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Jessica El-Asmar[1]
Hadi Jaafar[1]
Issam Bashour[1]
Mohammad T. Farran[1]
Imad P. Saoud[2]

[1]Department of Agriculture, American University of Beirut, Beirut, Lebanon
[2]Department of Biology, American University of Beirut, Beirut, Lebanon

Research Article

Hydrogel Banding Improves Plant Growth, Survival, and Water Use Efficiency in Two Calcareous Soils

Improving water use efficiency in the agricultural sector, particularly in arid regions, is becoming increasingly important in response to increasing global population and concomitant demand for food, water, and land. The authors performed experiments to determine whether the use of super-absorbent polymers, also known as hydrogels, can increase plant survival, plant growth, and plant water use efficiency. The effect of hydrogel application proportions and application methods on plant survival and growth in clay and sandy clay loam (SCL) soils was investigated. Two pot experiments using *Zea mays* and *Pinus pinea* as model plants were performed. The hydrogel was applied at concentrations of 0, 1, 2, 3, and 4 g kg^{-1} soil in one of two methods: Banding or mixing. Hydrogel effects on water retention in the two soil types were recorded. The results suggest that hydrogel banding at 0.4% application in SCL improves corn's fresh and dry above-ground biomass by 25%, and prolongs survival time of pine seedlings by 90%. Evapotranspiration was greater in soils banded with hydrogel at 0.4% and water use efficiency increased by 10–13% in both soils. Additionally, hydrogel increased water retention of SCL by up to 33% at 100 kPa, but had negligible effects when applied in clay soils. Accordingly, the efficacy of hydrogels in agriculture water conservation depends on using appropriate application methods and quantities.

Keywords: Drought; Pine; Super absorbent polymers; Water management; Water productivity

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1 Introduction

Demand for fresh water is increasing concomitant with an increase in world population and improving living standards as well as changing precipitation patterns. Moreover, growing populations are increasing demand for increasingly scarce resources such as suitable land, water, and energy. Because agriculture is the largest anthropogenic consumer of fresh water, requiring approximately 80–90% of global fresh water usage [1], any improvements in efficiency would have significant benefits in freshwater availability. That is, increasing water use efficiency through improved cultural practices and the adoption of novel technologies can result in considerable water savings in the agricultural sector [2, 3]. A major improvement would be to enhance water holding capacity of soils, especially in arid areas. This may be accomplished through soil amendments such as incorporation of super absorbent polymers (SAPs), more commonly known as hydrogels [4].

SAPs are long chains of cross-linked polymers that can absorb and retain water up to 1000 times their dry weight. SAPs come in various classes and chemical structures; agricultural hydrogels are mainly polyacrylamides containing functional groups most often in the form of acrylic acid units [5]. The effects of the addition of SAPs to soils vary depending on crops, soil types, and environment. Many studies report that the addition of hydrogels benefits the development of plants. Hydrogels were reported to help reduce irrigation frequency especially in coarse-textured soils in arid and semi-arid regions [6]. Amending soils with SAPs were also found to improve plant growth and increase both yield and water use efficiency [7]. Previous work shows that hydrogels induce faster and more robust growth of plants by increasing plant available water and by prolonging survival under harsh conditions [8, 9]. However, information about the suitability and potential benefits of hydrogel use under restricted plant available water in various types of soils is lacking.

Effects of SAPs on soil properties and plant growth reported in the literature are summarized in Table 1. Some studies report that greater amounts of hydrogel soil amendments can lower the saturated hydraulic conductivity of the soil [11]. Others found that the saturated hydraulic conductivity of the soil–hydrogel mixture initially decreases but then increases, possibly because of partial draining of swollen polymer granules caused by the hydraulic head [10]. Still other studies suggest that SAPs decrease the bulk density of the soil [11, 21], and reduce infiltration rates [13, 22], thereby reducing deep percolation. However, SAPs were also reported to improve water release rate from soils by causing the

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Correspondence: Prof. Hadi Jaafar, Department of Agriculture, American University of Beirut, PO Box 110236, Beirut, 1100 2020, Lebanon
E-mail: hj01@aub.edu.lb

Abbreviations: **C**, clay; **DMC**, dry matter content; **DW**, dry shoot weight; **ETc**, actual evapotranspiration; **FW**, fresh shoot weight; **SAP**, super absorbent polymer; **SCL**, sandy clay loam; **WUE**, water use efficiency.

Table 1. Summary results for the effect of Hydrogel amendment on soil properties and plant growth

Hydrogel effect studied	Studies reporting an increase in parameter value	Studies reporting a decrease in parameter value
Water holding capacity	[10]	
Saturated hydraulic conductivity	[10] – initially decreased and then increased	[11]
Bulk density		[12]
Infiltration		[13]
Heavy metal uptake		[14]
plants yield, growth	[8, 15, 16]	
Water use efficiency	[7, 17]	
Irrigation frequency		[6, 18]
Drought tolerance	[8, 9, 19]	[20]

soil water content to decrease uniformly during drying [4]. Other studies report that hydrogels mitigate the effects of salinity and improve water use efficiency in several crops such as corn [7], cucumber [17], and other vegetables and field crops [22, 23].

Presently available scientific literature contains contrasting reports about the effect of SAPs on the survival of tree seedlings. Several studies report positive effects on the survival of seedlings in Africa, Australia, and Uganda [6, 11, 24, 25], but others report negative effects on Aleppo pine grown on loam soil in Spain [20]. Some reports note that hydrogels increase water retention in soils in situ, but more research is required to prove that this increase results in an increase in water availability to plants grown in various soil types.

The objectives of the present work were to evaluate the effect of various application quantities and methods (banding and mixing) of a commercial hydrogel medium (STOCKOSORB® 660) on the aboveground biomass, evapotranspiration, and water use efficiency of an agricultural crop (*Zea mays*). Furthermore, the work evaluated treatment effects on survival of tree seedlings grown under Eastern Mediterranean conditions in prevailing calcareous soils within the area. The effect of the hydrogel on the available water holding capacity of two types of soils, clay (C) and silt clay loam (SCL) was also evaluated. To the authors' knowledge, few and limited work has been performed to evaluate the effect of the application method of the hydrogel on plant survival and water use efficiency, both in pots and in field conditions.

2 Materials and methods

2.1 Study area and soil characteristics

The present work was performed at the Department of Agriculture at the American University of Beirut. Two sets of pot experiments inside and outside greenhouses and a laboratory study were performed during the years 2013–2014. The experiments were done in a Mediterranean environment (Beirut, Lebanon), namely a subhumid climate with a reported mean annual rainfall of 727 mm, and an average annual temperature of 22°C. Two pot experiments were performed during the period 6 May to 18 June 2013 to test the effect of hydrogel amendment and application method on aboveground biomass of corn in two types of soils. Weather data for the experimental period is shown in Fig. 1. Another two pot experiments on pine tree seedlings (*Pinus pinea*) were performed during the period October 2013 and April 2014 to test the seedlings' drought resistance capability using various hydrogel application quantities and methods.

Soil samples from a plot in a semi-arid location (soil 1) as well as soil samples from an area typical of Mediterranean pine forests (soil 2) were collected, both for the laboratory study and for use in the pot experiments. Soil 1 was classified as clay (C), highly calcareous, slightly alkaline, non-saline, and containing a medium quantity of organic matter (Tab. 2). It contained sufficient amounts of nutrients to support good plant growth. Soil 2 was classified as sandy clay loam (SCL); calcareous, slightly alkaline, non-saline, with a medium quantity of organic matter and a lesser nutrient level than soil 1. In general, both soils were suitable for plant growth if provided with sufficient amounts of water. The superabsorbent polymer used in the present study was the commercial hydrogel STOCKOSORB® 660 Medium, a cross-linked potassium poly-acrylic acid. STOCKOSORB® 660 medium (Evonik Industries, Germany) was comprised of insoluble white granules, with a particle size of 0.2–0.8 mm. The granules swelled upon contact with water and formed a gel-like substance. When added to pure water at $1\,\mathrm{g\,L^{-1}}$, the pH of the medium ranged between 7 and 8. The manufacturer reported technical specifications of the hydrogel suggest that more than 95% of the water absorbed by the granules was available for plants. User manual recommended application was 0.1–0.2% of soil by mass.

2.2 Greenhouse corn (*Z. mays*) pot experiments

The first two experiments, performed from 6 May to 18 June 2013, assessed the effects of hydrogel quantity and method of application on fresh and dry shoot biomass of corn in both types of soils (C and SCL), as well as treatment effects on dry matter fraction of the plants, evapotranspiration, and water use efficiency. Corn was chosen as the model species because of its susceptibility to water stress as well as its practicality in pot experiments.

Two treatment categories were imposed on each of the two soil types: (i) Five hydrogel application quantities and (ii) two hydrogel application methods: Banding and mixing. A two-way factorial arrangement of treatments (2×5) was used in a complete randomized design with three replicates per treatment (a total of 60 pots; 30 pots per soil type). Both soil types were treated at 0, 0.1, 0.2, 0.3, and 0.4% hydrogel/soil (w/w), using each of the application methods. The 0.4% rate was twice the manufacturer recommended application rate. In each pot, the hydrogel mass was combined with 1.5 g of a soluble fertilizer (NPK 20:20:20). The combination was either entirely blended with the soil (mixing) or it was applied as a layer (banding). For banding, the hydrogel was placed in one layer at a depth of 15 cm below soil surface. Each pot, 0.2 m diameter, was uniformly filled with the same weight of air-dried soil for each soil type (6 kg for the clay soil experiment and 5 kg for the sandy clay loam experiment). On 6 May 2013, five seeds were directly planted in each pot. Following germination, the plants were thinned to three seedlings per pot. The pots were then weighed and soils irrigated to saturation. Thereafter, the soils were irrigated and weighed once a week for a period of 7 weeks. During the experiment, all pots

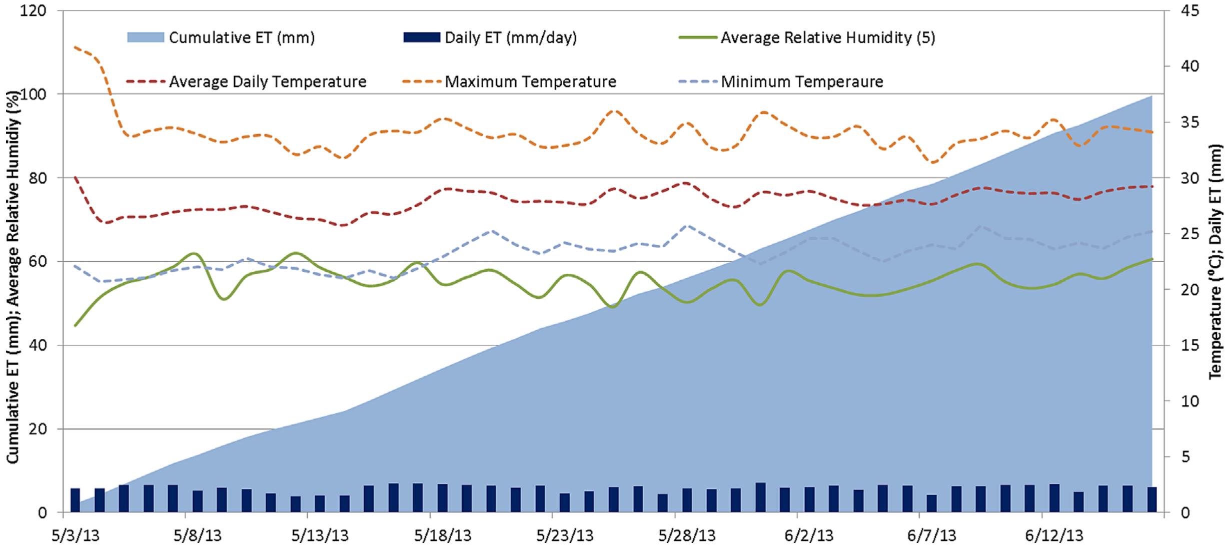

Figure 1. Greenhouse weather parameters for the duration of the corn pot experiment.

simultaneously received the same amount of water, which was measured with a graduated cylinder. Over the course of the experiment, the quantity of water added to every pot totaled 4.3 L, equivalent to 137 mm of irrigation during the seven weeks period.

At day 42 post planting, corn plants that were present in each pot were cut at 1 cm height above soil surface and above-ground biomass immediately weighed. Dry weight was calculated after placing the fresh mass in an oven at 65°C for 72 h. Evapotranspiration was determined using the simple soil water balance approach (based on the law of conservation of mass) [26] (Eq. (1)) (all parameters are in kg):

$$\mathrm{ET} = I - D_{\mathrm{p}} - \Delta S \qquad (1)$$

where ETc is the total actual crop evapotranspiration, I the total irrigation amount, D_{p} the deep percolation or drainage, and ΔS is the net change in soil water content. Rainfall is zero in the greenhouse. Deep percolation was monitored and determined to be zero on 9 May and no deep percolation was observed thereafter. All pots were carefully irrigated to field capacity weekly so as to avoid drainage. The change in soil water content equaled the difference in each pot's weight between 18 June and 9 May, averaged over the number of pots per replicate. Water use efficiency (WUE) was calculated by dividing the dry weight of above-ground biomass per pot (DW) by total evapotranspiration per pot [27] (Eq. (2)):

$$\mathrm{WUE} = \mathrm{DW(g)}/\Sigma\mathrm{ETc(mm)}. \qquad (2)$$

Accordingly, relative ETc and relative WUE were calculated by dividing the calculated ETc and WUE values at various hydrogel rates by ETc and WUE at 0% hydrogel for the respective application method and soil type. The data were analyzed using univariate and multivariate analysis of variance (ANOVA and MANOVA) according to a factorial concept of two-way classification. The hydrogel application methods (mixing and banding) and hydrogel rates (0, 0.1, 0.2, 0.3, and 0.4 g kg^{-1}) along with their interactions were modeled as fixed factors (a completely randomized block design

Table 2. Physical and chemical properties of soils used in the hydrogel supplementation experiments

Characteristic	Soil 1	Soil 2
Texture	Clay (C)	Sandy clay loam (SCL)
Sand	27%	47%
Silt	29%	19%
Clay	45%	34%
pH (soil/water, 1:2)	8.02	7.87
EC (dS/m) (soil/water, 1:2)	0.48	0.72
Na (mg/kg) (NH_4OAc extract)	115	95
K (mg/kg) (NH_4OAc extract)	550	120
P (mg/kg) ($NaHCO_3$ extract)	31	25
Ca (mg/kg) (NH_4OAc extract)	2975	685
Organic matter (%) (furnace burning)	2.11	1.90
$CaCO_3$ (%) (acid neutralization method)	21	12
Dry bulk density (g cm^{-3}) (cylinder method)	1.34	1.60
Water content at 30 kPa	42%	31%
Water content at 200 kPa	29.5%	23%
Water content at 1500 kPa	27%	21.5%
Available water content	0.130 m/m	0.105 m/m

with three replications). The *F*-statistics test was used to identify the treatments' main effects and interactions. Tukey's HSD multiple range test was used to determine differences ($p \leq 0.05$) among least squared means. All statistical analyses were performed using the JMP 11 software package [28].

2.3 Pine *(P. pinea)* survival experiments

The pine seedling survival study consisted of two pot experiments performed outside the greenhouse from October 2013 until April 2014 in a location protected from precipitation. The objective was to assess the effect of various hydrogel application quantities and methods on the survival of pine seedlings in the two soil types (C and SCL). *P. pinea* was chosen for the study because it is one of the tree species used for afforestation in the region. Three-month old homogenous seedlings were used in all replicates. A two-way factorial arrangement of treatments (2×4) for the hydrogel application methods and quantities was setup using a complete randomized design with three replicates per treatment. Seedlings were transferred into 0.02 m^3 (26 kg of soil) plastic containers treated with 0, 0.2, 0.3, and 0.4% hydrogel soil, using the two application methods (mixing or banding) described previously. Banding involved placing the hydrogel in one layer at a depth of 25 cm. Following transplantation, soils in all pots were irrigated to saturation and thereafter 0.002 m^3 of water was added every other day for 1 week. Irrigation was then halted. The survival of seedlings was monitored on a weekly basis by observing their appearance. Seedlings were considered dead when their leaves turned greyish (following Hüttermann et al. [19]). Statistical analysis of all results was similar to that described for corn in the previous experiment.

2.4 Soil water characteristics experiment

The third experiment performed was an assessment of effect of various hydrogel applications (0, 1, 2, 3, and 4% hydrogel) on soil water characteristics in the two planting media, C and SCL. The greatest application was selected to be double the manufacturer recommended application. A pressure plate apparatus (Soil Moisture Equipment, USA) was used to determine the soil water characteristic curves of the two soil types. A 20 g samples ($n = 3$) of each soil type were mixed with 0 (control), 0.02, 0.04, 0.06, and 0.08 g of the hydrogel. The water content by mass for the two soils was evaluated at the pressures of 15, 30, 100, and 200 kPa. Available water at matric potentials exceeding 200 kPa was considered to be negligible and hence the test was not extended beyond said value. (This value also exceeds the soil moisture deficit threshold for most crops.) The gravimetric method [29] was used to determine water content of the samples, and then the percent increase in gravimetric water content of samples as compared to the control was calculated.

3 Results

3.1 Effect on corn plant growth, evapotranspiration, and water use efficiency

3.1.1 Effect application method and rates in clay soil

In clay soil, hydrogel application quantity significantly affected fresh shoot weight (FW) of corn ($F = 5.84$; $p \leq 0.024$). Differences were significant between the lowest and highest doses, with FW 20% greater at the 0.4% application than FW at the 0% application. FW was not significantly different between application methods ($F = 1.1$; $p \geq 0.298$) (Tab. 3). In addition, there was no effect of the interaction between application method × hydrogel application on FW ($F = 0.47$; $p \geq 0.49$). Dry shoot weight (DW) showed significant differences among hydrogel application quantities ($F = 14.4$; $p \leq 0.0009$). Similarly to FW, there were no significant differences in DW among application method treatment means ($F = 1.1$; $p \geq 0.3$), and no significant effect of the interactions interaction between application method × hydrogel rates on DW ($F = 0.06$; $p \geq 0.8$). In both application methods there was an increasing trend in all treatment means as hydrogel supplementation quantities increased. There was no observed effect of application method or the hydrogel supplementation quantity on dry matter content (DMC).

ETc of corn in clay soil was not affected by either hydrogel supplementation ($F = 1.81$; $p \geq 0.167$) or application method ($F = 2.28$; $p \geq 0.1480$). No significant effect of interaction between application method × hydrogel supplementation quantity on ETc was noted in clay soil ($F = 1.87$; $p \geq 0.155$). Although WUE showed no statistically significant response to application methods ($F = 0.73$; $p \geq 0.3996$), there was a significant effect of hydrogel supplementation on WUE ($F = 4.31$; $p \leq 0.0484$). Only in the banding method, WUE values at 0.2–0.4% hydrogel supplementation were greater by an average of 10% than WUE at 0% hydrogel. However, WUE was not significantly affected by application method or the interaction between application method × hydrogel supplementation quantities.

3.1.2 Effect of application method and quantity in sandy clay loam soils

In sandy clay loam, FW was significantly different among hydrogel application treatments ($F = 22.98$; $p \leq 0.0001$), with FW being 25% greater at the 0.4% hydrogel application than at the 0 and the 0.1% applications (Tab. 3). Fresh weight means were also significantly different between application methods ($F = 56.7$; $p \leq 0.0001$), with values being 15% greater in the banding treatment than in the mixing treatments (Tab. 3). In the banding treatment, the interaction of application method × hydrogel application had a significant effect ($F = 15.87$; $p \leq 0.0005$) on FW, with an increasing trend in growth as application quantity increased. For the mixing treatment, the interaction between application method and hydrogel quantity had no effect on FW. There was no significant effect of hydrogel supplementation on DW. The application method did significantly affect DW ($F = 9.15$; $p \leq 0.006$) with values 12% higher in the banding method than in the mixing method. The interaction between application method and hydrogel supplementation did not affect DW. Results for DMC were similar to those of DW for all treatments variables.

Evapotranspiration means were significantly affected by hydrogel supplementation ($F = 26.47$; $p \leq 0.0001$), increasing concurrently with hydrogel supplementation. There were no significant differences in ETc between application methods ($F = 0.76$; $p \geq 0.39$). In the banding treatment, the interactions of application method × hydrogel supplementation quantity had a significant effect ($F = 3.77$; $p \leq 0.0213$) on ETc, with the greatest ETc occurring when the hydrogel was banded at 0.3 and 0.4% supplementation. Water use efficiency at a hydrogel supplementation of 0.4% was 10% greater than that of the control (0% hydrogel) using banding, with no differences among means observed in the mixing experiment. WUE

Table 3. Effect of hydrogel supplement, hydrogel application method, and the interaction of method × quantity on FW, DW, DMC, and ETc of pot-grown *Z. mays* in two types of soils

	Clay				Sandy clay loam			
	FW (g plant^{-1})	DW (g plant^{-1})	DMC	ETc (kg pot^{-1})	FW (g plant^{-1})	DW (g plant^{-1})	DMC	ETc (kg pot^{-1})
Hydrogel supplement (%)								
0	50.1b	13.63b	0.28a	5.51a	39.97b	13.00a	0.33ab	5.08c
0.1	54.95ab	14.42b	0.26a	5.57a	39.16b	13.21a	0.34a	5.22b
0.2	55.66ab	14.72ab	0.27a	5.55a	42.10ab	13.37a	0.32ab	5.31b
0.3	55.24ab	14.97ab	0.28a	5.68a	48.56a	14.10a	0.295b	5.46a
0.4	61.61a	15.89a	0.26a	5.68a	49.29a	14.37a	0.30ab	5.48a
Application method								
Banding	49.1a	13.78a	0.28a	5.64a	49.35a	14.30a	0.29b	5.11a
Mixing	51.1a	13.48a	0.27a	5.56a	36.37b	12.70b	0.35a	5.05a
Application method × hydrogel quantity								
Banding								
0	51.12a	13.78a	0.28a	5.56a	41.05bcd	13.22ab	0.33abc	5.11de
0.1	55.07a	14.39a	0.26a	5.59a	44.63bc	13.89ab	0.31abc	5.26cde
0.2	60.63a	15.28a	0.26a	5.52a	48.10b	14.06ab	0.29bc	5.39bc
0.3	56.16a	15.06a	0.28a	5.68a	57.38a	15.32ab	0.27c	5.63a
0.4	63.55a	16.12a	0.25a	5.83a	60.33a	15.55a	0.26c	5.61ab
Mixing								
0	51.12a	13.48a	0.275a	5.45a	38.89cd	12.79ab	0.33abc	5.05e
0.1	54.83a	14.46a	0.26a	5.56a	33.69d	12.52b	0.37a	5.18cde
0.2	50.69a	14.16a	0.28a	5.59a	36.06d	12.69ab	0.35ab	5.22cde
0.3	54.32a	14.9a	0.28a	5.68a	39.73cd	12.80ab	0.32abc	5.29cd
0.4	59.67a	15.66a	0.26a	5.50a	38.23cd	13.18ab	0.35abc	5.34c

Values within the same column with different letters are significantly different at $p < 0.05$, Tukey's HSD multiple range test.
Data are least square means of three replicates.

also showed significant differences between applications methods ($F = 7.811$; $p \leq 0.01$), with banding the hydrogel at 0.4% yielding a 6% greater WUE than mixing at the same rate. Finally, the interaction of application method × hydrogel supplementation quantity did not have any significant effect on WUE.

3.2 Pine seedlings survival experiment

3.2.1 Effect of application method and rates on survival in sandy clay loam soil

In SCL, survival time of pine seedlings in the hydrogel supplementation treatments differed significantly between control and all treatments ($F = 8.98$; $p \leq 0.0010$). There were no differences among the various treatment means although the 0.4% supplementation prolonged survival by three to four weeks (15%) as compared to other treatments. The survival time at 0.4% hydrogel supplementation was 25.67 weeks (60% more than survival of control plants) (Tab. 4). Application method of hydrogel in SCL had a significant effect on pine seedling survival ($F = 17.64$; $p \leq 0.0007$), with the banding method conferring 5.6 weeks longer survival time than the mixing method (Tab. 4). Interaction of application method × hydrogel supplementation quantity had a significant effect on survival time. Survival of seedlings in the banding treatment at 0.4% supplementation was significantly greater than survival in all the mixing treatments as well as the control in the banding treatment.

3.2.2 Effect of application method and rates on survival in clay soil

Survival of pine seedlings in clay soil in the banding treatment was significantly greater than in the mixing treatment (27 weeks vs. 24.6 weeks; $F = 8.76$; $p \leq 0.0092$) (Tab. 4). Additionally, hydrogel supplementation quantity had a significant effect on survival duration of pine seedlings ($F = 12.62$; $p \leq 0.0002$), where an increase in survival time was directly correlated with an increase in hydrogel supplementation. The interaction between application method ×

Table 4. Effect of hydrogel supplement, hydrogel application method, and interaction of method × quantity on survival of *P. pinea* seedlings in two types of soils

	Clay	Sandy clay loam
	Survival (weeks)	Survival (weeks)
Hydrogel supplement (%)		
0	22.17c	16.00b
0.2	24.83bc	22.67a
0.3	27.50ab	21.67a
0.4	28.67a	25.67a
Application method		
Banding	27.00a	24.33a
Mixing	24.60b	18.67b
Application method × hydrogel quantity		
Banding		
0	22.33c	16.00c
0.2	26.67abc	27.33ab
0.3	28.33ab	23.33abc
0.4	30.67a	30.67a
Mixing		
0	22.00c	16.00c
0.2	23.00bc	18.00bc
0.3	26.67abc	20.00bc
0.4	26.67abc	20.67bc

Values within the same column with different letters are significantly different at $p < 0.05$, Tukey's HSD multiple range test. Data are least square means of three replicates.

Table 5. Effect of hydrogel supplementation on gravimetric water content (%) of clay and sandy clay loam soils at four matric potentials

	Clay				Sandy clay loam			
	15 kPa	30 kPa	100 kPa	200 kPa	15 kPa	30 kPa	100 kPa	200 kPa
Hydrogel rate (%)								
0	38.2a	31.5a	24.1a	22.4a	24.1a	19.1b	17.3b	15.3b
0.1	38.3a	31.5a	24.2a	22.7a	24.7a	20.5b	17.4b	15.5b
0.2	39.2a	31.7a	24.5a	22.8a	25.4a	20.1b	18.4ab	16.7ab
0.3	40.4a	32.6a	24.7a	22.8a	28.5a	21.1ab	19.6a	17.3ab
0.4	42.4a	33.0a	25.0a	23.0a	28.5a	23.9a	18.1ab	18.4a

Values within the same column with different letters are significantly different at $p < 0.05$, Tukey's HSD multiple range test.
Data are least square means of two replicates.

hydrogel supplementation also had a significant effect on survival of pine seedlings in clay soils ($F = 1.12$; $p \geq 0.3698$).

3.3 Soil water characteristics results

Addition of the hydrogel did not have a significant effect on the soil water characteristics of clay soil (Tab. 5). However, in SCL, hydrogel supplementation significantly increased water retention. There was a significant difference between the water holding capacity at the 0.4% rate and that of the control at all matric potentials at or below field capacity, but the water holding capacity did not vary significantly between the control and hydrogel supplementation of <0.4% at all matric potentials, even though water content values increased with increasing hydrogel supplementation. The effect on soil water holding capacity was most pronounced between the 30 and the 100 kPa matric potentials, suggesting an increase in soil water holding capacity within the irrigation range of soil moisture. In both types of soils tested in the present work, there was a general increase in soil water content at any given pressure as the rate of the hydrogel increased (Fig. 2). This soil water content increase relative to control treatment was more prominent in the coarser textured soil (SCL) than in the finer textured soil (C). There was a noticeable increase in the water holding capacity (+33%) in the SCL soil at 0.4% hydrogel supplementation.

4 Discussion

A greater water holding capacity in SCL translated into more fresh weight and more dry weight of corn shoots, but only when the hydrogel was banded rather than mixed. Banding the hydrogel in SCL soil led to an increase in plant moisture content (a decrease in the DMC) as compared to mixing in the soil, irrespective of application rate. A possible explanation of the phenomenon observed is that banding the hydrogel created a water reservoir within the root zone of the plant. As the soil pores emptied from water, plant roots extracted water from the store in the hydrogel band. The hydrogel granules could better withstand the pressure load of soil when they were all spread in a uniform continuous layer that acted as a reservoir rather than being dispersed as individual granules within the soil. Additionally, banding the hydrogel granules together reduces the surface of contact between the hydrogel and the soil, thus reducing diffusion of water from the granule to the surrounding medium. A third possibility is that a hydrogel band would have allowed water diffusion below it when irrigation saturated the medium, but then retarded capillary movement upwards by creating a water retaining barrier between the lower and upper portions of the pots. In addition to banding, hydrogel supplementation per se also improved plant growth. This is in agreement with Bhardwaj et al. [10], who reported that soil water retention per gram of polymer increases with an increase in

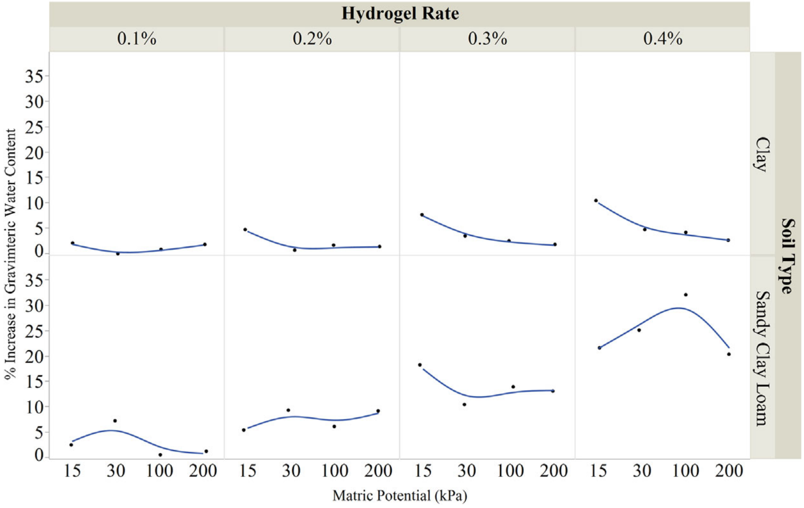

Figure 2. Percent increase in water content of clay and sandy clay loam soils (average of two samples) at various matric potentials.

the hydrogel application rate. However, increasing hydrogel supplementation beyond manufacturer-recommended amounts did not have a significant effect on corn plant growth. Accordingly, for hydrogel supplementation to be as effective as possible, farmers need to apply it properly. Banding might be feasible in pot agriculture but in field circumstances, it does not seem appropriate.

In plants, as above-ground biomass increases, ETc increases. The assumption of commercial hydrogel manufacturers is that their product reduces water loss from the soil. However, in the present work, under optimal soil moisture conditions (between field capacity and 50% of available soil water), evapotranspiration increased in hydrogel supplemented soils. This increase in ETc is in agreement with Hüttermann et al. [19] but in contrast to Akhter et al. [23], who found that hydrogel amendment decreased evapotranspiration. In the present work, the data suggests that in clay soils neither banding nor application quantity had an effect on growth or ETc which corroborates our statement on correlation of above-ground biomass and ETc. Because evapotranspiration includes losses from both soil and leaf surface and thus is affected by plant biomass, it is difficult to model the effects of hydrogel supplementation in the soil on ETc, especially that ETc varies among plant species. Accordingly, a more useful variable to calculate would be WUE.

Water use efficiency was not equal in the two treatments nor was it correlated to ETc. Although WUE increased in both clay and SCL soils in the banding treatment, the increase was more pronounced in the clay soil (Fig. 3). This can be attributed to the fact that plants in clay soil grew larger than in SCL, irrespective of hydrogel supplementation. Nevertheless, the hydrogel still caused an increase in growth in both substrates. In the banding treatment, WUE increased with increasing hydrogel rates in both soils. However, the effect of banding was more pronounced in clay soil than in SCL. This effect was probably because the hydrogel did not increase ETc in clay soil as it did in SCL. WUE in SCL increased as hydrogel supplementation increased. The increase in ETc was coupled with an increase in fresh and dry weight and an increase in water use efficiency (WUE) in SCL, which could be attributed to an increase in the water holding capacity of SCL at 0.4% (Fig. 2). The STOCKOSORB® 660 hydrogel used in the present work seemed to have differing effects on the water holding capacity of SCL soils. The magnitude of the increase in available water varied at different matric potentials. Although in the mixing treatment hydrogel supplementation had a trivial effect on the water holding capacity of clay soil, it did improve the water use efficiency of corn planted in said soil when applied at quantities equal to or greater than 0.2%. On the other hand, hydrogel supplementation increased relative ETc in SCL more than in clay soil, but the increase in relative WUE in clay was more than in SCL (Fig. 3).

The results suggest that application of STOCKOSORB® 660 hydrogel at 0.4% extended the irrigation range of SCL to >200 kPa (*i.e.*, at the 0.4% rate and at 200 kPa, the water content by mass of the soil–hydrogel mixture was 18%, almost equivalent to the water content by mass of the control soil at 30 kPa). The lesser amounts of hydrogel supplementation were found to be ineffective in improving the water holding capacity. This is interesting as the manufacturer-recommended rate of the hydrogel is in the range of 0.1–0.2%. Within the irrigation range of 30–100 kPa, the increase in water retention was between 25 and 33%. This is a significant improvement in the water retention capacity of the SCL.

When visually examining the hydrogel layer in clay soils, it appeared that the layer divided the soil into two distinct zones that could be easily separated as the dried soil block was removed from the pot. The thick soil–hydrogel layer had large pores. Soils examined in the pots where the hydrogel was mixed rather than banded showed smaller macro-pores. Apparently, when the hydrogel granules absorbed water they tended to swell considerably, even when they were confined by soil particles. As the plants absorbed water from the hydrogel granules, the volume of the granules was strongly reduced, leaving large air pores in the soil. This was observed in both types of soils. The continuous swelling and shrinking of the hydrogel particles appears to alter the pore sizes and distribution in the soil thus accentuating the heterogeneity of soil porosity and allowing more water to be held in

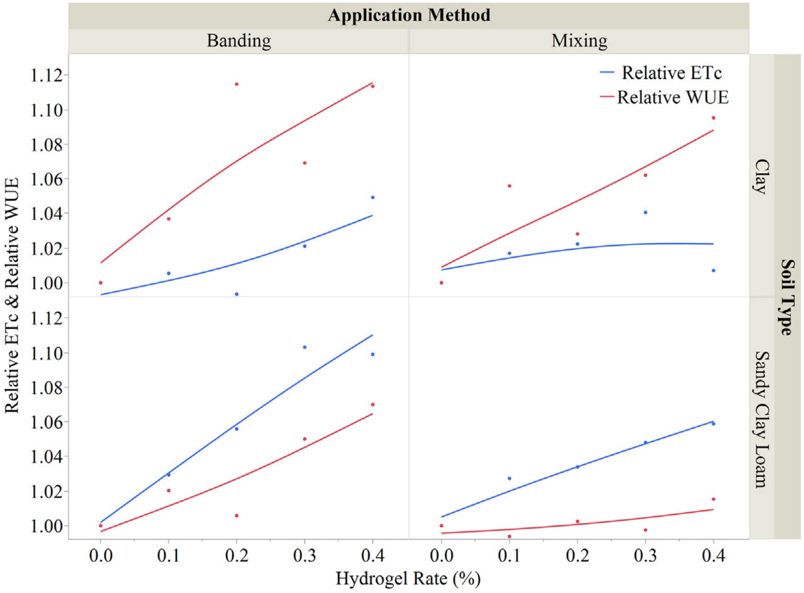

Figure 3. Relative ETc and relative WUE of corn in clay and sandy clay loam under various hydrogel application methods and quantities.

capillary pore spaces. This in turn makes water more available to plants.

The pine seedling survival experiment results show that the addition of hydrogel to SCL at 0.2% or more significantly increased the life span of pine seedlings compared to the control. Moreover, banding increased survival duration more than mixing. In clay soil, the lifespan increase of pine seedlings was not as large as in SCL soil. The increasing trend in survival time of the seedlings with a commensurate increase in hydrogel supplementation suggests that the increase in pore sizes within clay soil and the associated increase in water storage capacity helped plants last longer. Water stored in these large pores was more readily available for plant root abstraction when needed. This is in agreement with various published studies including those reporting improved survival of poplar plants with treated soils under water stress [8], those reporting improved survival of *P. halepensis* seedlings under water stress [19], and those reporting improved survival of seedlings for dryland afforestation [30]. Moreover, improved survival time and a higher leaf water potential of young citrus seedlings grown in perlite and peat media treated with hydrogel, reported by Arbona et al. [31] corroborates results of the present work on pine seedlings.

Survival time of control plants differed considerably between clay and SCL soils. However, the addition of SAPs to SCL soils improved survival time of the seedlings. These results strongly suggest that the addition of SAPs to SCL soil cause the soil to retain considerably more water while the effect on clays is less pronounced. The observation is corroborated by laboratory results that did not show a significant difference in the soil water characteristic curves between treated and non-treated clay soils. The significant increase in survival in both soils when the hydrogel was banded proves that the layers of hydrogel can act as a soil water reservoir that could be tapped into when soil water is depleted. The fact that mixing the hydrogel even at greater proportions did not significantly improve survival in the two soils is consistent with the above hypothesis. This reasoning is supported by studies on mixing clay and hydrogel in growing media that reported a positive effect on water holding capacity of the media [30]. Although mixing clay and hydrogel can increase water holding capacity of the media, only banding improves the availability of the water to the plant roots.

5 Concluding remarks

Water saving is one of the most pressing issues that arid and semi-arid areas are currently facing. With decreasing rainfall and sporadic precipitation events, more efficient water conservation practices in agriculture should be implemented [32]. Absorbent polymer (hydrogel) supplementation to soils is one such practice. Although the manufacturer recommends using the hydrogel at 0.1–0.2% of soil mass, the present results suggest a minimum effective supplementation of 0.4% in sandy clay loam. The present study also shows that using a cross-linked potassium poly-acrilic acid (STOCKOSORB® 660) as a soil amendment increased the available water content of SCL soil by 30% but only by 4% in clay soils. Moreover, the hydrogel application method has a significant effect on increasing the effectiveness of superabsorbent polymers. Mixing the hydrogel distributed the polymer's quantity uniformly in the pot, but did not have a profound effect on water retention and WUE. In a banded application, more water retention was possible within the root zone of the plant. Hydrogel appeared to improve plant water uptake under drought conditions, but only when it was banded as a layer in the soil. However, application of hydrogel banding on large agricultural areas remains technologically and economically restrictive. Technological improvements may change the situation in the near future.

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