Research Article

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A lysimeter study of nitrate leaching, optimum fertilisation rate and growth responses of corn (*Zea mays* L.) following soil amendment with water-saving super-absorbent polymer

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Abstract

BACKGROUND: Nitrate leaching and the resulting groundwater contamination from intensive cereal production has become a major concern for long-term farmland efficiency and environmental sustainability in northern China. The aim of this study was to evaluate a water-saving super-absorbent polymer (SAP) for minimising NO_3^- leaching from soil and optimising corn growth and yield. Thirty-six undisturbed soil lysimeters were installed in a field lysimeter facility in drought-affected northern China to study the growth and yield characteristics of summer corn (*Zea mays* L.) as well as the amount of NO_3–leaching losses under different fertiliser (standard, medium or 75% and low, or 50% of conventional fertilisation rate) and SAP (control, 0; level-1, 15 kg ha^{-1} and level-2, 30 kg ha^{-1}) treatments.

RESULTS: Corn yield fell by 19.7% under medium and 37.7% under low fertilisation; the application of SAP increased yield significantly by 44.4% on level-1 and 80.3% on level-2. Similarly, plant height, leaf area, number of grains as well as protein, soluble sugar and starch contents in the grain also increased with SAP treatment. Application of SAP at 30 kg ha^{-1} plus half of conventional fertilisation can reduce maximum (64.1%) nitrate leaching losses from soil.

CONCLUSIONS: Application of SAP at 30 kg ha^{-1} plus only half the amount of conventional fertiliser rate (150 kg urea, and 50 kg each of superphosphate and potassium sulfate) would be a more appropriate practice both for minimising nitrate leaching and sustainable corn production under the arid and semiarid conditions of northern China.

Keywords: corn; drought stress; lysimeter study; optimum fertilisation; super-absorbent polymer

INTRODUCTION

In arid and semiarid regions of northern China, serious water deficits and deteriorating environmental quality are threatening agricultural productivity and environmental sustainability. There is an increasing interest in using reduced rates of inorganic fertiliser along with water-saving super-absorbent polymer (SAP) for the production of field crops (such as corn). China is one of the world's most water-deficient economies and the scarcity of water 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.

The North China Plain (NCP) is one of the most important wheat and maize production areas in China. 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.[1] Irrigation is critical for maintaining high crop yield, especially in northern China, where about 75% of the agricultural land is irrigated, consuming 70–80% of the total water resource allocation in the region.[1] In recent years, however, increased water deficits associated with over-use of surface water, declining groundwater levels, water pollution, and soil salinisation are threatening the sustainability of agricultural production in the region.[1–3] 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 poor irrigation practices.[2,3]

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On the other hand, fertiliser consumption in China is also challenging the acceptance limit of resource and environment. Excessive application of inorganic fertiliser in China has become a 'fear factor' for long-term farmland efficiency and environmental sustainability. In arid and semiarid regions of NCP (double cropping wheat and corn areas), there is a common trend of excessive fertilisation (about 600 kg ha^{-1}) for better crop production and some recent studies[4–6] have shown that much of the applied fertiliser was lost through leaching, resulting in serious environmental hazards, including soil acidification, heavy metal contamination and greenhouse gas emission.

Nitrate (NO_3^-) leaching and groundwater contamination have been shown to be related to N fertiliser use in agricultural land worldwide.[7] Nitrogen fertilisers are necessary for profitable cereal production but there is concern that excessive rates may have adverse effects on groundwater quality.[8] About 90–98% of nitrogen leached from soil is in nitrate form. Furthermore, part of the nitrate is converted into the more harmful (NO_2) form, nitrite. The most important role influencing nitrogen leaching was the differing amounts of nitrogenous fertiliser applied.[7,9–11] In China, research has been conducted to determine NO_3^- contamination of groundwater in the North China Plains, which showed that about 45% agricultural land of the regions exceeded the World Health Organization drinking water standard (11.3 mg N L^{-1}), with the highest NO_3^- N concentration being 113 mg L^{-1}.[12,13]

Over-use of N fertiliser has already induced significant acidification in major Chinese croplands. From the 1980s to the 2000s, soil pH has declined across China by 0.13 to 0.80 pH units with the anthropogenic acidification driven by N fertilisation 10 to 100 times greater than that associated with acid rain.[14] Thus the acidification of soils from the use of excessive levels of N fertilisation will obviously impact negatively in the future sustainable crop production in China.

The N fertiliser use efficiency in China ranges from 30 to 35% compared with 45% in developed countries. The P fertiliser use efficiency in china is also as low as 10–20%. Based on the amount of fertiliser use in the field, a reduction of 10% of applied N fertilisers and 20% of P fertilisers could save 10.4 and 13.7 billion Yuan (1 Chinese Yuan = 0.15 USD) annually. Taking into consideration concerns about the sustainability of input-intensive agriculture and the economic, ecological and environmental effects of inorganic fertiliser over-use, it is clear that over all application should be reduced.

Soils in the NCP areas are mostly characterised by low water-holding capacity, high evapo-transpiration and excessive leaching of the scanty rainfall, leading to poor water and fertiliser use efficiency by crops. As a result, much of the double-cropped wheat and summer corn area (approximately 20–50%) in the north part of the NCP, including Beijing, Tianjin and Hebei, has now been replaced by mono-cropped spring corn areas.[15,16] Agricultural scientists and planners in the area are being confronted with the task of developing timely and viable alternative soil–water–crop management systems to counteract the current downward trends in environmental degradation and agricultural productivity.

The application of water-saving super-absorbent polymers (SAPs) to the soil could be an effective way to increase the efficiency of both water and nutrient use in crops.[17,18] When polymers are incorporated with 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 and nutrient supply.[19] Johnson[20] reported an increase of 171–402% 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.[19,21] The incorporation of super-absorbent polymer with soil improved soil physical properties,[22] enhanced seed germination and emergence,[23] crop growth and yield[24] and reduced the irrigation requirement of plants.[25,26] The use of hydrophilic polymer materials as carrier and regulator of nutrient release was helpful in reducing undesired fertiliser losses, while sustaining vigorous plant growth.[27]

Three classes of SAP are commonly used and are classified as natural, semi-synthetic and synthetic polymers.[27] Synthetic polyacrylamide with a potassium salt base manufactured by Beijing Hanlisorb Polywater Hi-tech. Co. Ltd used for this experiment is a cross-linked polymer developed to retain water and fertiliser in the agricultural and horticultural sector. Earlier, polymers were not used in agriculture due to their high prices. Recently, many polymer industries have developed around northern China and the prices have become comparatively cheaper (about 5 USD kg^{-1}); on the other hand, excessive application of fertiliser leads to an increase in compound (granular) fertiliser price (about 0.4 USD kg^{-1}). Polymers are safe and non-toxic and will finally decompose to carbon dioxide, water, ammonia, and potassium ions, without any residue.[27] Thus, the application of SAP along with a reduced rate of compound fertiliser in agriculture may be a viable water- and fertiliser-saving technology in arid and semi-arid regions of northern China. The polymers can retain soil moisture and fertiliser up to 5 years after application, which could also bring some additional economic and environmental advantages. Although the manufacturer's recommended rate of SAP for corn production varied between 15 and 30 kg ha^{-1}, our previous study has proved that 30 kg ha^{-1} is more appropriate for the areas around northern China. However, there is no particular scientific study to evaluate the amounts of nutrient leaching losses from soil and the amount of fertiliser to be saved if polymers were applied in the field. Therefore, our main objective was to study leaching loss and fertiliser saving properties of SAP to provide a recommended or reduced fertiliser and SAP ratio to be applied for sustainable summer corn production in northern China or other areas with similar ecologies.

MATERIALS AND METHODS

Experimental site

The study was conducted at the National Experimental Station for Precision Agriculture, Xiaotangshan (40° 10′ N, 116° 27′ E), Beijing, P. R. China. The climate in this area is a continental type and winter temperatures can be as low as −25 °C and summer temperature can rise above 40 °C; total rainfall is about 543 mm, being concentrated mainly in June–July. The soil was loamy sand and the background characteristics of the experimental plot, determined at the beginning of the experiment are presented in Table 1.

Soil lysimeter sampling and preparation

Thirty-six large, undisturbed soil monolith lysimeters (35 cm diameter, 150 cm depth and surface area 962.5 cm^2) were collected from a corn field of the National Experimental Station for Precision Agriculture, Beijing. The collection of undisturbed soil monolith lysimeters followed the procedure described in Cameron *et al.*[28] Each lysimeter casing consisted of a polyvinyl chloride (PVC) cylinder (35 cm internal diameter, 38 cm external diameter and

Table 1. Physical and chemical properties of the soil used for this study

Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Bulk density (g cm^{-3})	Total N (g kg^{-1})	Available K (mg kg^{-1})	Available P (mg kg^{-1})
0–20	17	20	63	1.39	86.2	83.5	21.5
20–40	19	22	59	1.41	54.1	78.3	18.3
40–60	23	23	54	1.45	26.8	71.2	13.7
60–80	31	21	48	1.51	17.5	54.7	8.1
80–100	37	22	41	1.54	13.3	32.1	4.3
100–120	41	26	33	1.58	11.4	23.6	3.4
120–140	41	26	33	1.58	9.8	17.4	3.2

150 cm in depth) (Fig. 1). The collection of lysimeters involved placing a PVC cylinder casing on the soil surface, digging around the casing, making sure to minimise disturbance to the soil inside, and gradually pushing the casing down by small increments. Once the casing had reached the desired depth (145 cm), the soil monolith was cut at the base with a cutting plate, secured on the lysimeter casing, and lifted out of the collection site. The gap between soil core and PVC casing was filled with liquefied petroleum jelly (medical Vaseline, whose melting point is 45 °C); once the jelly solidified, it formed an effective seal to prevent edge flow.[28] Twenty-five centimetres of soil from the base of each lysimeter was removed and filled by coarse sand (15 cm) and stone (10 cm) to enhance drainage. The basal end of lysimeter was closed by a PVC cap (38 cm internal diameter, 42 cm external diameter and 30 cm high). The lysimeters were transported to a field trench lysimeter facility (5 m long, 4 m wide and 2 m deep) at the National Experimental Station for Precision Agriculture.

The lysimeters were placed on top of PVC base plates (38 cm external diameter and 50 cm high). Once the lysimeters were installed in the trench facility, the surface of the lysimeters was at the same level as the rest of the field to ensure normal field plant growing conditions. Leachates were collected from each lysimeter in a plastic container, which was connected through a flexible plastic tube to the drainage outlet at the basal cap of each lysimeter. Each lysimeter contained six holes (30, 50, 70, 90 and 110 cm from upper case) to access a time domain reflectometry (TDR) probe and monitor soil nutrients status. The holes were sealed using rubber stopper after each measurement. The lysimeters were assembled between March and April 2010 and the experiment began on 15 June 2010.

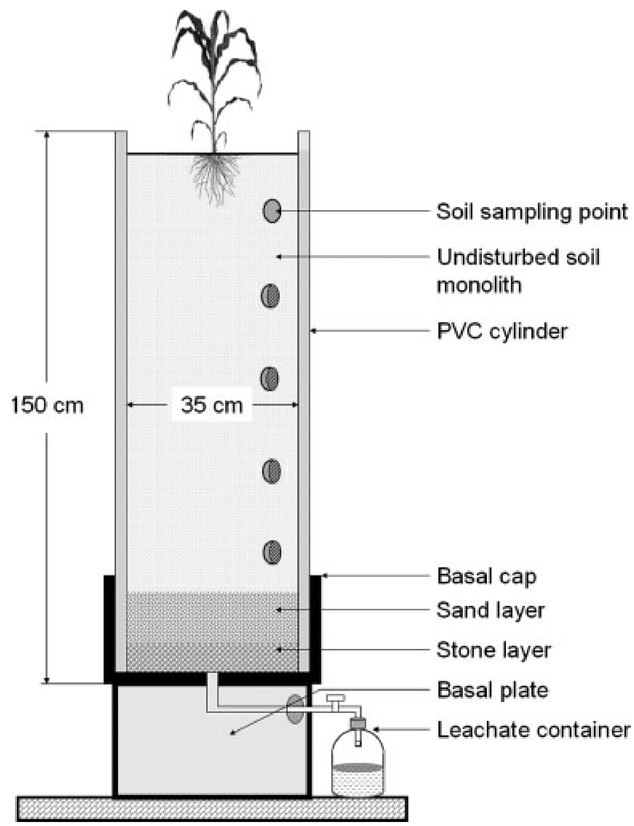

Figure 1. Schematic diagram of the lysimeter.

Treatments and maintenance

Super-absorbent polymer (granular) was applied to 20 cm depth into the lysimeter during seed sowing at 15 (level-1) and 30 kg ha^{-1} (level-2), whereas the control pots received only fertiliser but no SAP. The conventional application rate (ha^{-1}) of inorganic fertilisers for the experimental area was 300 kg urea (N), and 100 kg each of superphosphate (P) and potassium sulfate (K), which was considered as the standard application rate. The experiments were conducted under three fertilisation levels (conventional standard rate, 75% of standard rate or medium rate, and 50% of standard rate or low rate). The three SAP application rates and three fertiliser regimes were combined into a total of nine treatments. The treatments were replicated four times and arranged into a completely randomised design. Jing Dan 28, a commonly grown corn variety (*Zea mays* L.) in northern China was used for the experiment. Seeds were directly sown into the lysimeter on 15 June and harvested on 21 September in 2010. After emergence, seedlings were thinned to one stand per lysimeter.

Nitrogen (urea, 46% N) was split into base and dressing applications, and phosphate (superphosphate, 5.2% P) and potassium (potassium sulfate, 41.4% K) fertilisers were applied as base fertiliser. Irrigation was applied immediately after the N application according to standard practice in the region.

An automatic weather station was installed in the experimental field (near to the lysimeter facility) to record daily air temperature, rainfall and relative humidity during corn growing period (Fig. 2). Air temperature ranged from 5.6 to 40.7 °C and mean temperature was 25.0 °C. Total precipitation was 298.7 mm in 30 rainy days which was 51.3 mm lower than corn requirements.[1] Relative air humidity (daily average) ranged from 38.6 to 89.9% and mean value was 68.6%. Total irrigation was 60 mm in three spells which was maintained by observing drought status and plant requirements.

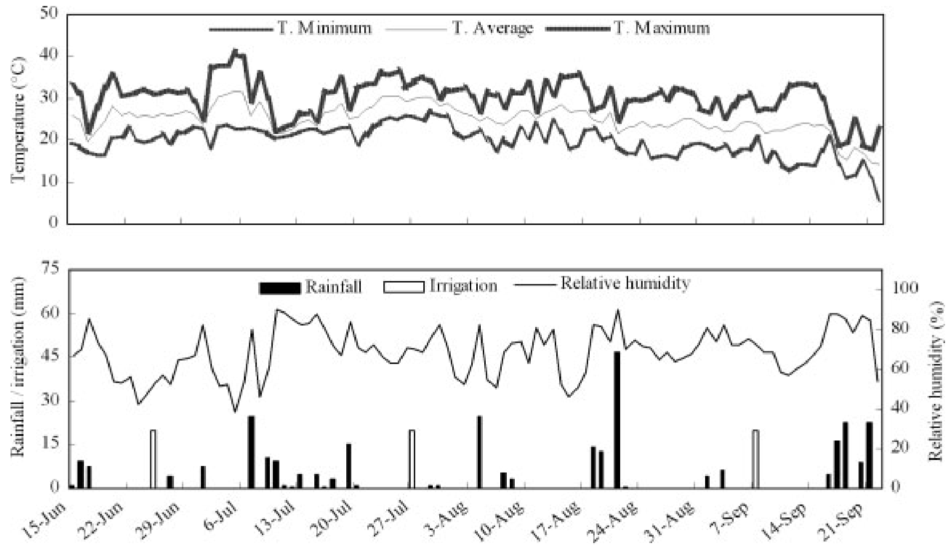

Figure 2. Daily air temperature, rainfall and relative humidity during corn growing season (15 June to 21 September, 2010).

Phenological measurements and calculation

Determination of plant growth (plant height, leaf area, grain yield and biomass accumulation) was carried out during harvest. Harvested samples were oven dried for grain yield and biomass determination. The (1000) grain weight was calculated from randomly sampled grains after harvest. Harvest index was calculated as the ratio between grain yield and shoot biomass.

Grain quality determination

Dried samples were ground and passed through a 1 mm sieve before analysis. Nitrogen content (%) was determined by the Kjeldhal method[29] and crude protein (CP) content was obtained by multiplying the Kjeldahl N values by 6.25. Starch and soluble sugar contents were also determined according to standard procedures.[29]

Soil moisture measurement

TDR was used to monitor temporal changes in soil water. The time domain reflectometry probe was inserted through the access hole and data were collected at 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, 80–100 cm and 100–120 cm depths from the lysimeter. The TDR access hole was sealed using a rubber stopper after each measurement. Soil moisture contents were measured once in a week over the corn growing period.

Leachate collection and analysis

Leachate samples were collected at 7-day intervals. The volume of leachate was recorded for each lysimeter and a subsample of 10 mL was immediately filtered and stored at 4 °C until analysis. Nitrate-N was determined using the UV spectrophotometric screening method. The total NO_3^- N leaching losses were calculated based on NO_3^- N concentrations in the leachate collected from each lysimeter and the volume of total drainage.

Statistical analysis

An analysis of variance was performed using the STATEVIEW (SAS Institute Inc., Cary, NC, USA) software to statistically partition the effect of super-absorbent polymer rate and fertiliser. Treatment means were compared using the Fisher's protected least significant differences (LSD) at the 5% level of probability.

RESULTS

Yield and yield components

Corn height was reduced significantly by 12.2% under medium and 17.9% under low fertilisation (Table 2). Across the fertilisation regimes, SAP increased plant height by 9.3 and 20.9% for level-1 (15 kg ha^{-1}) and level-2 (30 kg^{-1}) respectively. The corn leaf area was also reduced by 12.2 and 21.3% under medium and low fertilisation compared with standard rate (Table 2). The application of SAP substantially increased the leaf area by 12.2 on level-1 and 21.9% on level-2. Stem diameter decreased by 7.3 and 10.2% under medium and low fertilisation compared with standard rate and it increased following SAP treatment by 6.3 and 18.2% under level-1 and level-2 (Table 2). The number of grains per plant increased significantly by 11.7 and 19.9% following SAP applications (Table 2) and the highest number was obtained under standard fertilisation. Grain weight among the different treatments was lower under medium and low fertilisation. Although no marked changes were noted in grain weight following the application of SAP at level-1, grains with SAP level-2 were 14.0% heavier than those not treated.

The above-ground biomass of corn treated with SAP at level-1 and level-2 increased significantly by 27.3 and 53.0% with the highest value under standard fertilisation (Fig. 3). Compared with the standard fertiliser rate, the above-ground biomass was reduced by 13.7% under medium and 29.8% under low fertilisation. Grain yield was reduced by 19.7 and 37.7% under medium and low fertilisation compared with standard rate and application of SAP increased it significantly by 44.4% on level-1 and 80.3% on level-2 (Fig. 3).Among the fertiliser regimes, the application SAP at level-1 increased grain yield by 44.3, 32.9 and 62.2% for standard, medium and low fertiliser rates; under level-2, the corresponding increases were 64.7, 73.7 and 120.1%. The harvest index (Fig. 3) reduced under medium and low fertilisation compared with standard rate and the application of SAP increased it significantly by 14.5 and 19.6% at level-1 and level-2 respectively.

Grain quality

Crude protein (CP) contents in the grain increased only slightly following SAP application at level-1 but significantly by 16.7% under level-2 (Table 3). Among the fertilisation regimes, the highest CP was obtained at the standard rate, being 5.3% greater

Table 2. Plant height, leaf area, stem diameter, number of grains per plant and 1000 grain weight of corn under different fertilizer and super-absorbent polymer treatments

Treatment	Plant height (cm)	Leaf area (m^2)	Stem diameter (cm)	Grains/plant	1000 grain weight (g)
Fertilisation					
Standard	185.8 ± 5.5	0.50 ± 0.14	1.91 ± 0.043	400.7 ± 10.6	240.9 ± 4.6
Medium	163.2 ± 4.8	0.43 ± 0.12	1.77 ± 0.055	382.5 ± 10.8	225.8 ± 6.5
Low	152.3 ± 5.1	0.39 ± 0.14	1.71 ± 0.044	349.3 ± 10.2	207.6 ± 5.5
Super-absorbent polymer					
Without	151.8 ± 4.9	0.39 ± 0.15	1.66 ± 0.043	341.5 ± 9.7	211.2 ± 6.8
Level-1 (15 kg ha^{-1})	165.9 ± 5.6	0.44 ± 0.15	1.76 ± 0.035	381.5 ± 7.5	222.3 ± 6.0
Level-2 (30 kg ha^{-1})	183.5 ± 5.5	0.48 ± 0.16	1.96 ± 0.037	409.4 ± 9.8	240.8 ± 4.6
Mean	167.1	0.44	1.79	377.5	224.7
LSD (0.05)	10.66	0.025	0.088	19.85	13.32

LSD, least significant difference.

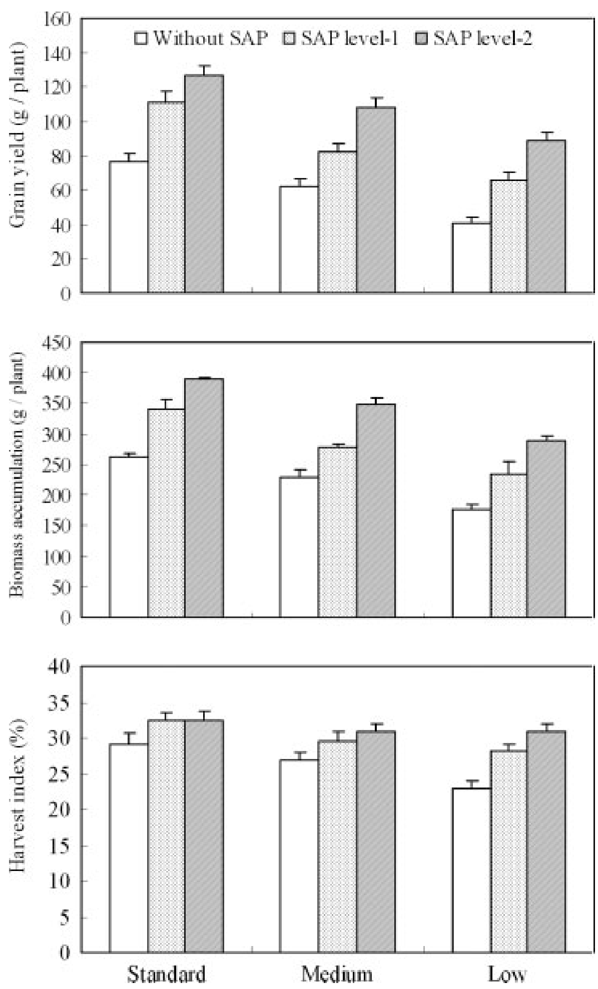

Figure 3. Grain yield, biomass accumulation and harvest index of corn at different fertiliser and super-absorbent polymer treatments. Small bars show standard errors.

than the medium rate and 16.1% ($P < 0.05$) greater than the low application rate. Soluble sugar contents in the grain decreased by 6.8 and 12.5% under medium and low fertiliser rate compared with the standard rate; the application of SAP increased it substantially by 16.9 and 22.6% for level-1 and level-2, respectively (Table 3). Starch content in the grain also reduced with the reduction in fertiliser rate and increased significantly following SAP treatments (Table 3).

Leaching losses

The cumulative volume of leached water (leachate) was reduced significantly with the application of SAP (16.3% at level-1 and 34.7% at level-2) (Table 4). Although no marked change was observed in the volume of leachate following fertiliser treatments, it increased marginally (4.5%) under medium and slightly (8.6%) under low fertilisation compared with standard rate. The total nitrate-N leaching was highest under standard fertilisation, and was reduced by 7.7% under medium and 26.2% low fertilisation (Table 4). Application of SAP significantly reduced NO_3^- N leaching by 28.3% under level-1 and as high as 56.06% under level-2. Among the fertiliser regimes, the application SAP at level-1 reduced NO_3^--N leaching loss by 23.6 under standard rate, 31.7 under medium rate and 30.1% under low fertiliser rate; at level-2 the corresponding reductions were 48.4, 57.0 and 64.1%.

Soil moisture content

The average soil moisture content at different depths in the lysimeter over the corn growing season (Table 5) was lower at the surface (0 to 20 cm) and comparatively increased with the depth when no polymer was added. A remarkable increase in soil moisture content was observed at 0 to 20 cm and 20 to 40 cm depth in the soil following SAP treatments. Average soil moisture content at other depths (except 0 to 40 cm depth) was almost same and no marked change was noted for SAP treatments. No significant changes in soil moisture content were noted among the fertiliser treatments.

DISCUSSION

Super-absorbent polymers (SAPs) have been used as water-retaining materials in the agricultural and horticultural fields[20,24,27,30] because when incorporated with soil, they can retain large quantities of water and nutrients. The stored water and nutrients are released slowly as required by the plant to improve growth under limited water supply[23,24,31] as our data have shown (Table 2, Fig. 3) under different fertilisation treatments.

TDR is a highly accurate and automated method for determination of soil water content[32] as it is easy to use and provides a

Table 3. Variation in crude protein, soluble sugar and starch content in corn grain under different super-absorbent polymer and fertilizer treatments

Treatment	Crude protein (%)	Soluble sugar (%)	Starch (%)
Fertilisation			
Standard	8.88 ± 0.28	7.65 ± 0.23	73.49 ± 1.90
Medium	8.41 ± 0.31	7.13 ± 0.34	69.29 ± 1.35
Low	7.45 ± 0.32	6.69 ± 0.34	65.22 ± 1.42
Super-absorbent polymer			
Without	7.62 ± 0.35	6.15 ± 0.88	63.26 ± 1.88
Level-1 (15 kg ha^{-1})	8.22 ± 0.26	7.19 ± 0.77	70.84 ± 1.71
Level-2 (30 kg ha^{-1})	8.89 ± 0.33	8.14 ± 0.59	73.89 ± 1.82
LSD (0.05)	0.82	0.57	3.70

LSD, least significant difference.

Table 4. Amount of leachate, nitrate concentration in the leachate and total amount of nitrate leached from the lysimeter under different fertiliser and super-absorbent polymer treatments

Treatment	Amount of leachate (L)	Nitrate conc. (mg L^{-1})	Total nitrate leaching (mg)
Fertilisation			
Standard	2.38 ± 0.14	45.98 ± 2.21	109.4 ± 9.47
Medium	2.49 ± 0.16	39.75 ± 1.83	98.9 ± 10.89
Low	2.59 ± 0.16	30.66 ± 2.22	79.4 ± 9.69
Super-absorbent polymer			
Without	3.00 ± 0.09	45.83 ± 2.14	137.5 ± 5.64
Level-1 (15 kg ha^{-1})	2.51 ± 0.07	39.17 ± 1.90	98.3 ± 4.64
Level-2 (30 kg ha^{-1})	1.96 ± 0.12	31.39 ± 2.51	61.5 ± 4.85
Mean	2.49	38.79	99.1
LSD (0.05)	0.28	3.45	10.94

LSD, least significant difference.

Table 5. Soil moisture content (vol.%) at different depths in the lysimeter under different fertiliser and super-absorbent polymer (SAP) treatments

	Soil depth (cm)					
Treatment	0–20	20–40	40–60	60–80	80–100	100–120
Without SAP						
Stand. fertiliser	6.4	11.2	13.2	14.5	17.2	19.9
Med. fertiliser	5.93	12.2	14.0	15.2	17.0	20.6
Low fertiliser	6.74	10.3	12.6	14.5	17.8	20.
Mean	6.3	11.2	13.2	14.7	17.3	20.3
SAP (level-1)						
Stand. fertiliser	8.28	15.1	13.7	15.5	18.1	20.3
Med. fertiliser	8.2	14.0	14.9	15.1	17.3	20.3
Low fertiliser	8.85	13.7	14.4	14.3	17.4	21.8
Mean	8.4	14.3	14.3	14.9	17.6	20.8
SAP (level-2)						
Stand. fertiliser	10.8	19.3	13.1	14.8	18.4	20.8
Med. fertiliser	11.1	18.4	11.8	15.6	17.5	21.2
Low fertiliser	11.3	17.3	13.3	16.2	18.3	21.7
Mean	11.0	18.3	12.7	15.8	18.1	21.3

reliable result in sandy soil.[33] During our experiments, soil moisture content at 0–40 cm depth was higher with SAP possibly due to storage of water inside the polymer[20,21,24,27] or the reduction in evaporation in presence of polymer particles.[25] Application of SAP could conserve different amounts of water in itself thereby increasing the soil's capacity for water storage, ensuring more available water; thus plant growth and yield increased under water stress.[34]

Application of SAP could be an effective management practice for corn cultivation in soils characterised by low water-holding capacity where rain or irrigation water and fertiliser often leach below the root zone within a short period of time, leading to poor water and fertiliser use efficiency by crops.[21,24] Under this situation excessive fertilisation would not bring any progressive change in crop performance and may rather cause some negative impact on the environment.

When aqueous nutrient-containing solutions are used to hydrate a polymer, a considerable amount of nutrient enters the polymer structure during expansion.[35,36] Hydrophilic polymers generally contain micro-pores that allow small molecules (such as NH_4) to diffuse through the hydrogel.[37] 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. Mikkelsen *et al.*[38] found that addition of polymer to the fertiliser solutions reduced N leaching losses from soil columns by as much as 45% during the first 4 weeks in heavily leached conditions compared with N fertiliser 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 fertilised with polymer compared with fertiliser alone. In a similar study, Magalhaes *et al*.[39] also found a remarkable reduction in NH_4, P and K leaching due to the presence of the polymer. Our result also showed a remarkable reduction in NO_3 leaching in presence of SAP (Table 4); at the same time protein content in the grain also increased (Table 3).

Differences in the responses of corn subjected to varying SAP application rates were evident during our observation. Although grain yield was reduced by 19.7% under medium and 37.7% under low fertilisation, the application of SAP increased it significantly by 44.4% on level-1 and 80.3% on level-2 (Fig. 3). Similarly, other growth parameters (Table 2) and grain quality (Table 3) also increased following SAP application.

Considering the trends in growth reduction (qualitative and quantitative) due to fertiliser reduction and the progressive influence of SAP on those parameters, it was clear that the application of SAP at 15 kg ha^{-1} (level-1) plus 75% of standard fertilisation or SAP at 30 kg ha^{-1} (level-2) plus 50% of conventional fertilisation could both achieve same yield as conventional fertiliser rate. Although the SAP level-1 (15 kg ha^{-1}) and SAP level-2(30 kg ha^{-1}) rates increased corn yield and harvest index, we suggest that the level-2 or 30 kg ha^{-1} with half of the conventional fertiliser rate would be more appropriate for corn cultivation, because it can reduce maximum (64.1%) nitrate leaching from the soil. Also in some cases, SAP level-1 may not maximise crop growth and yield under medium or low fertilisation level (Table 3). Application of SAP at 30 kg ha^{-1} plus only half the amount of conventional fertiliser rate (150 kg urea, and 50 kg each of superphosphate and potassium sulfate) would be a more appropriate practice both for minimising nitrate leaching and sustainable corn production and this model could change the fertilisation strategy in northern China.

Previously, the use of SAP for the amendment of agricultural soils was considered not economical. The application of SAP at our recommendation (30 kg ha^{-1}) will cost an additional 150 USD ha^{-1} (30 kg $\times$ 5 USD), whereas, it can save initially half the fertiliser cost or 60 USD ha^{-1} (market price of 150 kg urea, 50 kg superphosphate and 50 kg potassium sulfate). Moreover, SAP can retain soil moisture and fertiliser up to 3–5 years after application; at the same time it also increases quantity and quality of yield. Polymers are safe and non-toxic, they also reduce excessive nitrate loss from soil thereby preventing pollution of agro-ecosystem.

CONCLUSION

The application of SAP conserved different amounts of water and fertiliser and improved plant growth and yield under limited fertilisation. Application of SAP at 30 kg ha^{-1} plus only half the amount of conventional fertiliser rate (150 kg urea, and 50 kg each of superphosphate and potassium sulfate) was more appropriate for corn growth and productivity; at the same time it could reduce nitrate loss from the soil by 64.1%. Use of super-absorbent polymers with reduced fertilisation is a promising water and fertiliser saving strategy for the arid and semiarid regions of China or other areas with similar ecologies.

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