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Full Length Research Paper

Evaluation of a water-saving superabsorbent polymer for corn (*Zea mays* L.) production in arid regions of Northern China

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In arid and semiarid regions of northern China, there is an increasing interest in using water-saving superabsorbent polymer (SAP) for field crop production. Experiments were conducted during summer corn season in 2009 to study the growth and yield characteristics of summer corn (*Zea mays* L.) under different (control, 0; low, 5; medium, 10 and high, 15 kg ha^{-1}) rates of SAP in a drought-affected field of northern China. Corn yield increased slightly following SAP application at low and medium rate, but significantly at high rate by 37.5%. At the same time, plant height, stem diameter, leaf area, biomass accumulation, harvest index and relative water content, as well as protein, sugar and starch contents in the grain increased significantly following SAP treatments. The optimum application of superabsorbent polymer for corn cultivation in the study area would be 15 kg ha^{-1} as it best increased the grain yield and quality. Lower rates (5 and 10 kg ha^{-1}) may not be sufficient for corn requirements. We suggest that the application of SAP at 15 kg ha^{-1}could be an efficient and economic soil management practice for summer corn production in the drought affected regions of northern China or other areas with similar ecologies.

Key words: Corn, drought stress, northern China, superabsorbent polymer.

INTRODUCTION

In arid and semiarid regions of northern China, serious water deficits and deteriorating environmental quality are threatening agricultural productivity and environmental sustainability. Thus, there is an increasing interest in using water-saving superabsorbent polymer (SAP) for field crop (such as corn) production. China is one of the world's most water-deficient economies and water scarcity is viewed as a major threat to long-term food security. While the agricultural sector is still by far the largest user of China's water resources, rapid economic and population growth is generating rising demand for urban and industrial use, increasing pressure on water supplies.

China has a large region of dry land in the north, which accounts for about 56% of the nation's total land area but only 24% of country's water resources (Xin and Wang, 1999). The North China Plain (NCP) is one of the most important wheat and maize production areas in China. The main cropping system in this region is wheat and maize double cropping in a year producing about 29.6% of the nation's food, including about half of the wheat production and a third of the maize production (NBSC, 1998). The average requirement of water for crop production is about 810 mm (450 mm for wheat and 360 mm for maize) whereas the mean annual rainfall is only about 550 mm (Liu et al., 2001). Irrigation is critical for maintaining high crop yield, especially in northern China, where about 75% of the agricultural land is irrigated, consuming 70 to 80% of the total water resource allocation in the region (Liu et al., 2001). In recent years,

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however, increased water deficits associated with overuse of surface water, declining groundwater levels, water pollution, and soil salinization are threatening the sustainability of agricultural production in the region (Hu et al., 2005; Liu et al., 2001; Wang et al., 2001). The water supply for agricultural production will unavoidably decrease with the increasing demands from domestic and industrial water users. At the same time, the agricultural water use efficiency is still very low due to the poor irrigation practices and undeveloped infrastructure (Hu et al., 2005; Wang et al., 2001). Furthermore, negative impact of climate change greatly influences the water cycle and aggravates the water crisis situation in the NCP.

Soils in the NCP areas are mostly characterized by low water-holding capacity, high evapo- transpiration and excessive leaching of the scanty rainfall, leading to poor water and fertilizer use efficiency by crops. As a result, much of the double-cropped wheat and summer corn area (approximately 20 to 50%) in north part of the NCP including Beijing, Tianjin and Hebei has now been replaced by mono-cropped spring corn area (Zhiming et al., 2007; Yu et al., 2006). Agricultural scientists and planners in the area are being confronted with the task of developing timely and viable alternative soil-water-crop management system to counteract the current downward trends in environmental degradation and agricultural productivity.

The problem of inefficient use of rain and irrigation water by crops is most important in semiarid and arid regions, where shortage of water is frequently experienced and water is the main limiting factor for growth and yield of crops. In arid and semiarid regions of the world, intensive research on water management is being carried out and use of superabsorbent polymers (SAP) may effectively increase water and fertilizer use efficiency in crops (Islam et al., 2011a,b,c). The application of SAP for stabilizing soil structure resulted in increased infiltration and reduced water use and soil erosion in a furrow irrigated field (Lentz and Sojka, 1994; Lentz et al., 1998). When polymers are incorporated into the soil, it is presumed that they retain large quantities of water and nutrients, which are released as required by the plant. Thus, plant growth could be improved with limited water supply (Islam et al., 2011c). Johnson (1984) reported an increase of 171 to 402% in water retention capacity when polymers were incorporated in coarse sand. Addition of a polymer to peat decreased water stress and increased the time to wilt (Karimi et al., 2009; Gehring and Lewis, 1980). The incorporation of SAP improved soil physical properties (El-Amir et al., 1993), enhanced seed germination and emergence, crop growth and yield (Islam et al., 2011c; Yazdani et al., 2007) and reduced the irrigation requirement of plants (Islam et al., 2011a,b). The use of hydrophilic polymer materials as carrier and regulator of nutrient release was helpful in reducing undesired fertilizer losses, while sustaining vigorous plant growth (Mikkelsen, 1994).

Three classes of SAP are commonly used and are classified as natural, semi-synthetic and synthetic polymers (Mikkelsen, 1994). Synthetic polyacrylamide with potassium salt base (Figure 1) manufactured by Beijing Hanli-sorb Poly-water Hi-tech. Co. Ltd. used for this experiment is a cross-linked polymer developed to retain water and fertilizer in the agricultural and horticultural sector. Earlier, polymers were not used in the agricultural field due to their high prices. Recently, many polymer industries developed around northern China and the prices became comparatively cheaper (about 5 USD kg^{-1}), on the other hand, excessive fertilizer application leads to an increase in compound (granular) fertilizer price (about 0.4 USD kg $^{-1}$). Polymers are safe and non-toxic and it will finally decompose to carbon dioxide, water, ammonia, and potassium ion, without any remainder (Mikkelsen, 1994; Martin, 1997). To reduce undesired fertilizer losses from the soil, application of SAP in the agricultural field could be a viable water and fertilizer saving technology in arid and semi arid regions of northern China. Moreover, these polymers can retain soil moisture and fertilizer up to 5 years after application (Martin, 1997). Although the manufacturers' recommended rate of SAP for corn production varied between 10 to 15 kg ha^{-1}, there is no particular scientific study to evaluate and document the appropriate rate of SAP to be applied in the field. Therefore, the main objective of this study was to evaluate the effectiveness of different rates of superabsorbent polymer (0, 5, 10 and 15 ha^{-1}) on growth, biomass production, grain yield plus quality of summer corn in a drought affected field of northern China.

MATERIALS AND METHODS

Plant material and growth condition

The study was conducted under field conditions in the Shunyi county (40°13′ N, 116°65′ E), Beijing, northern China. The soil was sandy loam and the fundamental chemical properties of the soil are presented in Table 1. Plots were marked out with minimal pre-planting land preparation. Treatments comprised super absorbent polymers (SAP) applied in the sowing row mixing with inorganic fertilizer (standard rate) during seed sowing at low (5 kg ha^{-1}), medium (10 kg ha^{-1}) and high (15 kg ha^{-1}) rate. The levels of SAP applications (low, medium and high) followed manufacturer's recommendations for the area. The control plots received only compound granular fertilizers (NPK 15:15:15) at standard rate (300 kg ha^{-1}). ZhengDan 958, a commonly grown corn variety (*Zea mays* L.) in northern China was used for the experiment. Treatments were arranged into a completely randomized design with three replications; each treatment occupied a plot area of 3 × 8 m. Seeds were sown on 23rd June and harvested on 29th September in 2009. Standard seed rate and row spacing (60 cm) were used during seeding and irrigated once (60 mm) within one week after sowing.

Phenological measurements and calculation

Determination of plant growth (plant height, leaf area, stem diameter, grain yield and biomass accumulation) was carried out during harvest. Relative water content (RWC) of leaves was measured on fully expanded leaves at 3, 6 and 9 weeks after sowing (WAS).

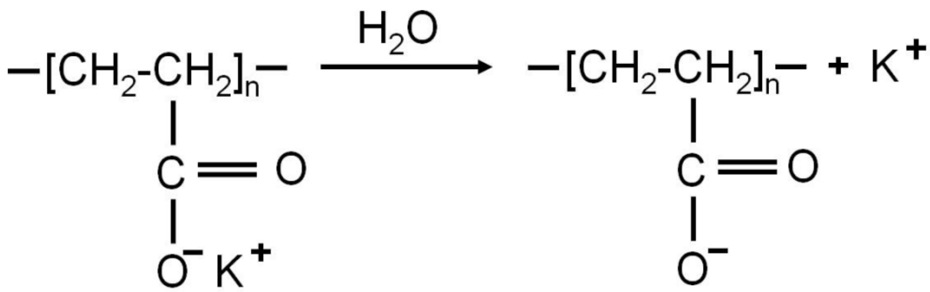

Figure 1. Chemical structure of superabsorbent polymer and its reaction with water.

Table 1. Fundamental chemical properties of the soil.

Items	Values		Unit
	0-15 cm	15-30 cm	
pH (H_2O)	6.8	6.78	
Electrical conductivity	0.73	0.70	mS/cm
Total nitrogen	107.8	92.6	mg/kg
Available phosphorus	32.8	19.7	mg/kg
Available potassium	72.6	68.9	mg/kg
Organic matter	12.2	8.3	g/kg

Leaves were cut and collected at midday to determine fresh weight (FW). Leaf blades were then placed with their cut end pointing down into a Falcon tube containing about 15 ml of 1 mM $CaCl_2$. The $CaCl_2$ was used to increase leaf cell integrity, with the aim of reducing cell lysis due to excessive rehydration. The turgid weight (TW) was then recorded after overnight rehydration at 4 °C. For dry weight (DW) determination, samples were oven-dried at 70°C for 48 h. Relative water content was calculated according to Schonfeld et al. (1988) thus:

$$RWC\ (\%) = [(FW - DW) / (TW - DW)] \times 100 \quad \ldots\ldots\ldots\ldots\ldots (1)$$

Plant height was taken on a ruler, leaf area was measured on the summation of each leaf area, stem diameter was measured by a digital calipers. The number of grain per plant was counted from randomly selected plant and the (1000) grain weight was calculated from randomly sampled grains after harvest. At maturity, a sample of 4 m^2 area for each plot was harvested for grain yield and biomass determination and data were taken after oven drying at 70°C for 72 h.

Soil analysis

Soils were sampled at the 0 to 15 cm and 15 to 30 cm soil depths from the sowing rows after harvest. Samples were air-dried and passed through 1 mm sieve before analysis. Soil organic matter was determined by ashing a 5 g scoop of the soil sample at 360°C for 2 h in a muffle furnace. The loss by weight of the sample during this ignition was calculated as the organic matter. Total N was determined by Kjeldhal method (AOAC, 1990). Available P was determined by molybdenum blue colorimetry after Bray-1 extraction (AOAC, 1990). Available K was measured by analyzing the filtered extract on an atomic absorption spectrophotometer set on emission mode at 776 nm (AOAC, 1990).

Grain quality determination

Dried samples were ground and passed through a 1 mm sieve before analysis. Nitrogen content (%) was determined by the Kjeldhal method (AOAC, 1990) and crude protein (CP) content was obtained by multiplying the Kjeldahl N values by 6.25. Starch and soluble sugar contents were also determined by official AOAC method.

Climatic measurement

An automatic weather station was installed in the experimental field to record daily air temperature, rainfall and relative humidity during corn growing period (Figure 2). Air temperature ranged from 12.0 to 38.1°C and mean temperature was 17.5°C. Total precipitation was 248 mm in 33 rainy days which was 112 mm lower than corn requirements (Liu et al., 2001). Relative air humidity (daily average) ranged from 31 to 89% and mean value was 68.1%.

Statistical analysis

An analysis of variance was performed using the STATEVIEW (SAS Institute Inc., Cary, NC, USA) software. Treatment means were compared using the Fisher's protected least significant differences (LSD) at the 5% level of probability.

RESULTS

Plant height

Plant heights were more or less increased with increasing

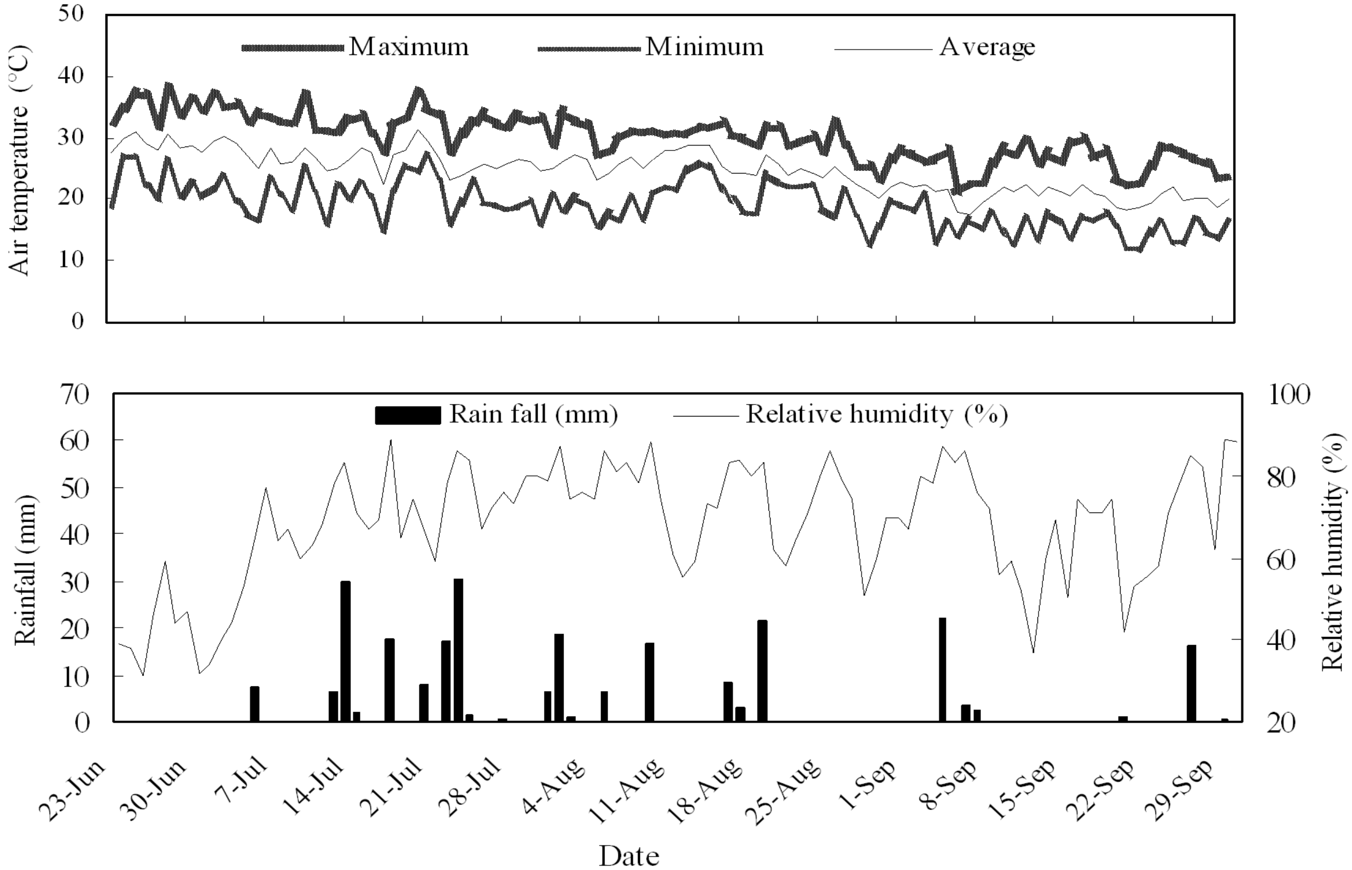

Figure 2. Daily air temperature, rainfall and relative humidity during corn growing season (23rd June to 29th September, 2009).

rates of SAP (Table 2). Although the differences were less noticed under low and medium rate, it increased significantly by 5.9% for the high rate compared with that without application of SAP or control.

Leaf area

Lead area in corn treated with SAP increased by 12.2% under low and 19.2% under medium SAP application, whereas it increased significantly by 32.3% under high rate (Table 2).

Stem diameter

Stem diameter (STDM) of corn plant under different SAP treatments was also presented in Table 2 did not changed under low rate and slightly under medium rate. The value increase significantly by 27.9% under high rate compared with plants without SAP or control.

Grain per plant

No significant difference in number of grains per plant was observed with application of SAP at low rate, whereas it increased significantly under medium and high rate by 31.0 and 45.4%, respectively (Table 2).

1000- grain weight

1000-Grain weight of corn under different treatment also presented in Table 2 increased with increasing rate of SAP. Although the effects were less noticed under low rate, application of SAP increased grain significantly by 6.5 % under medium and 7.5% under high rate.

Dry matter yield

The above-ground biomass (AGB) of corn under different treatments is presented in Figure 3, increases with increasing rate of SAP. Above-ground biomass increased by 6.1% for low, 18.5% for medium and 22.7% for high application of SAP.

Grain yield and harvest index

A remarkable increase in grain yield was observed

Table 2. Plant height, stem diameter, leaf area, grain per plant and 1000 grain weight of corn under different superabsorbent polymer (SAP) treatments.

Treatments	Plant height (cm)	Stem diameter (cm)	Leaf area (m^2)	Grains/plant	1000 grain weight (g)
CK	263.1 ± 1.6	2.1 ± 0.06	0.38 ± 0.022	432 ± 18.80	234.4 ± 2.3
Low	268.3 ± 1.5	2.1 ± 0.04	0.43 ± 0.018	496 ± 23.07	240.1 ± 2.7
Medium	272.4 ± 2.1	2.3 ± 0.04	0.46 ± 0.030	566 ± 23.46	249.6 ± 2.4
High	278.6 ± 2.4	2.7 ± 0.16	0.51 ± 0.024	628 ± 18.58	251.9 ± 2.2
Mean	270.6	2.3	0.45	530.5	244.0
LSD (0.05)	6.36	0.29	0.079	68.8	7.87

CK, control; LSD, least significant difference.

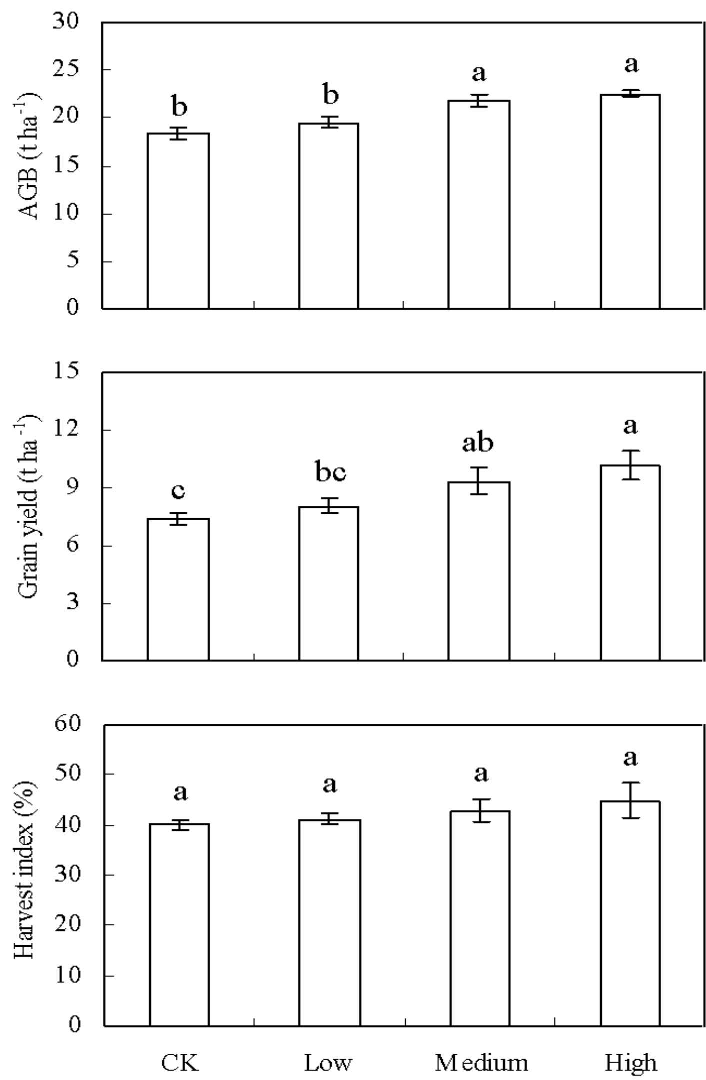

Figure 3. Grain yield, biomass accumulation and harvest index in corn at different superabsorbent polymer rates. Small bar shows standard errors.

following SAP application (Figure 3). Although the difference was less noticed under low application, it increased grain yield significantly by 26.9% under medium and 37.5% under high application level. Correspondingly

Table 3. Crude protein (CP), soluble sugar and starch content in corn grain under different superabsorbent polymer (SAP) treatments.

Treatments	CP (%)	Soluble sugar (%)	Starch (%)
CK	6.79 ± 0.22	3.83 ± 0.13	62.1 ± 2.7
Low	7.49 ± 0.41	4.42 ± 0.33	69.9 ± 3.8
Medium	7.86 ± 0.31	4.69 ± 0.39	71.7 ± 3.4
High	8.77 ± 0.39	5.39 ± 0.45	76.9 ± 3.4
Mean	7.73	4.58	70.15
LSD (0.05)	1.12	1.13	10.88

CK, Control; CP, crude protein; LSD, least significant difference.

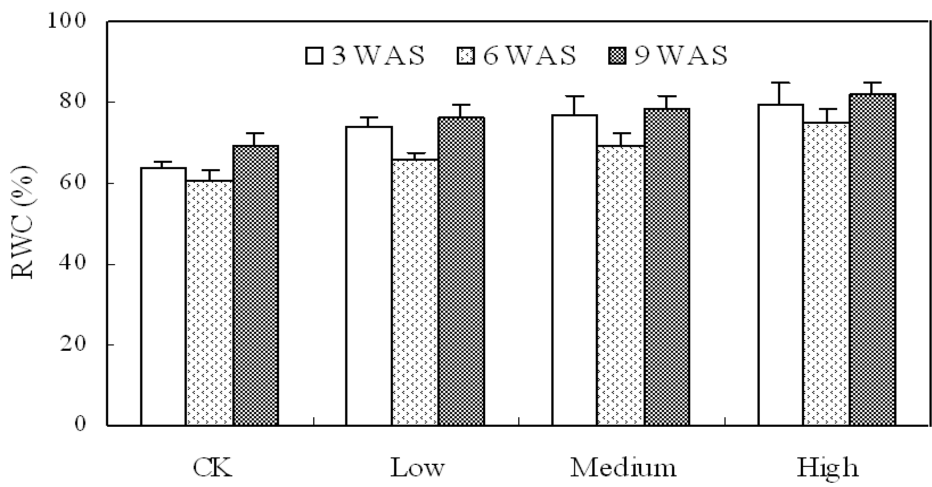

Figure 4. Variation in relative water contents (RWC) of corn leaves at different growth stages (3, 6 and 9 weeks after sowing) under different at different superabsorbent polymer treatments. Small bar shows standard errors.

harvest index in SAP treated corn also increased ranging from 2.9 to 12.2%, but not in a statistically significant manner (Figure 3).

Relative water content

Figure 4 showing the changes in relative water content (RWC) of fully expanded leaves for SAP treatments at different growth stages. Superabsorbent polymer had a remarkable effect in increasing RWC especially at high rate, whereas the effect of low and medium application of SAP on this parameter is not statistically significant. Application of SAP increased leaf RWC by 24.6% at 3 weeks after sowing (WAS), 23.5% at 6 WAS and 19.2% at 9 WAS for high rate compared with plants without SAP or control.

Grain quality

Crude protein (CP) contents in corn grain increased by applying SAP (Table 3) but the effect was less noticed under low and medium application levels. However, application of SAP increased CP significantly by 29.3% for high rate. Soluble sugar contents in the grain did not change for low SAP rate (Table 3) but increased remarkably under medium and high rate by 22.6 and 40.4% respectively. Grain starch content of wheat under different treatments also presented in Table 3, increased for SAP application ranging from 12.4 to 23.6 % and highest value was obtained on high rate.

DISCUSSION

Super absorbent polymers (SAP) have been used as water-retaining materials in the agricultural and horticultural fields (Islam et al., 2011a, b; Yazdani et al., 2007) because when incorporated in soil, they can retain large quantities of water and nutrients. These stored water and nutrients are released slowly as required by the plant to improve growth under limited water supply (Yazdani et al., 2007). Our data have shown that the applied SAP had a remarkable effect on corn growth (Table 2), yield (Figure 3) and quality (Table 3).

Relative water content (RWC) is an appropriate measure of plant water status in terms of the physiological consequence of cellular water deficit (Kramer, 1988). We found that the application of SAP substantially increased the RWC in corn leaves at different growth stages (Figure 4). Application of superabsorbent polymer could conserve different amounts of water in itself thereby increasing the soil's capacity for water storage, ensuring more available water; thus the RWC content in leaves, as well as plant growth and yield increased under water stress (Tohidi-Moghadam et al., 2009).

Application of SAP could be an effective management practice for corn cultivation in soils characterized by low water holding capacity where rain or irrigation water and fertilizer often leach below the root zone within a short period of time, leading to poor water and fertilizer use efficiency by crops (Johnson, 1984; Mikkelsen, 1994; Yazdani et al., 2007). Under this situation excessive fertilization would not bring any progressive change in crop performance and may rather cause some negative impact on the environment. Application of SAP along with inorganic fertilizer could change the fertilization strategy in arid and semiarid regions of China.

When aqueous, nutrient-containing solutions are used to hydrate a polymer, a considerable amount of nutrient enters into the polymer structure during expansion (Martin et al., 1993). Hydrophilic polymers generally contain micro pores that allow small molecules (such as NH_4) to diffuse through the hydrogel (Johnson and Veltkamp, 1985). The subsequent release of nutrient is then based on the diffusive properties of the polymer, its decomposition rate, and the nature of the nutrient salt. Thus plant growth, yield and quality increased following SAP application. Mikkelsen et al. (1993) found that addition of polymer to the fertilizer solutions reduced N leaching losses from soil columns as much as 45% during the first four weeks in heavily leached conditions compared with N fertilizer alone. At the same time, Fescue (*Festuca arundinacea* L.) growth was also increased as much as 40% and tissue N accumulation increased up to 50% when fertilized with polymer compared with fertilizer alone. In a similar study, Magalhaes et al. (1987) also found a remarkable reduction in NH_4, P and K leaching due to the presence of the polymer. The higher yield and quality of SAP treated corn achieved during our experiment possibly due to availability of soil water, as well as nutrient elements stored by polymer.

Conclusion

Differences in the responses of corn subjected to SAP application were evident during our observation. Although corn yield increased slightly for low and medium SAP application, it increased 37.5% for high rate (Figure 3). At the same time protein and sugar contents in the grain also increased following SAP treatment. Low (5 kg ha^{-1}) and medium (10 kg ha^{-1}) rate of SAP might be not enough to meet water and nutrient demands of corn, because it could not bring any remarkable progress in crop performance. Based on our findings, we suggest that the application of SAP could be an effective drought mitigation strategy for field crop production and its application at 15 kg ha^{-1} is appropriate for corn production in the arid and semiarid regions of northern China or the areas with similar ecologies.

Previously, the use of SAP for the amendment of agricultural soils was considered not economical. The application of SAP at our recommendation (15 kg ha^{-1}) will cost an additional 75 USD ha^{-1} (15 kg × 5 USD), whereas, it increased grain yield by 37.5%. Moreover, SAP can retain soil moisture and fertilizer up to 5 years after application; at the same time it improves soil nutrient status and also increases quality of yield. Polymers are safe and non-toxic and reduce excessive nutrient loss from soil thereby preventing pollution of agro-ecosystem.

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