HortScience 56(12):1486–1493. 2021. https://doi.org/10.21273/HORTSCI16089-21

Cornstarch-based, Biodegradable Superabsorbent Polymer to Improve Water Retention, Reduce Nitrate Leaching, and Result in Improved Tomato Growth and Development

Shivani Kathi
Department of Agriculture, Agribusiness, and Environmental Sciences, Texas A&M University-Kingsville, Kingsville, TX 78363; and Department of Plant and Soil Sciences, Texas Tech University, Lubbock, TX 79409

Catherine Simpson
Department of Plant and Soil Sciences, Texas Tech University, Lubbock, TX 79409

Alinna Umphres and Greta Schuster
Department of Agriculture, Agribusiness, and Environmental Sciences, Texas A&M University-Kingsville, Kingsville, TX 78363

Additional index words. cornstarch, drought, eutrophication, stress, superabsorbent polymers, yield

Abstract. **In arid and semi-arid climates, water scarcity and nutrient availability are major constraints for food production. Excess fertilization to make up for the limited nutrient availability in dry soils leads to nitrogen runoff and groundwater contamination. Reducing nitrogen leaching into surface water while providing adequate nutrition remains a major challenge. Superabsorbent polymers (SAPs) can reduce water loss and improve nutrient retention and therefore minimize leaching and increase crop yields. SAPs are made from petroleum or natural products, but plant-based SAPs have been gaining popularity because they have fewer long-term effects on the environment. However, there is little known about how SAPs made from cornstarch effect plant growth and production in tomatoes. So, we evaluated total nitrogen and water retention in SAP-treated soils and evaluated their effects on growth and development of tomatoes (*Solanum lycopersicum*). Soils were amended with different rates of cornstarch-based SAP (i.e., 0 kg SAP, 0 kg SAP+N, 0.5 kg SAP+N, 1 kg SAP+N, 1.5 kg SAP+N, and 2 kg SAP+N). Results indicate that the mean volume of water and nitrates retained in the soils amended with cornstarch-based SAPs increased with increasing rate of SAP. The treatment containing the highest dose (i.e., 2 kg SAP) decreased the amount of leachate and nitrates from soil 79.34% and 93.11% at 3 days after fertilization (DAF) and 78.84% and 81.58% at 9 DAF in comparison with the soil-only and fertilizer-only treatments, respectively. The results also indicate cornstarch-based SAP significantly improved plant growth and yield parameters compared with the treatments without SAP. Furthermore, the greatest number of leaves, flowers, fruits, and dry matter production were found in the 1-kg SAP treatment. Therefore, application of cornstarch-based SAPs can improve tomato production in times of drought stress by retaining more water and nutrients in the active rooting zone and can reduce environmental pollution by reducing nitrogen runoff.**

Water and nutrient availability play a major role in crop production. Water scarcity is one of the chief environmental factors affecting plant growth, development, and yield. Globally, approximately two-thirds of the population presently live in areas where water resources are limited for at least a month in a year and half a billion people face serious water shortages all year round (Mekonnen and Hoekstra, 2016). Over the next 50 years, food production will not be possible without better management of water and land resources (Molden, 2007). Environmental constraints like climatic change, land degradation and deterioration, and the need to protect aquatic and terrestrial ecosystems are further limiting the available water supply and its productive capacity (Janmaat, 2004; Murgai et al., 2001; Postel, 1999). To improve food security while maintaining the productivity of our land and water resources, proper water development and management strategies are necessary (Molden, 2007).

Exponential population growth, diminishing arable land, and degraded soils have increased the need for larger quantities of nutrients, especially nitrogen (N), phosphorus (P), and potassium (K), to maintain and improve crop yields (Azeem et al., 2014; Wen et al., 2016). The use of these fertilizers, especially N fertilizers, has increased food production in the world (Di and Cameron, 2002). Furthermore, the largest source of N inputs in agricultural production is from N fertilizers, exceeding classic contributions from biological N fixation, atmospheric deposition, and animal manures (Liu et al., 2010). However, more than half of the fertilizer N applied to grain crops such as maize (*Zea mays*), rice (*Oryza sativa*), or wheat (*Triticum aestivum*) is stored in the soil or lost to the environment (Cassman et al., 2002). Fertilizer N recovery efficiency of plants (i.e., the proportion of fertilizer N that is taken up by the crop) usually decreases with increasing N fertilizer application because the increased yield per unit of added N diminishes as total N supply approaches the yield-maximizing level (i.e., Law of Diminishing Returns) (Bhattacharya, 2019; de Wit, 1992). In addition to N uptake efficiency issues, leaching is another common problem in many areas and soils. Leaching is considered to be the prevailing cause for the increase of nitrate concentrations in groundwater, and directly responsible for ecosystem eutrophication, and soil and water quality degradation (Rivett et al., 2008; Robertson and Vitousek, 2009; Zhou et al., 2012). Excess usage of N fertilizers results in substantial soil acidification, with N leaching and emissions as direct causes of water and air pollution (Guo et al., 2010; Zhang et al., 2013; Zhao et al., 2012). This is because of negatively charged nitrate ions that are not able to readily sorb on soil particle surfaces due to lack of much affinity (Li, 2003).

These factors underscore the need for practices in agricultural systems that lead to improved efficiency, economic viability, and increased sustainability of diminishing resources (Spiertz, 2009). Scientists and consumers have been researching for alternatives to minimize the large-scale use of chemical inputs such as fertilizer N and pesticides and a variety of practices and products have proven to be effective (Kawalekar, 2013; Love and Nejadhashemi, 2011; Matson et al., 1997). Among these are gel-forming or superabsorbent polymers (SAPs) that act as soil conditioners and aid in plant establishment in drought-prone soils (Woodhouse and Johnson, 1991). Successful SAPs increase the availability of water to plants in coarse soils that lose water quickly (Guilherme et al., 2015; Johnson, 1984). When paired with fertilizer, this could translate to improved crop yields with fewer adverse effects on the environment through more efficient water–fertilizer coupling (Kong et al., 2019). SAPs have the

Received for publication 9 July 2021. Accepted for publication 26 Aug. 2021.
Published online 3 November 2021.
This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.
G.S. is the corresponding author: E-mail: Greta.Schuster@tamuk.edu.

potential to be an exceptional soil conditioner that decrease N leaching and increase N use efficiency by plants. SAPs benefit agricultural production when added to the soil by creating a water reserve in the vicinity of the rhizosphere zone (Han et al., 2010; Zohuriaan-mehr and Kabiri, 2008). In crops, this increased water availability has translated to improved growth, particularly in drought-sensitive species like tomatoes (Narjary and Aggarwal, 2014; Pill and Jacono, 1984).

Despite many useful benefits, applications of hydrogels or SAPs are hindered because most of the currently available products are petroleum-based synthetic polymers that are limited by high production costs and adverse environmental effects (Kiatkamjornwong et al., 2002). Among the adverse effects on the environment, is environmental persistence. Petroleum polymer-based SAPs are semipermanent in soil and water due to their poor degradability, thereby affecting the living organisms (Kenawy et al., 2021). After application and usage, degradation of petroleum-based SAPs was reported to be at rates of less than 10% per year. Furthermore, toxic compounds released during their slow degradation is also of great concern (Cannazza et al., 2014). Although the natural/biomass SAPs have been around for a long time, their usage is limited because of the complex extraction processes, which make them more expensive than synthetic SAPs (Chang et al., 2021). This illustrates the need for more sustainable and biodegradable SAPs for use in crop production practices that are cost-effective. Sustainable SAPs should have easier extraction processes and have physical and chemical properties that allow for degradation by conditions present in the soil or planting environment. Among these different degradation processes is the biodegradation aided by freely occurring microorganisms, such as bacteria, fungi, and algae (Sivan, 2011; Swift, 1998). Microorganisms are present in the soil and use N and carbon for their biological processes. These compounds are typically provided by organic matter from decomposing plant biomass (Chen et al., 2003); however, organic matter can be limited in areas with high temperatures and arid conditions (Yuste et al., 2011). Using bio-based SAPs, such as rice waste (Zhou et al., 2018), wheat straw (Rahman et al., 2020), and corncob (Wen et al., 2017), can benefit soils and microbial communities. Yet, bio-based, degradable SAPs have been explored only to a limited extent (Chang et al., 2021). Of these bio-based SAPs, cornstarch-based SAPs have been shown to hold promise in water-holding capacity, degradability, and nutrient sorption (Qiao et al., 2017). Cornstarch, apart from being a human and animal food source, also has many industrial applications. Approximately 60% of world's total corn is grown in China and the United States (Tabasum et al., 2019). Therefore, by using one of the most readily available plant biomasses (corn) instead of synthetic polymers or biomass-based polymers with complex extraction processes can maintain or improve sustainability in crop production.

Replacing synthetic polymers, reducing cost of extraction of polymers, maximizing water and nutrient retention in soil, minimizing fertilizer loss, reducing application of fertilizers, and lowering environmental pollution risk are the main focuses of using biomass-based SAPs in agricultural production. However, because of the variability of polymer production processes, crops, fertilizers, irrigation, and overall management, many factors must be studied to determine optimal rates for cornstarch SAPs use. These cornstarch-based SAPs have not been evaluated thoroughly to determine water-holding capacity, nutrient sorption, and how they may affect plant growth. Therefore, to evaluate the efficacy of cornstarch-based SAP, in an initial study, different rates were incorporated in soil with and without fertilizers. Leachate, nitrates, and plant growth were then monitored throughout the study. In an additional study, the effects of cornstarch-based SAP on tomatoes subject to different levels of water stress were examined. These findings will aid in understanding the influence of cornstarch-based SAP on soils, whether it has the potential to be an effective SAP and provide useful information for its use in tomato production in drought-prone areas.

Materials and Methods

Experimental design and setup

To evaluate the effects of cornstarch-based SAP on water retention, leachate, tomato growth, and production were examined in two studies over 11 weeks. These two studies were performed at the Texas A&M University-Kingsville, Department of Agriculture, Agribusiness, and Environmental Sciences greenhouse (Kingsville, TX, 27.530666, −97.887151). Early Girl tomato (*Solanum lycopersicum*), because of its great taste and maturity time (i.e., 50 d) was selected for use in both greenhouse experiments. Tomato seeds were first grown in trays then were transplanted into larger pots once they reached the 2- to 4-leaf stage. Tomato plants were grown in 1-gallon pots in the greenhouse with daytime temperatures of 70 to 80 °F (21 to 27 °C), and nighttime temperatures of 60 to 65 °F (16 to 18 °C). Pots were filled with a sandy clay loam field soil consisting of 60% sand, 29.5% clay, and 10.5% silt particles. The SAP used for this research was a cornstarch-based, biodegradable, superabsorbent soil enhancer made from a proprietary blend of starch-g-poly (2-propenamide-co-2-propenoic acid) potassium salt acquired from a private manufacturer.

Experimental setup. Study 1 was designed to evaluate the optimal rates of cornstarch-based SAP for reduction of water and nitrate leaching, and plant growth. This experiment consisted of six treatments, each with different concentrations of cornstarch-based SAP varying between 0 and 2 kg per 1000 kg of soil (Table 1), which are less than the recommended dose (i.e., 5 kg/1000 kg of soil) by the manufacturer. When plants reached the 2- to 4-leaf stage, they were transplanted into 1-gallon pots containing 1.13 kg (2.5 lb) of experimental sandy clay loam soil and cornstarch-based SAP according to treatment. For study 1, different rates of cornstarch-based SAP were mixed with the soil, as shown in Table 1. The cornstarch-based SAP was mixed with soil based on weight, then added to each pot for each treatment. This experiment was set up in a randomized complete block design and was replicated four times with eight plants for each treatment for a total of 32 plants per treatment. All treatments (except for control) were fertilized once every 15 d with 100 mL of a fertilizer solution composed of 3.75 g of water-soluble 30–10–10 (N–P–K) fertilizer dissolved in 1 gallon of water (Table 2). To determine water and nitrate retention, at 3 and 9 d post fertilization, the plants were irrigated with 400 mL water, and leachate was collected and analyzed for volume and nitrates. The total volume of leachate and nitrates in the leachate provided information regarding the amount of water and nitrates retained in soil. Also, measurements on plant height, chlorophyll content, and number of leaves were noted. No additional irrigation was applied.

Study 2 was designed to determine if irrigation could be reduced by using cornstarch-based SAP and without affecting tomato growth and production. In this experiment, tomato plants were again transplanted at the 2- or 4-leaf stage into 6-inch pots with the sandy loam soil and cornstarch-based SAP at a rate of 2 kg of SAP/1000 kg of soil. All the treatments were fertilized once every 30 d with 100 mL of a soluble fertilizer at a concentration of 3.75 g of 30–10–10 (N–P–K) fertilizer mixed in 1 gallon of water (Table 3). Tomatoes were irrigated with one of four different levels of deficit irrigation [Total Irrigation (TI)] at rates of 25%, 50%, 75%, and 100%, depending on treatment. TI was determined by gradually watering a pot with the same amount of experimental soil (i.e., 2.5 lb) until just before leaching, and the amount was recorded. Plants were arranged in a randomized complete block design and treatments were replicated two times with eight plants per treatment for a total of 16 plants per treatment.

Table 1. Treatments used in study 1.

Treatments	SAP in kg/1000 kg soil	Fertilizer application (mL)
Soil-only control	No SAP	No fertilizer
Fertilizer-only control	No SAP	100
SAP 0.5	0.5	100
SAP 1	1.0	100
SAP 1.5	1.5	100
SAP 2	2.0	100

SAP = superabsorbent polymer.

Table 2. Fertilization, irrigation, and measurements schedule for study 1.

Fertilization (DAT)	Irrigation (DAF)	Measurements (DAF)
15	3	3
	9	9
30	3	3
	9	9
45	3	3
	9	9
60	3	3
	9	9
75	3	3
	9	9

DAT = days after transplanting; DAF = days after fertilization.

Table 3. Treatments in study 2.

Treatments	SAP in kg/1000 kg of soil	Fertilizer application (mL)	% of TI	mL of water applied
25% of TI	2.0	100	25	100
50% of TI	2.0	100	50	200
75% of TI	2.0	100	75	300
100% of TI (control)	2.0	100	100	400

SAP = superabsorbent polymer; TI = total irrigation.

Measurements

In study 1, growth and leachate measurements began 3 d after first fertilization of the plants and continued to be taken on the day of irrigation after the plants were irrigated throughout the studies (Table 2). Data on chlorophyll content, number of leaves, plant height, number of flowers, and number of fruits were collected on the day of irrigation (i.e., 3 and 9 DAF) with the exception of flower and fruit numbers, which began after the initial flower was spotted (Table 2). The leachate volume was recorded and then analyzed for nitrate concentration using a pocket colorimeter II (Hach, Loveland, CO). A SPAD-502 plus chlorophyll meter (Konica Minolta, Ramsey, NJ) was used to measure absorbance of the leaf in two wavelength regions (red and near infrared) in SPAD units, which are correlated to chlorophyll content. For study 2, data were collected on chlorophyll content, number of leaves, plant height, number of flowers, and number of fruits once per week throughout the study.

After 12 weeks of each study, above-ground and below-ground parts were harvested from each plant, placed in separate bags and taken to the laboratory for further analysis. These parts were then washed, oven dried, and dry weight was recorded.

Data analysis

The effects of leachate volume and nitrates on plant growth parameters were analyzed using Statistical Analysis System (SAS) software version 9.4 (SAS Inc., Cary, NC). An analysis of variance was conducted using a general linear model procedure. Significance was determined at $P \leq 0.05$. Means were separated using Tukey highly significant difference where means with the same letter signified no significant differences between factors. Additional full factorial analyses were also performed using JMP Pro software to determine further effects of treatments on plant growth parameters.

Results

Effect of different rates of SAP (study 1) on moisture and nitrate retention in soil and plant growth and yield parameters of tomato

Moisture content retained in the soil. Different rates of cornstarch-based SAPs affected leachate volume significantly ($P < 0.0001$). Soil-only control treatments had the highest amount of leachate, whereas SAP 2 had the lowest volume of leachate followed by SAP 1.5, SAP 1, SAP 0.5, and fertilizer-only control. Even though there were differences in the volume of the leachate collected among the treatments at different periods, the cornstarch-based SAP treatments significantly lowered leachate volume compared with soil-only and fertilizer-only controls at both 3 d (Fig. 1A; P treatment < 0.0001) and 9 d (Fig. 1B; P treatment < 0.0001) after fertilization throughout the study. Furthermore, the treatments decreased the amount of leachate from soil ≈79.34% at 3 DAF and 78.84% at 9 DAF at increasing rates of SAP in comparison with the soil-only treatment (Table 4).

Nitrates retained in the soil. Similar to the results found in soil moisture (Fig. 1), nitrate concentrations in leachate were reduced with increasing rates of cornstarch-based SAP (Fig. 2). There were differences in the amount of nitrates leached from each treatment at different periods (3 d vs. 9 d), but the treatments remained significantly different (P treatment 3 d = <0.0001, P treatment 9 d = <0.0001). The lowest concentration of nitrates were found in the SAP 2 treatment followed by SAP 1.5,

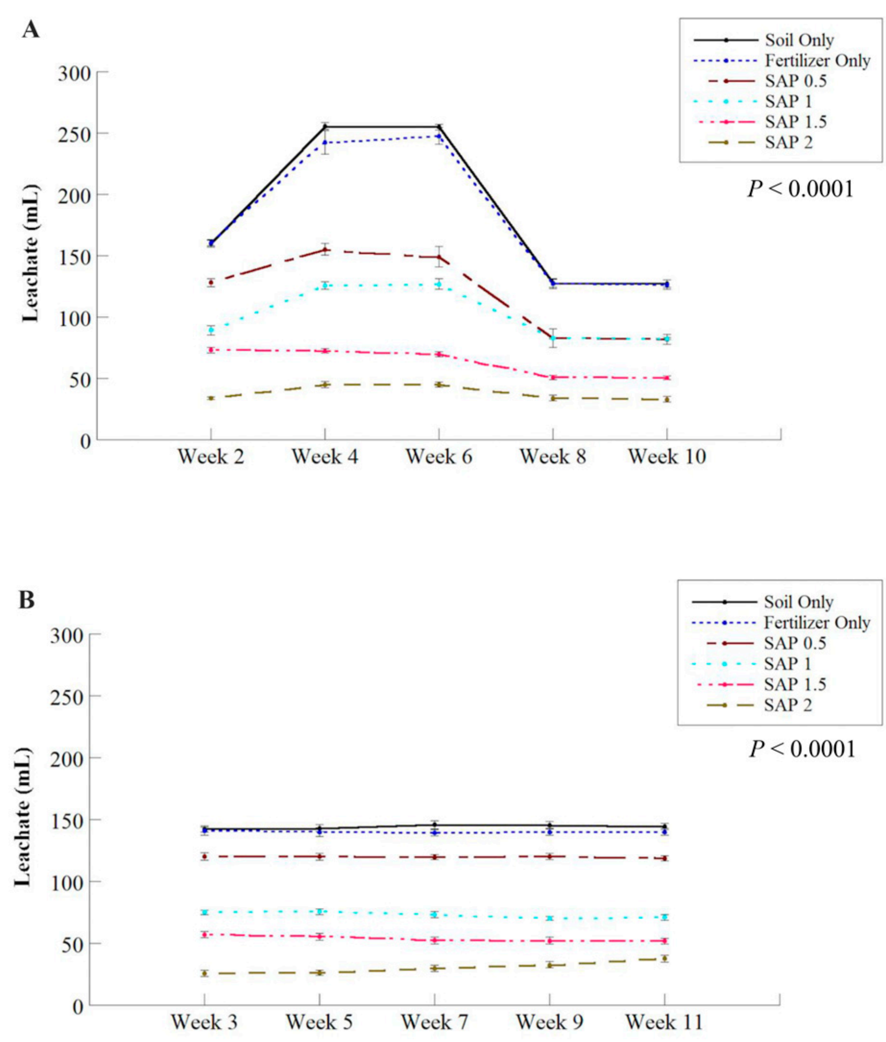

Fig. 1. The means of leachate volume (mL) at (**A**) 3 d after fertilization, and (**B**) at 9 d after fertilization observed in different treatments with superabsorbent polymer (SAP). Bars show ±1 SEM. The means of leachate volume (mL) of treatments at 3 and 9 d after fertilization are significantly less than the control (P treatment < 0.0001 for both 3 and 9 d after fertilization).

Table 4. Differences in average leachate volume (mL) and nitrates in leachate (mg/L) between the treatments. Percent difference of leachate volume of treatments from soil-only control and percent difference in nitrates in leachate of treatments from fertilizer-only control.

Treatments	3 DAF: Avg leachate volume (mL)	3 DAF: Avg nitrates in leachate (mg/L)	3 DAF: Percent difference in leachate volume from soil-only control	3 DAF: Percent difference in total nitrates from fertilizer-only control	9 DAF: Avg leachate volume (mL)	9 DAF: Avg nitrates in leachate (mg/L)	9 DAF: Percent difference in leachate volume from soil-only control	9 DAF: Percent difference in total nitrates from fertilizer-only control	3 DAF + 9 DAF: Total nitrates in leachate (mg)	3 DAF + 9 DAF: Percent diff. in total nitrates from fertilizer-only control
Soil-only control	185.15 a	1.10 f	–	−93.73	144.34 a	0.65 e	–	−77.71	0.29	−91.90
Fertilizer-only control	180.98 a	17.98 a	−2.25	–	140.06 b	3.01 c	−2.97	–	3.68	–
SAP 0.5	119.56 b	14.66 b	−35.42	−46.13	119.94 c	5.03 a	−16.91	43.12	2.36	−35.89
SAP 1	101.48 c	11.61 c	−45.19	−63.78	73.13 d	5.06 a	−49.34	−12.19	1.55	−57.86
SAP 1.5	63.36 d	8.74 d	−65.78	−82.99	53.88 e	4.60 b	−62.68	−41.19	0.8	−78.20
SAP 2	38.25 e	5.86 e	−79.34	−93.11	30.54 f	2.54 d	−78.84	−81.58	0.3	−91.79
P treatment	<0.0001	<0.0001	–	–	<0.0001	<0.0001	–	–	–	–

Values followed by the same letter are not significantly different at the $P < 0.05$ level.

DAF = days after fertilization; SAP = superabsorbent polymer.

SAP 1, SAP 0.5, and fertilizer-only. The fertilizer-only treatment had the highest concentrations of leachate of all treatments (Fig. 2). Furthermore, presence of cornstarch-based SAP at the highest rate (i.e., SAP 2) reduced nitrate leaching by 93.11% at 3 DAF and 81.58% at 9 DAF in comparison with fertilizer-only treatments (Table 4). In comparison with fertilizer-only treatment, up to 91.79% total nitrates (3 DAF + 9 DAF) were retained in soil by the SAP 2 treatment, which is similar to soil-only control that did not get treated with any fertilizer throughout the study (Table 4). This further illustrates that SAPs can be used to retain nutrients and water in soils where they are available for plant uptake.

Effect of cornstarch-based SAP on plant and reproductive growth. Presence of cornstarch-based SAP in the soil had a positive effect on the vegetative growth of the tomato plants. By end of the study there was a significant difference between treatments containing cornstarch-based SAP and the control in terms of plant height, number of leaves per plant, and chlorophyll (P treatments <0.0001). Treatments containing cornstarch-based polymer had plants with increased vegetative growth when compared with control (without SAP) and fertilizer-only treatments (Table 5). However, the relationship between growth factors and SAP were not proportional. More leaves were found in the SAP 1 treatment, highest SPAD values were in the SAP 1.5 treatment, and taller plants were recorded for the SAP 1.5 and SAP 2 treatments. Alternatively, the lowest values for all measured parameters were found in the soil-only (control) treatment (Table 5).

Tomato plants in treatments with cornstarch-based polymer had greater numbers of flowers and fruits compared with those in the fertilizer and soil-only treatments (Table 5). The greatest number of flowers were found in SAP 1 followed by SAP 0.5, SAP 1.5 and 2, fertilizer-only, and soil-only. Similarly, treatments with cornstarch-based polymer had a significantly increased number of fruits compared with treatments without SAP (Table 3; $P < 0.001$). However, there was no significant difference among the treatments with different rates of cornstarch-based SAP.

Effect of cornstarch-based SAP on dry matter production. There was also a significant difference in fresh and dry weight of aboveground parts and roots in treatments with and without cornstarch-based SAP (Table 6; $P < 0.001$). Fresh weight of aboveground tissues was greatest in SAP 1.5 and 2 treatments and lowest in soil-only and fertilizer-only treatments ($P < 0.0001$). Dry weight showed different results, with the greatest dry weight in the SAP 0.5 treatment and lowest values in the soil-only treatment. When % dry matter and moisture content were calculated, differences were found between treatments as well. Dry matter percentage was affected by treatment with the SAP 1 and 2 plants containing higher amounts of dry matter and only the control showing higher moisture content of aboveground tissues. Roots were also significantly affected by treatment (Table 6). Root fresh weight, dry weight, and % dry matter were lowest in the soil- and fertilizer-only treatments. Although root fresh weight was not significantly different in treatments with different rates of cornstarch-based SAP, dry weight and % dry matter varied with SAP concentration. Dry weight and % dry matter were greatest in the SAP 2 treatment compared with others. Moisture content of tissues was also higher in the soil-only and fertilizer-only treatments compared with all others.

Effect of different levels of irrigation deficit (study 2) on plant growth and yield parameters in the presence of cornstarch-based SAP

Vegetative and reproductive growth. Irrigation deficit treatments significantly affected number of leaves and height of tomato plants (Table 7). More leaves were found in the control (full irrigation) treatment compared with all other irrigation treatments. Plant height was also greatest in the control treatment, but was closely followed by the 50% TI treatment, then 25% and 75% TI treatments (P treatment <0.0001; Table 7). SPAD values were not significantly affected by irrigation treatments (P treatment $= 0.4188$). There was a significant difference in number of leaves, height, and number of flowers between the treatments ($P < 0.001$). More flowers were observed in 50% and 100% of TI, followed by 75% TI, and then 25% TI. Irrigation treatments showed no significant impact on the number of fruits produced ($P = 0.1690$).

Dry matter production. Irrigation treatments had significant effects on aboveground tissues but not on root tissues (Table 8). The fresh weight of the aboveground tissues was highest in the control treatment followed by the 75%, 50%, and 25% TI treatments. The dry weight followed this same pattern as well.

Discussion

The main way to stabilize agriculture in arid and semi-arid areas is by improving the effectiveness of applied irrigation and optimum use of water sources (Pirzad et al., 2014). SAPs, because of their ability to absorb and hold greater amounts of water (Ye et al., 2016), can aid in reducing water loss and improving crop yields (Khodadadi Dehkordi, 2016). Many studies have shown that different types of SAPs have varying effects on soil, water retention, and fertilizer retention; however, only a few have used SAPs made from naturally available resources, more specifically starch, which is a common and available biomass (Mao et al., 2000). In these studies, we used sandy clay loam soil collected from a field location and used an SAP derived from cornstarch that was biodegradable. Although there has been previous research that has assessed some SAPs, the variability of SAP chemistry and degradability, crops studied, fertilizers applied, irrigation rates, and management factors further illustrate the need of additional research

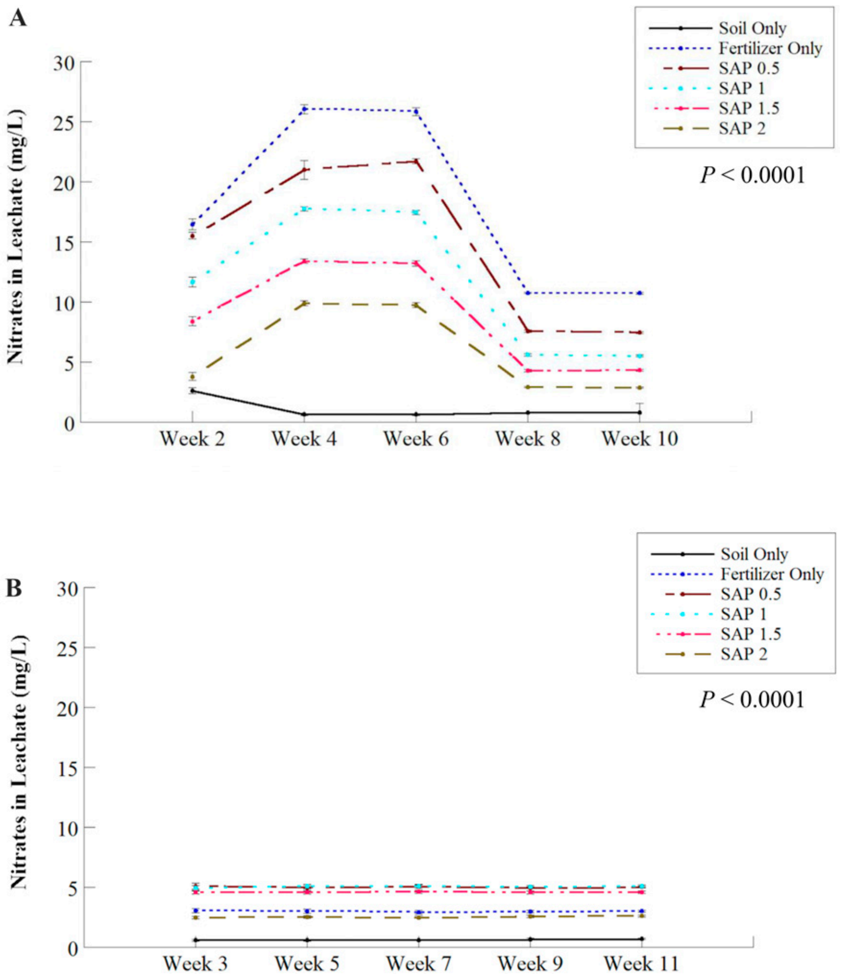

Fig. 2. The means of nitrates in the leachate (mg/L NO3-N) (**A**) at 3 d after fertilization, and (**B**) at 9 d after fertilization observed in different treatments with superabsorbent polymer (SAP). The means of nitrates in leachate of treatments (mg/L NO3-N) (**A**) at 3 and 9 d after fertilization are significantly different from the control ($P < 0.0001$).

to determine the extent to which SAP can succeed in improving water and nitrogen retention and plant growth in a wide variety of conditions and rates. These results can also be easily translated to field applications.

As in other studies, our results support findings demonstrating the effectiveness of SAPs in reducing leachate and increasing water availability to plants. These results show that cornstarch-based SAPs increased the water-holding capacity of the soil, retaining more water that preserved more N in the soil, thereby increasing water and nitrate availability to tomato plants compared with soil-only and soil with fertilizer-only treatments. Furthermore, the water and nutrient retention of between 35% and 91% depending on SAP rate is highly promising for water and nutrient conservation. The increased water availability is attributed to the increased nutrient availability as well. These findings were similar to those of Koupai et al. (2008), who used a synthetic polymer Superab A200 and found that SAPs decreased water demand of cypress and thereby reduced nitrate off-site pollution. Cornstarch-based SAP retention of water and fertilizers directly increased plant height, chlorophyll, and number of leaves, indicating better tomato performance in these treatments. This was similar to findings by Pill and Jacono (1984), who also found that the addition of potassium-based SAP to peat-lite at the rates of 4, 8, 12, and 16 kg/m^3 improved growth in ‘Heinz 1350’ tomato. However, these rates do not translate well to current greenhouse and field applications. Koupai et al. (2008) used a synthetic polymer Superab A200 and found that SAPs decreased water demand of cypress and thereby reduced nitrate off-site pollution.

Plant yield is complex and is dependent on various factors such as soil characteristics, weather, and various metabolic and biochemical interactions taking place during crop growth (Schaffer and Andersen, 2018). In addition to environmental factors, yield also depends on the production and mobilization of carbohydrates, and uptake of water and nutrients from the soil (Rouphael et al., 2012; Schonfeld et al., 1988). Tomato yield, in particular, can be maintained by sufficient N availability (Kuscu et al., 2014). Therefore, by making the N available to the plants, SAP can improve the yield and production by optimizing nutrient availability and moisture during plant development. The yield determining factors, such as number of flowers and number of fruits, increased with the presence of cornstarch-based SAP in the soil, with rates of 1 kg/1000 kg soil showing the greatest number of flowers and fruits, although number of fruits was not significantly different among cornstarch SAP treatments. However, all rates of cornstarch SAP showed higher numbers of fruits compared with treatments without, indicating that even low rates of cornstarch polymer incorporation can benefit plant yields. These impacts on yields through incorporation of SAPs have also been seen in soybean with synthetic anionic acrylic copolymer (ALCOSORB 400) (Sivapalan, 2001) and tomato with liquasorb (Meena et al., 2011). Tomato plant dry matter production was found to be superior at cornstarch SAP 1-kg rates compared with all other rates. Although this did not translate directly into higher yields at this rate, there is a high correlation between higher biomass and greater plant yields in most horticultural crops (Anderson et al., 2021; Marcelis et al., 1998). Similar results were observed by Zangooei-Nasab et al. (2012), who found that plant

Table 5. Number of leaves, height, SPAD values, number of flowers and fruits data of the treatments at the end of the study.

Treatments	Avg number of leaves	Avg SPAD values	Avg ht (cm)	Avg number of flowers	Avg number of fruits[z]
Soil-only control	8.02 e	19.08 c	30.03 d	0.11 d	0.02 c
Fertilizer-only control	10.13 d	34.93 ab	34.88 c	1.06 c	0.45 b
SAP 0.5	10.51 c	34.87 ab	35.35 b	1.69 ab	0.62 a
SAP 1	11.20 a	34.55 b	35.53 b	1.77 a	0.66 a
SAP 1.5	10.67 b	35.38 a	36.24 a	1.63 b	0.62 a
SAP 2	10.51 c	35.19 ab	36.33 a	1.63 b	0.63 a
P treatment	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

[z]Not all plants produced fruit within the study period, therefore, average numbers of fruits were less than 1.

Values followed by the same letter are not significantly different at the $P < 0.05$ level.

SAP = superabsorbent polymer.

Table 6. Fresh weight, dry weight, and percent dry matter of aboveground parts and roots of the treatments.

	Aboveground parts				Roots			
Treatments	Fresh weight (g)	Dry weight (g)	% Dry matter	% Moisture content	Fresh weight (g)	Dry weight (g)	% Dry matter	% Moisture content
Soil-only control	11.79 d	1.36 c	11.39 c	88.61 a	8.62 b	0.45 c	5.63 c	94.37 a
Fertilizer-only control	92.53 c	16.33 b	18.08 b	81.92 b	22.23 a	1.36 bc	6.54 c	93.46 a
SAP 0.5	98.88 b	27.21 a	21.75 a	78.25 b	32.66 a	2.27 ab	9.31 bc	90.69 ab
SAP 1	99.34 b	22.27 ab	22.49 a	77.51 b	27.21 a	3.63 a	13.14 a	85.86 b
SAP 1.5	112.04 a	22.68 ab	20.37 ab	79.63 b	22.68 a	3.17 a	12.99 ab	87.01 b
SAP 2	107.95 a	20.41 ab	19.23 ab	81.92 b	31.30 a	2.27 ab	9.25 bc	90.75 ab
P treatment	<0.0001	<0.0001	<0.0001	<0.0001	<0.001	<0.001	<0.001	<0.0001

Values followed by the same letter are not significantly different at the $P < 0.05$ level.
SAP = superabsorbent polymer.

Table 7. Number of leaves, height, and chlorophyll data of the treatments at the end of the study.

Treatments	Avg number of leaves	Avg ht (cm)	Avg SPAD values	Avg number of flowers	Avg number of fruits[z]
25% of TI	12.17 b	40.86 c	36.47	1.847 c	0.083
50% of TI	12.25 b	43.46 b	34.35	2.569 a	0.181
75% of TI	12.29 b	40.82 c	33.92	2.167 b	0.250
100% of TI (Control)	13.00 a	45.76 a	34.59	2.569 a	0.208
P treatment	*<0.001*	*<0.0001*	0.4188	*<0.0001*	0.1690

[z]Not all plants produced fruit within the study period, therefore, average numbers of fruits were less than one.
Values followed by the same letter are not significantly different at the $P < 0.05$ level. *P* values that are italicized indicate a significant difference.
TI = total irrigation.

height, dry weight of aerial organs, and root dry weight of Saxaul seedlings was improved by 0.1%, 0.2%, 0.3%, and 0.4% rates of Stockosorb. This was also found in a study using Superab-A200, with rates of 0.2%, 0.4%, 0.6%, 0.8%, and 1% w/w to improve chrysanthemum production conducted by Ghasemi and Khoushkhouy (2008). Our findings further supported this research, as increased rates of cornstarch polymer significantly increased root parameters at harvest in tomato as well. These improvements in plant growth parameters are directly related to water and N retention because they are available to plants for longer periods. Furthermore, when cornstarch-based SAP is added to the soil, the moisture content in plants (fresh weight) and plant growth parameters increase. However, there is some evidence that the benefits of SAPs are not exponential with increasing rates (El-Hady and Wanas, 2006). Because SAPs swell and fill vacant spaces in soil, overusing them can have detrimental effects on plants due to reduction in soil aeration (Abedi Koupai and Mesforoush, 2009). For example, Sarvaš et al. (2007) observed that by using 7 g per planting hole of SAP (Stockosorb) in soil with *Pinussylvestris* L. seedlings caused overdosing, and the plants were more likely to be exposed to *Fusarium* diseases and perished. This could explain some of the reductions in dry matter in our study, which showed reductions at higher rates of cornstarch SAP (>1 kg SAP/1000 kg soil). However, tomato fruit production was not significantly different between SAP rates, so these higher rates were not detrimental to yield. Therefore, optimal rates should be determined specifically for plant species and soil types before recommendations are made (Shooshtarian et al., 2012; Woodhouse and Johnson, 1991). This will ensure that economic as well as beneficial effects of cornstarch SAPs are realized without overapplication. With this in mind, a more conservative rate would likely be the best approach in studies such as ours. Hence, 1 kg cornstarch-based SAP is the minimum rate recommended for addition to soil for tomato plants grown in sandy clay loam soil as an ecologically viable tool to increase yield and decrease the amount of water and nutrients applied while also decreasing the amount of fertilizer leaching.

To further test the potential of cornstarch SAPs to improve water use efficiency by retaining soil moisture, an irrigation deficit study was also performed. In study 2, different deficit irrigation treatments were applied to tomato plants with 2 kg SAP/1000 kg soil added. Among the most promising results, was that there were no significant differences between numbers of fruit between the deficit irrigation treatments and the control. We also found that while aboveground dry matter was significantly reduced as water decreased, the roots remained unaffected by these deficits. These plants likely performed well even with reduced availability of water due to improved water use efficiency and dry matter production in the presence of soil with added SAP as described by Shooshtarian et al. (2012) and Woodhouse and Johnson (1991). Furthermore, the presence of cornstarch-based SAP provided sufficient availability of water without any loss in the form of leachate and indirect storage and supply of nitrates by cornstarch polymer to the plants, which in turn improved translocation of water, nutrients, and photo-assimilates, thereby improving growth and yield parameters (Meena et al., 2011). This is further supported by research conducted by El-Hady and Wanas (2006), who found that SAP (made of "polyacrylamide K polyacrylate 30% anionicity" and a "polyacrylamide allylamine hydrochloride 20% cationicity" hydrogel at the ratio of 2:3) aided in reduced water consumption and improved water and N use efficiency in cucumber under water stress conditions.

In conclusion, the cornstarch-based superabsorbent polymer had shown promising results in holding water and N in the soil and making it available to the plants compared with other synthetic polymers that are expensive and harmful to the environment. Furthermore, the rates used

Table 8. Fresh weight, dry weight, and percent dry matter of aboveground parts and roots of the treatments.

	Aboveground parts				Roots			
Treatments	Fresh weight (g)	Dry weight (g)	%DM	%MC	Fresh weight (g)	Dry weight (g)	%DM	%MC
25% of TI	29.48 c	3.17 c	11.00	89.00	15.88	1.81	11.20	88.80
50% of TI	36.29 b	4.08 bc	11.30	88.70	24.49	1.81	7.14	92.86
75% of TI	40.37 ab	4.54 b	11.30	88.70	19.50	1.81	10.80	89.20
100% of TI	43.54 a	5.44 a	13.17	86.83	22.23	1.81	8.91	91.09
P treatment	*<0.05*	*<0.0001*	0.346	0.346	0.052	0.951	0.1169	0.1169

Values followed by the same letter are not significantly different at the $P < 0.05$ level. *P* values that are italicized indicate a significant difference.
%DM = percent dry matter; %MC = percent moisture content; TI = total irrigation.

in this study are significantly less than those used in other studies, therefore, helping to reduce production costs and enabling usage of cornstarch-based SAP on a larger scale.

Conclusion

Cornstarch-based superabsorbent polymers improve the water and N retention in field soils, which helps plant production in times of drought stress by reducing water demands, as well as the frequency of irrigation and fertilizer application. By retaining N in soil and preventing leaching, cornstarch-based SAP has the potential to protect the environment from ecosystem eutrophication, and soil and water quality degradation. Cornstarch-based SAP also aids in plant growth and development by increasing the availability of moisture and nutrients, especially in times of drought stress.

Literature Cited

Abedi Koupai, J. and M. Mesforoush. 2009. Evaluation of superabsorbent polymer application on yield, water and fertilizer use efficiency in cucumber (*Cucumis sativus*). J. Irrigation and Drainage 3(2):100–111.

Anderson, N.T., K.B. Walsh, and D. Wulfsohn. 2021. Technologies for forecasting tree fruit load and harvest timing—from ground, sky and time. Agronomy (Basel) 11(7):1409, https://doi.org/10.3390/AGRONOMY11071409.

Azeem, B., K. Kushaari, Z.B. Man, A. Basit, and T.H. Thanh. 2014. Review on materials and methods to produce controlled release coated urea fertilizer. J. Control. Release 181(1):11–21, https://doi.org/10.1016/j.jconrel.2014.02.020.

Bhattacharya, A. 2019. Nitrogen-use efficiency under changing climatic conditions, p. 181–240. In: A. Bhattacharya (ed.). Changing climate and resource use efficiency in plants. Academic Press, Cambridge, MA, https://doi.org/10.1016/b978-0-12-816209-5.00004-0.

Cannazza, G., A. Cataldo, E. de Benedetto, C. Demitri, M. Madaghiele, and A. Sannino. 2014. Experimental assessment of the use of a novel superabsorbent polymer (SAP) for the optimization of water consumption in agricultural irrigation process. Water (Switzerland) 6(7):2056–2069, https://doi.org/10.3390/w6072056.

Cassman, K.G., A. Dobermann, and D.T. Walters. 2002. Agroecosystems, nitrogen-use efficiency, and nitrogen management. Ambio 31(2):132–140, https://doi.org/10.1579/0044-7447-31.2.132.

Chang, L., L. Xu, Y. Liu, and D. Qiu. 2021. Superabsorbent polymers used for agricultural water retention. Polym. Test. 94:107021, https://doi.org/10.1016/j.polymertesting.2020.107021.

Chen, G., H. Zhu, and Y. Zhang. 2003. Soil microbial activities and carbon and nitrogen fixation. Res. Microbiol. 154(6):393–398, https://doi.org/10.1016/S0923-2508(03)00082-2.

de Wit, C.T. 1992. Resource use efficiency in agriculture. Agr. Sys. 40(1–3):125–151, https://doi.org/10.1016/0308-521X(92)90018-J.

Di, H.J. and K.C. Cameron. 2002. Nitrate leaching in temperate agroecosystems: Sources, factors and mitigating strategies. Nutr. Cycl. Agroecosyst. 64(3):237–256, https://doi.org/10.1023/A:1021471531188.

El-Hady, O.A. and S.A. Wanas. 2006. Water and fertilizer use efficiency by cucumber grown under stress on sandy soil treated with acrylamide hydrogels. J. Appl. Sci. Res. 2(12):1293–1297.

Ghasemi G.M., and M. Khoushkhouy 2008. Effects of Superabsorbent polymer on irrigation interval and growth and development of Chrysanthemum (*Dendranthema* × *grandiflorum* Kitam.). Iran. J. Hort. Sci. Technol. 8(2):65–82.

Guilherme, M.R., F.A. Aouada, A.R. Fajardo, A.F. Martins, A.T. Paulino, M.F.T. Davi, A.F. Rubira, and E.C. Muniz. 2015. Superabsorbent hydrogels based on polysaccharides for application in agriculture as soil conditioner and nutrient carrier: A review. Eur. Polym. J. 72:365–385, https://doi.org/10.1016/j.eurpolymj.2015.04.017.

Guo, J.H., X.J. Liu, Y. Zhang, J.L. Shen, W.X. Han, W.F. Zhang, P. Christie, K.W.T. Goulding, P.M. Vitousek, and F.S. Zhang. 2010. Significant acidification in major chinese croplands. Science 327(5968):1008–1010, https://doi.org/10.1126/science.1182570.

Han, Y.G., P.L. Yang, Y.P. Luo, S.M. Ren, L.X. Zhang, and L. Xu. 2010. Porosity change model for watered super absorbent polymer-treated soil. Environ. Earth Sci. 61(6):1197–1205, https://doi.org/10.1007/s12665-009-0443-4.

Janmaat, J. 2004. Calculating the cost of irrigation induced soil salinization in the tungabhadra project. Agr. Econ. 31(1):81–96, https://doi.org/10.1111/j.1574-0862.2004.tb00223.x.

Johnson, M.S. 1984. The effects of gel-forming polyacrylamides on moisture storage in sandy soils. J. Sci. Food Agr. 35(11):1196–1200, https://doi.org/10.1002/jsfa.2740351110.

Kawalekar, J.S. 2013. Role of biofertilizers and biopesticides for sustainable agriculture. Edition J. Bio. 2(3):73–78. www.jbino.com.

Kenawy, E.-R., M. Seggiani, A. Hosny, M. Rashad, P. Cinelli, K.M. Saad-Allah, M. El-Sharnouby, S. Shendy, and M.M. Azaam. 2021. Superabsorbent composites based on rice husk for agricultural applications: Swelling behavior, biodegradability in soil and drought alleviation. J. Saudi Chem. Soc. 25(6):101254, https://doi.org/10.1016/j.jscs.2021.101254.

Khodadadi Dehkordi, D. 2016. The effects of superabsorbent polymers on soils and plants. Pertanika, J. Trop. Agr. Sci. 39(3):267–298.

Kiatkamjornwong, S., K. Mongkolsawat, and M. Sonsuk. 2002. Synthesis and property characterization of cassava starch grafted poly [acrylamide-co- (maleic acid)] superabsorbent via γ-irradiation. Polymer 43(14):3915–3924, https://doi.org/10.1016/S0032-3861(02)00224-0.

Kong, W., Q. Li, X. Li, Y. Su, Q. Yue, and B. Gao. 2019. A biodegradable biomass-based polymeric composite for slow release and water retention. J. Environ. Manage. 230:190–198, https://doi.org/10.1016/j.jenvman.2018.09.086.

Koupai, J.A., S.S. Eslamian, and J.A. Kazemi. 2008. Enhancing the available water content in unsaturated soil zone using hydrogel, to improve plant growth indices. Ecohydrol. Hydrobiol. 8(1):67–75, https://doi.org/10.2478/v10104-009-0005-0.

Kuscu, H., A. Turhan, N. Ozmen, P. Aydinol, and A.O. Demir. 2014. Optimizing levels of water and nitrogen applied through drip irrigation for yield, quality, and water productivity of processing tomato (*Lycopersicon esculentum* Mill.). Hort. Environ. Biotechnol. 55(2):103–114, https://doi.org/10.1007/s13580-014-0180-9.

Li, Z. 2003. Use of surfactant-modified zeolite as fertilizer carriers to control nitrate release. Microporous and Mesoporous Materials 61(1–3):181–188, https://doi.org/10.1016/S1387-1811(03)00366-4.

Liu, J., L. You, M. Amini, M. Obersteiner, M. Herrero, A.J.B. Zehnder, and H. Yang. 2010. A high-resolution assessment on global nitrogen flows in cropland. Proc. Natl. Acad. Sci. USA 107(17):8035–8040, https://doi.org/10.1073/pnas.0913658107.

Love, B.J. and A.P. Nejadhashemi. 2011. Water quality impact assessment of large-scale biofuel crops expansion in agricultural regions of Michigan. Biomass Bioenergy 35(5):2200–2216, https://doi.org/10.1016/J.BIOMBIOE.2011.02.041.

Mao, L., S. Imam, S. Gordon, P. Cinelli, and E. Chiellini. 2000. Extruded cornstarch-glycerol-polyvinyl alcohol blends: Mechanical properties, morphology, and biodegradability. J. Polym. Environ. 8(4):205–211, https://doi.org/10.1023/A:1015201928153.

Marcelis, L.F.M., E. Heuvelink, and J. Goudriaan. 1998. Modelling biomass production and yield of horticultural crops: A review. Scientia Hort. 74(1-2):83–111, https://doi.org/10.1016/S0304-4238(98)00083-1.

Matson, P.A., W.J. Parton, A.G. Power, and M.J. Swift. 1997. Agricultural intensification and ecosystem properties. Science 277(5325):504–509, https://doi.org/10.1126/science.277.5325.504.

Meena, M.K., C.M. Nawalagatti, and M. B. Chetti. 2011. Efficacy of Liquasorb on morphological characters and yield components in tomato. Intl. J. Plant Sci. 6(2):307–312.

Mekonnen, M.M. and A.Y. Hoekstra. 2016. Sustainability: Four billion people facing severe water scarcity. Sci. Adv. 2(2):e1500323, https://doi.org/10.1126/sciadv.1500323.

Molden, D.J. 2007. Water for food, water for life: A comprehensive assessment of water management in agriculture. Earthscan, London.

Murgai, R., M. Ali, and D. Byerlee. 2001. Productivity growth and sustainability in post-green revolution agriculture: The case of the Indian and Pakistan Punjabs. World Bank Res. Obs. 16(2):199–218.

Narjary, B., and P. Aggarwal. 2014. Evaluation of soil physical quality under amendments and hydrogel applications in a soybean–wheat cropping system. Commun. Soil Sci. Plant Anal. 45(9):1167–1180, https://doi.org/10.1080/00103624.2013.875191.

Pill, W.G. and C.C. Jacono. 1984a. Effects of hydrogel incorporation in peat-lite on tomato growth and water relations 1. Commun. Soil Sci. Plant Anal. 15(7):799–810, https://doi.org/10.1080/00103628409367519.

Pirzad, A., M. Jamali, and F. Shokrani. 2014. Effects on *Brassica napus* L. yield and yield components of super absorbent polymer under different irrigation regimes. Not. Sci. Biol. 6(3):368–373, https://doi.org/10.15835/nsb639336.

Postel, S. 1999. Pillar of sand - can the miracle of irrigation last? W.W. Norton and Co. Ltd., New York.

Qiao, D., L. Yu, X. Bao, B. Zhang, and F. Jiang. 2017. Understanding the microstructure and absorption rate of starch-based superabsorbent polymers prepared under high starch concentration. Carbohydr. Polym. 175:141–148, https://doi.org/10.1016/j.carbpol.2017.07.071.

Rahman, S., D. Petroudy, S.A. Kahagh, and E. Vatankhah. 2020. Environmentally friendly superabsorbent fibers based on electrospun cellulose nanofibers extracted from wheat straw. Carbohydr. Polym. 251(1):117087, https://doi.org/10.1016/j.carbpol.2020.117087.

Rivett, M.O., S.R. Buss, P. Morgan, J.W.N. Smith, and C.D. Bemment. 2008. Nitrate attenuation in groundwater: A review of biogeochemical controlling processes. Water Res. 42(16):4215–4232, https://doi.org/10.1016/j.watres.2008.07.020.

Robertson, G.P. and P.M. Vitousek. 2009. Nitrogen in agriculture: balancing the cost of an essential resource. Annu. Rev. Environ. Resour. 34(1):97–125, https://doi.org/10.1146/annurev.environ.032108.105046.

Rouphael, Y., M. Cardarelli, D. Schwarz, P. Franken, and G. Colla. 2012. Effects of drought on nutrient uptake and assimilation in vegetable crops, p. 171–195. In: Plant responses to drought stress: from morphological to molecular features. Springer, Berlin, Heidelberg, https://doi.org/10.1007/978-3-642-32653-0_7.

Sarvaš, M., P. Pavlenda, and E. Takáčová. 2007. Effect of hydrogel application on survival and growth of pine seedlings in reclamations. J. For. Sci. 53(5):203–209.

Schaffer, B. and P.C. Andersen. 2018. Handbook of environmental physiology of fruit crops. CRC Press, Exeter, UK, https://10.1201/9780203719299.

Schonfeld, M.A., R.C. Johnson, B.F. Carver, and D.W. Mornhinweg. 1988. Water relations in winter wheat as drought resistance indicators. Crop Sci. 28(3):526–531, https://doi.org/10.2135/cropsci1988.0011183x002800030021x.

Shooshtarian, S., J. Abedi-Koupai, and A. Tehranifar. 2012. Evaluation of application of superabsorbent polymers in green space of arid and semi-arid regions with emphasis on Iran. Intl. J. For. Soil Eros. 2(February):24–36.

Sivan, A. 2011. New perspectives in plastic biodegradation. Curr. Opin. Biotechnol. 22(3):422–426, https://doi.org/10.1016/J.COPBIO.2011.01.013.

Sivapalan, S. 2001. Effect of a polymer on growth and yield of soybeans (Glycine max) grown in a coarse textured soil. Toowoomba, Queensland, Australia. Proceedings Irrigation 2001 Regional Conference, 93–99.

Spiertz, J.H.J. 2009. Nitrogen, sustainable agriculture and food security: A review, p. 635–651. In: E. Lichtfouse, M. Navarrete, P. Debaeke, S. Véronique, and C. Alberola (eds.). Sustainable agriculture. Springer, Dordrecht, Netherlands, https://doi.org/10.1007/978-90-481-2666-8_39.

Swift, G. 1998. Requirements for biodegradable water-soluble polymers. Polymer Degradation and Stability 59(1–3):19–24, https://doi.org/10.1016/s0141-3910(97)00162-6.

Tabasum, S., M. Younas, M.A. Zaeem, I. Majeed, M. Majeed, A. Noreen, M.N. Iqbal, and K.M. Zia. 2019. A review on blending of corn starch with natural and synthetic polymers, and inorganic nanoparticles with mathematical modeling. Intl. J. Biol. Macromolecules 22:969–996, https://doi.org/10.1016/j.ijbiomac.2018.10.092.

Wen, P., Y. Han, Z. Wu, Y. He, B.C. Ye, and J. Wang. 2017. Rapid synthesis of a corncob-based semi-interpenetrating polymer network slow-release nitrogen fertilizer by microwave irradiation to control water and nutrient losses. Arab. J. Chem. 10(7):922–934, https://doi.org/10.1016/j.arabjc.2017.03.002.

Wen, P., Z. Wu, Y. He, B.-C. Ye, Y. Han, J. Wang, and X. Guan. 2016. Microwave-assisted synthesis of a semi-interpenetrating polymer network slow-release nitrogen fertilizer with water absorbency from cotton stalks. ACS Sustain. Chem. Eng. 4(12):6572–6579, https://doi.org/10.1021/acssuschemeng.6b01466.

Woodhouse, J. and M. S. Johnson. 1991a. Effect of superabsorbent polymers on survival and growth of crop seedlings. Agr. Water Mgt. 20(1):63–70, https://doi.org/10.1016/0378-3774(91)90035-H.

Ye, Z., M. Tang, X. Hong, and K.S. Hui. 2016. Sustainable composite super absorbents made from polysaccharides. Mater. Lett. 183:394–396, https://doi.org/10.1016/j.matlet.2016.07.067.

Yuste, J.C., J. Peñuelas, M. Estiarte, J. Garcia-Mas, S. Mattana, R. Ogaya, M. Pujol, and J. Sardans. 2011. Drought-resistant fungi control soil organic matter decomposition and its response to temperature. Glob. Change Biol. 17(3):1475–1486, https://doi.org/10.1111/j.1365-2486.2010.02300.x.

Zangooei-Nasab, S., H. Imami, A. Astaraei, and A.R. Yari. 2012. The effects of Stockosorb hydrogel and irrigation on growth and establishment of Saxaul plant [in Farsi]. 1st Nat. Conf. on Farm Water Management, 1–9.

Zhang, W.F., Z.X. Dou, P. He, X.T. Ju, D. Powlson, D. Chadwick, D. Norse, Y.L. Lu, Y. Zhang, L. Wu, X.P. Chen, K.G. Cassman, and F.S. Zhang. 2013. New technologies reduce greenhouse gas emissions from nitrogenous fertilizer in China. Proc. Natl. Acad. Sci. USA 110(21):8375–8380, https://doi.org/10.1073/pnas.1210447110.

Zhao, X., Y. Zhou, J. Min, S. Wang, W. Shi, and G. Xing. 2012. Nitrogen runoff dominates water nitrogen pollution from rice-wheat rotation in the Taihu Lake region of China. Agr. Ecosyst. Environ. 156:1–11, https://doi.org/10.1016/j.agee.2012.04.024.

Zhou, M., B. Zhu, K. Butterbach-Bahl, T. Wang, J. Bergmann, N. Brüggemann, Z. Wang, T. Li, and F. Kuang. 2012. Nitrate leaching, direct and indirect nitrous oxide fluxes from sloping cropland in the purple soil area, southwestern China. Environ. Pollut. 162:361–368, https://doi.org/10.1016/j.envpol.2011.12.001.

Zhou, T., Y. Wang, S. Huang, and Y. Zhao. 2018. Synthesis composite hydrogels from inorganic-organic hybrids based on leftover rice for environment-friendly controlled-release urea fertilizers. Sci. Total Environ. 615:422–430, https://doi.org/10.1016/j.scitotenv.2017.09.084.

Zohuriaan-mehr, M.J. and K. Kabiri. 2008. Superabsorbent polymer materials: A review. Iran. Polym. J. 17(6):451–477. https://doi.org/http://journal.ippi.ac.ir.