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Increased maize yield using slow-release attapulgite-coated fertilizers

Yu Guan · Chao Song · Yantai Gan · Feng-Min Li

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Abstract Slow-release fertilizers could improve the productivity of field crops and reduce environmental pollution. So far, no slow-release fertilizers are suited for maize cultivation in semiarid areas of China. Therefore, we tested attapulgite-coated fertilizers. Attapulgite-coated fertilizers were prepared by dividing chemical fertilizers into three parts according to the nutrient demand of maize in its three main growth stages and coating each part with a layer of attapulgite. This design is novel and unique, satisfying the demands of maize throughout the whole growing season with slow release of nutrients from the coated layers. A field experiment was conducted in 2010 and 2011, using three fertilizer rates, in kg/ha: 94.22 nitrogen (N) and 22.49 phosphorus (P), 139.09 N and 38.98 P, and 254.23 N and 50.98 P. Five types of fertilizers were compared: 20 and 30 % attapulgite-coated chemical fertilizer, 20 and 30 % attapulgite-mixed chemical fertilizer, and chemical fertilizer only. The results show that the soil mineral N and available P of attapulgite-coated fertilizer has a slow-release behavior that allows a better synchronization between nutrient availability and plant needs. Attapulgite-coated fertilizer increased the grain yield by 15.1–18.4 %. The use of attapulgite-coated fertilizers also improved partial factor productivity of N fertilizer by 10.0–26.7 % and P fertilizer by 11.0–26.7 %, compared with the control fertilized without coated formulas. Given their good performance, the attapulgite-coated fertilizers could be a promising alternative slow-release fertilizer for sustainable agriculture in semiarid areas.

Keywords Attapulgite · Fertilizer use efficiency · Maize · Rain-fed cropland · Slow-release fertilizer

1 Introduction

Global food demand is expected to double by 2050 (Tilman et al. 2002); this is mainly driven by the world's wealthy human population and the increased needs for feed, fiber and biofuel. To produce sufficient quantity of grain to meet this demand, the production of grain crops must increase by a staggering 140 % or more according to FAO estimates (Bruinsma 2009). A substantial increase of crop yields in developing countries will play a critical role in reducing the pressure of the global grain demand (Godfray et al. 2010) and securing food for the world (Chen et al. 2011). The second largest economy in the world, China, has been taking some drastic steps to increase grain production to feed its 1.3 billion people and satisfy various industrial needs while minimizing negative impacts of agricultural activities on the environment. During 2003–2011, the country increased its cereal production by about 30 %, more than double the world average (FAO 2012). In the next two to three decades, 30–50 % more food will be needed to meet China's projected demand (Zhang et al. 2011).

Fertilizers are the major input in production of grain crops, but in many cases, the amounts of fertilizers applied to crops exceed the requirements of crop growth. Excessive use of N fertilizers leads to losses through leaching, volatilization, and denitrification. The majority of soils in China's semiarid rain-fed agricultural areas are alkaline and calcareous (Zhang et al. 2006). When N fertilizers are applied to calcareous soils, there is inevitable ammonia volatilization, with N_2O produced in the nitrification–denitrification processes contributing to global climate change. However, in irrigated areas, N fertilizers, when converted into nitrate or ammonium, often move below the root zone and cannot be absorbed by crop roots (Miao et al. 2010). Moreover, calcareous soils have a strong ability to

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fix P, and phosphate fertilizer can be converted into forms (such as Ca8-P formula) difficult for plants to absorb and use, resulting in high total P (TP) but low available P for crop uptake (Samadi and Gilkes 1999).

Fertilizer use in agriculture can be reduced or fertilizer use efficiency increased. Slow-release fertilizers have been largely used to improve fertilizer use efficiency, reduce fertilizer input, and improve crop yield and quality (Shoji et al. 2001). The slow release of the nutrient components contained in the fertilizer is made possible by coating the fertilizer with various coating material such as sulfur, polyethylene, polyvinyl chloride, latex, oil, and other synthetic substances (Yan et al. 2008).

The first coated slow-release fertilizer was sulfur-coated urea, but its rapid release of N made it difficult to synchronize with the needs of plants (Zvomuya et al. 2003). Sulfur-coated urea applied at the pre-planting stage often produces crop yields equal to that for treatments receiving split applications of soluble N (Guertal 2000). To improve the efficiency of slow-release fertilizer, researchers have improved the coating materials and invented polymer-coated slow-release fertilizers. The nutrient release rate of polymer-coated fertilizers better matches the nutrient demands of crop plants, and thus significantly improves fertilizer use efficiency and crop yields (Nelson et al. 2009). However, polymer-coated slow-release fertilizers have a complicated manufactory process with a higher price (Yan et al. 2008). In addition, when applied to crops, some undesired residues of synthetic material are left in the fields and are difficult to decompose (Ni et al. 2012). In China, the application of slow-release fertilizers has not been regulated, with one kind of fertilizer being used in different locations and on different crops without taking account of differences in climate and soil type. The application of slow-release fertilizers is still at an early stage and the efficiency of use is often low (Yan et al. 2008).

The clay attapulgite, also known as palygorskite, is a natural nonmetal clay mineral (Fig. 1). It has a fibrous reticular structure with many nanoscale channels giving it unique physical and chemical properties, such as a large specific surface area, adsorption, suspension, slow releasing, dispersion, ion-exchanging, water adsorption and retention, and low specific gravity ($2.0\text{--}2.3\text{ g cm}^{-3}$). Attapulgite is sticky and plastic when wet and when drying shows little shrinkage (Murray 2000; Ye et al. 2013). Attapulgite contains a small amount of elements including Si, Al, Mg, Fe, K, Ca, and Mn and so is expected to be a source of many microelements (Xie et al. 2010). Studies have shown that attapulgite combined with compound fertilizer increases crop yields (Yang et al. 2010). Attapulgite has rich reserves, low price, and is environmentally friendly and so is believed to be the most feasible coating material for slow-release compound fertilizers.

The use of coated, compound fertilizers in accordance with the nutrient demands of crop plants at different growth stages can ensure the crop has sufficient amounts of nutrients throughout its whole growth stage. This would greatly

Fig. 1 The attapulgite powder used in the preparation of attapulgite-coated fertilizers (ACF) for maize

improve crop yield, reduce the waste of fertilizers, and lower production costs.

Maize (*Zea mays* L.) is a crop requiring a large amount of fertilizer to meet the needs of plant growth. In the present study, we prepared attapulgite-coated fertilizers (ACF) by dividing chemical fertilizers into three applications according to the nutrient demands of maize plants in different growth stages, with each part of the fertilizer coated with a layer of attapulgite. Our objective was to determine (1) whether the ACF had a slow-release effect and (2) its impact on crop yield and fertilizer use efficiency in maize. We hypothesized that ACF would significantly improve maize production because their slow release would meet the nutrient demand of maize during the whole growing period.

2 Materials and methods

2.1 Description of the study site

The experiment was conducted from March 2010 to October 2011 at the Semiarid Ecosystem Research Station of the Loess Plateau ($36^{\circ}02' \text{ N}$, $104^{\circ}25' \text{ E}$, 2,400 m above sea level) of Lanzhou University, China. Annual average precipitation is 320 mm, with 56 % of the precipitation occurring during July–September, and annual average free-water evaporation is 1,300 mm. The area has a medium temperate semiarid climate with an annual average temperature of 6° C . The soil is Heima soil (Calcic Kastanozem, FAO Taxonomy) with an average soil bulk density of 1.27 g cm^{-3} in the 0- to 200-cm layer and pH 8.5. No water resources are available for irrigation in this area, so precipitation is the major water resource for agriculture (Zhou et al. 2012). Annual precipitation was 308.7 mm in 2010 and 291.3 mm in 2011, close to the long-term average (Fig. 2).

2.2 Attapulgit-coated fertilizers

ACF were composed of spherical particles with three layers of fertilizers (i.e., inner, middle, and outer) and three respective layers of coating attapulgit (Table 1). The allocation rates of fertilizers in each of the three layers were based on the research results of Cui (2007), as follows: maize usually takes up 2.5 % of total N (TN) and 1.12 % of available P during the seedling stage (0–45 days after planting) from fertilizers; correspondingly 51.15 and 63.81 % in the main growth period (45–75 days after planting), and 46.35 and 35.07 % in the maturity stage (75–155 days after planting). The inner layer was the fertilizer expected to be released in the maturity stage of maize, the middle layer was that expected to be released in the main growth period, and the outer layer was that expected to be released in the seedling stage. The layer outside each fertilizer layer was attapulgit coating. For the coating ratios, 20 % attapulgit coating indicated a weight ratio of attapulgit:fertilizer of 20:80 and 30 % attapulgit coating indicated a corresponding ratio of 30:70.

ACF were prepared by pan granulation. Chemical fertilizer powder (below 110 mesh) of the inner layer was placed in a granulator and sprinkled with distilled water. When granules were formed, attapulgit powder (below 250 mesh) was added as a coating, then chemical fertilizer powder of the middle layer was added to adhere to the inner layer and was coated with attapulgit powder. Finally, chemical fertilizer powder for the outer layer was added to adhere to the middle layer and was coated with attapulgit powder. Granules of 3–6 mm in diameter were screened as ACF.

2.3 Experimental design

In each of the two growing seasons (2010 and 2011), three rates of fertilizers (low, medium and high) and five types of differently coated fertilizers were arranged in a factorial, randomized completed block design with three replicates. The low, medium and high fertilizer rates (all kg ha^{-1} —94.22 N and 22.49 P; 139.09 N and 38.98 P; and 254.23 N and 50.98 P, respectively) were determined according to conventional practice in the region. The five types of coated fertilizers were as follows (Table 1): (1) urea and superphosphate only, without attapulgit as the control (CK), (2) urea and superphosphate mixed with 20 % attapulgit (A20MF), (3) urea and superphosphate mixed with 30 % attapulgit (A30MF), (4) urea and superphosphate coated with 20 % of attapulgit (A20CF), and (5) urea and superphosphate coated with 30 % of attapulgit (A30CF) (Table 1).

According to the results in 2010, the A20CF treatments were deleted and A30MF added in 2011—thus there were twelve treatments in 2010 and nine in 2011. The experiment each year was conducted in a different field, but on soils with similar properties. Plot size was 3.6 m×5 m in 2010 and 5.5 m×4 m in 2011.

The pre-weighed fertilizers were applied to the top 20 cm of soils by rotary tillage after thawing in mid-March. Double ridges and furrows mulched with plastic film were applied in the maize planting at a seeding density of 37,500 plants ha^{-1} . Each year, maize was planted in late April with a planting depth of 2 cm and harvested in the beginning of October.

Fig. 2 Distribution of monthly rainfall (millimeters) at the experimental site during 2010 and 2011 and average rainfall for the past 30 years at the site

Table 1 Treatment structure and the detailed amounts of the inputs of N, P, and attapulgite in the slow-release fertilizers applied to maize crops in 2010 and 2011

Fertilizer rate	Fertilizer type	N input (kg ha ⁻¹)	P input (kg ha ⁻¹)	Attapulgite input (kg ha ⁻¹)
Low	CK	94.2	22.6	–
	A20MF	94.2	22.6	29.2
	A30MF	94.2	22.6	50.0
	A20CF Total	94.2	22.6	29.2
	Inner layer	43.8	7.9	12.9
	Middle layer	48.3	14.4	15.7
	Outer layer	2.1	0.3	0.6
	A30CF Total	94.2	22.6	50.0
	Inner layer	43.8	7.9	22.1
	Middle layer	48.3	14.4	26.9
	Outer layer	2.1	0.3	1.0
Medium	CK	139.0	39.0	–
	A20MF	139.0	39.0	44.5
	A30MF	139.0	39.0	76.3
	A20CF Total	139.0	39.0	44.5
	Inner layer	64.6	13.7	19.6
	Middle layer	71.3	24.9	24.1
	Outer layer	3.1	0.4	0.9
	A30CF Total	139.0	39.0	76.3
	Inner layer	64.6	13.7	33.6
	Middle layer	71.3	24.9	41.2
	Outer layer	3.1	0.4	1.5
High	CK	254.2	51.0	–
	A20MF	254.2	51.0	76.3
	A30MF	254.2	51.0	130.8
	A20CF Total	254.2	51.0	76.3
	Inner layer	118.1	17.9	34.0
	Middle layer	130.4	32.5	40.7
	Outer layer	5.7	0.6	1.6
	A30CF Total	254.2	51.0	130.8
	Inner layer	118.1	17.9	58.3
	Middle layer	130.4	32.5	69.8
	Outer layer	5.7	0.6	2.7

Low fertilizer rate denotes (all kilogrammes per hectare) 94.22 N and 22.49 P; medium denotes 139.09 N and 38.98 P; and high denotes 254.23 N and 50.98 P

CK chemical fertilizer without attapulgite, A20CF chemical fertilizer coating with 20 % attapulgite, A30CF chemical fertilizer coating with 30 % attapulgite, A20MF chemical fertilizer mixing with 20 % attapulgite, A30MF chemical fertilizer mixing with 30 % attapulgite

2.4 Sampling and measurements

Ten maize plants were harvested randomly in the middle of every plot. Then, plant height, stem diameter, ear length and diameter, grain number per ear, and 100-kernel weight were

measured. All vegetable samples were oven-dried at 105 °C for 1 h and then at 70 °C to a constant weight. The reported results related to vegetable samples refer to dry weight.

In each plot, three soil cores (diameter of 8 cm and height of 20 cm) at depths of 0–20 cm were taken randomly within the furrow before sowing and at harvesting in both 2010 and 2011. Soil available P was determined by the method of Olsen. Soil mineral N was analyzed with a FIA star 5000 Analyzer (FOSS, Sweden). Soil TN was measured by the dry combustion (450 °C) method using a CHNS-analyzer (Elementar Vario El, Elementar Analysensysteme GmbH, Hanau, Germany). TP was determined colorimetrically after soil digestion with perchloric acid: 1 g of finely ground (0.18 mm sieve) soil samples were extracted with 8 mL of sulfuric acid and 0.5 mL of perchloric acid.

Partial factor productivity (PFP)= Y/F , where Y is crop yield per unit area and F is fertilizer applied in the same area. PFP is a useful measure of fertilizer use efficiency (Cassman et al. 1996).

2.5 Measurement of release behavior

A side field experiment without plants was run in 2011 to determine the release behavior of different fertilizers. Three types of fertilizers were tested: attapulgite-coated fertilizer (ACF), attapulgite-mixed fertilizer (AMF), and chemical fertilizer only (CK). The fertilizer rates were 139.09 kg N ha⁻¹ and 38.98 kg P ha⁻¹. The experiment was a randomized complete block design with three replications, and each plot was 1 × 1 m. The pre-weighed fertilizers were applied to the top 20 cm of soils by tillage after thawing in mid-March, but no crop was planted. In each plot, three soil cores (diameter of 8 cm and height of 20 cm) at depths of 0–20 cm were taken randomly on every month from 28 April to 28 September. Then soil available P and mineral N were analyzed.

2.6 Statistical methods

All data were subject to analysis of variance (ANOVA) using the SAS statistical package (SAS Institute, USA) with fertilizer type and fertilizer rate as fixed factors, and year as a random factor. Due to significant treatment × year interactions for most of the variables evaluated, the data were presented for each of the 2 years. Treatment effects were determined using least significant difference at $P < 0.05$.

3 Results and discussion

3.1 The slow-release effect of ACF

Measured at 60 days after the application of fertilizers, the contents of mineral N and available P in the soil with applied AMF and ACF were significantly lower than for CK (Fig. 3),

showing a notable slow-release effect of attapulgite. During 90–120 days after fertilization, soil mineral N and available P in the ACF treatment were still significantly lower than in the CK and AMF treatments. Thereafter, there were no differences

in soil mineral N and available P among treatments. Overall, ACF had a significant slow-release effect (Fig. 3).

Attapulgite has a one-dimensional nanostructures and moderate cation exchange capacity that should allow the fertilizer

Fig. 3 Soil mineral N and available P in the 0- to 20-cm soil layer with the treatments in the field where nothing was planted during April–September 2011

nutrients to be released slowly (Xie et al. 2010). Attapulgit as a physical barrier minimized the burst release effect of nutrients and allowed the gradually release of N and P.

Maize plants are small and need lower amounts of nutrients during the seedling stage; however, nutrient requirements increase gradually and reach a peak in the middle of the growth stage. The slow release of nutrients from ACF allowed a better synchronization between nutrient availability and the plants' needs, thereby increasing crop production. Thus, ACF with a slower nutrient release rate was suitable for maize.

3.2 N and P utilization

ANOVA revealed significant effects of fertilizer type on partial factor productivity of N and P fertilizers, with significant interactions of fertilizer type with year. Averaged across years and fertilizer rate treatments, the maize receiving ACF produced significantly higher partial factor productivity of N and P fertilizers. The maize with 30 % ACF (A30CF) always had significantly higher partial factor productivity compared with other treatments (Table 2).

Table 2 Effect of various treatments on grain yield, aboveground biomass, partial factor productivity of nitrogen (N-PFP), partial factor productivity of phosphorus (P-PFP), and yield components of maize in 2010 and 2011

Year	Treatment		Grain yield (ton ha ⁻¹)	Aboveground biomass (ton ha ⁻¹)	N-PFP	P-PFP	Grain number (spike ⁻¹)	100-kernel weight (g)
	Fertilizer rate	Fertilizer type						
2010	Low	CK	4.9e	10.8e	51.9bc	217.4b	401c	35.1c
		A20CF	5.7abcd	12.4c	60.7a	254.4a	478a	39.2abc
		A30CF	5.8ab	12.7bc	62.0a	259.8a	554a	40.2a
		A20MF	5.0de	11.0de	52.8b	221.0b	438cd	38.0b
	Medium	CK	5.1cde	11.0de	36.2e	129.4de	410d	36.8cde
		A20CF	6.0a	13.9ab	43.4d	154.8cd	469cd	38.7abc
		A30CF	6.3a	13.9ab	45.9cd	163.9c	545a	39.8ab
		A20MF	5.1cde	11.6cde	36.4e	129.8de	449cd	35.8e
	High	CK	5.2bcde	11.9cde	20.2f	101.2f	412d	36.2de
		A20CF	5.8abc	14.1a	22.7f	113.4ef	482cd	38.4abc
		A30CF	6.4a	14.2a	25.1f	125.8ef	535ab	39.4ab
		A20MF	5.2bcde	12.1cd	20.5f	102.4f	458cd	35.1bcd
2011	Low	CK	3.8e	8.5f	40.2b	168.3b	308e	34.3f
		A30CF	4.1cde	9.5de	43.7a	183.2a	342cd	36.5d
		A30MF	3.8e	8.6ef	40.5b	169.7b	329de	35.6e
	Medium	CK	4.0de	9.7cd	28.7d	102.3cde	353cd	36.3de
		A30CF	4.4bc	10.7b	31.8c	113.6c	396b	37.4bc
		A30MF	4.2cd	10.1bcd	30.1cd	107.5cd	362c	36.6cd
	High	CK	4.6b	10.5bc	18.1e	90.5e	404b	37.4b
		A30CF	5.1a	11.6a	19.9e	99.6de	442a	38.3a
		A30MF	4.7b	10.6b	18.4e	92.0e	416b	37.6b
ANOVA <i>P</i> value								
Year		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	
Type (Ty)		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	
Rate (Ra)		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	
Ty×Ra		0.941	0.966	0.663	0.853	0.935	0.982	
Ty×year		0.003	0.006	0.011	0.014	0.037	0.048	
Ra×year		0.135	0.427	<0.001	0.001	0.242	0.446	
Ty×Ra×year		0.886	0.692	0.728	0.850	0.811	0.792	

Low fertilizer rate denotes (all kilograms per hectare) 94.22 N and 22.49 P; medium denotes 139.09 N and 38.98 P; and high denotes 254.23 N and 50.98 P. Values with a column followed by the same letters do not differ at $P < 0.05$

CK chemical fertilizer without attapulgit, A20CF chemical fertilizer coating with 20 % attapulgit, A30CF chemical fertilizer coating with 30 % attapulgit, A20MF chemical fertilizer mixing with 20 % attapulgit, A30MF chemical fertilizer mixing with 30 % attapulgit, PFP partial factor productivity and is calculated as the ratio of the grain yield of maize per unit area to the fertilizer applied in the same area

Shoji et al. (2001) found that polymer-coated urea as a slow-release fertilizer significantly increased N use efficiency in potato (*Solanum tuberosum*). Nyborg et al. (1998) found in greenhouse and field tests that the slow release of polymer-coated fertilizer P into soil markedly increased P recovery by barley (*Hordeum vulgare* L. “Leduc”) and increased yields. Ni et al. (2012) developed a novel slow-release fertilizer coated with attapulgite which effectively reduced nutrient loss in runoff or leaching. In the present study, the use of ACF significantly increased partial factor productivity of N and P fertilizer in maize. ACF had a slow-release behavior which allowed N and P to be gradually released (Fig. 3), so the potential loss of nutrients was reduced.

In 2010 and 2011, the mineral N contents in all treatments significantly declined by the end of the growing season compared with the initial value at sowing. However, the mineral N content at harvest in the ACF treatment was significantly higher than those in AMF and without attapulgite treatments in both years (Table 3).

In a maize experiment, Cartagena et al. (1995) obtained higher residual mineral N from plots treated with controlled-release fertilizers compared with soluble N fertilizers, which suggested the need for a cover crop following maize harvest if controlled-release fertilizers were used. In semiarid areas, due to poor soil aggregate structure, nutrients are easily lost with surface runoff, resulting in lower contents of various total and available nutrients (Li et al. 2003). The slow-release behavior of ACF could prevent nutrient loss, so the residual mineral N was higher than those for the chemical fertilizer treatment. Results from the present study suggest that more soil nutrient accumulation occurred after harvest with the use of ACF and that this was beneficial for crops in the following year.

3.3 Grain yield and aboveground biomass

ANOVA revealed significant effects of fertilizer type on grain yield and aboveground biomass, with significant interactions of fertilizer type with year. Averaged across years and fertilizer rates treatments, the maize receiving ACF produced significantly higher grain yield with greater biomass among treatments (Table 2). The maize with 30 % ACF always had significantly higher grain yield than for other treatments.

The magnitude of the effect of slow-release fertilizers on maize productivity differed between the two study years (Table 2), with better results in 2010 than in 2011. During April–June, rainfall was above average in 2010 but below average in 2011 (Fig. 2). In 2010, with more water to dissolve the coating, ACF supplied sufficient nutrients to maize. However, in 2011 the coating layer outside ACF did not open completely because of the limited rainwater which hindered nutrient supply.

In 2010, at the low fertilizer rate, maize grain yield was significantly higher by 17 % in the 20 % ACF treatment, and significantly higher by 19.5 % in the 30 % ACF treatment, compared with fertilizer without attapulgite. At the medium fertilizer rate, grain yield was significantly higher by 19.7 % in the 20 % ACF treatment, and significantly higher by 26.7 % in the 30 % ACF treatment, compared with fertilizer without attapulgite treatment. At the high fertilizer rate, grain yield was significantly higher by 24.3 % in the 30 % ACF treatment compared with fertilizer without attapulgite treatment.

Similar trends of treatment effects on grain yield were found in 2011, but the magnitude of the yield increase with coated fertilizer differed in 2011 from that in 2010. At the low fertilizer rate, the grain yield of maize in the 30 % ACF treatment was similar to the other treatments. However, grain yield in the 30 % ACF treatment was 11 % higher than for the fertilizer without attapulgite treatment at the medium fertilizer rate; and correspondingly 10 % greater at the high fertilizer rate. Increased grain yield with ACF was largely due to increased grain numbers per ear and 100-kernel weight (Table 2).

In both 2010 and 2011, the use of ACF improved maize biomass significantly compared with fertilizing with AMF or fertilizer without coating in most cases (Table 2). However, this effect interacted with fertilizer rates. In 2011, at the low and medium fertilizer rates, the aboveground biomass of

Table 3 Residual soil mineral N content at the 0- to 20-cm depth at harvest with the treatments in 2010 and 2011

Fertilizer rate	Fertilizer type	2010 (mg kg ⁻¹)	2011 (mg kg ⁻¹)
Low	CK	8.5d	15.1c
	A20CF	15.4ab	—
	A30CF	16.8a	30.7b
	A20MF	8.8d	—
	A30MF	—	20.6bc
Medium	CK	10.4c	14.6c
	A20CF	13.9b	—
	A30CF	15.3ab	35.2a
	A20MF	10.5bc	—
	A30MF	—	15.0c
High	CK	9.8cd	14.0c
	A20CF	15.6ab	—
	A30CF	15.4ab	34.8a
	A20MF	9.4cd	—
	A30MF	—	14.5c

Low fertilizer rate denotes (all kilograms per hectare) 94.22 N and 22.49 P; medium denotes 139.09 N and 38.98 P, and high denotes 254.23 N and 50.98 P. Values with a column followed by the same letters do not differ at $P < 0.05$

CK chemical fertilizer without attapulgite, A20CF chemical fertilizer coating with 20 % attapulgite, A30CF chemical fertilizer coating with 30 % attapulgite, A20MF chemical fertilizer mixing with 20 % attapulgite, A30MF chemical fertilizer mixing with 30 % attapulgite

maize in the 30 % ACF treatment was significantly higher than that in the fertilizer without attapulgite treatment; at the high fertilizer rate, the biomass of maize in the 30 % ACF treatment was significantly higher than other treatments.

Hutchinson et al. (2002) found that polymer-coated urea significantly improved potato tuber yield compared with ammonium nitrate. Yang et al. (2010) found in a field experiment that compared with the control group without fertilization, a single application of attapulgite increased the yield of *Radix hedydysari* by up to 17.4 %, and if combined with compound fertilizer it increased yield from 52 to 78 %. In the present study, the magnitude of yield increase with coated fertilizers mainly depended on the timely release of nutrients coated within the three layers of fertilizer. As an effective barrier to chemical fertilizer, attapulgite coating reduced nutrient loss in the early growing stage, which provided benefits for maize plants to obtain nutrients in the middle and late growing stages. Consequently, ACF improved maize grain yield significantly. The AMF did not effectively control nutrient release and resulted in a small to nonsignificant improvements in maize yield.

Nutrient release from coated fertilizer may be dependent on coating thickness (Shaviv et al. 2003). In the present study, ACF with a coating ratio of 30 % had better performance than a coating ratio of 20 %, suggesting that if the coating thickness is further increased, crop production may increase further accordingly. The optimization of coating thickness requires further research.

4 Conclusions

ACF were prepared according to maize demand for nutrients at different growth stages. This design was novel and unique, satisfying the demands of maize throughout the whole growing season with the slow release of nutrients. The results of the present work indicated that ACF may have wide potential applications for optimizing maize productivity in semiarid regions. Moreover, the research showed promises in utilizing a natural resource such as attapulgite in the production of coating material, which could reduce production costs and make the technique quite environmentally friendly. It is recommended that further experiments on a variety of sites and different crops be conducted to fully examine the potential of this product. Further studies are also required to optimize the coating thickness in fertilizer preparation.

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