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Palygorskite-coated fertilizers with a timely release of nutrients increase potato productivity in a rain-fed cropland

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ABSTRACT

In many semiarid areas of China, potato production is often limited by poor soil fertility and low fertilizer use efficiency, but topdressing to deeper soil layers in the late growing period is difficult. With the aim of improving fertilizer use efficiency and minimizing negative impacts on the environment, a new palygorskite-coated slow-release fertilizer was prepared. According to the nutrient requirements of potato in its three main growth stages, the product consisted of three parts of chemical fertilizers with each part coated by palygorskite. A two-year study was undertaken to investigate the controlled release behavior of the product, and its impact on potato yield and fertilizer uptake was also evaluated. Two coating ratios (20 and 30%) of palygorskite-coated vs. palygorskite-mixed chemical fertilizer and chemical fertilizers only were applied with three rates (all kg ha^{-1}): (1) low (94.5 N and 4.5 P), (2) medium (137.9 N, 16.5 P and 10.5 K), and (3) high (223.4 N, 24.0 P and 81.0 K). The results both from soil (mineral N and available P) and crop (leaf nitrate N) indicated a controlled release characteristic of palygorskite-coated fertilizer which synchronized better with nutrient demands of potato plants. The palygorskite-coated fertilizer treatment resulted in the highest total tuber yield, 14.6–20.3% higher than the control. Partial factor productivity of N, P and K fertilizer was also significantly increased by palygorskite-coated fertilizer. The palygorskite-coated fertilizer could be promising for potato production and be beneficial to agricultural sustainability in semiarid areas.

1. Introduction

Potato (*Solanum tuberosum* L.) is the world's most important non-grain food crop and plays a pivotal role in world food production and security (Xu et al., 2011). China is the world's leading potato producer (Wang et al., 2011). The semiarid Loess Plateau of northwestern China, with favorable growth conditions such as cool temperatures, adequate sunlight and a large differential between day and night temperatures, is one of the largest potato-producing areas in China (Jansky et al., 2009).

However, the soil fertility of the Loess Plateau is poor (Zhou et al., 2012). Farmers often applied insufficient fertilizer to their fields due to poverty (Miao et al., 2010). Fertilizer has been applied prior to the time of seeding, although the majority of crop nutrient uptake occurs later in the growing season when the crop is growing rapidly. Nitrogen (N) present in the soil prior to crop uptake is subject to loss by ammonia volatilization, nitrate (NO_3^-) leaching and nitrous oxide emission (Cartagena et al., 1995; Linquist et al., 2013). Phosphorus (P) often combines with calcium (Ca) in alkaline soils, forming poorly soluble compounds and resulting in low available P for crops to uptake (Sharma, 1979; Liu et al., 2013). Moreover, the shallow root system of potato usually makes its recovery of fertilizer quite low (Zvomuya et al., 2003). Low fertilizer use efficiency not only leads to reduced crop yields, but also exacerbates soil degradation, which jeopardizes agricultural sustainability in this region (Tan et al., 2005; Hu et al., 2013). Potato has high nutrient requirements, but its fertilizer recovery is often quite low partly due to a shallow root system (Zvomuya et al., 2003). To compensate for the inefficient rooting system and extreme sensitivity to deficiencies, enhancing fertilizer efficiency in potato is particularly important (Hopkins et al., 2008).

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Controlled release fertilizers (CRFs), which provide a gradual nutrient supply for a long period, may overcome the problems farmers face concerning nutrient limitations. CRFs are made of soluble fertilizers coated with materials including sulfur, polymer, latex, oil and other synthetic substances (Yan et al., 2008). These products have been used successfully to limit nutrient losses (Shoji et al., 2001). However, CRFs tend to be more expensive than conventional fertilizer, may have nutrient release that is difficult to predict and some coating materials can even harm the environment (Azeem et al., 2014). Furthermore, most CRFs focus on regulating N release without considering other indispensable nutrients such as P and potassium (K), which may not meet the requirements of plants for multiple nutrients (Zhao et al., 2010). All these shortages limit the application of CRFs on field crops (Yan et al., 2008). Low cost, easily fabricate and environmentally friendly controlled release fertilizers are urgently needed in semiarid rain-fed areas.

The clay mineral palygorskite, also known as attapulgite, is one of the world's most important and useful industrial minerals. Due to its fibrous reticular structure with large specific surface area, palygorskite has good absorbability and a slow-release effect (Murray, 2000; Ye et al., 2013a). Palygorskite also contains many microelements (e.g., Si, Al, Mg, Fe, K, Ca and Mn) that benefit crop growth (Xie et al., 2010). Palygorskite deposits are rare and valuable in the world. However, rich reserves of 2500 million tons were found in Gansu Province of China (Liu et al., 2001). All above make palygorskite a promising coating material for slow-release compound fertilizers. Several experiments have shown positive responses in some crops to compound fertilizer mixing or coating with palygorskite (Yang et al., 2010; Guan et al., 2014).

To our knowledge, there are no records in the literature using palygorskite to produce fertilizer according to the nutrient demands of potato plants at different growth stages. The technology may provide another method of providing nutrients in a controlled manner to more accurately meet crop needs while protecting quality of the environment and conserving natural resources.

In the present study, palygorskite-coated fertilizers (PCF) were prepared by dividing chemical fertilizers into three parts and coating each part with palygorskite, based on the nutrient requirements of potato plants at different growth stages. We hypothesized that there would be differences in potato production between PCF and conventional fertilizer. Consequently, the objectives of this study were to (i) explore the nutrient release dynamics of PCF and (ii) evaluate the effects of PCF vs. conventional fertilizer on potato yield and fertilizer use efficiency.

2. Materials and methods

2.1. Field site

This study was conducted for two years (2010–2011) on different fields at the Semiarid Ecosystem Research Station of Loess Plateau (36°02′N, 104°25′E and 2400 m above sea level) of Lanzhou University, China. The soil had a mean soil bulk density of 1.27 g cm^{-3} and pH 8.5 (Zhou et al., 2012). The mean annual precipitation is 320 mm and annual average free-water evaporation is 1300 mm. The site has a medium temperate semiarid climate with a mean annual temperature of 6 °C. The annual rainfall was 308.7 mm in 2010 and 291.3 mm in 2011, near the long-term average.

2.2. Fertilizer

A novel palygorskite-coated fertilizer was compared with conventional fertilizer and palygorskite-mixed fertilizer treatments. N, P and K were applied as urea (46.4% N), superphosphate (12% P_2O_5) and potassium sulfate (20% K_2O), respectively.

2.3. Experimental design

Five types of fertilizers varying in coating were evaluated (Table 1): (1) N, P and K fertilizer only without palygorskite as the check (CK); (2) N, P and K fertilizer mixed with 20% palygorskite (P20MF); (3) N, P and K fertilizer mixed with 30% palygorskite (P30MF); (4) N, P and K fertilizer coated with 20% palygorskite (P20CF); and (5) N, P and K fertilizer coated with 30% palygorskite (P30CF). The 20% and 30% indicated that the weight ratio of palygorskite to fertilizer was 20:80 and 30:70, respectively.

CK, P20MF, P20CF and P30CF were tested in 2010; and then according to the results, CK, P30CF and P30MF were tested in 2011. Each fertilizer had three application rates as follows (all kg ha^{-1}): low (94.5 N and 4.5 P), medium (137.9 N, 16.5 P and 10.5 K) and high (223.4 N, 24 P and 81 K), determined according to recommendations for potato production. Thus there were 12 treatments in 2010 and nine in 2011. The experiment was arranged in a completely randomized block design with three replications. Each plot was 3.6 m × 5 m in 2010 and 5.5 m × 4 m in 2011.

PCF were composed of spherical particles with three parts (Fig. 1): the inner part was the fertilizer expected to be released in the tuber bulking and maturation stage of potato, the middle part was fertilizer expected to be released in the vegetative stage and the outer part was fertilizer expected to be released in the seedling stage. Outside each part was a layer of palygorskite coating. The allocation rates of fertilizers in each of the three parts were determined by the description of Li (2009) as follows: potato usually takes up 6% of total N, 8% of available P and 9% of K in the seedling stage (0–40 days after planting) from fertilizers; correspondingly 38, 34 and 36% in the vegetative stage (40–75 days); and 56, 58 and 55% in the tuber bulking and maturation stage (75–150 days). The detailed formulation is shown in Table 1.

Plastic film mulching was used when potato planting at a seeding density of 31,000 plants ha^{-1}. Each year, cut seed pieces (55–85 g each) were hand-planted in late April with a planting depth of 20 cm and harvested in the beginning of October.

2.4. Sampling and measurements

In order to determine leaf NO_3^--N concentration, leaf samples were collected from each plot at several dates from 30 June to 30 August in 2011. Leaf samples were taken from the fourth leaf from the growing point of 10 randomly chosen plants per plot, and then washed with water and dried with filter paper. Leaf samples (5 g) were mixed with 1 ml of 30% trichloroacetic acid (to suppress nitrate reductase activity) and 29 ml of distilled water, and then triturated in a blender until a homogeneous mass was attained. The homogeneous mass was centrifuged at 4000 r/min for 10 min, and then 2 ml of the supernatant was transferred to a 100 ml volumetric flask and the volume completed with distilled water. NO_3^--N in this solution was analyzed with a FIA star 5000 Analyzer (FOSS, Sweden). To obtain the desired concentrations of NO_3^-, the solution was diluted with water before injection into the FIA system. For each determination, three replicates were performed.

Crop samples were harvested manually at maturity from four non-border rows at the center of each plot, and the tubers were size-graded and weighed for total and marketable yield. Marketable yield was calculated by subtracting misshapen (cull) and undersized (<85 g) tuber yields from the total yield. The number of tubers per plant, tuber yield per plant and mean tuber weight were determined from 10 randomly selected plants in each subplot prior to harvest. All samples of herbage and tubers were oven-dried at 105 °C for 1 h and