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Review

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

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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 ($pH \leq 6.0$) 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 ($pH \geq 8.0$). 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.

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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