Use of Polymers for Alleviating Moisture Stress and Improving Water Use Efficiency in Different Crops in Rainfed Areas

K. Sammi Reddy*, K. L. Sharma, A. G. K. Reddy, A. K. Indoria, K. Srinivas, K. S. Reddy, B. Srinivas and B. Venkateswarlu

Central Research Institute for Dryland Agriculture, Santoshnagar, Saidabad P. O., Hyderabad, Andhra Pradesh (500 059), India

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Correspondence to

**E-mail*: ksreddy_iiss39@yahoo.com

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Abstract

This article reviews and summarizes the effect of incorporation of polymers into soil on water holding capacity, soil properties, crop growth, water use efficiency in crops and factors affecting the performance of polymers in increasing the water use efficiency. Earlier studies clearly showed that application of super absorbent polymers (SAP) in to the soil increase water use efficiency in crops. But the determination of optimum amount of polymer for the best performance is influenced by many factors including, climate, polymer type, soil type, temperature, plant species etc. In India, very little research work has been done on use of polymers in agriculture. Of late, polymers are being introduced in India by many firms with different trade names with an aim to promote their use in dryland agriculture for saving water as well as fertilizer nutrients. The rate of application of polymers recommended by different polymer suppliers varies from 2.5 kg ha^{-1} to 60 kg ha^{-1} depending upon type of polymer, method of application, crop etc. Because of the above factors, based on the work done abroad, it is difficult to make general recommendations of polymers to different rainfed or dryland crops grown by Indian Farmers in diversified climate, soil and management without systematic research under local conditions and economic evaluation. Thus, it is essential to research on the type, quantity and quality of the polymers under rainfed conditions. This review paper comprehensively highlights the scope of research on use of polymers for enhancing water use efficiency in rainfed conditions.

1. Introduction

The problem of inefficient use of rain & irrigation water by crops is most important in rainfed agriculture in semiarid and arid regions. Application of water-saving super absorbent polymers (SAP) in to the soil could be an effective way to increase both water and nutrient use efficiency in crops (Lentz et al., 1998). When polymers are incorporated with soil, it is presumed that they retain large quantities of water and nutrients, which are released as required by the plant. Thus, plant growth could be improved with limited water and nutrient supply (Gehring and Lewis, 1980).

Super absorbents were introduced to the markets in early 1960s, by the American company, Union Carbide (Dexter and Miyamoto, 1995). The product absorbed water thirty times as much as its weight and did not last long and was sold to greenhouse retail markets. Soon it was determined that the product was unsuccessful in market because of its low swell (high cost per unit of water held) and short life (Joao et al., 2007). In fact materials having the capacity to absorb water 20 times more than their weights are considered as a super absorbent (Abedi-Koupal and Sohrab, 2004). But due to development of more cross linked polymers with high water holding capacity (400 times & in some cases even up to 2000 times of their weight) and comparatively low cost than earlier ones has rejuvenated interest on the use of polymers in agriculture. This paper reviewed the key aspects of use of polymers in agriculture, highlighting current research in this field and the future needs in India.

2. Types of Polymers

Both water soluble and insoluble polymers have been marketed for agricultural use. Water-soluble polymers do not form gels and are used as soil conditioners. These include poly (ethylene glycol), (poly vinyl alcohol), polyacrylates and polyacrylamides. Water soluble polymers were developed primarily to aggregate and stabilize soils, combat erosion and improve percolation, and by doing so, improve crop yields on very droughty and structureless soils. Although some of these materials (polyacrylates and polyacrylamides) use the same chemical building blocks as the gel-forming polymers, soil conditioners possess what chemists refer to as linear chain molecular structure and do not form water-absorbing gels.

Insoluble water-absorbing polymers were first introduced for agricultural use in the late1970s and early 1980s. Depending on the type of polymer and the conditions during synthesis, water absorbing polymers have the ability to absorb up to 1,000 times (or more) of their weight in pure water and form gels. Because of their tremendous water-absorbing and gel-forming abilities, they are referred to as super absorbents or hydrogels. There are three main groups of hydrogels, (i) Starch-graft co-polymers, (ii) Polyacrylates, (iii) Acrylamide-acrylate co-polymers.

3. Effects of Polymer Application on Soil and Crop

3.1. Effect of application of polymers on soil moisture storage and water use efficiency

When polymers are incorporated into a soil or soilless medium, they retain large quantities of water and nutrients. These stored water and nutrients are released as required by the plant. Thus, plant growth could be improved, and/or water supplies conserved. It has been reported that a 171% to 402% increase in the water retention capacity is recorded when polymers were incorporated in coarse sand (Ekabafe et al., 2011). It has been reported that increased water retention capacity attributed to polymer addition significantly reduced irrigation frequency (Flannery and Busscher, 1982) and the total amount of irrigation water required. Regarding the available moisture, the best results were obtained with application of PR3005A polymer in levels of 4 and 8 g kg^{-1} in loamy soils. The moisture amount in this situation was increased by 2 to 4 times respectively (Ghaiour, 2000). Sivapalan (2006) stated that the retained water in sandy soil was equal to 23 and 95% with application of polymer at 0.03 and 0.07% of its weight, respectively. Johnson (1984) estimated that applying super absorbent to sandy soils cause an increment in water holding capacity from 171 to 204%.

3.2. Effect on soil and its erosion

Super absorbent polymers affect water penetration rate, density, structure, compactness, texture and crust hardiness of soil, aggregate anchorage (Helalia and Letey, 1989) and evaporation (Tayel and El-Hady, 1981), soil infiltration and aeration, size and number of aggregates, soil's water tension, available water, soil crispiness[18] and finally cause better water management practices in soil.

Non-cross-linked anionic polyacrylamides (PAM, containing <0.05% AM) having very high molecular weight ($12\text{-}15\times10^6$ g mol^{-1}), have also been used to reduce irrigation-induced erosion and enhance infiltration. Its soil stabilizing and flocculating properties improve runoff water quality by reducing sediments, N-dissolved reactive phosphorus (DRP), chemical oxygen demand (COD), pesticides, weed seeds, and microorganisms in runoff.

3.3. Effect on crop growth

Super absorbent polymers cause improvement in plant growth by increasing water holding capacity in soils (Boatright et al., 1997) and delaying the duration to wilting point in drought stress (Gehring and Lewis, 1980). Water conservation by gel creates a buffered environment being effectiveness in short term drought tension and losses reduction in establishment phase in some plant species. Totally, proficiency in water consumption and dry matter production are positive plant reactions to super absorbent application (Woodhouse and Johnson, 1991). Poly (ethylene oxide) hydrogel, polyacrylamide hydrogel and cross-linked poly (ethylene oxide)-co-polyurethane hydrogel were attempted to alleviate the plant damage that resulted from salt-induced and water deficient stress (Shi et al., 2010).

4. Factors Affecting Super Absorbent Polymer Performance

Although many researchers have documented increased water-holding capacity, reduced irrigation frequency, greater water use efficiency, enhanced infiltration rates, reduced compaction tendency and increased plant performance with hydrogel use, others have failed to see such benefits (Nus, 1982). Perhaps a critical assessment of the variables that affect hydrogel performance will help explain why. These variables include polymer type, rate and grind size, method of application, salinity of the soil solution, effects of specific ions, soil texture, temperature, intended use etc.

4.1. Type of polymer

As sated earlier, there are three main groups of hydrogels. They differ widely in their total absorbency, time needed to hydrate, structural integrity and longevity in the soil. Starch-graft co-polymers may take up to a few hours to hydrate completely. However, starch graft co-polymers do not possess the gel strength or longevity that cross linked acrylamide-acrylate co-polymers does (Grula and Huang, 1982). Activity of starch-graft co-polymers is usually limited to a single season, whereas, the cross linked acrylamide-acrylate co-polymers remain active for five to seven years or longer.

In addition to differences between polymer groups, there are hydrogels within a group that may differ substantially. For instance, some cross-linked acrylamide-arylate co-polymers can absorb only 30-40 times their weight of deionized water compared to a more common 400x absorbency factor for many cross-linked arylamide-acrylate co-polymer hydrogels. However, these lower absorbing co-polymers are less affected by salinity than their higher-absorbing counterparts.

4.2. Particle size of polymer

Water absorbing polymers are available in various particle sizes, from powders to coarse granules greater than 2 mm in diameter. The effect of powders versus coarse granules on root zone characteristics such as oxygen diffusion rate and water absorption may be very different. The aim is to amend the soil to substantially increase the water-holding capacity without decreasing the ability for gaseous exchange. If a continuous layer of powder is applied, gas exchange to the roots may be severely reduced. Research that compares powders to fine and coarse-grade granules for their ability to affect gaseous exchange is badly needed.

4.3. Soil texture

Potential benefit of polymers on water storage also depends on the soil texture. Coarse textured soils with large pores tend to retain less water than fine textured soils. Thus, the amount of water that may be retained by incorporating a polymer would be greater in coarse textured soils than in fine textured soils. The bulk density of loamy and sandy soils reduced with polyacrylamide (PAM) addition compared to the control while there was a small increase in bulk density of clayey soil. Conversely, porosity increased with increasing PAM rates for clay loam and sandy soils. However, macro pore size increased in clay soil while it decreased in clay loam and sandy loam soils (Table 1) (Uz et al., 2008). Available water contents of loamy and clay soils showed highly significant increase (108% and 105%, respectively) with the highest 0.67% PAM rate applied due to increase in water content at Field Capacity (FC) and decrease in water content at Wilting Point (WP). Meanwhile, plant available water content of sandy soil increased by 55% since water content at WP increased.

4.4. Salt concentration in water and soil solution

Johnson (1984) reported that water holding properties of polymers significantly affected by nature and dissolved salts concentration in water of irrigation. Saline water reduces absorption and conservation of water. Akhtar et al. (2004) evaluated effect of water kind on amount and rate of absorption and reported that the maximum time for absorption with distilled water, tap water and saline water were 7, 4 and 12 hr, respectively and the amount of absorption in 1 hr was measured as 505, 212 and 140 g g^{-1} , respectively. Increase in water salinity in amount of more than 2.5 dS m^{-1} caused reduction in polymer effectiveness in loamy sandy soils and the plants irrigating with 5 dS m^{-1} used 42% more than that of with 1.6 d S m^{-1} (Bhat et al., 2009). Among various NO_3^- containing salts, hydration of a cross linked polyacrylamide was inhibited most by the presence of Al^{3+}. Similarly, divalent cations (Ca^{2+} and Mg^{2+}) had a greater inhibitory effect on polymer expansion than did monovalent cations (NH_4^+, Na^+, and K^+). The effect of NH_4^+ based salts on polymer expansion (where the cation remained constant but the anion changed) was much less, indicating that the source of cation has a much greater effect on polymer hydration than does the source of anion.

Table 1: Effect of application of different rates of PAM on bulk density and porosity of different soils

Soil property	Soil type	PAM Rates (% by weight)					
		0	0.03	0.10	0.17	0.33	0.67
Bulk Density	Loam	1.48	1.48	1.46	1.45	1.40	1.41
	Clay	1.39	1.38	1.39	1.38	1.41	1.42
	Sandy loam	1.50	1.49	1.49	1.47	1.46	1.39
Porosity	Loam	0.44	0.44	0.45	0.45	0.47	0.47
	Clay	0.48	0.48	0.48	0.48	0.47	0.46
	Sandy loam	0.44	0.44	0.44	0.44	0.45	0.48

Source: Uz (2008)

4.5. Rate of application of polymers

Polyacrylamide (PAM) rates applied to soil may need to be adjusted based on soil properties, slope, and type of erosion targeted. Older PAM formulation required hundreds of kilograms of PAM per hectare. However, PAM with newer longer-chain polymers is more effective even in lower rates (Wallace and Wallace, 1986). Many researchers found that application of 20 kg ha^{-1} PAM prior to sprinkler irrigation increased infiltration rates and reduced runoff and erosion (Stern et al., 1992).

In some cases, overusing of hydrogels causes reverse results, because it reduces soil air followed by filling vacant spaces and gel swelling. There are many reports of no effect or low effect of gels in overused application of them in soil in growth indices of plants. The main reason as mentioned is due to occupation of many vacant spaces of soil resulting in sever soil ventilation (Abedi-Koupai and Mesforoush, 2009). Sarvas et al. (2007) in an experiment on *Pinus sylvestris* L. seedlings observed that by over using of super absorbent in soil; plants were more likely to exposure to Fusarium diseases and mostly perished. They suggested that some investigation needs to be carried out to find out the most suitable amount of hydrogel in different situation and plant species.

Application of 28 kg water absorption polymer (Bhagiratha) per hectare along with recommended rates of fertilizers to pigeon pea maintained higher soil moisture level in sandy loam soil at different growth stages of crop and produced higher seed yield and nitrogen uptake by 12 and 10%, respectively as compared to control (only fertilizers) (Mondal, 2011). Use of 0.75% (w/w) water soluble polymers with 50% Attainable Moisture Depletion (AMD) to tomato in sandy loam soil produced the highest yield (59.6 t ha^{-1}) and maximum water use efficiency (153.6 kg m^{-3}) as compared to other levels of polymer application (0, 0.25, 1.25 and 1.75%) (Lakshmi, 2011). Application of carboxymethyl cellulose at 2% and 4% rate with 5 tonne compost ha^{-1} resulted in increase of maize yield by 25 and 34%, respectively over the untreated sandy soil. The combined effect of both soil conditioners on water and nutrient use efficiency were better than that of their sole application (Table 2).

4.6. Method of application of polymers

The performance of the gel on plant growth depends on the method of application as well. It was shown that spraying the hydrogels as dry granules or mixing them with the entire root zone is not effective (Flannery and Busscher, 1982). Better results seemed to be obtained when the hydrogels are layered, preferably a few inches below soil surface. However, generalizations should be avoided when interpreting results as a number of factors such as types of gel, particle size, rate of application, and type of plant has to be taken into consideration.

4.7. Biodegradation of polymer

The persistence of a particular polymer in the soil may affect its usefulness as a device to delay the release of water and nutrients. In general, naturally occurring polymers are readily degraded by soil microorganisms, while synthetic polymers are more resistant to biological breakdown. Many of the natural polymers contain chemical bonds that may be broken through common enzymatic hydrolysis in soils. The synthetic polymers typically demonstrate much greater resistance to biological attack, since soil microbes have not yet developed the polymer-specific enzymes required for rapid decomposition.

4.8. Temperature

In soil, polyarylamide polymers degrade at rates of at least 10% per year as a result of physical, chemical, biological and photochemical processes (Tolstikh et al., 1992). Intense UV radiation in the open is known to increase the breakdown rates. Bhat et al. (2009) investigated the effects of high temperatures on the performance of PAM polymers using ornamental plant (*Concarpus lancifolius*) in sandy soil under three temperature regimes, viz., Variable Ambient Temperature (VAT, daily maximum and minimum temperatures ranging from 33-49°C and 25-35°C, respectively), Environment Controlled Greenhouse (GH, daily maximum and minimum temperatures ranging from 27-41°C and 20-35°C, respectively) and indoor temperature regimes (LAB, daily maximum and minimum temperatures ranging from 21-26°C and 20-24°C, respectively). The plants grown at 0.4% PAM required 33.8, 38.1 and 30.7% less water than control (no PAM) in VAT, GH, LAB conditions, respectively. The reduced effectiveness of polymers in the VAT regime to a large extent may be related to their degradation due to high temperature and light intensity (Tolstikh, 1992).

Table 2: Effect of compost (C) and /or carboxymethyl cellulose (CMC) on marketable yield, water and fertilizers use efficiency by maize crops

Treatment	Rate of application	Yield (kg ha^{-1})	Water use efficiency (kg m^{-3})	Fertilizer Use Efficiency (kg grain $unit^{-1}$ of added nutrient)		
				N	P	K
Untreated soil	0	1230	15.24	10.3	82	25.6
CMC1	2%	2673	16.68	22.3	178	55.7
CMC2	4%	3010	17.03	25.1	201	62.7
Compost (C_1)	5 t ha^{-1}	2543	15.72	21.2	170	53.0
CMC1 +C_1	2%+5 t ha^{-1}	2997	18.41	25.0	200	62.4
CMC2+C_1	4%+5 t ha^{-1}	3070	20.07	27.5	220	68.8
LSD (p=0.05)		24.6	-	-	-	-

Source: Ali (2011)

5. Conclusions

The determination of amount of gel for the best performance is influenced by many factors including, climate, substance type, soil type, plant species etc. Thus, studies have to be carried out to determine the most suitable amount of hydrogel for each species of plant, climate and substance, individually. In India, very little research work has been done on polymers comparatively. The rate of application of polymers varies from 2.5 kg ha^{-1} to 60 kg ha^{-1} depending upon type of polymer and crop. Another issue is the longevity of polymers in soils. Systematic field studies under arid and semi-arid conditions of India are needed to develop appropriate rate, frequency and method of application of different polymers to various crops and to assess economics of use of different polymers.

6. Future Strategy

There is a need to assess the effect of application of polymers on fertilizer efficiency along with water use efficiency in various crops under variety of soil conditions and different nutrient management systems. The effect of different methods of application of polymers such as seed treatment, soil application (Broad casting, dibbling, deep placement, row application, wet patch application, etc), root dipping needs to be evaluated on establishment of crops and their growth in dryland areas which is very critical for farmers livelihood.

7. References

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

Abedi- Koupai, J., Sohrab, F., 2004. Effect of super absorbent application on water retention capacity and water potential in three soil textures. Journal of Science and Technology of. Polymers 17(3), 163-173.

Akhtar, J., Mahmood, K., Malik, K.A., Mardan, A., Ahmad, M., Iqbal, M.M., 2004. Effects of hydrogel amendment on water storage of sandy loam and loam soils and seedling growth of barley, wheat and chickpea. Plant, Soil and Environment 50(10), 463-469.

Ali, L. K.M., 2011. Significance of applied cellulose polymer and organic manure for ameliorating hydro-physico-chemical properties of sandy soil and maize yield. Australian Journal of Basic and Applied Sciences 5, 23-35.

Bhat, N.R., Suleiman, M.K., Al-Menaie, H., Al-Ali, E.H., AL-Mulla, L., Christopher, A., Lekha, V.S., Ali, S.I., George, P., 2009. Polyacrylamide polymer and salinity effects on water requirement of Conocarpus lancifolius and selected properties of sandy loam soil. European Journal of Science Research 25(4), 549-558.

Boatright, J.L., Balint, D.E., Mackay, W.A., Zajicek, J.M., 1997. Incorporation of a hydrophilic polymer into annual landscape beds. Journal of Environmental Horticulture 15, 37-40.

Dexter, S.T., Miyamoto, T., 1995. Acceleration of water uptake and germination of sugar beet seed balls by surface coatings of hydrophilic colloids. Agronomy Journal 51, 388-389.

Ekabafe, I.O., Ogbeifun, D.E., Okieimen, F.E., 2011. Polymer applications in agriculture. Biokemistri 23(2), 81-89.

Flannery R.L., Busscher, W.J., 1982. Use of a synthetic polymer in potting soils to improve water holding capacity. Communications in Soil Science and Plant Analysis 13(2), 103 -111.

Gehring, J.M., Lewis, A.J., 1980. Effect of hydrogel on wilting and moisture stress of bedding plants. Journal of American Society of Horticultural Sciences 105, 511-513.

Ghaiour, F.A., 2000. Effect of moisture absorbent materials on soil water holding potential. Ministry of Agriculture. Isfahan Research, Center of Animal and Natural Resources. Isfahan, Iran.

Grula, M.M., Huang, M., 1982. Interactions of polyacrylamides with certain soil pseudomonads. Developments in Industrial Microbiology 22, 415-457.

Helalia, A.M., Letey, J., 1989. Effects of different polymers on seedling emergence, aggregate stability and crust hardiness. Soil Science 148,199-203.

Joao, C.M., Bordado, P., Gomez, J.F., 2007. New technologies for effective forest fire fighting. International Journal of Environmental Studies 64(2), 243-251.

Johnson, M.S., 1984. Effect of soluble salts on water absorption by gel-forming soil conditioners. Journal of Science, Food and Agriculture 35, 1063-1066.

Lakshmi, V., (2011) M. Tech. (Agril. Engg) Thesis, Department of Soil and Water Engineering, UAS, Dharwad, Karnataka.

Lentz, R.D., Sojka, R.E., Robbins, C.W., 1998. Reducing phosphorus losses from surface-irrigated fields: Emerging polyacrylamide technology. Journal of Environmental Quality 27, 305-312.

Mondal, U.K., 2011. CRIDA Annual Report (2010-11), Central Research Institute for Dryland Agriculture, Hyderabad.

Nus, J., 1982. Water absorbing polymers. Golf course management, June issue, 26-40.

Sarvas, M., Pavlenda, P., Takacova, E. 2007. Effect of hydrogel application on survival and growth of pine seedlings in reclamations. Journal of Forestry Science 53(5), 204-209.

Shi, Y., Li, J., Shao, J., Deng, S., Wang, R., Li, N., Sun, J., Zhang, H., Zheng, X., Zhou, D., Huttermann, A., Chen, S., 2010. Effects of Stockosorb and Luquasorb polymers on salt and drought tolerance of Populus popularis. Science of Horticulture 124, 268-273.

Sivapalan, S., 2006. Some benefits of treating a sandy soil with a cross-linked type polyacrylamide. *Australian Journal of Experimental Agriculture* 46, 579-584.

Stern, R., Van Der Merwe, A.J., Laker, M.C., Shainberg, I., 1992. Effect of soil surface treatments on runoff and wheat yields under irrigation. Agronomy Journal 84, 114-119.

Tayel, M.Y., El-Hady, O.A., 1981. Super gel as a soil conditioner and its effects on some soil-water retentions. Acta Horticulture 119, 247-256.

Tolstikh, L.I, Akimov, N.I., Golubeva, I.A., Shvetsov, I.A., 1992. Degradation and stabilization of polyarylamide in polymer under flooding conditions. Journal of Polymeric Materials 17, 177-193.

Uz, B.Y., Sabit, E., Demiray, E., Erta, E., 2008. Analyzing the Soil Texture Effect on Promoting Water Holding Capacity by Polyacrylamide. International Meeting on Soil Fertility Land Management and Agroclimatology, Turkey, pp. 209-215.

Wallace, A., Wallace, G.A., 1986. Effect of polymeric soil conditioners on emergence of tomato seedlings. Soil Science 141, 321-323,

Woodhouse, J.M., Johnson, M.S., 1991. Effects of soluble salts and fertilizers on water storage by gel forming soil conditioners. Acta Horticulture 294, 261-269.