted rice. Fertil. Res. 51, 85–94.

Singh, S., Prasad, R., Singh, B.V., Goyal, S.K., Sharma, S.N., 1990. Effect of green manuring, blue-green algae and neem-cake-coated urea on wetland rice (*Oryza sativa* L.). Biol. Fertil. Soils 9, 235–238.

Slaton, N.A., Golden, B.R., Norman, R.J., 2009. Rice response to urea and two polymer-coated urea fertilizers. AAES Res. Ser. 581, 211–219.

Snitwongse, P., Satrusajang, A., Buresh, R.J., 1988. Fate of nitrogen fertilizer applied to lowland rice on a Sulfic Tropaquept. Fertil. Res. 16, 227–240.

Soares, J.R., Cantarella, H., de Campos Menegale, M.L., 2012. Ammonia volatilization losses from surface-applied urea with urease and nitrification inhibitors. Soil Biol. Biochem. 52, 82–89.

Street, J.E., Bollich, P.K., 2003. Rice production. In: Smith, C.W., Dilday, R.H. (Eds.), Rice: Origin, History, Technology, and Production. John Wiley & Sons, Inc., New Jersey.

Thomas, J., Prasad, R., 1987. Relative efficiency of prilled urea, urea super granules, sulphur coated urea and nitrification inhibitor. J. Agron. Crop Sci. 159, 302–307.

USDA, 2013. United States Department of Agriculture. http://www.ers.usda.gov/data588products/fertilizer-use-and-price.aspx#26727. Checked June 3, 2013.

Vlek, P.L.G., Stumpe, J.M., 1978. Effects of solution chemistry and environmental conditions on ammonia volitilization losses from aqueous systems. Soil Sci. Soc. Am. J. 42, 416–421.

Vyas, B.N., Godrej, N.B., Mistry, K.B., 1991. Development and evaluation of neem extract as a coating for urea fertilizer. Fertil. News 2, 19–25.

Wassmann, R., Pathak, H., 2007. Introducing greenhouse gas mitigation as a development objective in rice-based agriculture: II. Cost-benefit assessment for different technologies, regions and scales. Agric. Syst. 94, 826–840.

Wilson Jr., E., Norman, R.J., Wells, B.R., 1990. Dicyandiamide influence on uptake of preplant-applied fertilizer nitrogen by rice. Soil Sci. Soc. Am. J. 54, 1157–1161.

Wolt, J.D., 2004. A meta-evaluation of nitrapyrin agronomic and environmental effectiveness with emphasis on corn production in the Midwestern USA. Nutr. Cycl. Agroecosyst. 69, 23–41.

Ye, Y., Liang, X., chen, Y., Liu, J., Gu, J., Guo, R., Li, L., 2013. Alternate wetting and drying irrigation and controlled-release nitrogen fertilizer in late-season rice. Effects on dry matter accumulation, yield, water and nitrogen use. Field Crops Res. 144, 212–224.

Zhu, J.G., Han, Y., Liu, G., Zhang, Y.L., Shao, X.H., 2000. Nitrogen in percolation water in paddy fields with a rice/wheat rotation. Nutr. Cycl. Agroecosyst. 57, 75–82.