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Effects of Coal Combustion By-Product–Encapsulated Ammonium Nitrate on Wheat Yield and Uptake of Nitrogen and Metals

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A B S T R A C T

Ammonium nitrate (AN) is an essential plant nutrient for plant growth. Ammonium nitrate is also an ingredient in explosives. Research is being conducted on reducing the explosiveness of AN by encapsulating it with the use of coal by-products. The objective of this greenhouse pot study was to determine the effects of class C and F fly ash and flue gas desulfurization–gypsum–encapsulated AN on biomass, grain, and straw yield and nitrogen and metals uptake by wheat. Encapsulated AN was mixed with a low-nitrogen soil at 56 and 112 kg N ha^{-1}, as well as unencapsulated AN as a control, and planted with wheat (*Triticum aestivum* L.). The biomass yield was significantly higher than the other treatments for the high rate of class C fly ash–encapsulated AN treatment only. Grain yields were significantly higher for plants grown on the high rate of encapsulated AN treatments compared with treatments with low and high rates of unencapsulated AN. Coal by-product–encapsulated AN did not significantly affect nitrogen concentration in wheat biomass and grain compared with the unencapsulated AN treatments. In this pot study, encapsulated AN fertilizer was as effective as unencapsulated AN for wheat growth and grain yield, with no significant increase in tissue metal concentrations.

A R T I C L E I N F O

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Keywords: coal by-products; FGD-gypsum; fly ash; wheat; nitrogen; fertilizer

1. Introduction

1.1. Previous studies

Nitrogen (N) is an essential plant macronutrient. Ammonium nitrate (AN) supplied about 2.5% of the 14 Mt of N fertilizer used in the United States in 2002, and it is also an ingredient in explosives (Food and Agriculture Organization of the United Nations, 2002; Science Daily, 2007; IHS Chemical, 2011). As a result of the bombing of the Alfred P. Murrah Federal Building in downtown Oklahoma City in 1995, new regulations on the sale and shipping of AN have been introduced in the United States and Canada (WorkSafe, 2005; USA Today, 2011). There are concerns by U.S. farmers that a possible ban on AN would reduce the supply of a major N source used in agriculture. Research conducted by Taulbee et al. (2009) to reduce the explosive effects of AN has demonstrated that encapsulation of AN pellets with coal combustion by-products reduces its explosive effects.

1.2. Fly ash

Fly ash (FA) is a fine residue produced during the combustion of coal. Of the more than 67 Mt of FA produced in the United States in 2010, only about 4% was used in agriculture (American Coal Ash Association, 2010). Several studies have been conducted over the years on the use of FA in agriculture as a soil amendment to improve soil fertility and crop production (Sikka and Kansal, 1995; Codling and Wright, 1998; Wright et al., 1998). However, there are concerns that trace elements in coal are excessively concentrated in FA (Punshon et al., 2001). Codling and Wright (1998) observed

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Table 1
Characteristics of soil, ammonium nitrate, and coal by-product–encapsulated ammonium nitrate

Parameter	Soil	AN	AN+FAC	AN+FAF	AN+FGD
Soil texture	Sandy loam	N/A	N/A	N/A	N/A
pH	5.31	4.53	7.40	6.37	5.53
EC (mS/cm)	0.11	170	155	154	150
Ca (g kg^{-1})	0.50	<0.01	25.1	5.12	39.7
Al (g kg^{-1})	7.00	<0.01	12.0	5.76	0.015
As (mg kg^{-1})	3.49	<0.01	3.41	6.94	0.179
Cu (mg kg^{-1})	6.39	0.05	21.2	39.2	5.88
Cd (mg kg^{-1})	0.04	<0.01	0.09	0.09	<0.01
Fe (mg kg^{-1})	8820	<0.01	2620	14700	176
Mn (mg kg^{-1})	25.4	<0.01	16.8	30.6	2.33
Pb (mg kg^{-1})	11.2	<0.01	4.23	3.56	2.91
Zn (mg kg^{-1})	38.7	<0.01	18.6	25.2	7.17

Note: AN = ammonium nitrate; AN+FAC = ammonium nitrate + class C fly ash; AN+FAF = ammonium nitrate + class F fly ash; AN+FGD = ammonium nitrate + flue gas desulfurization gypsum; N/A = not applicable; EC = electrical conductivity; mS/cm = millisiemens per centimeter.

significant reduction in annual ryegrass yield, along with increased tissue As, Se, and Mo, when 80 g kg^{-1} FA was added to soil.

1.3. Flue gas desulfurization by-products

Flue gas desulfurization (FGD) by-product is produced by coal power plants when sulfur is removed from waste gases using CaO or $CaCO_3$ as an extractant (Electric Power Research Institute [EPRI], 2007; American Coal Ash Association, 2010). Depending on the conditions of the extraction, either calcium sulfate ($CaSO_4{\cdot}2H_2O$, or gypsum) or calcium sulfite hennebachite ($CaSO_3{\cdot}1/2H_2O$) are the primary by-products of this process (Miller, 1995; Punshon et al., 2001). In recent years, there has been increased interest in utilizing FGD by-products as a soil amendment (Kost et al., 2005). Some FGD by-products have been shown to be effective when used as a calcium and sulfur fertilizer and for the amelioration of acidic and sodic soils (Dick et al., 2006; EPRI, 2006, 2007). Shainberg et al. (1989) and Punshon et al. (2001) suggested that some FGD by-products could provide an alternative to the use of lime while others could be used as commercial gypsum.

Generally, FGD by-product does not contain large amounts of trace elements; however, when FGD by-product is stabilized with FA, the level of trace metals is increased. There are concerns of potential increases in As, B, Se, Mo, Pb, and Hg in the environment when FA-stabilized FGD by-product is used in agriculture (DeSutter and Cihacek, 2009). Codling and Wright (1998) observed increased concentrations of As, Se, and Mo in annual ryegrass when an FGD by-product was used, although yield was not affected. Another possible constraint on the agricultural use of some FGD by-products is that excess $CaCO_3$ or $Ca(OH)_2$ could increase soil pH. Punshon et al. (2001) observed an increase in soil pH from 5.5 to 8.1 when a $CaCO_3$ FGD by-product was used. Clark et al. (2001) stated that excess Ca from high-Ca FGD by-product could disturb the Mg, K, and P balance in soils and plants or displace Al from soil exchange sites and induce Al toxicity in plants. Punshon et al. (2001) concluded from a study conducted with an FGD-gypsum collected from a power plant in South Carolina that to reduce potential trace element toxicity, soil application of the FGD by-product should not exceed 2.5%.

Unlike FGD by-product that is fly ash stabilized, contains excess $CaCO_3$ or $Ca(OH)_2$, or both, FGD-gypsum by-product is produced using the wet scrubber method and therefore contains little or no excess $CaCO_3$ or $Ca(OH)_2$. With the exception of mercury (Hg), there is little or no trace element present in this material. Of the more than 130 million tons of coal combustion by-products produced in the United States in 2010, 22 million tons were FGD-gypsum (American Coal Ash Association, 2010). However, only about 2% of the FGD-gypsum produced in 2010 was used in agriculture (American Coal Ash Association, 2010), but there has been increased interest recently in increasing that amount.

1.4. Coal by-product–encapsulated AN

The encapsulation of AN with coal combustion by-products has proven effective in reducing the explosive effects of AN (Taulbee et al., 2009). Coal by-product–encapsulated AN could be an N source for farmers. However, potential metal uptake from soil fertilized with encapsulated AN has not been fully investigated. The objective of this study was to measure wheat biomass and grain yield and uptake of N and metals by wheat grown on soil fertilized with AN and coal by-product–encapsulated AN.

2. Methods

2.1. Soil analysis

The coal by-product–encapsulated AN used in this study was provided by Dr. Darrell Taulbee, University of Kentucky Center for

Table 2
Summary of statistical analysis of biomass, grain, and straw yields of wheat grown in soil fertilized with ammonium nitrate and coal by-product–encapsulated ammonium nitrate

		Biomass yield		Grain yield		Straw yield	
Source	DF	*F* value	*p* value	*F* value	*p* value	*F* value	*p* value
N source	3	4.77	0.014	3.90	0.028	3.65	0.035
Rate	1	3.17	0.094	25.1	0.0001	9.02	0.008
N source × rate	3	1.97	0.159	2.84	0.071	2.51	0.095

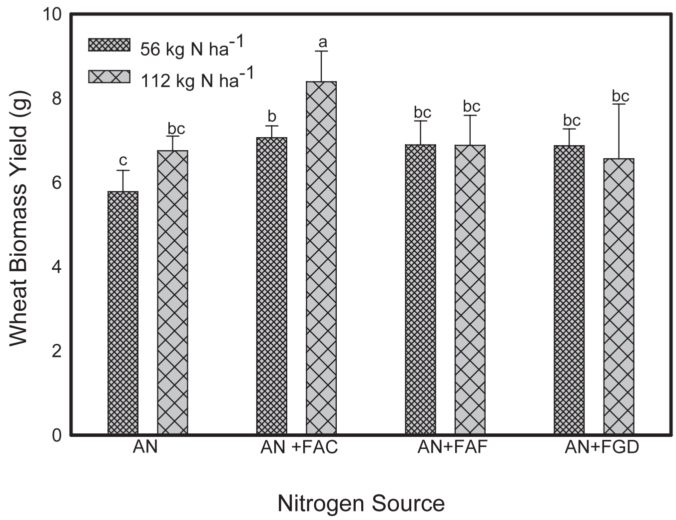

Fig. 1. Wheat biomass yield at boot stage as affected by fertilization with ammonium nitrate (AN) alone or encapsulated with coal combustion by-product of class C fly ash (AN+FAC), class F fly ash (AN+FAF), and flue gas desulfurization gypsum (AN+FGD). Error bars denote 1 SD of the mean. Columns having the same letter are not significantly different at the $p < 0.05$ level.

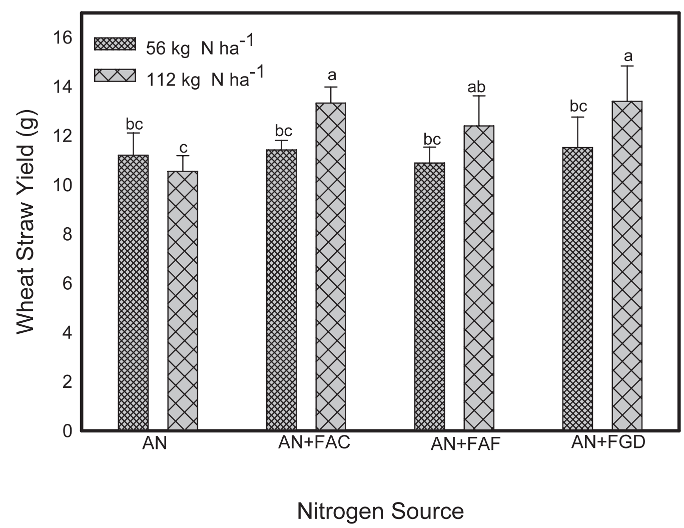

Fig. 3. Wheat straw yield as affected by fertilization with ammonium nitrate (AN) alone or encapsulated with coal combustion by-product of class C fly ash (AN+ FAC), class F fly ash (AN+FAF), and flue gas desulfurization gypsum (AN+FGD). Error bars denote 1 SD of the mean. Columns having the same letter are not significantly different at the $p < 0.05$ level.

Applied Energy Research. AN, which is 33% N, was encapsulated with class C or class F fly ash or with FGD-gypsum using a rolling drum with water as a binder. The AN prills were coated with either 21.1% class C fly ash, 22.7% class F fly ash, or 20% FGD-gypsum. The resulting material contained 18%, 22%, or 19% N for class C fly ash, class F fly ash, and FGD-gypsum, respectively. The soil was a Rumford loamy sand (coarse-loamy, siliceous, mesic Typic hapludult) collected from the U.S. Department of Agriculture–Agricultural Research Service farm in Beltsville, MD. Soil was air dried and stored in a plastic trash can until use. Soil texture was determined by the hydrometer method (Gee and Bauder, 1986). Soil and fertilizer pH were determined in a 1:1 soil deionized water slurry after 1 hour of equilibration using a combined electrode. Electrical conductivity was determined in a 1:2 soil:deionized water suspension after 1 hour using an Orion conductivity meter (Boston, MA). Total N was determined by combustion using an Elementar carbon, nitrogen, and sulfur analyzer (Mt. Laurel, NJ). Total nutrients and metals were extracted from soil and coal by-product–encapsulated AN using aqua regia digestion (McGrath and Cunliffe, 1985). Nutrient and metal concentrations in the extracted solution were determined using inductively coupled plasma optical emission spectrophotometry (ICP-OES). At each harvest, a soil sample was taken from each pot for measurement of pH and of exchangeable ammonium and nitrate as outlined by Mulvaney (1996).

2.2. Experimental procedure

The experimental design was a randomized complete block with 1 soil × 4 N sources × 2 fertilizer rates (56 and 112 kg ha^{-1}) × 3

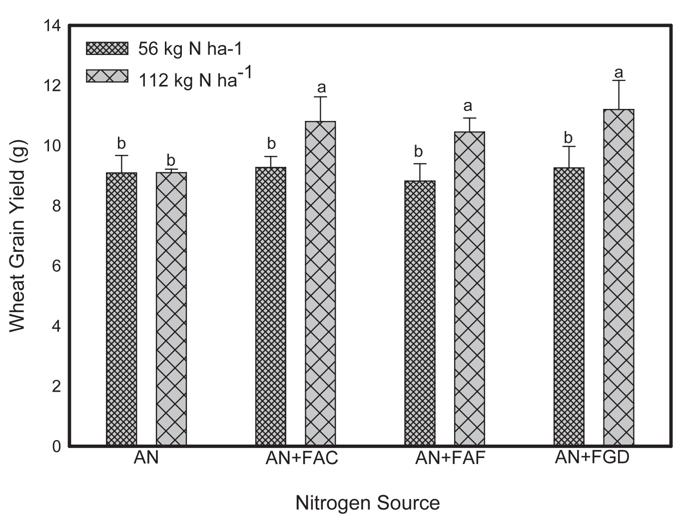

Fig. 2. Wheat grain yield as affected by fertilization with ammonium nitrate (AN) alone or encapsulated with coal combustion by-product of class C fly ash (AN+FAC), class F fly ash (AN+FAF), and flue gas desulfurization gypsum (AN+FGD). Error bars denote 1 SD of the mean. Columns having the same letter are not significantly different at the $p < 0.05$ level.

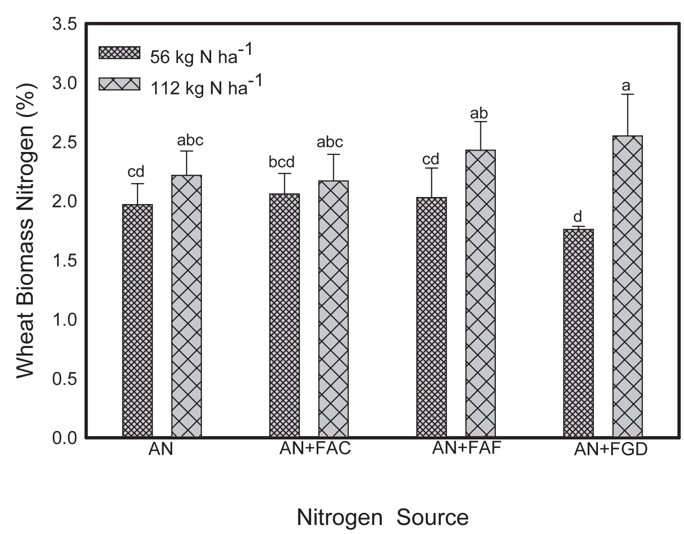

Fig. 4. Wheat biomass nitrogen concentration at boot stage as affected by fertilization with ammonium nitrate (AN) alone or encapsulated with coal combustion by-product of class C fly ash (AN+FAC), class F fly ash (AN+ FAF), and flue gas desulfurization gypsum (AN+FGD). Error bars denote 1 SD of the mean. Columns having the same letter are not significantly different at the $p < 0.05$ level.

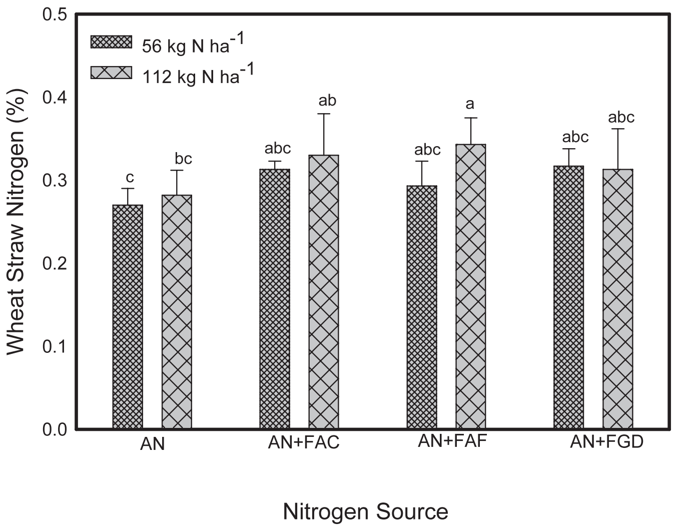

Fig. 5. Wheat straw nitrogen concentration as affected by fertilization with ammonium nitrate (AN) alone or encapsulated with coal combustion by-product of class C fly ash (AN+FAC), class F fly ash (AN+FAF), and flue gas desulfurization gypsum (AN+FGD). Error bars denote 1 SD of the mean. Columns having the same letter are not significantly different at the $p < 0.05$ level.

replications. The N sources were reagent-grade AN and AN encapsulated with class C fly ash (FAC), class F fly ash (FAF), and flue gas desulfurization gypsum (FGD-gypsum). Soil pH was adjusted to near pH 7.0 with calcium and magnesium carbonate. After pH incubation, 2 kg of soil was mixed with an N source, placed into a 15-cm-diameter × 15-cm-high plastic pot, and incubated moist (near field capacity) for 4 weeks. Eight seeds of 'Grandin' hard red spring wheat (*Triticum aestivum* L.) were planted in each pot. The pots were placed in a growth chamber with environmental conditions as follows: day length, 16 hours; day temperature, 24 ± 1°C; night temperature, 19 ± 1°C. Pots were placed in a plastic saucer to collect any leachate, which was returned to each pot after watering. After germination, plants were thinned to four plants per pot and fertilized with 56 kg P ha^{-1} as KH_2PO_4, 60 kg Mg ha^{-1} as $MgSO_4$, and an additional 67 kg K ha^{-1} as KCl. One half of the experiment was harvested at the boot stage, and the other half was harvested for grain and straw. Plant tissue and grain were dried at 65°C for 72 hours, after which samples were ground using a Wiley mill. Total N in plant tissue was determined using an Elementar C, N, and S analyzer. Other elements in plant tissue were determined as outlined by Codling et al. (2002).

Analysis of variance was used to determine statistical significance of differences between treatments (SAS Institute, 2008). Separation of means was performed using Duncan's multiple range test at $p \leq 0.05$ (Steel and Torrie, 1980).

3. Results and Discussion

3.1. Characteristics of soil and by-products

Characteristics of soil and fertilizer amendments are presented in Table 1. The pH of FA-encapsulated AN was higher than those of either the soil or the other fertilizer amendments as a result of the presence of highly alkaline Ca oxide in FA. Electrical conductivity of encapsulated AN was lower than that of the unencapsulated AN control. Ca concentration was highest in the FGD-gypsum–encapsulated AN, a result of the use of a $CaCO_3$-based material for extracting sulfur during the combustion process (American Coal Ash Association, 2008; Punshon et al., 2001). The FGD-gypsum–encapsulated AN had lower trace metal concentrations compared with the fly ash because FGD-gypsum is a product of gases plus extractant, whereas fly ash consists of particulates on which trace metals can accumulate during the combustion process (Miller, 1995).

3.2. Yield of wheat biomass, grain, and straw

Biomass yield at the boot stage was significantly affected by N source but not by rate or the rate × source interaction (Table 2). At the boot stage, biomass yield was elevated in wheat grown in soil fertilized with the AN+FAC treatment, compared with the unencapsulated AN control, whereas biomass yield in wheat grown in soil fertilized with the AN+FAF and AN+FGD treatments did not differ significantly from the unencapsulated AN control (Figure 1). Wheat grain and straw yields were significantly affected by N source and rate but not their interaction (Table 2). Grain and straw yields of wheat grown in soil fertilized with the low rate of coal by-product–encapsulated AN were not significantly different from those of the unencapsulated AN control (Figures 2 and 3). With the exception of wheat straw grown in soil fertilized with the high rate of AN+FAF, grain and straw yields increased significantly when the coal by-product–encapsulated AN rate was increased from 56 to 112 kg N ha^{-1}. A possible reason for the increased grain and straw yield at the high rate of the coal by-product–encapsulated AN application might have been the presence of macro and micro plant nutrients in the coal combustion by-products used for encapsulation (Table 1).

Table 3
Arsenic (As), calcium (Ca), copper (Cu), manganese (Mn), and zinc (Zn) concentrations in biomass of wheat grown in soil fertilized with ammonium nitrate and coal by-product–encapsulated ammonium nitrate

N source	Rate (kg ha^{-1})	As (μg kg^{-1})	Ca (g kg^{-1})	Cu (mg kg^{-1})	Mn (mg kg^{-1})	Zn (mg kg^{-1})
AN	56	145 ab[1]	2.86 cd	3.97 ab	6.63	20.4 a
AN	112	161 ab	3.02 cd	3.34 ab	6.53	11.4 b
AN+FAC	56	138 b	2.60 d	2.85 b	6.76	10.3 b
AN+FAC	112	148 ab	3.20 bc	3.24 ab	6.97	11.3 b
AN+FAF	56	126 b	2.83 cd	3.07 ab	6.27	10.4 b
AN+FAF	112	161 ab	3.63 ab	3.67 ab	6.84	13.1 ab
AN+FGD	56	144 ab	2.79 bc	2.9 b	7.96	10.3 b
AN+FGD	112	183 a	3.95 a	4.15 a	6.54	13.5 ab

Note: AN = ammonium nitrate; AN+FAC = ammonium nitrate + class C fly ash; AN+FAF = ammonium nitrate + class F fly ash; AN+FGD = ammonium nitrate + flue gas desulfurization gypsum.
[1] Means within columns with the same letters are not significantly different at the $p < 0.05$ level.

Table 4
Arsenic (As), calcium (Ca), copper (Cu), manganese (Mn), and zinc (Zn) concentrations in grain of wheat grown in soil fertilized with ammonium nitrate and coal by-product–encapsulated ammonium nitrate

N source	Rate (kg ha^{-1})	As (μg kg^{-1})	Ca (mg kg^{-1})	Cu (mg kg^{-1})	Mn (mg kg^{-1})	Zn (mg kg^{-1})
AN	56	34.4	304	2.79	12.2	16.8
AN	112	56.2	318	2.85	17.9	17.8
AN+FAC	56	47.8	328	2.75	17.4	16.4
AN+FAC	112	23.1	323	2.84	6.40	16.9
AN+FAF	56	39.4	307	2.96	16.0	18.6
AN+FAF	112	23.4	312	2.96	8.93	17.9
AN+FGD	56	64.5	322	2.76	20.3	17.2
AN+FGD	112	22.5	329	2.98	7.69	16.3

Note: AN = ammonium nitrate; AN+FAC = ammonium nitrate + class C fly ash; AN+FAF = ammonium nitrate + class F fly ash; AN+FGD = ammonium nitrate + flue gas desulfurization gypsum.

3.3. N in wheat biomass, grain, and straw

Biomass N concentration was not significantly different for wheat grown in soil fertilized with the coal by-product–encapsulated AN compared with that grown in soil fertilized with the unencapsulated AN control. Biomass N concentration at the boot stage increased slightly with increased N application rate (Figure 4); however, only for wheat grown in soil fertilized with the AN+FAF and AN+FGD treatments were the differences significant. Biomass N concentration increased from 2.03% to 2.43% and from 1.76% to 2.55% when the N application rate was increased from 56 to 112 kg N ha^{-1} for the AN+FAF and AN+FGD treatments, respectively. In most cases, N concentration in wheat biomass at the boot stage was within the range (2.0–3.0%) considered to be sufficient for wheat at that stage of growth (Mills and Jones, 1996). However, N levels in this study were near the low end of the sufficient range, possibly because the plants were grown in pots in which the roots were restricted compared with those grown in the field. Grain N concentration was not significantly different for wheat grown in soil fertilized with the unencapsulated AN control compared with that grown in soil fertilized with coal by-product–encapsulated AN (data not shown). In all cases, grain N concentration was within the range (1.2–4.0%) reported by Kemanian et al. (2007) for wheat grain. Straw N concentration was slightly higher for plants grown in the soil fertilized with encapsulated AN compared with the unencapsulated AN control, but only for the high rate of the AN+FAF treatment was the difference significant (Figure 5). Straw N concentration was within the 0.2–1.3% reported by Kemanian et al. (2007) for wheat straw. As expected, regardless of the N source, N concentration in wheat tissue was highest in plants harvested at the boot stage of growth, with the levels in grain and straw progressively lower.

3.4. Concentrations of As, Ca, Cu, Mn, and Zn in wheat biomass, grain, and straw

3.4.1. Wheat biomass at the boot stage

At the boot stage of growth, biomass As concentration in wheat grown in soil fertilized with the encapsulated AN and the unencapsulated AN control was similar (Table 3). There was a slight increase in As concentration at the higher application rate for all N source treatments, but the differences were not significant. Concentrations of As in this study were much lower than those observed by Codling and Ritchie (2005) when Eastern gamagrass was grown on high-As orchard soils. Only for wheat grown in soil fertilized with the high rate of AN+FAF and AN+FGD was the biomass Ca concentration significantly different from that of the unencapsulated AN control (Table 3). Even though Ca concentration in the AN+FGD fertilizer was seven times higher than that of the AN+FAF fertilizer, there was no significant difference in tissue Ca concentration between the two treatments, indicating that there was enough Ca available in the soil for crop uptake (Table 1). Clark et al. (2001) also observed no excessive accumulation of Ca in maize leaf tissue when grown in soil fertilized with FGD-gypsum. In all cases, Ca concentration was within the range of 2.5–5.0 g kg^{-1}, which is considered sufficient for wheat at the boot stage

Table 5
Arsenic (As), calcium (Ca), copper (Cu), manganese (Mn), and zinc (Zn) concentrations in straw of wheat grown in soil fertilized with ammonium nitrate and coal by-product–encapsulated ammonium nitrate

N source	Rate (kg ha^{-1})	As (μg kg^{-1})	Ca (g kg^{-1})	Cu (mg kg^{-1})	Mn (mg kg^{-1})	Zn (mg kg^{-1})
AN	56	170	2.16 b[1]	1.27 ab	4.71	2.74 ab
AN	112	256	2.63 a	1.37 a	7.32	2.80 ab
AN+FAC	56	233	2.30 ab	1.19 ab	6.78	2.89 ab
AN+FAC	112	175	2.27 ab	1.33 ab	3.05	3.47 a
AN+FAF	56	224	2.48 ab	1.15 b	5.89	2.67 b
AN+FAF	112	219	2.57 ab	1.33 ab	2.89	2.98 ab
AN+FGD	56	294	2.28 ab	1.21 ab	4.32	2.76 ab
AN+FGD	112	174	2.30 ab	1.25 ab	5.68	2.55 b

Note: AN = ammonium nitrate; AN+FAC = ammonium nitrate + class C fly ash; AN+FAF = ammonium nitrate + class F fly ash; AN+FGD = ammonium nitrate + flue gas desulfurization gypsum.
[1] Means within columns with the same letters are not significantly different at the $p < 0.05$ level.

Table 6
KCl-extractable nitrate (NO_3^-) and ammonium (NH_4^+) in soil fertilized with ammonium nitrate and coal by-product–encapsulated ammonium nitrate after wheat harvest at two growth stages

		After boot stage		After grain	
N source	Rate (kg ha^{-1})	NO^- (mg kg^{-1})	NH_4^- (mg kg^{-1})	NO_3^- (mg kg^{-1})	NH_4^+ (mg kg^{-1})
AN	56	8.13	3.80 ab[1]	4.67	12.1
AN	112	9.00	3.37 ab	4.67	13.3
AN+FAC	56	7.37	3.27 b	4.83	11.9
AN+FAC	112	7.57	3.63 ab	5.83	13.4
AN+FAF	56	8.07	3.73 ab	4.37	12.9
AN+FAF	112	8.03	4.17 a	6.10	13.8
AN+FGD	56	8.07	3.80 ab	5.93	12.8
AN+FGD	112	8.03	3.12 b	4.97	13.5

Note: AN = ammonium nitrate; AN+FAC = ammonium nitrate + class C fly ash; AN+FAF = ammonium nitrate + class F fly ash; AN+FGD = ammonium nitrate + flue gas desulfurization gypsum.
[1] Means within columns with the same letters are not significantly different at the $p < 0.05$ level.

of growth (Mills and Jones, 1996). Biomass Cu and Mn concentrations were not significantly affected when soil was fertilized with encapsulated AN at either rate compared with the unencapsulated AN control (Table 3). At the low rate of N application, biomass Zn concentration was significantly lower in wheat grown in soil fertilized with the encapsulated AN treatments, compared with the unencapsulated AN control, but there was no such difference at the high rate of N application. In all cases, Cu, Mn, and Zn concentrations were below the ranges of 5–25, 25–100, and 15–70 mg kg^{-1}, respectively, which are considered sufficient for wheat at the boot stage (Mills and Jones, 1996). The low levels of wheat tissue Cu, Mn, and Zn observed may have resulted from high soil pH, which was greater than 7.5 for all treatments after the biomass harvest. Mills and Jones (1996) reported that Cu, Zn, and Mn in plant tissue can be reduced when grown in soil with pH greater than 7.5.

3.4.2. Wheat grain and straw

Concentrations of As, Ca, Cu, Mn, and Zn in wheat grain grown in soil fertilized with encapsulated AN were not significantly different from those of the unencapsulated AN control (Table 4). There was also no significant change in the concentrations of these elements when N rates were increased, although there was a decreasing trend in grain As and Mn with increased application rate of the encapsulated AN treatments. Grain As concentration ranged from 22.5 to 64.5 μg kg^{-1}, which was less than the 41–101 μg kg^{-1} observed by Zhao et al. (2010) for wheat grain grown in soils with high As. Calcium and metal concentrations in the straw of wheat grown in soil fertilized with encapsulated AN were not significantly different from those of the unencapsulated AN control (Table 5). However, there was a slight reduction in Mn concentration with increased AN+FAC and AN+FAF treatment.

3.5. Soil-extractable nitrate and ammonium

Concentrations of soil-extractable nitrate and ammonium were not significantly affected by N source or rate after either the boot-stage or the grain-stage harvests (Table 6). In general, extractable nitrate was slightly higher in the soil after the boot-stage harvest compared with after grain harvest. Uptake of nitrate by the crop during grain development after the boot stage of growth may have been the reason for the lower extractable nitrate after grain harvest. In contrast, the concentration of soil-extractable ammonium was four times higher in the soil at grain harvest compared with the soil that was extracted after harvesting the wheat at the boot stage. However, there were no significant differences in soil-extractable ammonium concentrations between the N source or application rates.

4. Conclusions

In this pot study, biomass, grain, and straw yields for wheat plants fertilized with three types of coal by-product–encapsulated AN were greater than or equal to those of wheat grown in soil fertilized with unencapsulated AN control. Similarly, N concentrations of biomass and grain of wheat grown in soil fertilized with coal by-product–encapsulated AN were greater than or equal to those of the unencapsulated AN control. Concentrations of As, Cu, Mn, and Zn in tissue of wheat grown in soil fertilized with coal by-product–encapsulated AN were less than or equal to those of the unencapsulated AN control. Metal concentrations in tissue and grain of wheat grown in soil fertilized with coal by-product–encapsulated AN were at levels that would not be considered harmful to human or animals when consumed.

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