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Assessing Fertilizer Nitrogen Sources and Application Timing for Water-Seeded Rice Systems

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Assessing Fertilizer Nitrogen Sources and Application Timing for Water-Seeded Rice Systems

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ABSTRACT

In California's water-seeded rice systems, both high yields and nitrogen (N) use efficiency are achieved when the pre-plant N fertilizer (usually aqueous-ammonia; aqua-N) is injected into a dry seedbed before flooding and planting. However, there are situations where applying N fertilizer in this manner is not possible. The objective of this study was to evaluate N management practices by testing different N sources and application times. Over two growing seasons (three site-years) we evaluated different N sources including aqua-N, granular urea, ammonium sulfate, and three enhanced efficiency nitrogen fertilizers (EENFs). Application times for the EENFs, urea, and ammonium sulfate were one day after flooding and 2 weeks after flooding. Urea and ammonium sulfate were also applied in a 4-way split (ratio of 20:30:30:20 applied every two weeks). In 2021, additional treatments were added with aqua-N, ammonium sulfate, and urea applied before flooding; and urea applications at 3, 4, and 5 weeks after flooding. Grain yield and agronomic nitrogen use efficiency (ANUE) were measured and used to make comparisons. All fertilizer N treatments increased grain yields and ANUE relative to the zero-N control. The EENF treatments performed similarly to or worse than urea applied alone. Splitting urea applications was the best option for applying N fertilizer after the field was flooded. Only one split N treatment was evaluated in this study; this warrants further research on fine-tuning the best N splits for these systems.

1. INTRODUCTION

In rice (Oryza sativa L.) production, nitrogen (N) is required in the largest amounts compared to any other nutrient and is the largest input cost for rice farmers (Roberts et al., 2021). However, fertilizer N is highly susceptible to losses whereby only 47% of the N added from fertilizer onto cropland is converted into harvested products, while the rest either remains in the soil or is lost (Lassaletta et al. 2014, Davidson et al. 2015). In rice systems around the world, the primary fertilizer N loss pathways are ammonia volatilization, denitrification, leaching, and runoff (Choudhury et al., 2005; Normal et al., 2002; Mikkelsen, 1987). Accordingly, minimizing fertilizer N loss is one of many ways to mitigate the immediate and long-term consequences caused by reactive N escaping into the environment, such as eutrophication of water systems, atmospheric pollution, and climate change. With over half the world's population relying on rice as their staple food (GRiSP, 2013) and with the population projected to reach 9.7 billion by 2050 (United Nations, 2019), it is critical to implement more efficient N management systems in order to meet global rice production demands without negatively impacting the environment.

California produces approximately 20% of total US rice production [(dataset) USDA NASS, 2020-2021]. California rice is primarily grown in a water-seeded continuously flooded crop establishment system. In this system, land is dry plowed, disked, and leveled prior to flooding the fields to a depth of 8-10 cm. Pregerminated seeds (soaked for 24 hours, drained for 24 hours) are broadcast into the flood water by aircraft. The fields remain flooded throughout the growing season and are drained 2-4 weeks before harvest. As for N fertilizer management, farmers primarily use aqueous ammonia (aqua-N; 28% N) as it is the cheapest N source (USDA, 2014). Aqua-N is injected into dry soil as one of the last operations in seedbed preparation and before the field is flooded for planting (Williams, 2010). In addition to aqua-N, about 30% of the N rate is applied as part of a starter blend or top-dress (Williams, 2010; Rehman et al., 2022). Prior research has shown that pre-flood aqua-N applications resulted in higher grain yields and fertilizer N recovery efficiency than surface-applied N urea (Linquist et al., 2009). This has been the primary mode of application and results in the least amount of N loss due in part to the reduced state of the subsoil layer after flooding, which protects fertilizer N from nitrification (Broadbent et al., 1968; Norman et al., 2002; Linquist et al., 2009) and results in little to no leaching (Liang et al., 2014) or ammonia volatilization (Chuong et al., 2020).

While a pre-flood application of aqua-N is optimal for water-seeded rice systems, there are situations where it is not feasible. First, aqua-N may not always be accessible, as when in 2020 supply chain issues limited its availability. Second, if heavy rains occur before the aqua-N is applied, tractor operations are impaired and the risk of N loss increases as applying the aqua-N into a wet soil will result in nitrification and later denitrification losses when the field is flooded (Nelson et al., 1982).

Extensive research on EENFs and split N applications has been conducted in transplanted and in dry-seeded rice systems. In these systems, improved N management practices include splitting the N rate (Wilson et al., 1989; Jing et al., 2007), the use of EENFs (Linquist et al., 2013), and deep placement of urea briquettes (Mazid et al., 2016). However, little research has been conducted on alternative N management practices using EENFs and split applications in water-seeded systems. The objective of this study was to evaluate N management practices that could serve as an alternative to pre-flood aqua-N. In this study, we evaluated different N sources and application times and measured their effects on grain yield and agronomic N use efficiency (ANUE) at two locations across two years (three-site years).

2. MATERIALS AND METHODS

2.1 Description of Sites

Field experiments took place in the Sacramento Valley to evaluate changes in rice yield and ANUE based on a combination of fertilizer N source and application timing. In 2020, a field trial was established at the Rice Experiment Station (RES, 39°27’32” N, 121°44’20” W) on a clay loam Esquon–Neerdobe complex (fine, smectitic, thermic Xeric Epiaquerts and Duraquerts). In 2021, field trials were conducted at the RES and at an on-farm site (39°27’31” N, 121°42’12” W) on a sandy clay loam Duric Xerarents-Eastbiggs (Fine, mixed, active, thermic Abruptic Durixeralfs). At all sites, rice was grown in the previous year. Residues from the previous season were chopped, tilled, and incorporated into the soil. The RES site was winter flooded in both years, whereas the on-farm site was not.

The Sacramento Valley has a Mediterranean climate characterized by warm and dry conditions during the growing season (May to October). The average precipitation during the growing season for both years was 12 mm. The average minimum and maximum air temperature was 13.8° C and 31.5° C, respectively (CIMIS, 2021). Climate data was collected from an automated CA Irrigation Management Information System weather station located approximately 20 km from the sites.

At each location, soil samples (0-15 cm) were collected throughout the field prior to fertilization and flooding. The composited soil samples were air-dried and crushed to pass through a 2-mm sieve prior to analysis. Soil pH was measured using a saturated paste and pH meter (Schofield et. al, 1955), soil organic matter was determined by weight-loss-on ignition (Schulte et. al, 1996), particle size was determined using the hydrometer method (Sheldrick et. al, 1993), and total nitrogen was determined using the combustion method (AOAC, 1997). Soils at both locations were acidic. The RES had heavier clay soil while the on-farm site had more sandy textured soil (Table 1).

Table 1. Selected soil properties at the Rice Experiment Station (RES) and on-farm site.

Location	Organic matter (%)	Soil pH	Cation Exchange Capacity (meq/100g)	Texture (%)			Total Nitrogen (%)
				Sand	Silt	Clay	
RES	2.5	5.3	32.4	34	24	42	0.120
On-Farm	1.9	6.4	14.9	54	21	25	0.167

2.2 Field management

Land preparation at the RES and on-farm began in early/mid-April and consisted of chisel-plowing and discing, followed by final seedbed preparation with a triplane and roller before rice planting. Rice was grown in a continuously flooded water-seeded cropping system, which is the conventional establishment practice for California rice. Pre-germinated rice seed (variety M-206) was broadcast into flooded basins at 150 kg ha^{-1} in 2020 and at 200 kg ha^{-1} in 2021. Fields were kept flooded throughout the growing season and were drained at least two weeks before harvest. Seeding rates and flooding practices reflect commercial rice management in the region.

In both years at the RES, potassium, phosphate, and sulfur were applied as a blanket application via airplane per recommended guidelines (UCCE, 2018). At the farm site, mono/dicalcium phosphate ($Ca(H_2PO_4)_2$/ $CaHPO_4$) at 56 kg $ha^{-1}$and potassium sulfate (K_2SO_4) at 56 kg ha^{-1} were broadcast in each plot by hand. For all site-years, zinc sulfate ($ZnSO_4$) at 10 kg ha^{-1} was applied. Pests, diseases, and weeds were managed also following California recommended guidelines. The dates of key agronomic events are listed in Table 2.

Table 2. Selected dates of agronomic management events

Event	RES 2020	RES 2021	On-Farm 2021
Pre-flood urea	27 May	19 May	23 April
Flooded	28 May	20 May	29 April
Seeding	29 May	21 May	30 April
Post-flood urea	29 May	21 May	30 April
Harvest	23 & 24 Sept.	5 Oct.	23 Sept.

2.3 Experimental design

For all site-years, ANUE and yield response to N source and application timing was quantified in experiments arranged as a randomized complete block design with four replications. In 2020, there were 13 treatments and in 2021 there were 19 treatments. The plot size was 4 m^2 and 9.3 m^2 in 2020 and 2021, respectively.

Treatments were a combination of N source and timing (Table 4). A zero N treatment served as a control. All treatments received N at a rate of 150 kg ha^{-1}. This N rate was chosen because it is lower than what is typically applied to achieve maximum yields. Typical N rates are

180 to 220 kg N ha^{-1} (Linquist et al., 2009). Thus, using a lower N rate allows us to observe variations in grain yield due to differences in N uptake between treatments. Six N sources were tested: aqua-N (28%N), granular urea (46% N), ammonium sulfate (21% N), and three types of urea-based EENFs.

Table 3. Product information of the enhanced-efficiency nitrogen fertilizers (EENFs) tested at all site-years

Company	Product	Fertilizer Characteristics	Active Ingredients
ICL	Agrocote® 1-2	short-term controlled-release	urea + proprietary polymer coating
	Agrocote® 2-3	long-term controlled-release	urea + proprietary polymer coating
Koch	Anvol®	urease inhibitor	Duromide + NBPT
	SuperU®	urease and nitrification inhibitor	urea + NBPT + DCD

Abbreviations: N-(n-butyl) thiophosphoric triamide (NBPT); Dicyandiamide (DCD)

Notes: Agrocote® 1-2 formula is made to release N one to two months after application. Agrocote® 2-3 formula is made to release N two to three months after application.

The EENFs included: Agrocote [proprietary polymer coated urea, 43% N], Anvol-treated urea [combination of a.i. NBPT and Duromide (a patented molecule), both at proprietary rates], and SuperU [combination of a.i. NBPT and a.i. DCD, both at proprietary rates, 46% N] (Table 3). Two different polymer coatings were tested: Agrocote 1-2, a shorter-term coating made to release N one to two months after application; and Agrocote 2-3, a longer-term formula made to release N two to three months after application. Anvol, a liquid surface coating, was sprayed onto untreated agricultural-grade urea at a rate of 1.5 quarts per ton of urea. After spraying, the treated urea was mixed by hand to ensure even and uniform distribution.

Application times for the EENFs, urea, and ammonium sulfate were one day after flooding and 2 weeks after flooding. Urea and ammonium sulfate were also applied in a 4-way split, with applications at 2, 4, 6, and 8 weeks after flooding at a ratio of 20:30:30:20%. Additional treatments were added in 2021, with aqua-N, ammonium sulfate, and urea applied to dry soil one day before flooding and seeding; and urea applied at 3, 4, and 5 weeks after flooding (Table 4).

Table 4. Nitrogen fertilizer treatments in 2020 and 2021. A treatment consisted of a combination of one N source (N rate = 150 kg ha^{-1}) and application time. In the split application treatment, the total N rate was applied at four distinct times: 20% at week 2; 30% at week 4; 30% at week 6; and 20% at week 8.

Timing of N application	Source	Year
Control	0 N	2020, 2021
1 day before flood	Aqua-N Urea Ammonium Sulfate	2021
1 day after flood	Agrocote 2-3 Anvol SuperU Urea Ammonium Sulfate	2020, 2021
2 weeks after flood	Agrocote 1-2 Anvol SuperU Urea Ammonium Sulfate	2020, 2021
3 weeks after flood	Urea	2021
4 weeks after flood	Urea	2021
5 weeks after flood	Urea	2021
Split	Urea Ammonium Sulfate	2020, 2021

2.4 Grain yield and agronomic N use efficiency

In 2020, grain yield was determined at physiological maturity from a 1.0 m^2 quadrat in each plot. All rice plants within the quadrat were cut at the ground level. The fresh weight was determined and a weighed subsample (~25% of total) was used for analysis. The subsample was oven dried to a constant dry weight at 60°C. The grain was separated from the straw and cleaned with a seed blower to remove chaff and residues before obtaining a final weight. In 2021, at both the RES and on-farm site, grain yield was obtained by collecting rice plants at physiological maturity using a small plot combine harvester. The combine harvested an area of 6 m^2 from each plot. For all site-years, the grain yield was adjusted and is presented at 14% moisture.

2.5 Data Analysis

The agronomic N use efficiency (ANUE) was calculated using the formula below.

$$\mathrm{ANUE} = \frac{\text{Yield from treatment } \left({}^{\mathrm{kg}}/_{\mathrm{ha}}\right) - \text{Yield from 0N control } \left({}^{\mathrm{kg}}/_{\mathrm{ha}}\right)}{\text{N rate } \left({}^{\mathrm{kg}}/_{\mathrm{ha}}\right)}$$

A two-way analysis of variance (ANOVA) was used to evaluate the effects of site-year, treatment, and their interaction on the grain yield and ANUE of rice. The ANOVA was initially performed using data from all site-years (i.e. RES-20, RES-21, on-farm-21) using a linear mixed effects model in R Studio (version 2022.02.2, R Core Team, 2020). The model designated site-year, treatment, and the interaction between site-year and treatment as fixed effects, with the interaction between block and site-year designated as a random effect. In this model, the treatments consisted of 19 independent categories (as presented in Table 4) with a single category consisting of a combination of one N source and one application time.

Due to a significant year by treatment interaction, data for yield and ANUE were subsequently analyzed separately by site-year. Linear mixed effects models designated treatment as a fixed effect and block as a random effect. Significant differences between the means of N treatments were analyzed based on Tukey's pairwise comparisons ($P<0.05$) using the emmeans and multcomp packages in R (Lenth, 2020; Hothorn et. al, 2008).

3. RESULTS AND DISCUSSION

3.1 General yields and response to N fertilizer

Rice grain yields averaged across all treatments receiving N fertilizer were 10,699; 9801; and 8696 kg ha^{-1} for RES-20, RES-21, and on-farm-21, respectively. Despite using a below-optimum N rate and even though some of the N treatments performed poorly, these yields are in-line with California statewide yields which averaged 9777 and 10,144 kg ha^{-1} in 2020 and 2021, respectively [(dataset) USDA NASS, 2020-2021]. The ANUE averaged 42, 29, and 21 kg kg^{-1} for RES-20, RES-21, and on-farm-21, respectively. Modern cereal production systems should achieve a target ANUE of 20-35 kg kg^{-1} (Dobermann, 2007) and at least one treatment in each location had an ANUE within this range, although overall the ANUE was lower at the on-farm-21 site.

Table 5. Analysis of variance P values for treatments measured by yield and ANUE as affected by site-year

Source	df	Grain Yield	df	ANUE
Site year	2	< 0.001	2	< 0.001
Treatment	18	< 0.001	17	< 0.001
Site year x Treatment	30	< 0.001	28	< 0.001

Grain yields without added N averaged 5054 kg ha^{-1} (range 4231 to 5564 kg ha^{-1}). At all locations there was a significant response to the application of N fertilizer; however, the response to N fertilizer and ANUE varied significantly between sites and there was a site by treatment interaction (Table 5); therefore, the results are analyzed and discussed separately. One reason for this interaction was that the response to the different N treatments at the RES-21 site was similar across all N treatments (i.e. no significant differences in yield or ANUE among applied N treatments). Importantly, in considering the yield response to applied N fertilizer, an N rate of 150 kg N/ha was used for all N treatments. This N rate is lower than the 180 to 220 kg N ha^{-1} typically used in CA (Yuan et al., 2021; Williams et al., 2010). A lower N rate was chosen for this study with the intent of being able to detect differences in N uptake based on grain yield. However, optimal N rates can vary from site to site and year to year (Rehman et al., 2022; Linquist et al., 2009). We hypothesize that the optimal N rate at the RES-2021 site was close to 150 kg N ha^{-1} (supported by other studies at this location in 2021); and thus, differences in N uptake between the different N treatments were not detected in yield and ANUE.

3.2 EENFs were no better than a single or split application of urea

The rationale behind using EENFs or splitting applications is that N is supplied when the crop demands it (IPNI, 2012). This is the first study that we are aware of that examines the potential of using EENFs specifically for water-seeded rice systems. In water-seeded systems (and other direct-seeded rice systems), crop demand is highest between 4 weeks (when rice begins to tiller) and 7 weeks (around panicle initiation) after planting (Linquist et al., 2009; Wilson et al. 1989). Therefore, it is critical that adequate N is available during this period.

The results indicate that all EENFs significantly increased yields relative to the zero-N control (Table 6). However, in no case did any of the EENF treatments have significantly higher yields or ANUE than urea applied as a single dose (at the same time as the EENF application) or when urea was applied as a split application. In fact, at the RES-20 and on-farm-21 sites, Agrocote 2-3 applied 1 day after flooding had significantly lower yields than the split applications of urea. Overall, applying urea as a split application resulted in some of the highest yields at each site, but this was not always significant.

A meta-analysis of EENFs in rice systems indicated that across studies, EENFs increased yields and N uptake by 5.7% and 8.0% respectively, compared to urea applied at the same time and rate (Linquist et al., 2013). It is not clear why there was no benefit to yields from the use of EENFs in this study, however, there are some possible reasons. First, Linquist et al. (2013) found little to no response to EENFs in soils with a pH less than 6.0, and the greatest response being in soils with a pH greater than 8.0. In this study, the soil pH was 5.3 at the RES and 6.4 on-farm (Table 1). Prior studies have shown that low pH soils (pH 4.9-7.6) degrade NBPT more rapidly (Engel et al. 2015, Hendrickson, 1993), whereas alkaline soils (pH >7.5) result in greater volatilization (Francis et al., 2008; Nelson et al., 1982) and nitrification losses (Norton, 2008). Generally, volatilization losses from California rice soils (most having a pH less than 6.3) are low, with less than 2% of applied N being lost (Chuong et al., 2020). That said, EENFs may have a limited effect given these soil properties. In water-seeded rice systems, average seasonal water temperatures after flooding or planting and until canopy development (about 35 -40 days after planting) are higher than air temperatures (Sharifi et al., 2018). Accordingly, it is possible that high floodwater temperatures may have degraded the EENFs and released N faster than intended, as shown for DCD, an ingredient in SuperU (Kelliher et al., 2008). When means were pooled across site-years, Agrocote 2-3 had significantly lower yields compared to all other treatments. Agrocote 2-3 is intended to release N two to three months after application, which may have resulted in low N availability earlier in the season when the crop is tillering. It is possible that the timing of N release occurred too late.

Split applications of urea resulted in higher yields and ANUE when compared to a single post-flood dose of urea or compared to the EENF treatments, although this was not always significant. This finding is consistent with other studies comparing single and split applications of urea in transplanted rice (Linquist et al., 2003). While we will discuss split applications later, our results indicate that if the application of N is required after the field has been flooded, the most efficient N use is achieved by applying the N in splits rather than applying in a single dose or using EENFs (Table 6).

Table 6. Comparisons of yield and ANUE between all EENF and urea treatments. The timing of fertilizer application occurred either one day after flooding, two weeks after flooding, or in split doses. Lowercase letters indicate the mean separation groupings for each treatment within each site-year. Within columns, values followed by the same letter are not significantly different according to Tukey's pairwise comparisons at $P < 0.05$. The last column includes the combined means of treatments across all 3 site-years.

Timing	Source	RES 2020		RES 2021		On-Farm 2021		Combined Means	
		Yield	ANUE	Yield	ANUE	Yield	ANUE	Yield	ANUE
		kg N ha^{-1}	kg kg^{-1}	kg N ha^{-1}	kg kg^{-1}	kg N ha^{-1}	kg kg^{-1}	kg N ha^{-1}	kg kg^{-1}
Control	0 N	4231 ^{a}		5365 ^{a}		5564 ^{a}		5093 ^{a}	
1 day after flooding	Urea	10515 ^{bc}	42 ^{ab}	9531 ^{b}	26 ^{a}	7934 ^{bc}	15^{ab}	9345 ^{c}	27 ^{ab}
	Agrocote 2-3	8862 ^{b}	30 ^{a}	8707 ^{b}	22 ^{a}	7543 ^{b}	13 ^{a}	8374 ^{b}	22 ^{a}
	Anvol	11392 ^{c}	47 ^{b}	9899 ^{b}	30 ^{a}	8368 ^{bc}	19 ^{ab}	9886 ^{cd}	32 ^{bc}
	Super U	10317 ^{bc}	40 ^{ab}	9848 ^{b}	30 ^{a}	7888 ^{b}	16 ^{a}	9351 ^{c}	28 ^{b}
2 weeks after flooding	Urea	10856 ^{c}	43 ^{ab}	10281 ^{b}	33 ^{a}	7896 ^{b}	16 ^{a}	9678 ^{cd}	31 ^{bc}
	Agrocote 1-2	11664 ^{c}	43 ^{ab}	9419 ^{b}	27 ^{a}	8162 ^{bc}	17 ^{ab}	9748 ^{cd}	29 ^{b}
	Anvol	10841 ^{c}	43 ^{ab}	9672 ^{b}	29 ^{a}	7879 ^{b}	15 ^{a}	9464 ^{c}	29 ^{b}
	Super U	10987 ^{c}	44 ^{b}	9667 ^{b}	29 ^{a}	7809 ^{b}	15 ^{a}	9487 ^{c}	29 ^{b}
Split	Urea	11571 ^{c}	48 ^{b}	10272 ^{b}	33 ^{a}	9409 ^{c}	26 ^{b}	10417 ^{d}	35 ^{c}

Note. ANUE, agronomic N use efficiency; AS, Ammonium sulfate; EENF, enhanced efficiency nitrogen fertilizer;

3.3 Preflood aqua-N and urea versus splitting urea

In 2021, treatments at both locations allowed for a comparison of pre-flood N applications (aqua-N and urea) with split applications of urea. For both the RES-21 and the on-farm-21 sites, there was no significant difference in yield or ANUE when comparing pre-flood aqua-N and pre-flood urea (Figure 1). This finding is similar to the results of Choung et al. (2020), where comparisons of aqua-N and pre-flood broadcasted urea showed no significant difference between grain yield, N uptake, and fertilizer recovery efficiency. Similarly, Adviento-Borbe et al. (2016) found no difference in grain yield between broadcasted granular urea and deep-banded urea (which behaves in a similar fashion to the injected aqua-N). Aqua-N is effective because it is injected deep (7-10 cm) into the soil where the N remains in a reduced soil layer, protected from nitrification/denitrification reactions and NH_3 volatilization losses if soils remain flooded (Linquist et al. 2009). For similar reasons, other studies have reported that deep placement of urea briquettes also increases N use efficiency (Mazid et al., 2016).

There are several reasons why pre-flood, broadcasted urea performed similarly to aqua-N in terms of yields and N use efficiency. First, when urea is broadcast onto the soil, the seedbed is dry and cloddy, allowing urea fertilizer granules to fall into crevices below the soil surface (Chuong et al., 2020). Consequently, a large portion of N lies below the soil surface, protected from nitrification, denitrification, and NH_3 volatilization losses after flooding (Norman et al., 2002; Chuong et al., 2020). Second, flooding the field after broadcasting N fertilizer facilitates the downward movement of urea (Broadbent et al., 1958). In dry-seeded rice systems, others have noted the importance of applying urea to dry soil before a permanent flood, as applications to wet saturated soils have resulted in increased N losses from nitrification, denitrification, or ammonia volatilization loss (Norman et al., 2009; Dillon e. al., 2012).

When comparing the split urea treatment to the single, pre-flood application of aqua-N or urea, we found no significant differences in yield or ANUE at either site (Figure 1). This implies that split urea applications can serve as an alternative to aqua-N or pre-flood urea. However, this is a more expensive option because it requires an airplane to apply the fertilizer and because urea is more costly than aqua-N.

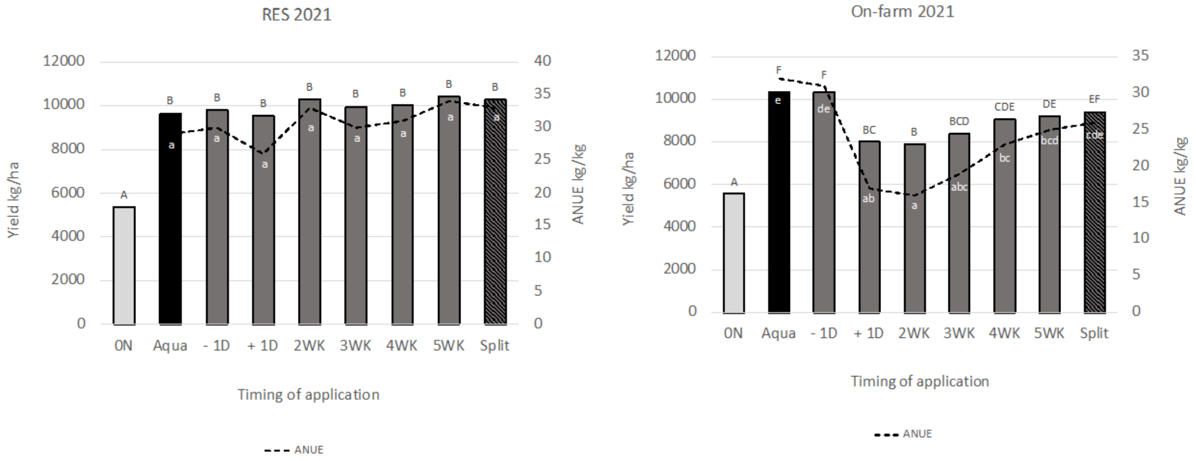

Figure 1. Yield and ANUE response to: (1) aqua-N applied one day before flood; (2) urea applied 1 day before flooding; (3) urea applied as a single dose either 1 day, 2 weeks, 3 weeks, 4 weeks, or 5 weeks after flooding; and (3) urea applied in split applications (20% of the total N rate applied at week 2; 30% at week 4; 30% at week 6; and 20% at week 8). See Table 4. Uppercase letters correspond to significant differences in yield means. Lowercase letters correspond to significant differences in ANUE means. Analysis conducted by using Tukey comparison ($p < 0.05$)

3.4 Fine-tuning split N applications

In this study, the N rate was applied in 4 splits with the first application occurring two weeks after flooding followed by subsequent applications every 2 weeks. Further research should focus on determining if the timing and amount of N in each split could be optimized. Such experiments have been done in transplanted rice, which found that increasing ANUE is possible when less N is allocated at the early vegetative phase (Peng et al., 2006). Given that N demand in water-seeded systems is low in the first four weeks (Linquist et al., 2009), broadcasting the first post-flood N application at two weeks may not be the most optimum timing.

Toward the goal of fine-tuning split N applications, five post-flood application times were examined for urea in 2021. The total N rate was applied as a single dose either 1 day after flooding or at two, three, four, or five weeks after flooding. All post-flood urea treatments resulted in significantly higher yields than the control (Figure 1). At the RES-21 site, application timing had no significant effect on yield or ANUE. As discussed previously, it is possible that the optimal N rate for this location was lower or close to the N rate used in this study, resulting in no yield responses when some N may have been lost. At the on-farm-21 site, applications of urea 1 day or 2 weeks after flooding produced significantly lower yields and ANUE compared to a later application occurring 5 weeks after flooding (Figure 1). Thus, when splitting the N rate, greater yields and ANUE may be achieved if the first split application occurs later (e.g. three or four weeks after flooding) or if the N ratio was higher for the split doses applied later in the season. This is in line with other studies (Stevens et al., 2001; Fageria et al., 1999) which have shown that broadcasting N into floodwater is most effective when the first N application is delayed until active tillering.

3.5 Urea versus ammonium sulfate

It is well documented that in rice systems, broadcasted urea is more prone to volatilization than broadcasted ammonium sulfate. This is because the hydrolysis of urea produces an alkaline environment surrounding the fertilizer granule, which can maintain or initiate ammonia volatilization (Chien et al., 2011; Mikkelsen, 1987; Keeney et al., 1986). Despite the great potential for loss, there was no significant difference between urea and ammonium sulfate at any location in terms of yield and ANUE when compared at each application time (Table 7). These findings agree with other studies comparing grain yield and ANUE of urea to ammonium sulfate in both transplanted (Craswell et. al, 1981), dry-seeded (Bufogle et al., 1998; Reddy et al., 1978) and water-seeded (Pittlekow et al., 2014) rice systems. Ammonium sulfate may have been expected to be a better source if sulfur was deficient. However, sulfur was not deficient in this study as it was added to all plots via potassium sulfate and zinc sulfate.

Table 7. Comparisons of yield and ANUE between all urea and ammonium sulfate treatments. The timing of fertilizer application occurred either one day before flooding, one day after flooding, two weeks after flooding, or in split doses. Within columns, values followed by the same letter are not significantly different according to Tukey's pairwise comparisons at $P < 0.05$.

Timing	Source	RES 2020		RES 2021		On-Farm 2021	
		Yield	ANUE	Yield	ANUE	Yield	ANUE
		kg N ha^{-1}	kg kg^{-1}	kg N ha^{-1}	kg kg^{-1}	kg N ha^{-1}	kg kg^{-1}
Control	0 N	4231^{a}		5364^{a}		5564^{a}	
1 day before flooding	Urea			9812^{b}	30^{a}	10336^{d}	31^{b}
	Ammonium Sulfate			10136^{b}	32^{a}	9925^{cd}	30^{b}
1 day after flooding	Urea	10414^{bc}	40^{ab}	9531^{b}	26^{a}	8027^{b}	17^{a}
	Ammonium Sulfate	9427^{b}	34^{a}	9628^{b}	28^{a}	8061^{b}	17^{a}
2 weeks after flooding	Urea	10856^{bc}	43^{ab}	10281^{b}	33^{a}	7896^{b}	16^{a}
	Ammonium Sulfate	10782^{bc}	43^{ab}	9767^{b}	30^{a}	8452^{b}	20^{a}
Split	Urea	11571^{c}	48^{b}	10272^{b}	33^{a}	9409^{c}	26^{b}
	Ammonium Sulfate	11184^{c}	46^{b}	9742^{b}	29^{a}	9738^{cd}	28^{b}

4. CONCLUSIONS

Our research evaluated different fertilizer N sources and application times in a 2-year field trial grown under a continuously flooded, water-seeded rice cropping system. To determine the most optimal N fertilizer practice, grain yield and ANUE were measured and used to make comparisons. Applying EENFs after flooding did not produce significantly higher yields or ANUE than urea applied in splits. Given that EENFs did no better and are more expensive, fertilizers such as urea and ammonium sulfate are a more economic option. The standard practice is to apply aqua-N to dry soil before the field is flooded for planting. Compared to aqua-N, urea applied in splits and urea applied to dry soil before flooding produced similar yields and ANUE. These results indicate that the current fertilizer-N practice remains the best option for water-seeded rice systems. If it’s not possible to apply fertilizer-N to dry soil before flooding, splitting the N rate is the next best option. Further research on fine-tuning the best N splits for these systems should be explored.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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