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A Comparative Study of the Cellular Microscopic Characteristics and Mechanisms of Maize Seedling Damage from Superabsorbent Polymers

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ABSTRACT

Superabsorbent polymers (SAPs) as soil moisture conditioners have been increasingly used in agriculture, but conflicting results were reported regarding the effects of SAPs on crop growth. In this study, both laboratory cultivation and analysis were conducted to investigate the effects of different SAPs on the growth and physiology of crops under water-saving agricultural practices. Maize (*Zea mays* L.) seedlings were cultivated using distilled water or three different SAP hydrogels, sodium polyacrylate (SP), potassium polyacrylate (PP), and sodium polyacrylate embedded with phosphate rock powder (SPP), as growth media. Growth characteristics of the model plant and damage were assessed using scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The results showed that both the SP and PP treatments had pronounced negative effect on the hydrogels of growth of maize seedlings. The SPP treatment appeared to facilitate the stem-leaf growth and had no obvious adverse effect on root growth. All the three hydrogel treatments caused varying degrees of damage to the organizational structure and cellular morphology of the roots, with the SP and PP treatments causing the most severe damage; the membrane system of root cells was damaged by both SP and PP treatments. An excessive accumulation of sodium and reduction of calcium occurred in the roots may be responsible for the observed damage to the cell membrane system, which, in turn, may have promoted the wilting of the cells.

Key Words: damage mechanism, nutrient concentration, root tip cell, SAP hydrogels, soil moisture conditioners, water-saving agriculture

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INTRODUCTION

Water-saving technologies have been developed to overcome the challenge of limited water resource for agriculture. Cross-linked superabsorbent polymers (SAPs), which are capable of absorbing and retaining water tens to thousands of times their own weight, have been studied as soil moisture conditioners, and the application of these materials in agriculture and forestry is increasing (Zohuriaan-Mehr and Kabiri, 2008; Hüttermann *et al.*, 2009; Han *et al.*, 2010; Fan *et al.*, 2015).

Proper use of SAPs has been shown to improve physical properties of soils (Bai*et al.*, 2010; Han *et al.*, 2010), increase water-holding capacity of the soil, reduce water and nutrient loss (Abedi-Koupai *et al.*, 2008; Han *et al.*, 2013), enhance the drought resistance of seedlings (Apostol *et al.*, 2009; Agaba *et al.*, 2010), and promote crop growth (Hüttermann *et al.*, 1999; Akhter *et al.*, 2004; Yang *et al.*, 2014). However, studies also indicated that the benefits of SAPs on seedling growth are inconsistent, and SAPs were also reported to inhibit root growth and decrease plant biomass (Tripepi *et al.*, 1991; Huang *et al.*, 2002; Zhang *et al.*, 2007; Islam *et al.*, 2011). This inhibitory effect was more severe at a high SAP dosage (Du *et al.*, 2006, 2007; Ngobeni *et al.*, 2007; Yang *et al.*, 2009). The SAPs are three-dimensional network polymers that form hydrogels when moistened. Plant roots can penetrate through the hydrogels and absorb water and ions present in the hydrogels. To date, few studies have been conducted to understand how SAPs influence the ability of plants in absorbing nutrients. Taylor and Halfacre (1986) have suggested that SAPs decrease the contents of calcium (Ca), magnesium (Mg), and iron (Fe) in plant tissue, but failed to explain the

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mechanisms of the reduced nutrient uptake. Silberbush (1993) reported that a particular SAP (Agrosoak) enriched the soil solute with sodium (Na^+) and reduced crop yield. Therefore, the negative effect of SAPs may be related to their chemical composition.

The goal of this study was to investigate the effects of three different SAPs on the growth characteristics of maize (*Zea mays* L.) seedlings. The maize seedlings were treated with one of the three water-saturated SAP hydrogels. The damage of maize seedlings by the SAPs was investigated using scanning electron microscopy (SEM) and transmission electron microscopy (TEM), as well as plant analysis.

MATERIALS AND METHODS

SAP materials

The three SAPs studied were sodium polyacrylate (SP, Beijing Hanli Polywater Hitech Company, Beijing, China), potassium polyacrylate (PP, Department of Chemical and Bioengineering, North Carolina Agricultural and Technical State University, Greensboro, USA), and sodium polyacrylate embedded with phosphate rock powder (SPP) at the rate of 30% dry weight according to the previously reported method (Zhong *et al.*, 2013). The water uptake capacity of the SAPs was 382.5, 306.8, and 387.03 g g^{-1} for SP, PP, and SPP, respectively. Their water uptake capacity in 90 kg L^{-1} NaCl solution was 43.82, 44.78, and 44.41 g g^{-1} for SP, PP, and SPP, respectively. The SAPs were first soaked in distilled water at the ratio of 1:500 (weight:weight) for 24 h, followed by filtration for 1 h to obtain water-saturated hydrogels. Then, 150 g of the water-saturated hydrogel was added to plastic cups (8 cm in height, 7.5 cm and 5.5 cm in upper and lower diameters, respectively), and used as the growth media for the experiment. The nutrient contents of the SAP hydrogels are listed in Table I. Forty replicates were prepared for each type of SAP hydrogel to monitor reproducibility.

Laboratory cultivation experiment

Maize seeds (Waxy Maize-2008, provided by South China University of Agriculture, Guangzhou, China) were first soaked in distilled water and germinated for 2 d at 25 °C prior to the experiment. Three germinated seeds were then planted into each cup with an SAP hydrogel (SP, PP, or SPP) or distilled water as a control (CK). The cups were placed in a growth chamber under the controlled conditions: day/night, 12h/12h; illumination, 20 000 lx; temperature, 25 °C; and relative humidity, 700 ± 10 g kg^{-1}. Each treatment was repeated with 6 cups.

Sampling and measurement

Seeding growth and biomass determination. For each treatment, 3 representative seedlings were selected for photo taking on days 3 and 6. All the seedlings were harvested on day 7, washed with distilled water, and blot dried with absorbent paper. The fresh weights of root and stem-leaf were recorded.

Root morphology analysis. Fifteen maize seedlings were randomly selected, and their root morphology was analyzed using an automatic root scanner (Model LA600 with WinRHIZO package, Regent Instruments Inc., Quebec, Canada). The root length, root surface area, root volume, root diameter, and root tip number were recorded.

Plant tissue analysis. For determination of nutrient concentration in the plants, subsamples of oven-dried seedlings (1.0 g) were ashed. The resultant ash was dissolved in 10 mL of 1.2 mol L^{-1} HCl solution and analyzed for minerals (K, Na, Ca, Mg, Fe, Mn, and Zn) using atomic absorption spectrophotometry (Z-2300, Hitachi, Tokyo, Japan).

SEM analysis. For SEM analysis, fresh roots were first washed with distilled water. The root-end was prepared by removing 1 to 2 cm of the apex at a

TABLE I

Elemental composition of the superabsorbent polymer (SAP) hydrogels used in this study

SAP hydrogel[a)]	Exchangeable cation				Total content		
	K	Na	Ca	Mg	Fe	Mn	Zn
	mg kg^{-1}						
SP	1.0c[b)]	256.3a	0.98b	0.406b	0.096b	0.003b	0.011b
PP	405.4a	5.4c	nd[c)]	0.123c	0.063b	0.002c	0.004b
SPP	8.3b	190.5b	12.66a	3.355a	5.249a	0.719a	0.167a

[a)]SP = sodium polyacrylate; PP = potassium polyacrylate; SPP = sodium polyacrylate embedded with phosphate rock powder.
[b)]Means followed by the same letter within the same column are not significantly different at $P < 0.05$ by Duncan's multiple range test ($n = 4$).
[c)]Not detected.