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Evaluation of effects of water-saving superabsorbent polymer on corn (*Zea mays* L.) yield and phosphorus fertilizer efficiency

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Abstract: There is growing interest in using a reduced rate of mineral fertilizer along with water-saving superabsorbent polymer (WSAP) for field crop production in arid and semiarid regions of the world. The overall objective of this study was to evaluate the effects of hydrogel applications on the phosphorus fertilizer efficiency parameter, yield, and selected physiological properties of corn (*Zea mays* L.) grown at different levels of water deficiency in greenhouse conditions. The experimental design consisted of 3 completely randomized blocks in a factorial arrangement, with 9 hydrogel doses (0%, 0.01%, 0.02%, 0.04%, 0.08%, 0.12%, 0.2%, 0.4%, and 0.6%), 4 phosphorus fertilizer doses (0, 80, 160, and 240 kg ha^{-1}), and 4 water deficiency levels (50%, 65%, 80%, and 100%). Overall, 432 pots were used in this study. We found that the irrigation interval of 0.0% WSAP (control) application treatment at water deficient conditions (WDC 50%) was 6 days, although this value could be increased to 11 days with 0.4% WSAP application treatment. The highest yield was obtained from 0.40% WSAP with 240 kg ha^{-1} P application dose at 35% deficient irrigation conditions according to leaf relative water content, the chlorophyll reading value of corn plants, and P fertilizer efficiency parameters such as agronomic efficiency, physiological efficiency, use efficiency, and apparent recovery efficiency values. These findings suggest that the application of 0.40% WSAP with 240 kg ha^{-1} P and economic soil management practice could provide an efficient corn production operation in drought-affected regions such as eastern Turkey and other areas with similar ecologies.

Key words: Corn, fertilizer efficiency, phosphorus, superabsorbent polymer, water deficiency

1. Introduction

Water availability in soil is key for fertilizer use efficiency and increased crop yields (Ghooshchi et al., 2008). Therefore, improving the effectiveness of water application and optimum use of water and nutrient sources have been considered as the main targets for stable agriculture in dry and semidry regions. According to this approach, one of the ways to increase fertilizer use efficiency with limited water supply in soil is application of a superabsorbent polymer that provides water and necessary nutrients to crop roots during the growth period of the plant (Pawlowski et al., 2009). Superabsorbent polymers (SAPs), or hydrogels, are loosely cross-linked, three-dimensional networks of flexible polymers, with few width-wise connections (Kiatkamjornwong, 2007). SAPs are able to absorb and store hundreds of times their dry weight in water (Rafiei and Nourmohammadi, 2013).

SAPs increase the capacity of water storage in soil (Akhter et al., 2004; El-Hady and Wanas, 2006; Sarvas et al., 2007) by decreasing water and nutrient percolation below the root zone. This leads to a decrease in water evaporation from the surface (Sivapalan, 2001; Akhter et al., 2004; Sarvas et al., 2007) and an increase in the aeration of the soil (Orzeszyna et al., 2006).

Koupai and Sohrab (2006) estimated that 2–8 g of hydrogel per 1 kg of soil increased the moisture content by roughly 100%–260%, respectively, in comparison with the control. Poormeidany and Khakdaman (2006) reported that the use of a polymer during planting reduced the irrigation rate and intervals with acceptable seedling survival rate. The addition of a polymer to peat decreased the water stress of the plant and increased the time to wilt (Karimi et al., 2009). The incorporation of SAPs into the soil improved its physical properties; enhanced seed germination and emergence, crop growth,

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and yields (Yazdani et al., 2007); and reduced the irrigation requirements of plants (Taylor and Halfacre, 1986; Blodgett et al., 1993).

The main objective of this study was to evaluate the effectiveness of a water-saving superabsorbent polymer (WSAP) on the P fertilizer use efficiency in corn plants grown in soil with different irrigation conditions such as water deficit, moderate water, adequate water, and excessive water.

2. Materials and methods

2.1. Plant material and growth conditions

Corn plants (*Zea mays* L. 'OSSK-664') were grown in pots in controlled greenhouse conditions in Erzurum, Turkey. Soil samples were taken from a depth of 0–30 cm from agricultural fields in Erzurum Province (39°55′N, 41°61′E) of Turkey and were dried indoors until they could be crumbled to pass through a 4-mm sieve for the pot experiment and a 2-mm sieve for analysis of physical and chemical properties. The soil was classified as Aridisol according to Soil Survey Staff taxonomy (Soil Survey Staff, 1992), with parent materials mostly consisting of volcanic, marl, lacustrine residual, and transported materials. Polyethylene pots (50 cm in diameter and 70 cm in depth) were filled with 5 kg of soil. The experimental design consisted of three completely randomized blocks in a factorial arrangement, with 9 hydrogel doses (0%, 0.01%, 0.02%, 0.04%, 0.08%, 0.12%, 0.2% 0.4%, and 0.6% w/w), 4 phosphorus fertilizer doses (0, 80, 160, and 240 kg ha^{-1}), and 4 water deficiency levels (50%, 65%, 80%, and 100% available water content at 60-cm root depth). Therefore, a total of 432 pots were used in the experiment. The polymer was Stockosorb K 410 (Stockhausen, Krefeld, Germany), which is a highly cross-linked polyacrylamide with approximately 40% of the amide group hydrolyzed to carboxylic groups. Prior to hydrogel and P applications, soil samples were taken from each pot, and select physical and chemical properties were determined (Table 1). Initially, the soil moisture content of all pots was adjusted to field capacity. Field capacity was determined at 0.33 atm pressures using a membrane extractor (Soil Moisture, Santa Barbara, CA, USA) as described by Richards (1948). Measured values were also calibrated with a TDR (TDR 300, Spectrum Technologies, USA), and readings were made and used in subsequent soil water content measurements. The total usable soil water content within the top 0.6 m of the soil profile was 119.9 mm. To impose water deficient conditions (WDC 50%), water moderate conditions (WMC 35%), water adequate conditions (WAC 20%), and water excess conditions (WOC 0%), irrigation treatments consisting of 60, 78, 96, and 119 mm of water were applied to the pots, meaning that soil moisture was consumed at 60, 42, 24, and 1 mm at the effective rooting depth (0.6 m) (Allen et al., 1998).

Table 1. Some physical and chemical properties of the experimental soil (n = 10).

Properties	Value
pH (1:2.5 s/w)	7.45 ± 0.35
Organic matter (%)	1.40 ± 0.22
Total N (%)	0.12 ± 0.05
$CaCO_3$ (%)	0.82 ± 0.12
K (cmol kg^{-1})	2.42 ± 0.15
Ca (cmol kg^{-1})	12.48 ± 1.13
Mg (cmol kg^{-1})	2.12 ± 0.03
Na (cmol kg^{-1})	0.35 ± 0.01
Available P (mg kg^{-1})	5.20 ± 0.40
Electrical conductivity (dS m^{-1})	1.20 ± 0.03
Field capacity (cm^3 water cm^{-3} soil)	42.13 ± 1.80
Wilting point (cm^3 water cm^{-3} soil)	26.63 ± 0.96
Bulk density (g cm^{-3})	1.29 ± 0.02
Sand (%)	30.70 ± 1.12
Silt (%)	35.90 ± 0.95
Clay (%)	33.40 ± 1.40
Texture	Loam

Two plants were harvested for each replicate 90 days after sowing (DAS). Chlorophyll content, leaf relative water content (LRWC), membrane leakage (ML) in fresh plants, and dry weight were measured. The plant material was dried at 70 °C for 2 days to determine dry weight and P content. Plant water use efficiency was calculated and expressed as kg of marketable yield produced by each m^3 of irrigation water (Hillel, 1971).

2.2. Fertilizer use efficiency parameter

Fertilizer use efficiency can be described as agronomic efficiency (AE, kg of corn yield increase per kg of phosphorus applied), physiological efficiency (PE, kg of corn yield increase per kg of phosphorus taken up), apparent recovery efficiency (ARE, kg of phosphorus taken up per kg of phosphorus applied), and use efficiency (UE, kg of corn yield increase per kg of phosphorus applied) (Moll et al., 1982).

Agronomic efficiency (AE): AE (kg kg^{-1}) = Gf – Gu / Na, where Gf is the grain or fruit yield of the fertilized plot (kg), Gu is the grain or fruit yield of the unfertilized plot (kg), and Na is the quantity of P applied (kg).

Physiological efficiency (PE): PE (kg kg^{-1}) = BYf – Byu / Nf – Nu, where BYf is the total yield (grain or fruit and shoot) of the fertilized plot (kg), BYu is the total yield of the unfertilized plot (kg), Nf is the P uptake (grain or fruit and shoot) of the fertilized plot (kg), and Nu is the P uptake (grain or fruit and shoot) of the unfertilized plot (kg).

Apparent recovery efficiency (ARE): ARE (%) = (Nf – Nu / Na) × 100, where Nf is the P uptake (grain or fruit and shoot) of the fertilized plot (kg), Nu is the P uptake (grain or fruit and shoot) of the unfertilized plot (kg), and Na is the quantity of P applied (kg).

Use efficiency (UE): UE (kg kg^{-1}) = Gf – Gu / Na, where Gf is the total yield of the fertilized plot (kg), Gu is the total yield of the unfertilized plot (kg), and Na is the quantity of P applied (kg).

2.3. Photosynthesis

Pn, Tr, and Gs were measured using an Li-6400 Portable Photosynthesis System (LI-COR Biosciences, Lincoln, NE, USA). Leaf WUE (amount of CO_2 assimilated by the plant per unit mass of water) was measured following the Fischer and Powel methods (Fischer and Turner, 1978; Powel et al., 1984): WUE = Pn / Tr (µmol CO_2 $mmol^{-1}$ H_2O).

2.4. Soil analysis

For initial determination of physical and chemical properties of the soil, soil samples were air-dried, crushed, and passed through a 2-mm sieve before analysis. Particle size distribution was determined with a hydrometer following methods described by Page et al. (1982). Cation exchange capacity (CEC) was determined using an inductively coupled plasma spectrophotometer (PerkinElmer, Optima 2100 DV, ICP/OES, Shelton, CT, USA) after an exchange using 1 N sodium acetate (buffered at pH 8.2) and 1 N ammonium acetate (buffered at pH 7.0), as described by Sumner and Miller (1996). Total nitrogen was determined using a digestion/distillation unit according to the Kjeldahl method (Bremner, 1996), while plant-available P was determined using sodium bicarbonate with a Shimadzu UV 1208 model spectrophotometer according to the Olsen method (Olsen et al., 1954). Electrical conductivity (EC) was measured in saturation extracts according to Rhoades (1996). Soil pH was determined in 1:2 soil:water extracts using a pH meter. Calcium carbonate concentrations were determined using a calcimeter method that measures the amount of carbon dioxide released with HCl for dissolution of $CaCO_3$, as described by McLean (1982). Organic soil matter was determined using the Smith–Weldon method according to Nelson and Sommers (1982). Exchangeable cations were measured using an inductively coupled plasma spectrophotometer (Perkin-Elmer, Optima 2100 DV, ICP/OES), after an exchange using ammonium acetate buffered at pH 7 (Thomas, 1982). Physical and chemical properties of the soil are presented in Table 1.

2.5. Available soil water content and irrigation interval

For the determination of available soil water content (ASWC) and irrigation interval, the time domain reflectometry method was used, which has been proven to be quick and reliable, irrespective of soil type (Filintas, 2003).

2.6. Plant analysis

Plant samples were oven-dried at 68 °C for 48 h and ground to pass through a 1-mm sieve. Phosphorus was determined after wet digestion of dried and ground subsamples using a HNO_3-H_2O_2 acid mixture (2:3 v/v) in a microwave (Bergof Speedwave Microwave Digestion Equipment MWS-2) (Mertens, 2005a). Tissue P was determined using an inductively coupled plasma spectrophotometer (Perkin-Elmer, Optima 2100 DV, ICP/OES) (Mertens, 2005b).

2.7. Chlorophyll reading value (CRV)

A portable chlorophyll meter (SPAD-502, Konica Minolta Sensing, Inc., Japan) was used to measure the leaf greenness of the corn plants. Measurements were taken at four locations on each leaf, two on each side of the midrib on all the youngest fully expanded leaves of plants per plot (replicate), and then averaged (Khan et al., 2003).

2.8. Measurement of membrane leakage (ML)

To measure the ML, 20 leaf disks (10 mm in diameter) from the young fully expanded leaves from two plants per replicate were placed in 50-mL glass vials and rinsed with distilled water to remove electrolytes released during leaf disk excision. Electrical conductivity of the bathing solution was determined at the end of the incubation period (EC1). Vials were heated in a temperature-controlled water bath at 95 °C for 20 min, then cooled to room temperature, and the electrical conductivity was measured again (EC2). Membrane leakage was calculated as a percentage of EC1/EC2 (Shi et al., 2006).

2.9. Leaf relative water content (LRWC)

Three leaves were collected from the young fully expanded leaves of three plants per replicate. Individual leaves were first detached from the stem and then weighed to determine fresh weight (FW). To determine turgid weight (TW), leaves were floated in distilled water inside a closed petri dish. At the end of imbibition period, leaf samples were placed in a preheated oven at 80 °C for 48 h to determine dry weight (DW). Values of FW, TW, and DW were used to calculate LRWC using the equation below (Kaya et al., 2003):

LRWC (%) = [(FW – DW) / (TW – DW)] × 100.

2.10. Statistical analysis

The data were subjected to analysis of variance (ANOVA) and mean values were separated according to Duncan's multiple range tests using SPSS.

3. Results

3.1. ASWC and irrigation interval

The ASWC and irrigation interval were significantly ($P < 0.05$) influenced by WSAP application. Increasing WSAP application doses raised the ASWC value. Regression analysis allowed for determination of the maximum value (164.2 mm) from 0.39% WSAP application doses (Figure 1). The irrigation interval of 0.0% WSAP (control)

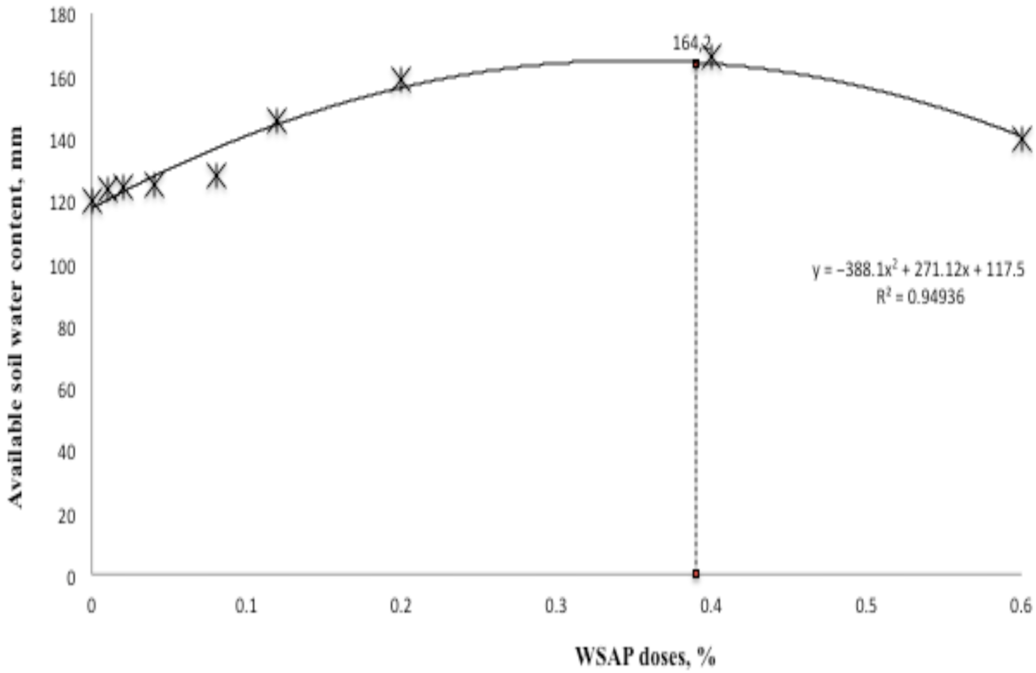

Figure 1. Effects of WSAP doses on available soil water content under different water deficiencies.

application treatment at WDC 50% was 6 days, and this value increased to 11 days with 0.4% WSAP application treatment. A similar trend was obtained from WMC 35%, WAC 20%, and WOC 0% with 0.4% WSAP application (Figure 2).

3.2. Yield of corn

The dry weight of maize plants was significantly influenced by WSAP, P application treatments, and their interactions ($P < 0.05$). The dry weight of maize plants was dramatically decreased with deficient irrigation treatment, although this reduction was reversed by P application treatments (Table 2). Maize crop yield was reduced with decreasing irrigation amounts, while maximum values of crop yield were obtained with WMC 35% treatments. Increases in dry matter production at 0, 80, 160, and 240 kg ha^{-1} P application were 28.1%, 37.5%, 47.6%, and 54.5% for WDC 50% at 0.40% WSAP application compared to the control (without WSAP and P application), respectively.

3.3. P fertilizer use efficiency parameters: AE, PE, ARE, and UE

The P leaf tissue concentration was significantly affected by both WSAP and P fertilizer applications and their interaction ($P < 0.05$). With increase of WSAP and P fertilizer treatments, P concentration increased in all deficit irrigation conditions. AE, PE, ARE, and UE of P fertilizer were significantly affected by both WSAP and P fertilizer applications. AE, PE, UE, and APR values increased in both WSAP and P fertilizer treatments with all deficit irrigation conditions, except for WOC 0%. The highest AE, PE, UE, and APR values of P fertilizer were obtained from 0.40% WSAP at WMC 35%, and 240 kg ha^{-1} P application dose.

The increasing rates of AE, PE, UE, and APR of P fertilizer at WDC 50% were 53.5%, 67.1%, 54.5%, 57.9%, 90.4%, 89.1%, and 105.7% at 0.40% WSAP application as compared to the control (without WSAP and P application), respectively (Tables 3–6).

3.4. LRWC, CRV, and ML

LRWC and CRV values of maize plants were significantly influenced by WSAP, water deficiency conditions, and their interaction ($P < 0.05$). WSAP treatment increased LRWC and CRV values. This increase varied depending on water deficiency treatment, but not on P fertilizer doses application. LRWC and CRV values of the 0.0% WSAP (control) application treatment were 44% and 32 SPAD, although these values were 70% and 55 SPAD when 0.6% (w/w) WSAP was applied, respectively (Tables 7 and 8).

The ML value of corn plants decreased with increased WSAP treatment, although P application had no effect on ML. ML value for the 0.0% WSAP (control) application treatment was 85%, but this value was 58% with 0.6% (w/w) WSAP application. The lowest value for ML was obtained from 0.6% WSAP application dose, and the decreasing rate was 31% (Table 7).

4. Discussion

There was a significant interaction effect between amount of polymer and irrigation levels on ASWC. High amounts

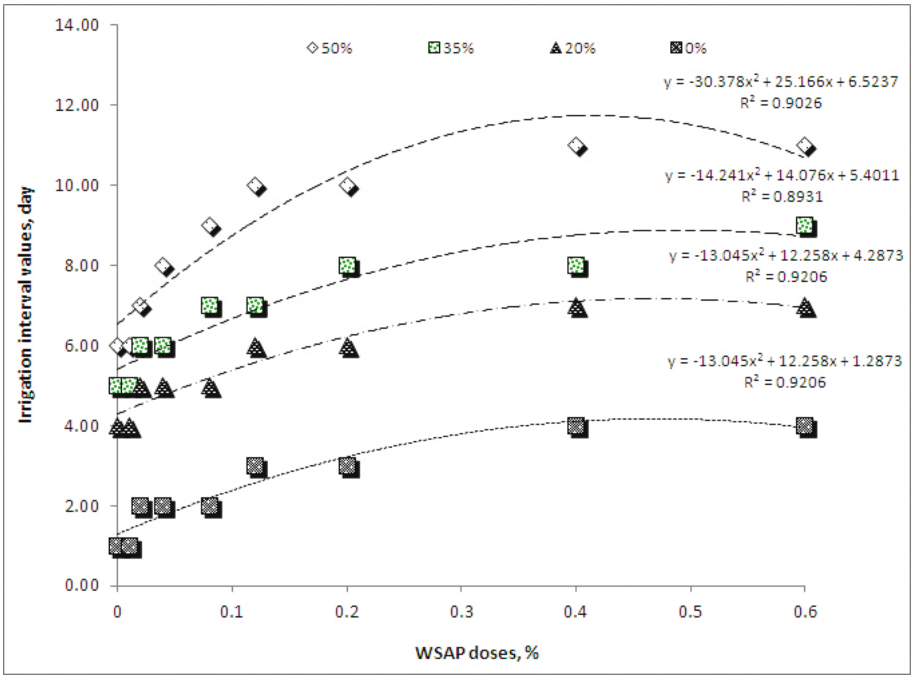

Figure 2. Effects of WSAP doses on irrigation interval values under water deficient conditions (WDC 50%), water moderate conditions (WMC 35%), water adequate conditions (WAC 20%), and water excess conditions (WOC 0%).

of polymer contributed to the highest water use efficiency. Lowest water use efficiency was observed without WSAP application treatment. When WSAP was applied, water was stored and readily available to the plant. WSAP released the water over longer periods of time, which sustained prolonged plant water and nutrient uptake. This led to decreased water use, as well as improvement of physical conditions. Additionally, this probably provided proper access to necessary nutrients for the plant. Overall, the performance of dry matter was substantially increased.

It can be concluded that the application of polymer can increase irrigation intervals for maize, which suggests that it can be planted in regions with limited water supply or irrigation.

These results show that increased water deficits result in relatively lower plant dry matter production and height, which is also evident from some of the previous studies carried out by various groups (Huttermann et al., 1999; Yazdani et al., 2007; Islam et al., 2009).

The subsequent release of nutrients is largely based on the diffusive properties of the WSAP. Therefore, plant growth, yield and quality were substantially increased following WSAP application. The higher yields and superior quality of WSAP-treated corn were possibly due to availability of soil water, increasing phosphorus use efficiency, and nutrient elements stored by the polymer.

Application of WSAP could be an effective management practice for corn cultivation in soils characterized by low water-holding capacity. In these types of areas, rain, 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. In this situation, excessive fertilization would not bring any progressive change in crop performance and may instead cause negative impacts on the environment. Application of WSAP along with inorganic fertilizer could change the fertilization strategy in arid and semiarid regions of Turkey.

Water stress causes water loss from plant tissues, which seriously impairs both membrane structure and function (Buchanan et al., 2000). The cell membrane is one of the first targets of plant stresses. Thus, the ability of plants to maintain membrane integrity in drought conditions determines drought tolerance (Vieira da Silva et al., 1974). Our ML measurements showed that membrane integrity was conserved for drought tolerance compared to susceptible varieties, which is in agreement with the findings of Martin et al. (1987) and Vasques-Tello et al. (1990), who showed that ML was correlated with drought tolerance. The leakage was due to damage to cell membranes that become more permeable (Senaratna and McKersie, 1983). This demonstrates the importance of this test in selecting among tolerant and sensitive corn plants with different water deficiencies.

In conclusion, the results indicate that ASWC and irrigation interval are significantly influenced by WSAP application. Increasing the WSAP application doses raised

Table 2. Effects of WSAP doses on dry weight of maize plants under water deficient conditions (WDC 50%), water moderate conditions (WMC 35%), water adequate conditions (WAC 20%), and water excess conditions (WOC 0%).

Water deficiency level	50%				35%				20%				0%			
	P doses, kg ha^{-1}															
WSAP doses, %	0	80	160	240	0	80	160	240	0	80	160	240	0	80	160	240
0.00	142g*	144g	145g	145g	146f	147g	147f	147f	147f D	155g C	160g B	168f A	146cd C	147e C	164c B	176b A
0.01	145f C**	146g C	168e B	174f A	163e C	164f C	188de B	194e A	183e C	183f C	210e B	217e A	149c C	149d C	171bc B	176b A
0.02	152e C	153f C	159f B	178e A	171de C	171e C	178e B	199e A	192d C	192e C	199f B	222e A	156b C	156cd C	162cd B	181ab A
0.04	155de D	164e C	170e B	180e A	174d D	184d C	190de B	201e A	196cd D	206d C	213e B	225e A	159ab D	167b C	173b B	183a A
0.08	158d C	172d B	176d B	188d A	178c D	193c C	197d B	210d A	200c D	216c C	220d B	235d A	162a C	175a B	179a A	180ab A
0.12	160d D	188c C	192c B	196c A	180c C	211b B	215c AB	219cd A	202c D	236b C	240c B	245c A	160a C	168b B	170bc AB	172bc A
0.20	167c D	190bc C	205b B	215b A	198b C	226a B	229b B	240b A	230a C	253a B	268a A	268b A	159ab B	160c B	165c A	166c A
0.40	182a D	198a C	214a B	224a A	205a D	229a C	239a B	250a A	222b C	255a B	257b B	280a A	145cd C	155cd B	159d A	160cd A
0.60	176b C	192b B	195c B	200c A	197b D	215b C	218c B	223c A	221b D	241b C	244c B	250c A	144d C	150d B	155d AB	158d A
Average	160 D	172 C	180 B	189 A	179 D	193 C	200 B	209 A	199 D	215 C	223 B	234 A	153 D	159 C	166 B	172 A
	175 C				195 B				218 A				163 D			

*Lowercase letters show significance in columns. **Uppercase letters show significance in rows.

Table 3. Effects of WSAP doses on agronomic efficiency of maize plants under water deficient conditions (WDC 50%), water moderate conditions (WMC 35%), water adequate conditions (WAC 20%), and water excess conditions (WOC 0%).

Water deficiency level	50%			35%			20%			0%		
	P doses, kg ha^{-1}											
WSAP doses, %	80	160	240	80	160	240	80	160	240	80	160	240
0.00	3.51g* A**	1.90g B	1.33e C	3.77f A	2.12g B	1.54g C	4.07e A	2.51f C	2.65d B	3.58f A	2.15c B	1.62b C
0.01	3.56g A	2.21e B	1.60d C	4.19e A	2.71e B	2.04f C	4.81d A	3.30d C	3.42f B	3.63ef A	2.24bc B	1.62b C
0.02	3.73f A	2.09f B	1.63d C	4.39e A	2.57f B	2.09e C	5.04d A	3.12e C	3.50e B	3.80d A	2.12cd B	1.65a C
0.04	4.00e A	2.23e B	1.65d C	4.71d A	2.75e B	2.11e C	5.40c A	3.34d C	3.54e B	4.07b A	2.27b B	1.67a C
0.08	4.19d A	2.31d B	1.72c C	4.94c A	2.84d B	2.21d C	5.66c A	3.46d C	3.70d B	4.27a A	2.35a B	1.65a C
0.12	4.58c A	2.52c B	1.80b C	5.40b A	3.10c B	2.30c C	6.19b A	3.77c B	3.85c B	4.10b A	2.23bc B	1.58c C
0.20	4.73b A	2.69b B	1.97a C	5.80a A	3.31b B	2.52b C	6.65a A	4.20a B	4.22b B	3.90c A	2.17c B	1.52d C
0.40	5.40a A	3.18a B	2.05a C	5.87a A	3.45a B	2.63a C	6.69a A	4.03b C	4.41a B	3.78d A	2.09d B	1.47e C
0.60	4.68b A	2.56c B	1.83b C	5.51b A	3.15c B	2.35c C	6.32b A	3.83c B	3.93c B	3.66e A	2.03e B	1.45e C
Average	4.26 A	2.41 B	1.73 C	4.95 A	2.89 B	2.20 C	5.65 A	3.51 B	3.69 B	3.87 A	2.18 B	1.58 C
	2.80 C			3.35 B			4.28 A			2.54 D		

*Lowercase letters show significance in columns. **Uppercase letters show significance in rows.

the ASWC value and irrigation interval. The control treatment in this study had an irrigation interval of 6 days. This interval was increased to 11 days with 0.4% WSAP application treatment. WSAP with P fertilizer application at different water deficiencies caused increased yield of corn and P fertilizer use efficiency parameters such as AE, PE, UE, and APR. The highest yield was obtained from 0.40% WSAP with 240 kg ha^{-1} P application dose at 35% deficient irrigation. To reach the highest yield, at least 400 kg ha^{-1} WSAP needs to be used on soil and its price is approximately 140 euro per hectare. The use of a superabsorbent polymer could be an effective means for field crop production in the arid conditions of northern Turkey or areas with similar ecologies. Application at 0.40% WSAP with 240 kg ha^{-1} P was most appropriate for corn production.

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Table 4. Effects of WSAP doses on physiological efficiency of maize plants under water deficient conditions (WDC 50%), water moderate conditions (WMC 35%), water adequate conditions (WAC 20%), and water excess conditions (WOC 0%).

Water deficiency level	50%				35%				20%				0%			
	P doses, kg ha^{-1}															
WSAP doses, %	0	80	160	240	0	80	160	240	0	80	160	240	0	80	160	240
0.00	263a* A**	222a B	167c C	152a D	256a A	250a B	222a C	204a D	238a A	227a B	182a C	149a D	333d A	331a B	248c C	225a D
0.01	256b A	213b B	185a C	147b D	229b A	190b B	165b C	131b D	195b A	162b B	141b C	112b D	382a A	317b B	276a C	219a D
0.02	256b A	204c B	182a C	139c D	229b A	182c B	162b C	124c D	195b A	155c B	138b C	106c D	382a A	304c B	271a C	207b D
0.04	250c A	182d B	172b C	133c D	223c A	162d B	154c C	119d D	190c A	138d B	131c B	102cd D	372b A	271d B	257b C	198c D
0.08	250c A	182d B	167c C	128d D	223c A	162d B	149d C	114e D	190c A	138d B	127c C	98d D	372b A	271d B	248c C	191cd D
0.12	238d A	172e B	152d C	125d D	213d A	154e B	135e C	112e D	181d A	131d B	115d C	95d D	354c A	257e B	225d C	186d D
0.20	227e A	154f B	135f C	109e D	186f A	137f B	121g C	97f D	159f A	117f B	103e C	83e D	310e A	229g B	201f C	162e D
0.40	217f A	147g B	116g C	111e C	162g A	131f B	117g C	99f D	138g A	112f B	100e C	85e D	271f A	219h B	196f C	165e D
0.60	227e A	167e B	143e C	112e D	203e A	149e B	128f C	100f D	173e A	127e B	109de C	86e D	338d A	248f B	213e C	167e D
Average	243 A	183 B	158 C	128 D	214 A	169 B	150 C	122 D	184 A	145 B	127 C	102 D	346 A	272 B	237 C	191 D
	178 B				164 C				140 D				262 A			

*Lowercase letters show significance in columns. **Uppercase letters show significance in rows.

Table 5. Effects of WSAP doses on phosphorus apparent recovery efficiency of maize plants under water deficient conditions (WDC 50%), water moderate conditions (WMC 35%), water adequate conditions (WAC 20%), and water excess conditions (WOC 0%).

Water deficiency level	50%			35%			20%			0%		
	P doses, kg ha^{-1}											
WSAP doses, %	80	160	240	80	160	240	80	160	240	80	160	240
0.00	8.10e* A**	5.44e B	3.99f C	7.35g A	4.13g B	3.00f C	6.53e A	5.50e B	4.69f C	5.55d A	4.13bc B	3.26d C
0.01	8.58de A	5.67e B	4.93e C	10.76f A	7.11f B	6.17e C	14.13d A	9.32d B	8.08e C	5.87d A	3.88c B	3.36d B
0.02	9.37d A	5.47e B	5.34d B	11.76e A	6.85f B	6.68e B	15.43d A	8.98d B	8.75e B	6.42c A	3.74c B	3.64c B
0.04	11.28c A	6.16d B	5.63d C	14.15d A	7.72f B	7.04d B	18.57c A	10.13c B	9.22d C	7.72b A	4.21bc B	3.83bc C
0.08	11.83c A	6.60d B	6.11c B	14.84d A	8.27e B	7.65cd C	19.47c A	10.85c B	10.01c B	8.10ab A	4.51b B	3.93b C
0.12	13.63b A	7.92c B	6.53c C	17.10c A	9.93d B	8.18c C	22.45b A	13.02b B	10.71c C	8.19ab A	4.71ab B	3.85bc C
0.20	15.44ab A	9.48b B	8.24a C	20.59a A	11.86b B	10.31a C	27.03a A	16.27a B	13.49a C	8.74a A	5.13a B	4.28a C
0.40	16.83a A	11.50a B	8.40a C	21.80a A	12.72a B	10.50a C	28.46a A	16.01a B	13.78a C	8.85a A	5.08a B	4.03b C
0.60	14.40b A	8.53bc B	7.42b C	18.07b A	10.69c B	9.28b C	23.71b A	14.02b B	12.15b C	7.56b A	4.56b B	3.94b C
Average	12.16 A	7.42 B	6.29 C	15.16 A	8.81 B	7.65 C	19.53 A	11.57 B	10.10 C	7.44 A	4.44 B	3.79 C
	8.62 C			10.54 B			13.73 A			5.22 D		

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Table 6. Effects of WSAP doses on phosphorus use efficiency of maize plants under water deficient conditions (WDC 50%), water moderate conditions (WMC 35%), water adequate conditions (WAC 20 %), and water excess conditions (WOC 0%).

Water deficiency level	50%			35%			20%			0%		
	P doses, kg ha^{-1}											
WSAP doses, %	80	160	240	80	160	240	80	160	240	80	160	240
0.00	18.00f* A**	9.06g B	6.04f C	18.38f A	9.19f B	6.13e C	19.38g A	10.00e B	10.50f B	18.34d A	10.24c B	7.35c C
0.01	18.25f A	10.50e B	7.25e C	20.44e A	11.75e B	8.10d C	22.89f A	13.15c B	13.57e B	18.60d A	10.68bc B	7.35c C
0.02	19.13e A	9.94f B	7.42de C	21.42e A	11.12e B	8.29d C	23.99e A	12.44d C	13.89e B	19.49c A	10.11cd B	7.52b C
0.04	20.50d A	10.63e B	7.50d C	22.96d A	11.89e B	8.38cd C	25.72d A	13.30c B	14.04d B	20.89b A	10.81b B	7.61a C
0.08	21.50c A	11.00d B	7.83d C	24.08c A	12.31d B	8.75c C	26.97c A	13.77c B	14.67d B	21.91a A	11.19a B	7.50b C
0.12	23.50b A	12.00c B	8.17c C	26.32b A	13.43c B	9.12b C	29.48b A	15.03b B	15.29c B	21.00b A	10.63bc B	7.17d C
0.20	23.75b A	12.81b B	8.96b C	28.28a A	14.31a B	10.00a C	31.67a A	16.75a B	16.75b B	20.00c A	10.31c B	6.92e C
0.40	24.75a A	13.38a B	9.33a C	28.63a A	14.94a B	10.42a C	31.88a A	16.04a C	17.50a B	19.38c A	9.94d B	6.67f C
0.60	24.00ab A	12.19c B	8.33c C	26.88b A	13.64b B	9.31b C	30.11b A	15.26b B	15.60c B	18.75d A	9.69e B	6.58f C
Average	21.49 A	11.28 B	7.87 C	24.15 A	12.51 B	8.72 C	26.90 A	13.97 C	14.65 B	19.82 A	10.40 B	7.19 C
	13.55 C			15.13 B			18.51 A			12.47 D		

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Table 7. Effects of WSAP doses on LRWC and ML of maize plants under water deficient conditions (WDC 50%), water moderate conditions (WMC 35%), water adequate conditions (WAC 20%), and water excess conditions (WOC 0%).

Water deficiency level	LRWC				ML			
WSAP doses, %	50%	35%	20%	0%	50%	35%	20%	0%
0.00	44g* D**	48f C	52g B	62f A	85a A	78a B	69a C	54a D
0.01	50f D	55e C	58f B	68e A	80b A	72b B	65b C	51b D
0.02	54e D	57de C	61ef B	77d A	77c A	69bc B	58c C	42c D
0.04	58de C	59d C	66e B	79d A	72d A	66c B	52d C	39d D
0.08	62d D	68c C	75d B	85c A	69d A	60d B	49e C	33e D
0.12	67c C	69c C	79c B	89b A	65e A	59d B	42f C	30f D
0.20	71b D	80b C	86b B	90b A	62f A	55e B	39g C	29f D
0.40	76a D	82b C	88a B	92a A	60fg A	53ef B	37g C	22g D
0.60	77a D	85a C	89a B	93a A	58g A	47f B	33h C	20g D
Average	62 D	67 C	73 B	82 A	70 A	62 B	49 C	36 D

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Table 8. Effects of WSAP doses on chlorophyll content of maize plants under water deficient conditions (WDC 50%), water moderate conditions (WMC 35%), water adequate conditions (WAC 20%), and water excess conditions (WOC 0%).

Water deficiency level	50%				35%				20%				0%			
	P doses, kg ha^{-1}															
WSAP doses, %	0	80	160	240	0	80	160	240	0	80	160	240	0	80	160	240
0.00	32e* C**	32e C	33 e B	34g A	35g	35h	36g	36h	52g C	53g B	54f A	54g A	55d	56e	56e	56d
0.01	33e D	34e C	35de B	36f A	37g C	37h C	38g B	39h A	58f C	59f B	59e B	60f A	59c B	60d B	62cd A	54d C
0.02	37d B	37d B	37d B	38e A	42f D	43g C	44f B	45g A	61e D	62e C	63d B	64e A	62c C	63c B	63c B	65c A
0.04	41c D	42c C	43c B	44d A	47e C	48f B	48e B	49f A	66d	67d	66c	67d	68a	69b	69b	69b
0.08	43c B	43c B	44c AB	45d A	51d C	51e C	52d B	53e A	70c C	71c B	73b A	73c A	69a D	71a C	73a B	74a A
0.12	55b D	56b C	57b B	58c A	57c C	58d B	59c A	59d A	72b D	73b C	75b B	76b A	65b C	68b B	69b A	69b A
0.20	56b C	59a B	59ab B	60b A	63b D	64c C	65b B	66c A	73b D	74b C	75b B	77b A	60c D	61c C	63c B	65c A
0.40	59a B	59a B	62a A	62a A	64ab D	68a C	69a B	70a A	75a C	77a B	79a A	79a A	58c D	59d C	61d B	63c A
0.60	55b C	57ab B	60ab A	60b A	65a C	66b B	68a A	68b A	74a B	76a A	77ab A	76b A	50e D	53f C	55e B	56d A
Average	46	47	48	49	51	52	53	54	67	68	69	70	61	62	63	63
	47 D				53 C				68 A				62 B			

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