Hydrogels: a boon for increasing agricultural productivity in water-stressed environment

Aniket Kalhapure, Rajeew Kumar, V. P. Singh and D. S. Pandey*

India ranks 41st among 181 countries of the world with regard to water stress. More than 60% of the net cultivated area is under dryland condition. Also, more than 30% of the area faces the problem of insufficient rainfall. Hydrogel may prove as a practically convenient and economically feasible option to achieve the goal of agricultural productivity under conditions of water scarcity. It can be easily applied directly in the soil at the time of sowing of field crops and in the growth medium for nursery plantation. The low application rate (i.e. 2.5–5.0 kg/ha) of hydrogel is effective for almost all the crops in relation to soil type and climate of India. The improvement in growth and yield attributing characters and yield of different field, ornamental and vegetable crops has been reported with the application of hydrogel. Agricultural hydrogels are not only used for water saving in irrigation, but they also have tremendous potential to improve physico-chemical and biological properties of the soil. Bulk density, porosity and water holding capacity of the soil are improved with the application of hydrogel. Agricultural hydrogels are eco-friendly, because they are naturally degraded over a period of time, without leaving any toxic residue in the soil and crop products. Hence application of hydrogel will be a fruitful option for increasing agricultural production with sustainability in water-stressed environment.

Keywords: Crop growth and yield, hydrogel, soil properties, water productivity.

Status of water stress in India

IN India rainfed agro-ecologies contribute 60% of the net sown area, 100% of the forest and 66% of the livestock. About 84–87% of pulses and minor millets, 80% of horticulture, 77% of oilseeds, 66% of cotton and 50% of cereals are cultivated under this region[1]. The area under dryland condition is 85 m ha (60% of total cultivated area), which receives average annual rainfall less than 1150 mm. Also, more than 30% of total geographical area of the country comes under low rainfall (less than 750 mm). About 84 districts in India fall in the category of low rainfall area.

India ranks 41st among 181 countries with regard to water stress, with average score of 4.2 on the 0–5 scale system. (Water stress measures how much water is withdrawn every year from rivers, streams and shallow aquifers for domestic, agricultural and industrial uses. Scores above 4 on a scale of 0–5 indicate that, for the average water user, more than 80% of the water available is withdrawn annually.) The 4.2 score indicates that India is in the high risk zone with regard to water stress[2].

India accounts for 2.45% of land area and 4% of water resources of the world, but it has 16% of the world's population. Total utilizable water resource in the country has been estimated to be about 1123 BCM (690 BCM from the surface and 433 BCM from groundwater), which is just 28% of the water derived from precipitation. About 85% (688 BCM) of water usage is being diverted for irrigation in agriculture; it may increase to 1072 BCM by the year 2050 (ref. 3). By 2025, demand for domestic and industrial water usage may increase to 29.2 BCM. Thus water availability for irrigation is expected to reduce to 162.3 BCM.

A per capita availability of less than 1700 m^3 is termed as a water-stressed condition while per capita availability below 1000 m^3 is termed as a water scarcity condition. Table 1 indicates that India is headed towards becoming a country with water scarcity conditions[4].

Table 1. Average annual per capita availability of water in India[4]

Year	Population (million)	Per capita water availability (m^3/year)
2001	1029	1816
2011	1210	1545
2025	1394	1340
2050	1640	1140

Aniket Kalhapure is in the Department of Agronomy, Mahatma Phule Krishi Vidyapeeth, Rahuri 413 722, India and presently at G.B. Pant University of Agriculture and Technology, Pantnagar 263 145, India; Rajeew Kumar, V. P. Singh and D. S. Pandey are in the Department of Agronomy, G.B. Pant University of Agriculture and Technology, Pantnagar 263 145, India.
*For correspondence. (e-mail: aniketmpkv@gmail.com)

Hence, there is an urgent need for efficient water resource management through enhanced water use efficiency. As water utilization is less in industrial (15%) and domestic (5%) sectors compared to agriculture (85%), and there are no further chances to reduce quantity of water in these sectors, the focus should be on agriculture sector for water saving without compromising on crop production.

Different methods for conserving water and reducing water use in agriculture

Ex situ methods

These are generally mechanical measures of water harvesting, e.g. bench terracing, countour bunding, creek bunding, etc. Microirrigation systems (viz. drip and sprinkler irrigation) also come under this category.

In situ methods

(a) Tillage: zero tillage, conservation tillage, minimum tillage, etc. (b) Cultural practices: opening of furrows between rows of crop and sowing on ridges; furrow method, compartmental bunding, mulching, etc. (c) Use of chemicals: anti transpirants and hydrogel.

What is a hydrogel?

Hydrogels are cross-linked polymers with a hydrophilic group which have the capacity to absorb large quantities of water without dissolving in water[5]. Water absorption capacity arises from the hydrophilic functional groups attached to the polymer backbone while their resistance to dissolution arises from cross-links between network chains.

Polyacrylamide $(C_3H_5NO)_n$ is widely used as a synthetic hydrogel and is a polymer formed from acrylamide subunits (Figure 1). It can be synthesized as a simple linear chain structure or cross-linked. Linear linked polyacrylamide will dissolve in water and cannot be used as a hydrogel for water absorption. Cross-linked polymers are synthesized as hydrogel using *N*,*N*′-methylenebisacrylamide (Figure 2). Cross-linked variants of polyacrylamide have shown greater resistance to degradation; hence, they are more stable for longer periods (2–5 years). Acrylamide is toxic (neurotoxic), but polyacrylamide is non-toxic. It is highly water-absorbent and forms a soft gel when hydrated[6].

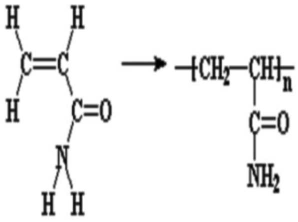

Figure 1. Acrylamide and polyacrylamide.

Water absorption mechanism of hydrogel

The hydrophilic groups (viz. acrylamide, acrylic acid, acrylate, carboxylic acid, etc.) of the polymer chain are responsible for water absorption in hydrogels. The acid groups are attached to the main chain of the polymer. When these polymers are put in water, the latter enters into the hydrogel system by osmosis and hydrogen atoms react and come out as positive ions. This leaves negative ions along the length of the polymer chain. Hence the hydrogel now has several negative charges down its length (Figure 3). These negative charges repel each other. This forces the polymer chain to unwind and open up. They also attract water molecules and bind them with hydrogen bonding[7].

Hydrogel can absorb more than 400 times its weight of water by this mode. When its surroundings begin to dry out, the hydrogel gradually dispenses up to 95% of its stored water. When exposed to water again, it will rehydrate and repeat the process of storing water. This process can last up to 2–5 years, by which time biodegradable hydrogel decomposes.

General uses of hydrogel

Due to the large water absorption capacity, hydrogels are used in many products having importance in our daily

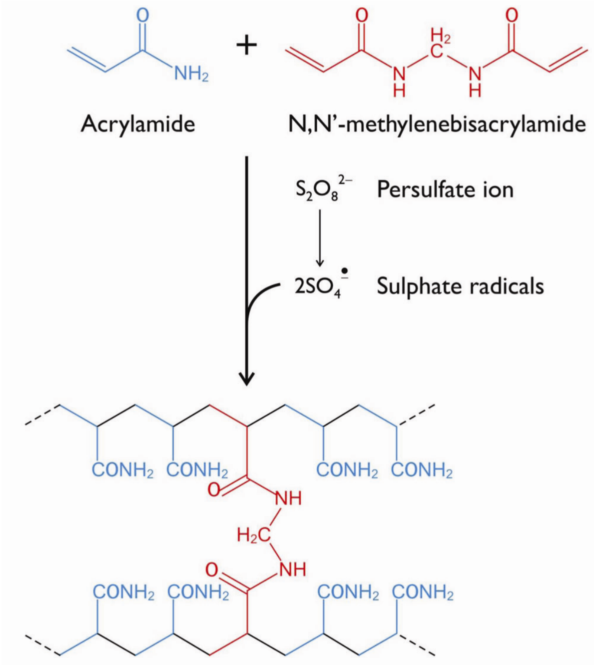

Figure 2. Cross-linked polyacrylamide.

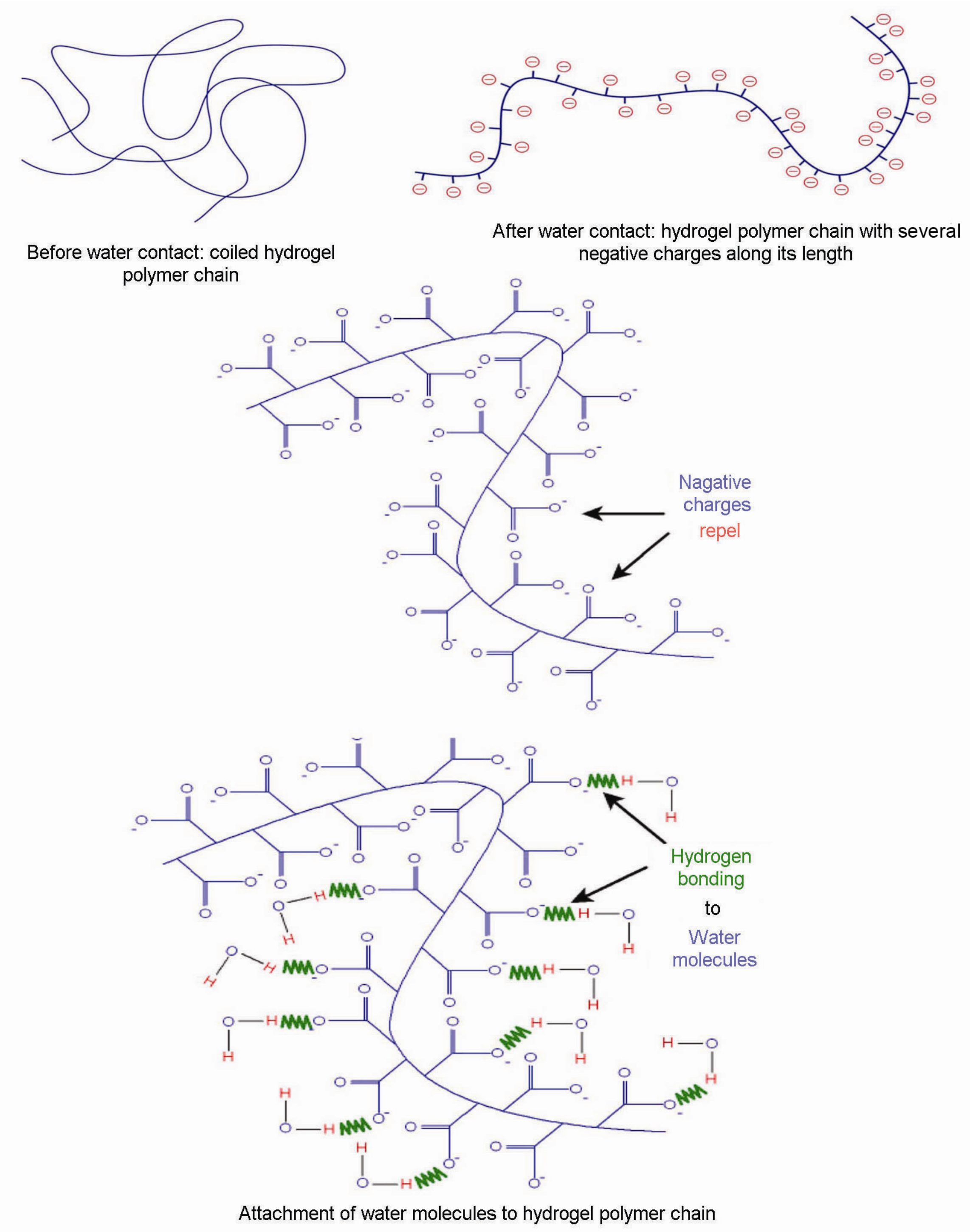

Figure 3. Water absorption mechanism of hydrogel polymer.

life, including diapers, hair gels, sanitary napkins, sweat soaking body powder, sealing, artificial snow[8], agriculture[9], drug delivery systems[10], pharmaceuticals[11], biomedical applications[12], tissue engineering and regenerative medicine[13,14], wound dressing material[15], separation of biomolecules or cells[16], and barrier materials to regulate biological adhesion[17,18].

Use of hydrogel in agriculture

Hydrogels are used to improve the ability of soil to absorb water. They are prepared by grafting and cross-linking of water-absorbent polymers (polyacrylamide) onto a cellulose derivative backbone polymer chain (carboxymethyl cellulose). These hydrogels are more biodegradable and therefore safer to the environment[19]. Unlike superabsorbent polymers employed in hygienic applications which must possess the fast rate of fluid absorption and ability to retain it under high load, the agricultural hydrogels should not only have the ability to absorb water, but must release the same gradually according to specific requirements of the plants.

Preparation of hydrogel

When cellulytic derivatives get irradiated, the radiation breaks some of carbon bonds of glucose molecules in the cellulose chain, resulting in free radical sites on the polymeric backbone (Figure 4). Cellulose radicals formed during irradiation add to one side of the acrylamide to form cellulose–acrylamide graft copolymer[20].

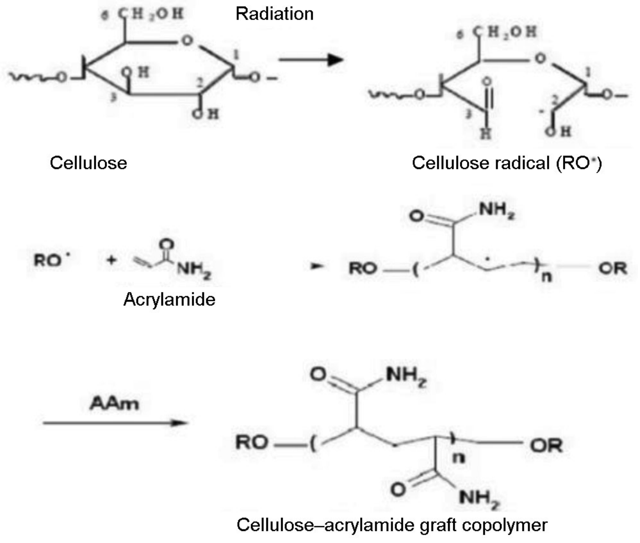

Figure 4. Synthesis of agricultural hydrogels with cellulose backbone and polyacrylamide copolymer.

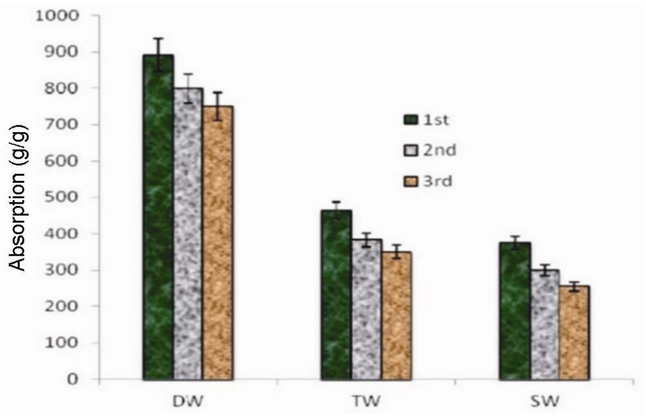

Figure 5. Absorption of distilled water (DW), tap water (TW) and saline water (SW) by hydrogel during first, second and third wetting and drying cycles.

Absorption capacity of hydrogels

Water contains Ca^{++} and Mg^{++} ions. When hydrogel absorbs water these ions react with negative sites in the polymeric chain resulting in the formation of non-soluble salts which block the negative ion sites. This blockage increases with the salinity of water and further cycles of wetting and drying. The water absorption capacity of hydrogels decreases due to these two factors (Figure 5)[21].

Key characteristics of agricultural hydrogels

Agricultural hydrogels are natural polymers containing a cellulose backbone (Figure 6). They can also perform well at high temperatures (40–50°C) and hence are suitable for semi-arid and arid regions. They can absorb a minimum of 400 times of their dry weight of pure water and gradually release it according to the needs of the crop plant. Because of their neutral pH, they do not affect nutrient availability, soil chemical composition, action of other agro chemicals, viz. fertilizers, herbicides, fungicides, insecticides, etc. Hydrogels are found to improve the physical properties of soils (viz. porosity, bulk density, water holding capacity, soil permeability, infiltration rate, etc.)[22]. Table 2 discusses the effect of hydrogels on soil properties[23]. The details regarding commercial availability of hydrogel for agricultural use in India are given in Table 3 with trade names and manufacturing company names.

Increase in porosity results in improvement in seed germination and rate of seedling emergence, root growth and density, and reduced soil erosion due to reduction in soil compaction. It also increases biological/microbial activities in the soil, which increase oxygen/air availability in root zone of the plant[24]. Hydrogels help plants withstand extended moisture stress by delaying the onset of

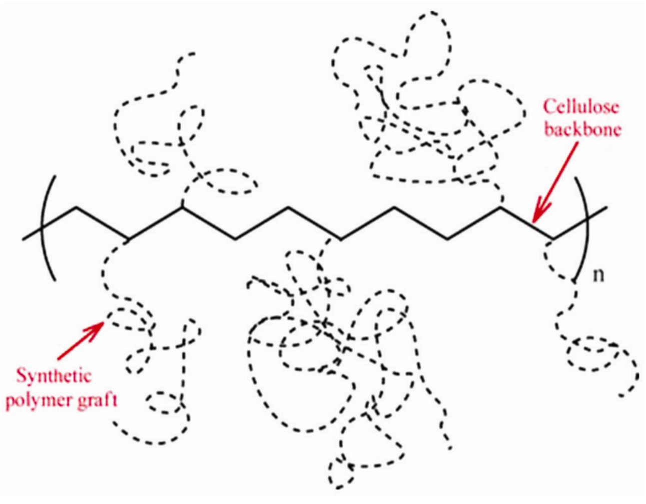

Figure 6. Structure of agricultural hydrogel.

Table 2. Effect of hydrogel on soil properties[23]

Treatment	BD (g/cm^3)	Total porosity (%)	WHC (%)	pH	Dehydrogenage activity (ml H_2/g dry soil /24 h)	Total bacterial count (× 10^6 cfu)
Control	1.613	39.13	22.96	7.75	5.1	150
Compost @ 12 t/ha	1.592	39.92	24.18	7.40	29.3	480
Compost @ 24 t/ha	1.579	40.42	25.09	7.36	39.6	510
Hydrogel @ 24 kg/ha	1.556	41.28	26.36	7.30	18.5	320
Hydrogel @ 48 kg/ha	1.543	41.77	27.0	7.27	19.9	360

BD, Bulk density; WHC, Water holding capacity.

Table 3. Agricultural hydrogel products available in India

Trade name	Manufacturing company
Pusa Hydrogel	IARI, New Delhi
Waterlock 93N	Acuro Organics Ltd, New Delhi
Agro-forestry water absorbent polymer	Technocare Products, Ahmedabad
Super absorbent polymer	Gel Frost Packs Kalyani Enterprises, Chennai
Hydrogel	Chemtex Speciality Ltd, Mumbai
Rain drops	M5 Exotic Lifestyle Concepts, Chennai

permanent wilting point and reducing irrigation requirements of crops due to reduced water loss through evaporation. The water held in root zone of the crop and leaching of nutrients in the soil are also reduced.

Application of 5 kg/ha of hydrogel significantly increases soil moisture content at different depths of soil (viz. 0–15, 15–30 and 30–45 cm) at all stages of crop growth in fodder sorghum[25]. Different enzymatic activities which are indicators of microbial population in the soil (viz. acid phosphatase, alkaline phosphatase, dehydrogenase, protease and urease) are increased with the application of hydrogel in sandy soils[26].

Agricultural hydrogel can be used for all crops and all soil types. Its benefits are most easily noticed in nurseries and seedling beds, crops sensitive to moisture stress, crops requiring large quantities of water, and container gardens – pot cultures.

Rate of application of agricultural hydrogel depends upon the texture of soil – for clay soil: 2.5 kg/ha (at the soil depth of 6–8 inches). For sandy soil: up to 5.0 kg/ha (at the soil depth of 4 inches).

Application methods

- For field crops: Prepare an admixture of hydrogel and fine dry soil in 1 : 10 ratio and apply along with the seeds/fertilizers or in the opened furrows before sowing. For best results, hydrogel should be close to seeds.
- In nursery bed for transplants: Apply 2 g/m^2 (or according to recommended rate) of nursery bed mix of hydrogel uniformly in the top 2 inches of the nursery bed. In pot culture, mix 3–5 g/kg of soil before planting.
- While transplanting: Thoroughly mix 2 g (or according to recommended rate) of hydrogel per litre of water to prepare a free-flowing solution; allow it to settle for half an hour. Dip the roots of the plant in the solution and then transplant in the field.

The results of field experiment in wheat in different wheat-growing zones of India (viz. northeastern plain zone, central and peninsular zone) show that application of 5 kg/ha of hydrogel produced significantly higher grain yield with all the levels of irrigation (viz. no irrigation, two and four irrigations). Also, the equivalent yield of four irrigations with no hydrogel was obtained with only two irrigations when 5 kg/ha of hydrogel was applied[27].

Application of 2.5 kg/ha of hydrogel produced significantly higher growth and attributing characters and yield in aerobic rice compared to control in all the types of lands (viz. flat bed sowing, ridge sowing and raised bed sowing)[28].

Coating of pearl millet seed with 10 and 20 g of hydrogel/kg of seed resulted in the production of significantly higher effective tillers, ear length, test weight, grain and stover yield compared to control and water-soaking treatment[29].

Results of application of 200 kg/ha of hydrogel in peanut were found to be significantly superior in respect of all the growth and yield characters (viz. seed yield, biomass yield, pod yield, number of branches per plant and 100 seed weight) in sandy soil of Iran with hot and arid climate[30].

Yield of wheat was found to increase by 8.48% over control with the application of 5 kg/ha of hydrogel in clay loam soil with 100% recommended dose of fertilizers[26].

The results obtained from farmers field demonstration conducted by ICAR at different locations in Uttar Pradesh evidenced that soil application of hydrogel @ 5 kg/ha along with three irrigations in different wheat varieties is able to produce grain yield equivalent to irrigating wheat crop with five times without hydrogel application (Table 4). It indicates that soil application of hydrogel can save two irrigations in wheat without reducing the grain yield. Increasing doses of hydrogel from

Table 4. Demonstrations in farmers' fields conducted by ICAR in collaboration with ITC group of companies

Zone	No. of villages	Average yield (t/ha)* Three irrigations without hydrogel	Five irrigations without hydrogel	Three irrigations with 5 kg/ha hydrogel	LSD 5%
Hathras, UP	5	3.65	4.20	4.30	0.28
Hardoi, UP	2	3.75	4.38	4.62	0.33
Gonda, UP	2	3.95	4.80	4.65	0.39
Lucknow, UP	1	4.05	4.75	4.70	0.22

*Average of five varieties (PBW 343, PBW 502, PBW 373, PBW 550 and Pusa Unnat).

Table 5. Effect of hydrogel in *Coleus* after 180 days of transplanting

Hydrogel treatment	Plant height (cm)	Stem diameter (cm)	No. of branches	No. of leaves
Control	44.86	8.59	6	35
0.1% (4 g)	50.47	12.64	7	45
0.2% (8 g)	54.00	13.62	8	52
0.25% (10 g)	55.41	16.28	9	54
0.30% (12 g)	57.06	17.44	9	58
0.5% (20 g)	59.64	18.79	11	66

Note: 4 kg of soil medium was used for each pot[32].

0.1% to 0.5% of soil medium in indoor ornamental plants, viz. coleus, resulted in increased plant height, stem diameter, number of branches and leaves (Table 5).

Field performance

The performance of Pusa Hydrogel has been evaluated at various levels, viz. Institute farms, farmers' fields (by licensees and the Institute) and multilocation trials in collaboration with other institutes, namely, Central Potato Research Institute, Shimla; Directorate of Groundnut Research, Junagadh; Project Directorate of Soybean Research, Indore; Indian Institute of Sugarcane Research, Lucknow and Project Directorate of Farming Systems Research, Modipuram, Meerut, and All India Coordinated Research Project on Wheat. The evaluation has been carried out in several crops, namely wheat, groundnut, potato, soybean, mustard, onion, tomato, cauliflower, carrot, strawberry, opium, maize, sugarcane, paddy, turmeric, chrysanthemum, cotton, etc.

Salient findings

- A low rate of application, ranging from 1 to 2 kg/acre is effective in most of the crops.
- Lesser effect of fertilizer and salt solutions on the swelling ratio of hydrogel.
- Compared to control, the hydrogel amended sandy loam soil and medium without soil, e.g. sand, cocopit, etc. (used to raise vegetable and flower nurseries) exhibited delay in the onset of permanent wilting point (2–6 days).
- In hitech horticulture, the application hastened seedling growth and establishment period of chrysanthemum cuttings (18 days) compared to control crop (28 days).
- Reduced the frequency of drip fertigation in horticultural crops raised under protected and open field conditions respectively.
- Significant improvement in yield and water use efficiency in hi-tech cultivation compared to control in most of the test crops.

Hydrogels are environment friendly

Biodegradable hydrogels contain labile bonds either in the polymer backbone or in the cross-links used to prepare the hydrogels. The labile bonds can be broken under physiological conditions either enzymatically or chemically over a period of time. End-products after degradation are CO_2, water and ammonia[31]. Acrylamide, a monomer used for hydrogel preparation is neurotoxic, but polyacrylamide itself is non-toxic. The polyacrylamide can never reform its monomer. Hence there is no residual amount of acrylamide present in the soil after degradation of hydrogel, especially when cellulose is used as backbone. Acrylamide residue is also not detected in crop products which are grown with hydrogel application.

Conclusion

Hydrogel application increases productivity in almost all the test crops (cereals, vegetables, oilseeds, flowers, spices, etc.) in terms of crop yield. It also helps improve the quality of agricultural produce in terms of plant biomass, fruit and flower size and colour with improvement in hydro-physical and biological environment of the soil. Hence hydrogels may become a practically convenient and economically feasible option in water-stressed areas for increasing agricultural productivity with environmental sustainability.

---

1. Report of National Rainfed Area Authority, New Delhi, 2014.
2. *The Times of India*, 14 December 2013.
3. Ground Water Year Book- India 2010–11, Central Ground Water Board, Ministry of Water Resources. Government of India; http://www.cgwb.gov.in
4. Water in India: situation and prospects, Report by UNICEF, 2013.
5. Schacht, E. H., Polymer chemistry and hydrogel systems. *J. Phys.: Conf. Ser. 3*, 2004, 22–28.
6. Ahmed, E. M., Hydrogel: preparation, characterization, and applications. *J. Adv. Res*., 2013; http://dx.doi.org/10.1016/j.jare.2013.07.006
7. Vicky, W., Hydrogels: water-absorbing polymers. *Catalyst*, 2007, **18**(1), 18–21.
8. Singh, A., Sharma, P. K., Garg, V. K. and Garg, G., Hydrogels: a review. *Int. J. Pharm. Sci. Rev. Res*., 2010, **4**(2), 97–105.
9. Saxena, A. K., Synthetic biodegradable hydrogel (Pleura Seal) sealant for sealing of lung tissue after thoracoscopic resection. *J. Thoracic Cardiovasc. Surg*., 2010, **139**(2), 496–507.
10. Hamidi, M., Amir, A. and Pedram, R., Hydrogel nanoparticles in drug delivery. *Adv. Drug Deliver*., 2009, **60**(15), 1638–1649.
11. Kashyap, N., Kumar, N. and Kumar, M., Hydrogels for pharmaceutical and biomedical applications. *Crit. Rev*., *Drug Carrier Syst*., 2005, **22**, 107–149.
12. Stamatialis, F., Papenburg Bernke, J., Miriam, G., Saiful, S., Bettahalli Srivatsa, N. M., Stephanie, S. and Matthias, W., Medical applications of membranes: drug delivery, artificial organs and tissue engineering. *J. Membr. Sci*., 2008, **308**(1–2), 1–34.
13. Zhang, L., Li, K., Xiao, W., Zheng, L., Xiao, Y. and Fan, H., Preparation of collagen–chondroitin sulfate–hyaluronic acid hybrid hydrogel scaffolds and cell compatibility *in vitro*. *Carbohydr. Polym*., 2011, **84**(1), 118–125.
14. Justin Saul, M. and Williams David, F., Hydrogels in regenerative medicine. In *Principles of Regenerative Medicine*, Elsevier, London, 2011, 2nd edn, pp. 637–661.
15. Sikareepaisan, P., Uracha, R. and Pitt, S., Preparation and characterization of asiaticoside-loaded alginate films and their potential for use as effectual wound dressings. *Carbohydr. Polym*., 2011, **83**(4), 1457–1469.
16. Wang, F., Zhenqing, L., Khan, M., Kenichi, T. and Periannan, K., Injectable, rapid gelling and highly flexible hydrogel composites as growth factor and cell carriers. *Acta Biomater*., 2010, **6**(6), 1978–1991.
17. Roy, D., Cambre, J. N. and Brent, S., Sumerlin, future perspectives and recent advances in stimuli-responsive materials. *Prog. Polym. Sci*., 2010, **35**(12), 278–301.
18. Peter, K., McCann Thomas, E., Thu-Trang, T., Laabs Tracy, L., Geller Herbert, M. and Libera Matthew, R., Length-scale mediated adhesion and directed growth of neural cells by surfacepatterned poly (ethylene glycol) hydrogels. *Biomaterials*, 2009, **30**(5), 721–729.
19. Fidelia, N. and Chris, B., Environmentally friendly superabsorbent polymers for water conservation in agricultural lands. *J. Soil Sci. Environ. Manage*., 2011, **2**(7), 206–211.
20. Swantomo, D., Rochmadi, Basuki, K. T. and Sudiyo, R., Synthesis and characterization of graft copolymer rice straw cellulose-acrylamide hydrogels using gamma irradiation. *Atom Indones*., 2013, **39**(2), 201–213.
21. Ali, S. S., Qidwai, A. A., Anwar, F., Ullah, I. and Rashid, U., Improvement in the water retention characteristics of sandy loam soil using a newly synthesized poly (acrylamide-co-acrylic acid) superabsorbent hydrogel nanocomposite material. *Molecules*, 2012, **17**, 9397–9412.
22. Bhaskar, N., Aggarwal, P., Kumar, S. and Meena, M. D., Significance of hydrogel and its application in agriculture. *Indian Farming*, 2013, **62**(10), 15–17.
23. El-Hady, O. A. and Abo-Sedera, S. A., Conditioning effect of composts and acrylamide hydrogels on a sandy calcareous soil. II-physico–biochemical properties of the soil. *Int. J. Agric. Biol*., 2006, **8**(6), 876–884.
24. EI-Rehirn Abd, H. A., Hegazy, E. S. A. and Abd El-Mohdy, H. L., Radiation synthesis of hydrogels to enhance sandy soils water retention and increase performance. *J. Appl. Polym. Sci*., 2004, **93**, 1360–1371.
25. Dass, A., Singh, A. and Rana, K. S., *In-situ* moisture conservation and nutrient management practices in fodder-sorghum (*Sorghum bicolor*). *Ann. Agric. Res*., 2013, **34**(3), 254–259.
26. Borivoj, S., Rak, L. and Bubenikova, I., The effect of hydroabsorbent on selected soil biological and biochemical characteristics and its possible use in revitalization. *Ecologia*, 2006, **25**(4), 422–429.
27. Directorate of Wheat Research Progress Report 2013, Vol. II.
28. Rehman, A., Ahmad, R. and Safdar, M., Effect of hydrogel on the performance of aerobic rice sown under different techniques. *Plant Soil Environ*., 2011, **57**(7), 321–325.
29. Singh, H., Effect of hydrogel on growth, yield and water use efficiency in pearl millet (*Pennisetum glaucum*) production. *Forage Res*., 2012, **38**(1), 27–28.
30. Langaroodi, N. B. S., Ashouri, M., Dorodian, H. R. and Azarpour, E., Study effects of super absorbent application, saline water and irrigation management on yield and yield components of peanut (*Arachis hypogaea* L.). *Ann. Biol. Res*., 2013, **4**(1), 160–169.
31. Ekebafe, L. O., Ogbeifun, D. E. and Okieimen, F. E., Polymer applications in agriculture. *Biokemistri*, 2011, **23**(2), 81–89.
32. Namita, T. Janakiram and Anupama, Pusa hydrogel for growing healthy indoor plants. *IARI News*, 2012, **18**(4), 1.

Received 7 April 2015; revised accepted 18 July 2016

doi: 10.18520/cs/v111/i11/1773-1779