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RESEARCH PAPER

Evaluating the performance of new stabilized urea fertilizer (AGROTAIN incorporated urea) in maize-wheat system

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Abstract: The nitrogen use efficiency of available urea fertilizer is low and it ranged from 30-50% in major food crops due to high volatilization and leaching losses. Nitrification and urease inhibitors and neem coating are the suggested means to reduce the nitrogen losses, thereby increasing crop nitrogen use efficiency (NUE). To improve the NUE, a study was conducted during 2020-21 to evaluate the performance of neem coated urea (NCU) (nitrification inhibitor) and Agrotain incorporated urea (AIU) (urease inhibitor) in maize-wheat system. The experiment comprised of control (No nitrogen), 100% NCU, 100% AIU, 80% AIU and 60% AIU in a randomized complete block design with four replications. The SPAD and NDVI values at different crop growth stages in maize-wheat system found at par with 100% AIU and 100% NCU. As compared to 100% NCU, grain yield of maize and wheat increased by 6.0% and 4.9% with 100% AIU, respectively. However, the system yield (wheat equivalents) was 5.6 and 1.9% higher with 100 and 80% AIU, respectively in comparison to 100% NCU. The 100% and 80% AIU recorded the higher net returns in maize by 7.7% and 3.0% as compared to 100% NCU, respectively. The system net returns were 6.2% higher with 100% AIU over 100% NCU. The agronomic efficiency of N (AE_N) and partial factor productivity of N (PFP_N) was decreased with the increased doses of N. Higher AE_N was observed with 100% AIU as compared to 100% NCU. Compared to NCU, AE_N and PEP_N of the system increased 30% and 27.4% under 80% AIU. Our study revealed that new stabilized urea fertilizer (AIU) saved 20% (30 kg N ha^{-1}) of NCU at similar or higher yields and N-use efficiency in maize-wheat system of north-west India. The AIU urea with neem was more efficient than neem alone and may play a great role in reducing the N-losses. thereby improving productivity while reducing the environmental footprints. AIU with neem could allow farmers to achieve equal to or higher yields to neem alone while using 20% less nitrogen fertilizer.

Keywords: Agrotain incorporated urea · Maize-wheat system · Net returns · Nitrogen use efficiency · System yield

Introduction

Urea and nitrogen based fertilizers are commonly used to supply nitrogen (N) to agricultural crops (Heffer and Michel, 2016). Urea is one of the most extensively used N fertilizers due to its high solubility and N concentration and lower cost of production (Behera *et al.,* 2013; Li *et al.,* 2015), it accounts for over 55% of all N fertilizers (IFA, 2017). According to the reports of FAI (2019-2020), the consumption of urea in India grew moderately at a growth rate of ~1.3% from 31.9 MT (2016) to 33.6 MT (2020). However, domestic urea production remained unchanged at 24.5 MT in 2020 compared to 24.1 MT in 2019 and ~27% of the urea demand was met through imports in 2020. The efficiency of the use of nitrogen from urea based fertilizer is low in many instances ~30-50% due to complex transformation of N in soil which led to loss of N (Afshar *et al.,* 2018; Panday *et al.,* 2020). Approximately 60% of global N fertilizer is majorly used

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for producing cereals: rice, wheat and maize**.** On average, the recovery rate of the urea N fertilizer was 34% for wheat (Galindo *et al.,* 2021), 46% for rice (Ladha *et al.,* 2005) and 33% for maize (Sindelar *et al.,* 2015).

However, urea can be an inefficient source of N in soil because it can be lost through multiple pathways such as volatilization, nitrate leaching and nitrous oxide emissions (Zaman and Blennerhassett, 2010). Urea undergoes rapid hydrolysis by urease enzyme releasing carbon dioxide and ammonia, which might be lost from soil to the atmosphere through volatilization (Dawar *et al.,* 2011; Soares *et al.,* 2012). The hydrolysis of urea increased the soil pH and favours ammonia volatilization; these nitrogen losses can be higher than 35% of the applied N (Cai *et al.,* 2002; Soares *et al.,* 2012). A main focus for ensuring the sustainability of crop productivity is to increase N use efficiency by optimized N management practices that reduce the risk of NO_3 leaching and NH_3 emission. Use of urease and nitrification inhibitors to urea fertilizer is one approach to improve N use efficiency of fertilizer. Common urease and nitrification inhibitors are N-(n-butyl) thiophosphoric triamide (NBPT) and neem coated urea (NCU), respectively. Nitrification inhibitors slow down the conversion of NH_4^+ to NO_3^- by deactivating ammonia oxidation by ammonium-oxidizing bacteria, leading to a reduction in the emission of N_2O from soils (Ruser and Schulz, 2015).

Ammonia volatilization is a major source for N losses and the main cause of low N use efficiency of urea-based fertilizers (Li *et al.,* 2008). However, the efficiency of urea based fertilizers can be improved with use of urease inhibitors to delay hydrolysis, prolonged urease diffusion interval and allow the urea to move to deeper layers of soil along with rainfall (Rawluk *et al.,* 2001). There are several compounds that have been developed to delay urea hydrolysis and behave as urease inhibitors, but only NBPT (N-(n-butyl) thiophosphoric triamide) traded as "Agrotain" has been used outside of India (North America, South America, Europe, Australia and Southern Africa) for more than 20 years. The application of NBPT has been reported to reduce urease activity in soil and thus reducing NH_3 emission (Sanz-Cobena *et al.,* 2012; Sanz-Cobena *et al.,* 2014). When NBPT is applied to soil it gets converted into its oxygen analogue NBPTO (N-(n-butyl) phosphoric triamide) which strongly competes with the urease enzyme for active sites on urea and slows down the hydrolysis of urea (Sigurdarson *et al.,* 2018). NBPT can block urea hydrolysis for 7 to 10 days after its application and results in smaller increase of soil pH around the urea granule reduces the ammonia volatilization losses (Fu *et al.,* 2020). Recent literatures have revealed that urea coated with NBPT has reduced the volatilization losses from the soil surface under various soil and environmental conditions (Pan *et al.,* 2016; Silva *et al.,* 2017; Cantarella *et al.,* 2018).

The objectives of this study was to evaluate the performance of agrotain incorporated urea (AIU) on nitrogen use efficiencies (agronomic efficiency and partial factor productivity), crop yields, net returns yield attributes, chlorophyll content and NDVI, in maize-wheat system. We hypothesized that application of Agrotain incorporated urea (AIU) would increase crop yield, thereby decreasing nitrogen losses, maintaining leaf chlorophyll content, and maximizing above-ground plant attributes.

Materials and methods

Site description and experiment details

A field study was conducted during 2020-2021 with maize (*Kharif* season) and wheat (*Rabi* season) crops at ICAR (Indian Council of Agricultural Research)-CSSRI (Central Soil Salinity Research Institute) research farm Karnal (29°708625N, 76°7956765E and at an elevation of 243 m above msl), India. This region has a sub-tropical climate with wet summers and dry winters, with annual precipitation 670 mm of which 75–80% occurs in June - September (monsoon season). The soil texture was silty loam (0-15 cm layer) with medium in organic carbon (0.69%), low in available N (157 kg ha^{-1}), low in P (18.5 kg ha^{-1}), K (210 kg ha^{-1}) and neutral pH (7.45). Different soil chemical properties analysed prior to treatment application are given in Table 1. The experiment was conducted in plot size of 20 m^2 (5 m × 4 m) in a randomized complete block design with four replications. The five treatments were; T1- untreated control (control), T2- 100% (150 kg N ha^{-1}) neem coated urea (NCU), T3- 100% (150 kg N ha^{-1}) agrotain incorporated urea (AIU), T4- 80% (120 kg N ha^{-1}) agrotain incorporated urea (AIU), T5- 60% (90 kg N ha^{-1}) agrotain incorporated urea (AIU). The source of the AIU was Koch Agronomic Services (Wichita, Kansas, USA) and all the AIU was treated with neem after granulation.

Table 1. Initial soil properties of the experimental site

Soil parameters	Soil depth (cm)		
	0–15	15–30	30–45
Soil pH	7.45	7.61	7.61
EC (dS m^{-1})	0.70	0.65	0.67
SOC (%)	0.69	0.40	0.24
Available N (kg ha^{-1})	157	133	108
Available P (kg ha^{-1})	18.5	14.1	10.0
Available K (kg ha^{-1})	210	210	237

Crop management

Before sowing, field was levelled at zero level and ploughed well before implementation of different treatments as per protocols. Cultivar CP 838 of maize was sown on 7th June and row to row spacing of 67.5 cm was maintained. The seed rate of 20 kg ha^{-1} was adopted for optimum plant population. In *Rabi season*, wheat cultivar HD-2967 was sown on 5th November with multi crop planter. Inter row distance of 22.5 cm was maintained at a seed rate of 100 kg ha^{-1}. Irrigation was applied at all the critical crop growth stages of both the crops. Recommended plant protection measures were implemented for keeping crop free from weeds, insects, pests and diseases. Both maize and what crop was harvested at physiological maturity.

Fertilizer management

Maize and wheat were fertilized with recommended dose of 150 kg N+ 60 kg P+ 60 kg K per hectare. During the experiment, full dose of P (60 kg ha^{-1}) and K (60 kg ha^{-1}) were applied as basal at the time of sowing in the form of single super phosphate and muriate of potash, respectively, while N fertilizer was split into two equal doses, half applied at 21 days after sowing (DAS) and remaining half at 50 DAS. To determine the agronomic efficiency of applied N, partial factor productivity of N (PFP_N) was calculated using Eq. 1 & 2 and expressed in kg grain per kg of N applied.

Agronomic efficiency of N (AE_N) = $(Y-Y_0) / F$ ...(1)

Partial factor productivity of N (PFP_N) = Y / F ...(2)

Where

Y= yield under nutrient applied plot, Y_0 = yield under control plot (with not nutrient applied), F = amount of N-nutrient applied

Crop observations

For physiological studies, Minolta 502 SPAD chlorophyll meter was used to determine the leaf chlorophyll content at different intervals of time. The normalized difference vegetation index (NDVI) was measured using a portable N tech "Greenseeker" NDVI meter at different intervals of time. Measurements were taken horizontally across the plot from the middle rows in the plot to avoid border effects. NDVI and SPAD readings were taken from 11:00 h to 14:00 h under stable and clear sky to prevent data fluctuations. Plant height, no. of grains per cob/spikelet, 1000-grain weight, spike length, and grain yield were recorded for each plot. The yield attributes of maize and wheat crop were determined during the crop growth period as per the standard procedures.

Maize and wheat were harvested and threshed manually. At maturity, the grain and straw yields of both maize and wheat were determined on a total area of 14 m^2. Grain yield was expressed as Mg ha^{-1} at 14% and 12% grain moisture content for maize, and wheat, respectively. To compare the productivity of maize and wheat crop and total system productivity of both the crops, the grain yield of maize was converted into wheat equivalent yield (WEY) (Mg ha^{-1}) and calculated using the Eq. (3).

WEY (Mg ha^{-1}) = [maize yield (Mg ha^{-1}) * MSP of respective crop (INR Mg ha^{-1})]

/ MSP of wheat (INR Mg ha^{-1})] ...(3)

Where, MSP is minimum support price of Govt. of India, INR is Indian Rupee

Economics

The data on crop management practices like tillage, irrigations, seed, pesticides, fertilizer, labour use, etc. and their costs under each treatment were recorded using a standard data format. Variable costs of each treatment were summed up to calculate the total cost of production. Gross returns were calculated on the prevailing market prices of the produce (grain and straw). Net returns were calculated by deducting the total cost of production from the gross returns. The gross returns, net returns and BC ratio were statistically analysed using analysis of variance (ANOVA) at 5% level of significance. The total net return of maize-wheat system was calculated by subtracting total cost of production from gross returns of system.

Statistical analysis

The data for different parameters were analysed by ANOVA (analysis of variance) using SAS 9.1 software (SAS Institute, Cary, NC). Fisher's least significant difference (LSD) test was used for comparing differences between two means at the 5% probability level.

Results and Discussion

Crop growth attributes

SPAD and NDVI values changed with the crop stage, highest value at 60 days after sowing (DAS) (Figure 1 & 2). At the respective crop stages, there was no much difference with respect to the varied N-fertilizer doses in both maize and wheat crop. But it was significant with the control (No N-fertilizer) for SPAD and NDVI values. The treatment of 100% AIU resulted in higher SPAD and NDVI numerical values than 100% NCU (30, 44, 50, 60 and 72 DAS). At 44 and 50 DAS, SPAD values showed increment of 3% and 3.5% with 100% AIU over 100% NCU treatment. At 60 DAS, 100% NCU (40.38 and 0.76) showed the highest value followed by 100% AIU (39.68 and 0.74). SPAD and NDVI value were observed higher by 3.0-56.8% than control at different intervals of time. A positive correlation exists between N and leaf chlorophyll content with addition of urease inhibitor (Buscaglia and Varco, 2002; Kawakami *et al.,* 2012) due to increased nitrogen uptake as N is a chief structural component of chlorophyll in plants (Makino and Osmond, 1991).

Crop yield attributes

Yield attributes data (Table 2) indicated a significant treatment effect for no. of grains per cob and 100-grains (seed index) of maize crop. Results showed no

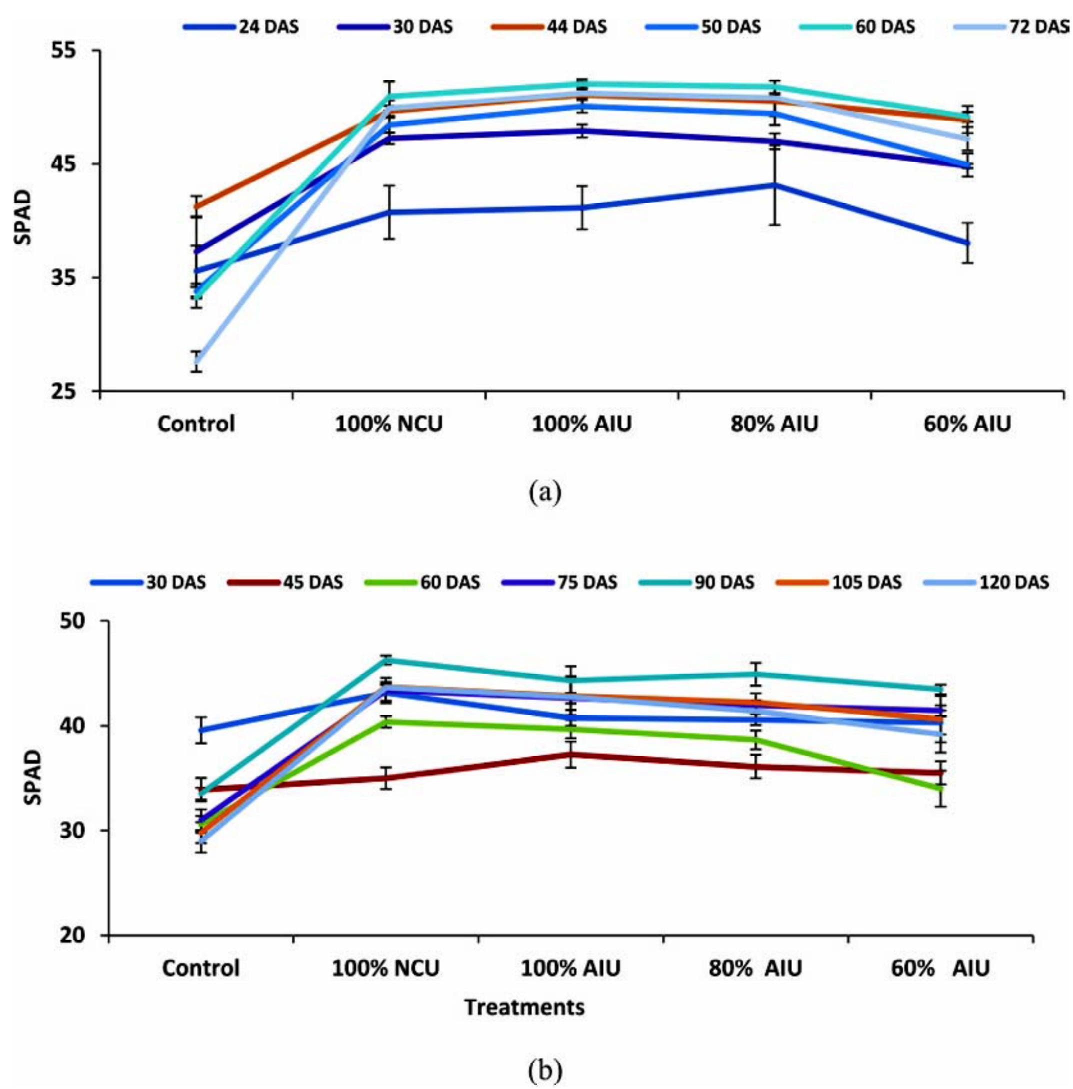

Figure 1. SPAD values of (a) maize (b) wheat under different N-doses (error bars indicate SE of the mean)

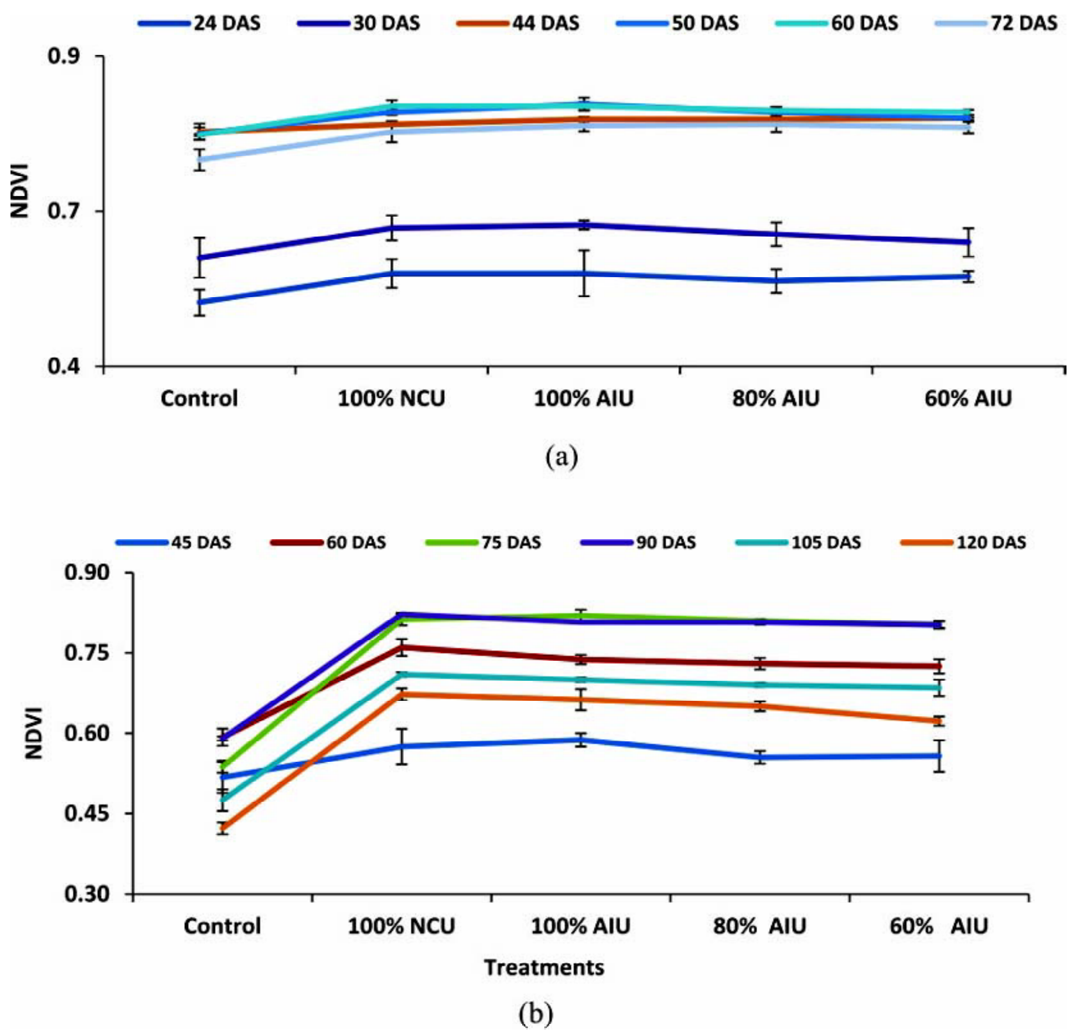

Figure 2. NDVI values of (a) maize (b) wheat under different N doses (error bars indicate SE of the mean)

Table 2. Effect of different N- doses on yield attributes of maize and wheat

Treatment	Maize		Wheat		
	No. of grains per cob	100- grains weight	Spike length(cm)	No. of grains per spike	1000- grains weight
Control	507.60b*	27.64c	13.00b	29.33c	38.16a
100% NCU	607.05a	31.84ab	15.80a	59.35ab	39.19a
100% AIU	627.70a	33.95a	15.90a	63.23a	41.36a
80% AIU	624.60a	33.12a	15.78a	61.90a	39.28a
60% AIU	581.80ab	30.71b	15.49a	55.85b	39.00a

*Means followed by a similar lowercase letters within a column are not significantly different at 0.05 level of probability using LSD test

differences in no. of grains per cob between 100% NCU (607.1), 100% AIU (627.7), 80% AIU (624.6), and 60% AIU (581.8) however all the N fertilized treatments was significantly higher over control (507.6). Meanwhile, the grains weight of 100 seeds was improved by 6.6% and 4% with 100% AIU and 80% AIU as compared to 100% NCU, respectively.

In wheat, spike length was recorded similar under all N fertilized treatments but significantly decreased under control. The 80% AIU was on par with 100% AIU and 100% NCU with respect to the no. of grains per spike. Compared to 100% NCU, the no. of grains per spike with 100% AIU and 80% AIU were increased by 6.5% and 4.3%, respectively. The 1000-grains weight of wheat under different treatments was found similar but with 100% AIU it was 5.5% higher over 100% NCU. These results are consistent with studies of Dawar *et al.* (2011); Curitiba *et al.* (2013) and Khan *et al.* (2014) as they reported the improvement in yield parameters with application of NBPT incorporated urea as compared to urea.

Crop and system productivity

The Result showed that grain yield of maize with 80% AIU (9.14 Mg ha^{-1}) was on par with 100% AIU (9.49 Mg ha^{-1}) and 100% NCU (8.95 Mg ha^{-1}). The lowest yield was recorded with control treatment and it was followed by 60% AIU (Table 3). The maize yield was increased by 6% with 100% AIU as compared to 100% NCU. Stover yield was also observed similar with all N fertilized treatments. The highest stover yield of 13.21 Mg ha^{-1} was recorded with 100% AIU which was 5.8% higher than 100% NCU (12.49 Mg ha^{-1}). The application of urea along with urease inhibitor generally exhibited higher yield and N use efficiency by inhibiting N losses through regulating transformation of inorganic N in soil (Abalos *et al.,* 2014). Previous studies on urease inhibitor (NBPT) also concluded that application of the urea along with NBPT improve maize yields as compared to conventional urea (Venterea *et al.,* 2011; Qiao *et al.,* 2015; Zhao *et al.,* 2017). Similarly, Mohd Zuki *et al.,* (2020) also reported that NBPT-coated urea at normal rate and 20% lower rate improved the maize yield by 42% and 48% in comparison to urea. Wheat grain yield with 100% AIU (6 Mg ha^{-1}) was found at par with 100% NCU (5.72 Mg ha^{-1}). Straw yield under different N fertilized treatments varied from 7.21 Mg ha^{-1} to 8.03 Mg ha^{-1} (Table 3). Meanwhile, application of 100% AIU increased the grain and straw yield by 4.9% and 4.4% as compared to 100% NCU. The outcomes showed a strong agreement with Silva *et al.,* (2017); as their meta-analysis results directed that urease inhibitor treated urea can increase crop yield potential up to 5.3-7.5% for major crops. Similar results were found by McClallen (2014), where the addition of urease inhibitor (NBPT) significantly increased wheat yield production. In literature, the field trials showed increased yield of different crops species following the use of new urease inhibitor (Zaman *et al.,* 2009; Khan *et al.,* 2015).

Highest system yield (WEY) of 14.99 Mg ha^{-1} was recorded with 100% AIU and the lowest with control (7.46 Mg ha^{-1}) (Table 5). System yield exhibited a statistical difference only between the control and 60% AIU treatments ($P < 0.05$). The system yield under 100% NCU, 100% AIU and 80% AIU were recorded at par, which varied from 14.19 Mg ha^{-1} to 14.99 Mg ha^{-1}. The 100% AIU increased the system yield by 5.6% compared 100% NCU in maize-wheat system. Correspondingly, meta-analysis study of Linquist *et al.* (2013) revealed that when enhanced efficiency nitrogen fertilizers were analysed, urease inhibitor (NBPT) and neem product suggest increased yield and N uptake of rice systems under different soil conditions.

Crop and system net returns

The seasonal cost of production, gross return, net return and BC ratio for maize and wheat crop are presented in Table 4. The total production costs of maize varied from 35,720 to 43,370 INR ha^{-1} under different treatments. In maize, 100% AIU resulted in highest gross (1, 77,472 INR ha^{-1}) and net return (1, 34,104 INR ha^{-1}) which was 6.1% and 7.7% higher over the 100% NCU. This was due to lower cost of production and higher net incomes from 100% AIU. Results indicated highest B:C ratio was recorded with 100% AIU (3.1) and found at par with 100% NCU and 80% AIU treatment.

In wheat, 100% AIU recorded highest cost of production, gross and net return than other treatments; however, it was at par with 100% NCU and 80% AIU in terms of gross and net returns. The gross and net income under 100% AIU was higher by 4,456 INR ha^{-1} (3.2%)

Table 3. Effect of different N- doses on grain yield, stover or straw yield, agronomic efficiency of N (AE_N) and partial factor productivity of N (PFP_N) of maize–wheat system

Treatment	Maize				Wheat			
	Grain yield (Mg ha^{-1})	Stover yield (Mg ha^{-1})	AE_N (kg grain kg N^{-1})	PFP_N (kg grain kg N^{-1})	Grain yield (Mg ha^{-1})	Straw yield (Mg ha^{-1})	AE_N (kg grain kg N^{-1})	PFP_N (kg grain kg N^{-1})
Control	4.9c*	8.53b	-	-	2.81c	3.94c	-	-
100% NCU	8.95a	12.49a	26.93c	59.63c	5.72ab	7.69a	20.48d	38.13d
100% AIU	9.49a	13.21a	30.53b	63.27c	6.00a	8.03a	22.31c	40.00c
80% AIU	9.14a	12.92a	35.25a	76.17b	5.81ab	7.84a	26.32b	48.42b
60% AIU	7.95b	11.05ab	33.75a	88.31a	5.43ab	7.21b	30.85a	60.33a

*Means followed by a similar lowercase letters within a column are not significantly different at 0.05 level of probability using LSD test

Table 4. Economics of maize-wheat cultivation under different N fertilizer treatments

Treatment	Maize				Wheat			
	TCP (INR ha^{-1})	GR (INR ha^{-1})	NR (INR ha^{-1})	BCR	TCP (INR ha^{-1})	GR (INR ha^{-1})	NR (INR ha^{-1})	BCR
Control	35720d*	91795d	56075d	1.6c	30454e	67349c	36895c	1.2c
100% NCU	42714b	167248b	124534b	2.9a	36506b	137981a	101475ab	2.8ab
100% AIU	43370a	177472a	134104a	3.1a	36506a	142437a	105930a	2.9a
80% AIU	42511b	170803ab	128292ab	3.0a	36075c	137838a	101762ab	2.8ab
60% AIU	40658c	148591c	107933c	2.7b	35648d	128813b	93165b	2.6b

*Means followed by a similar lowercase letters within a column are not significantly different at 0.05 level of probability using LSD test
**TCP-total cost of production, GR-gross return, NR-net return, BCR- benefit-cost ratio

and 4,455 INR ha^{-1} (4.3%) compared to 100% NCU (Table 4). The BC ratio was 3.6% higher with 100% AIU (2.9) compared to conventional urea (2.8). Higher crop yields along with lower production costs in 100% AIU resulted in higher profitability compared with commonly adopted fertilizer sources. Our results lined up with Allende-Montalbán *et al.* (2021), they recorded increase in net economic benefit with application of urease inhibitor (NBPT) as compared with equal amount of urea in maize-wheat rotation. However, Zheng *et al.,* (2021) observed the economic benefit with nitrification inhibitor and urease inhibitor as compared to urea. The economic analysis of system revealed the highest net returns with 100% AIU (2, 40,033 INR ha^{-1}) and it was higher by 6.2% compared to 100% NCU (Table 4). Similar results have been reported by Liu *et al.,* (2022), reported that use of urea with inhibitors improved the net economic returns by 24.7% on average compared with the farmers' N practice in the wheat-maize rotation.

N-use efficiencies (AE_N and PFP_N)

Results showed that different nitrogen treatments influenced the N-use efficiencies i.e. agronomic efficiency of N (AE_N) and partial factor productivity of N (PFP_N) of maize (Table 3). The highest AE_N was recorded with 80% AIU (35.25 kg grain kg N^{-1}) and the lowest with 100% NCU (26.93 kg grain kg N^{-1}). AE_N under 100% AIU was increased by 15.4% in contrast to 100% NCU. The PFP_N was recorded higher with 60% AIU (88.31 kg grain kg N^{-1}) and it was followed by 80% AIU (76.17 kg grain kg N^{-1}) in maize. Application of 100% AIU and 80% AIU had higher PFP_N than 100% NCU with an increment of 6.1% and 27.7%, respectively. Urease inhibitor has capability to delay the hydrolysis of urea and improved the use efficiencies of nitrogen by crop. Numerous researchers have done meta-analysis on urease inhibitor (NBPT) and showed positive effect of urea with NBPT in reducing the N losses and increasing nitrogen use efficiency under different crops (Abaldos *et al.,* 2014; Silva *et al.,* 2017; Cantarella *et al.,* 2018). Silva *et al.* (2011) also reported that the agronomic efficiency of AIU at lower N rate (96 kg N ha^{-1}) was higher and had the potential to perform better in increasing the NUE than higher N rates (120 kg N ha^{-1}).

The AE_N and PFP_N exhibited increased trend with decreased N fertilization in which higher values under 60% AIU than other N- fertilized treatments in wheat crop. With

Table 5. System yield (wheat equivalents), net returns, agronomic efficiency and partial factor productivity of N (AE_N and PFP_N) of maize-wheat system

Treatment	System yield (Mg ha^{-1})	System net returns (INR ha^{-1})	AE_N (kg grain kg N^{-1})	PFP_N (kg grain kg N^{-1})
Control	7.46c*	92969d	-	-
100% NCU	14.19a	226009b	22.43a	47.31c
100% AIU	14.99a	240033a	25.09a	49.95c
80% AIU	14.46a	230054ab	29.19a	60.27b
60% AIU	12.95b	201098c	30.55a	71.97a

*Means followed by a similar lowercase letters within a column are not significantly different at 0.05 level of probability using LSD test

100% AIU, the AE_N and PEP_N was increased by 8.9% and 4.9% as compared to 100% NCU, respectively. However, our results indicating a benefit of incorporating agrotain to urea fertilizer on agronomic use efficiency of N are consistent with the study of Mozaffari *et al.,* (2007) and Li *et al.,* (2015). Furthermore, Kawakami *et al.,* (2012) reported that use of AIU in silt loam soil increased N uptake and N use efficiency by 17% and 41%, respectively.

The PFP_{N-} of system ranged from 47.32 to 71.97 kg grain kg N^{-1}. The AE_N of maize-wheat system with 60% AIU was increased by 36.2%, 21.8% and 4.7% as compared to 100% NCU, 100% AIU and 80% AIU, respectively (Table 5). The increase in AE_N was not significant at $P<0.05$. The highest PEP_N was recorded with 60% AIU (71.97 kg grain kg N^{-1}) followed by 80% AIU (60.27 kg grain kg N^{-1}). As compared to 100% NCU, increase of 5.5% and 27% was observed with 100% AIU and 80% AIU, respectively.

Conclusions

This study provides a better understanding on the effect of urease inhibitors like Agrotain (NBPT), which improves the nitrogen use efficiency in maize-what system under western IGP. In the maize-wheat system, 80% AIU with neem was on par with 100% AIU and 100% NCU with respect to growth attributes, yield attributes, yields (grain and straw/stover) and net returns. It is concluded that with, similar yield and net returns can be obtained in maize-wheat system. With the use of AIU, 20% nitrogen can be saved because of higher N-use efficiencies in maize-wheat system. This would help in developing new methodology or strategies for more efficient utilization of input resources in soil and enhancement of sustainable crop production.

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References

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

Afshar, R. K., Lin, R., Mohammed, Y. A. & Chen, C. (2018). Agronomic effects of urease and nitrification inhibitors on ammonia volatilization and nitrogen utilization in a dryland farming system: Field and laboratory investigation. *Journal of Cleaner Production,* **172**: 4130–4139.

Allende-Montalbán, R., Martín-Lammerding, D., Delgado, M. D. M., Porcel, M. A. & Gabriel, J. L. (2021). Urease inhibitors effects on the nitrogen use efficiency in a maize–wheat rotation with or without water deficit. *Agriculture,* **11**(7): 684.

Behera, S. N., Sharma, M., Aneja, V. P. & Balasubramanian, R. (2013). Ammonia in the atmosphere: a review on emission sources, atmospheric chemistry and deposition on terrestrial bodies. *Environmental Science and Pollution Research,* **20**(11): 8092–8131.

Bloom, A. J. (2015). The increasing importance of distinguishing among plant nitrogen sources. *Current Opinion in Plant Biology,* **25**: 10–16.

Buscaglia, H. & Varco, J. (2002). Early detection of cotton leaf nitrogen status using leaf reflectance. *Journal of Plant Nutrition,* **25**: 2067.

Cai, G., Chen, D., White, R. E., Fan, X. H., Pacholski, A., Zhu, Z. L. & Ding, H. (2002). Gaseous nitrogen losses from urea applied to maize on a calcareous fluvo-aquic soil in the North China plain. *Australian Journal of Soil Research,* **40**(5): 737–748.

Cantarella, H., Otto, R., Rodrigues, J., Gomes, A. & Silva, D.B. (2018). Agronomic efficiency of NBPT as a urease inhibitor: a review. *Journal of Advance Research,* **13**: 19–27.

Christianson, C. B., Byrnes, B. H. & Carmona, G. (1990). A comparison of the sulfur and oxygen analogs of phosphoric triamide urease inhibitors in reducing urea hydrolysis and ammonia volatilization. *Fertility Research,* **26**: 21–27.

Creason, G. L., Schmitt, M. R., Douglass, E. A. & Hendrickson, L. L. (1990). Urease inhibitory activity associated with N-butyl thiophosphoric triamide is due to formation of its oxon analog. *Soil Biology and Biochemistry,* **22**(2): 209–211.

Curitiba Espindula, M., Soares Rocha, V., Alves de Souza, M., Campanharo, M. & de Sousa Paula, G. (2013). Rates of urea with or without urease inhibitor for topdressing wheat. *Chilean Journal of Agricultural Research,* **73**(2): 160–167.

Dawar, K., Zaman, M., Rowarth, J. S., Blennerhassett, J. & Turnbull, M. H. (2011). Urease inhibitor reduces N losses and improves plant-bioavailability of urea applied in fine particle and granular forms under field conditions. *Agriculture, Ecosystems & Environment,* **144**(1): 41–50.

Dawar, K., Zaman, M., Rowarth, J. S. &Turnbull, M. H. (2012). Applying urea with urease inhibitor (N-(n-butyl) thiophosphoric triamide) in fine particle application improves nitrogen uptake in ryegrass (*Lolium perenne* L.). *Soil Science and Plant Nutrition,* **58**: 309–318.

Ding, W. X., Yu, H. Y. & Cai, Z. C. (2011). Impact of urease and nitrification inhibitors on nitrous oxide emissions from fluvo-aquic soil in the North China Plain. *Biology and Fertility of Soils,* **47**(1): 91–99.

Fu, Q., Abadie, M., Blaud, A., Carswell, A., Misselbrook, T. H., Clark, I. M. & Hirsch, P. R. (2020). Effects of urease and nitrification inhibitors on soil N, nitrifier abundance and activity in a sandy loam soil. *Biology and Fertility of Soils,* **56**(2): 185–194.

Galindo, F. S., da Silva, E. C., Pagliari, P. H., Fernandes, G. C., Rodrigues, W. L., Biagini, A. L. C., Baratella, E. B., da Silva Junior, C. A., Neto, M. J. M., Muraoka, T. & Teixeira Filho, M. C. M. (2021). Nitrogen use efficiency and recovery in a wheat-corn rotation under tropical savannah conditions. *Nutrient Cycling in Agroecosystems,* **119**(3): 291–305.

Heffer, P. & Michel Prud'homme (2016). *Global nitrogen fertilizer demand and supply: Trend, current level and outlook*. In: International Nitrogen Initiative Conference. Melbourne, Australia.

Hemerly, A. (2016). *Genetic controls of biomass increase in sugarcane by association with beneficial nitrogen-fixing bacteria.* In: Plant and Animal Genome XXIV Conference. Plant and Animal Genome, during month of January.

IFA (2017). *Fertilizer outlook 2017–2021*. IFA annual conference – May 2017, Marrakech (Morocco).

Kawakami, E. M., Oosterhuis, D. M., Snider, J. L. & Mozaffari, M. (2012). Physiological and yield responses of field-grown cotton to application of urea with the urease inhibitor NBPT and the nitrification inhibitor DCD. *European Journal of Agronomy,* **43**: 147–154.

Khan, M. J., Malik, A., Zaman, M. & Khan, Q. (2014). Nitrogen use efficiency and yield of maize crop as affected by agrotain coated urea in arid calcareous soils. *Soil Environment,* **33**: 1–6.

Khan, A. Z., Ali, B., Afzal, M., Wahab, S., Khalil, S. K., Amin, N., Ping, Q., Qiaojing, T. & Zhou, W. (2015). Effects of sulphur and urease coated controlled release urea on dry matter yield, N uptake and grain quality of rice. *Journal of Animal and Plant Sciences,* **25**: 679–685.

Ladha, J. K., Pathak, H., Krupnik, T. J., Six, J. & van Kessel, C. (2005). Efficiency of fertilizer nitrogen in cereal production: Retrospects & prospects. *Advances in Agronomy,* **87**: 85–156.

Li, H., Liang, X., Chen, Y., Tian, G. & Zhang, Z. (2008). Ammonia volatilization from urea in rice fields with zero-drainage water management. *Agricultural Water Management,* **95**(8): 887–894.

Li, Q., Yang, A., Wang, Z., Roelcke, M., Chen, X., Zhang, F., Pasda, G., Zerulla, W., Wissemeier, A. H. & Liu, X. (2015). Effect of a new urease inhibitor on ammonia volatilization and nitrogen utilization in wheat in north and northwest China. *Field Crops Research,* **175**: 96–105.

Liu, C., Ren, D., Liu, H., Zhang, Y., Wang, L., Li, Z. & Zhang, M. (2022). Optimizing nitrogen management diminished reactive nitrogen loss and acquired optimal net ecosystem economic benefit in a wheat-maize rotation system. *Journal of Cleaner Production,* **331**: 129964.

Makino, A. & Osmond, B. (1991). Effects of nitrogen nutrition on nitrogen partitioning between chloroplasts and mitochondria in pea and wheat. *Plant Physiology,* **96**: 355–362.

McClallen, M. W. (2014). Wheat, rice and corn response to the urease inhibitor n-(n-butyl) thiophosphoric triamide in a dimethyl sulfoxide /propylene glycol solution. Master's Thesis, West Texas A&M University Canyon, Canyon, TX, USA.

Mohd Zuki, M. M., Sakimin, S. Z. & Yusop, M. K. (2020). N-(n-Butyl) thiophosphoric triamide (NBPT)-coated urea (NCU) improved maize growth and nitrogen use efficiency (NUE) in highly weathered tropical soil. *Sustainability,* **12**(21): 8780.

Mozaffari, M., Slaton, N. A., Long, J., Kelley, J., Chlapecka, R. & Wimberley, R. (2007). Effect of urea and urea treated with Agrotain™ on corn grain yield in Arkansas. *Soil Fertility Studies,* **38**.

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

Panday, D., Mikha, M. M., Collins, H. P., Jin, V. L., Kaiser, M., Cooper, J., Malakar, A. & Maharjan, B. (2020). *Optimum rates of surface-applied coal char decreased soil ammonia volatilization loss,* **49**(2): 256–267.

Qiao, C., Liu, L., Hu, S., Compton, J. E., Greaver, T. L. & Li, Q. (2015). How inhibiting nitrification affects nitrogen cycle and reduces environmental impacts of anthropogenic nitrogen input. *Global Change Biology,* **21**(3): 1249–1257.

Rawluk, C. D. L., Grant, C. A. & Racz, G. J. (2001). Ammonia volatilization from soils fertilized with urea and varying rates of urease inhibitor NBPT. *Canadian Journal of Soil Science,* **81**(2): 239–246.

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

Sanz-Cobena, A., Sánchez-Martín, L., García-Torres, L. & Vallejo, A. (2012). Gaseous emissions of N_2O and NO and NO^{3-} leaching from urea applied with urease and nitrification inhibitors to a maize (*Zea mays*) crop. *Agriculture, Ecosystems & Environment,* **149**: 64–73.

Sanz-Cobena, A., Lassaletta, L., Estellés, F., Del Prado, A., Guardia, G., Abalos, D., Aguilera, E., Pardo, G., Vallejo, A., Sutton, M. A. & Garnier, J. (2014). Yield-scaled mitigation of ammonia emission from N fertilization: the Spanish case. *Environmental Research Letters,* **9**(12): 125005.

Sigurdarson, J. J., Svane, S. & Karring, H. (2018). The molecular processes of urea hydrolysis in relation to ammonia emissions from agriculture. *Reviews in Environmental Science and Bio-Technology* **17**(2): 241–258.

Silva, D. R. G., Pereira, A. F., Dourado, R. L., Silva, F. P. D., Avila, F. W. & Faquin, V. (2011). Productivity and efficiency of nitrogen fertilization in maize under different levels of urea and NBPT treated urea. *Ciencia e Agrotecnologia,* **35**: 516–523.

Silva, A. G., Sequeira, C. H., Sermarini, R. A. & Otto, R. (2017). Urease inhibitor NBPT on ammonia volatilization and crop productivity: A meta-analysis. *Agronomy Journal,* **109**(1): 1-13.

Sindelar, A. J., Coulter, J. A., Lamb, J. A. & Vetsch, J. A. (2015). Nitrogen, stover, and tillage management affect nitrogen use efficiency in continuous corn. *Agronomy Journal,* **107**(3): 843-850.

Soares, J. R., Cantarella, H., & Menegale, M. L. de C. (2012). Ammonia volatilization losses from surface-applied urea with urease and nitrification inhibitors. *Soil Biology and Biochemistry,* **52**: 82–89.

Venterea, R. T., Maharjan, B. & Dolan, M. S. (2011). Fertilizer source and tillage effects on yield-scaled nitrous oxide emission in a corn cropping system. *Journal of Environmental Quality,* **40**: 1521–1531.

Zaman, M., Saggar, S., Blennerhassett, J. D. & Singh, J. (2009). Effect of urease and nitrification inhibitors on N transformation, gaseous emissions of ammonia and nitrous oxide, pasture yield and N uptake in grazed pasture system. *Soil Biology and Biochemistry,* **41**(6): 1270–1280.

Zaman, M. & Blennerhassett, J. (2010). Effects of the different rates of urease and nitrification inhibitors on gaseous emissions of ammonia and nitrous oxide, nitrate leaching and pasture production from urine patches in an intensive grazed pasture system. *Agriculture, Ecosystem & Environment,* **136**: 236–246.

Zhao, Y. & Lobell, D. B. (2017). Assessing the heterogeneity and persistence of farmers' maize yield performance across the North China Plain. *Field Crops Research,* **205**: 55–66.

Zheng, J., Wang, H., Fan, J., Zhang, F., Guo, J., Liao, Z. & Zhuang, Q. (2021). Wheat straw mulching with nitrification inhibitor application improves grain yield and economic benefit while mitigating gaseous emissions from a dry land maize field in northwest China. *Field Crops Research,* **265**: 108125.