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Actual Performance versus Theoretical Advantages of Polyacrylamide Hydrogel throughout Bedding Plant Production

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***Abstract*. An appropriate blend of growing media components increases water holding capacity and reduces irrigation frequency. Synthetic commercial materials, referred to as hydrogels, have remarkable hydrating properties, but can add significantly (about 15%) to the cost of growing media. The literature generally states that the physical characteristics of hydrogels, such as polyacrylamide (PAM), are altered by the presence of divalent cations (Ca^{2+} and Mg^{2+}). Few studies, however, have simultaneously investigated plant growth and development and media characteristics on a daily basis throughout plant production. Thus, the mechanisms explaining the reported beneficial and/or detrimental effects from PAM incorporation remain hidden. In this study, canopy ground cover of two species [pansy (*Viola* ×*wittrockiana* Gams) and new guinea impatiens (*Impatiens hawkeri* Bull)] was measured daily, from transplanting to marketable size, using digital imaging to determine growth differences of plants grown in media containing different amounts of PAM. Media water content was determined with time-domain reflectance probes every 10 minutes in media treatments. Total number of irrigation events, time between irrigation events, root development after 4 and 8 weeks of growth, flower number, flower longevity, and dry masses of the shoot were also measured. Scanning electron microscopy revealed significant structural differences in hydrated PAM depending on water quality. The pansy canopy coverage was significantly greater with hydrogels, and root growth early in production was enhanced with PAM. No such effect was observed for new guinea impatiens. Total flower numbers and flower longevity of new guinea impatiens decreased with increasing amount of PAM (16.7% or higher) in the media. PAM incorporation reduced the need for irrigation early in production for both species, but by the end of production, those new guinea impatiens plants were smaller (less shoot dry mass) and required irrigation as often as plants grown without PAM. This effect coincided with reduced media volume, air capacity, and total porosity in PAM-containing media. Theoretical analysis of the potential benefits from hydrogels confirms the potential benefit early in production with little to no benefit later in production and in post-production. These data will assist growers in determining if the benefits derived from the use of PAM justify the added cost of medium.**

In the late 1970s and early 1980s, several new products were introduced that had remarkable hydrating properties and appeared to be ideal for use in crop production. These products purportedly provided water to the roots and retained it as well, or better than other soilless media components such as peat and vermiculite. These materials could be classified into several categories: 1) polysaccharide-based polymers, 2) polyacrylamide (PAM), 3) polyvinylalcohol copolymers, 4) propenoate-propenamide copolymers, and 5) polyvinyl acetates, which have water absorbing capacities of 20 to 1000 times their own weight (Fonteno and Bilderback, 1993; Foster and Keever, 1990; Johnson, 1984; Nadler, 1993; Nadler et al., 1996). One of the most popular of these materials, PAM, is being used successfully as an irrigation amendment in field agriculture to reduce water runoff and increase infiltration rates and amounts (Barvenik, 1994; Laird, 1997; Nadler et al., 1994 1996; Sojka et al., 1998; Trout et al., 1995).

The physical properties of PAM have been extensively characterized, and there is agreement in the literature that the water holding capacity is greatly altered in the presence of salts, and more specifically, salts containing divalent cations such as Ca^{2+} and Mg^{2+} (Bowman et al., 1990; Foster and Keever, 1990; Johnson, 1984). Even tap water, with an average Ca^{2+} content of only 5 mM across much of the United States, can reduce the water holding capacity of PAMs by ≥70%. PAMs have also been well characterized in terms of pH, temperature, and salt responses, and there is widespread agreement that PAMs do not behave as advertised in commercial container production conditions (Blodgett et al., 1995; Fonteno and Bilderback, 1993; Ingram and Yeager, 1987; Lamont and O'Connell, 1987; Wang and Gregg, 1990). It is not well documented if wetting and drying cycles with different water qualities influence PAM function, and there are few studies that measure physical characteristics of PAM-containing media during production (i.e., water-holding capacity, porosity, etc.). These characterizations would assist in determining the mechanism for PAM function during production.

There are many studies that demonstrate a delay in wilting and an extension in crop life and quality during the postproduction periods for the plant, which would reduce labor costs, watering needs, and crop loss in retail outlets (Bearce and McCollum, 1977; Eikhof et al., 1974; Jobin et al., 2004; Savé et al., 1995; Still, 1976; Wallace, 1987). However, there are many other studies that show no effect or a detrimental effect of PAM or other hydrogels in plant performance (Austin and Bondari, 1992; Keever et al., 1989; Tu et al., 1985; Wang, 1989). The question remains: do hydrogels work as media amendments for container agriculture?

Few studies have determined the role of PAM throughout the production period from transplant establishment through marketable size, instead drawing conclusions from single, destructive harvests after production is complete. Real-time performance analysis would greatly assist in understanding why the materials do or do not work effectively, and therefore help to explain the apparent discrepancies in the literature. As a reflection of this confusion, the use of PAM is not uniform nationwide, with some regions relying heavily on PAM to produce high-quality plants. The value of PAM during production, therefore, should be explained based on plant responses and physical characterizations *throughout* plant production.

It would also be helpful to perform a basic, mathematical evaluation of the amount of water that can be stored in the PAMs compared to the water use of the plant, predict the effect the environment may have on the demand of that water, and finally a calculation of the reduced watering frequency that would be realistic to expect given certain-sized plants and evaporative demands.

In this study, we used a peat-based media amended with different amounts of polyacrylamide hydrogel to produce pansy and new guinea impatiens. We used further laboratory characterizations of polyacrylamide hydrogel to assist in explaining the observations of plant

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production and performance. Finally, we calculated the expected benefit of polyacrylamide hydrogel to predict its utility under low- and high-water-demand situations.

Materials and Methods

Physical properties of polyacrylamide hydrogel: Expt. 1. Three replicate 1-g samples of polyacrylamide hydrogel (Soil Moist, JRM Chemical, Inc., Cleveland, Ohio) were hydrated for 24 h with water purified by reverse osmosis (RO), tap water, and aqueous solutions of $Ca(NO_3)_2$ in concentrations ranging from 0.005 to 1.0 M $Ca(NO_3)_2$ and weighed to determine hydration ratios (volume of sample after 24 h hydration period divided by mass of dried PAM sample). The tap water contained 1.3 mM Ca, 0.2 mM Mg, 0.3 mM S, and <0.1 mM of all other elements. The RO and tap water samples were dried for 48 h in a drying oven at 60 °C, and then rehydrated for 24 h with the same water type. This process was repeated four times to determine the re-wetting capacities of the hydrogel with tap or RO water. Samples originally hydrated with the aqueous $Ca(NO_3)_2$ solution were discarded after determining their hydration ratio.

To determine the reversibility of salt-imposed reduction in hydrating capacity of PAM, three 1-g PAM samples were hydrated with 0.1 M $Ca(NO_3)_2$ for 24 h, weighed, and dried. The dried samples were then rehydrated with RO water for 24 h, weighed, and dried (four cycles).

Samples of each treatment that were hydrated with RO water, tap water, 0.05 M $Ca(NO_3)_2$ and 0.1 M $Ca(NO_3)_2$ were frozen in liquid N_2 and lyophilized overnight. Dried samples were coated with 40 nm gold, fractured with a razor blade, and coated again with 20 nm gold. Prepared samples were viewed with a scanning electron microscope (SEM) (Hitachi model 3500 and model S-4700, Hitachi Inc., Tokyo, Japan). Beam voltage was 15.0 kV for all magnification up to 3,000×.

Pansy cell pack: Expt. 2. Experiment 2 was performed from 16 Sept. to 5 Nov. 2003. Pansy ('Bingo Clear Yellow') plugs (20 to 30 mm tall with 5 cm^3 root substrate volume) were obtained from a commercial greenhouse facility (Green Circle Greenhouses, Oberlin, Ohio) and transplanted into six-cell market packs. These market packs contain six plants, each within its own 40 × 40 × 55-mm (88-cm^3) planting cell. Sphagnum peatmoss and perlite were mixed (70:30 by volume), amended with 3 g·L^{-1} of hydrated lime and 0.45 g·L^{-1} Micromax (Grace-Sierra Horticultural Products, Milpitas, Calif.), and hydrated to field capacity by adding tap water to runoff. Polyacrylamide hydrogel was then hydrated in RO water and mixed at 0%, 16.7%, and 28.6% (0 L, 1:6 L and 2:7 L hydrated hydrogel–peat mix) by hydrated volume and placed in a greenhouse with temperature set points of 27/22 °C (day/night). Plants within a cell pack were considered a single replication. Plants were arranged in a randomized complete block design with six blocks and two replications of each PAM-media mix in each block. For the first 30 d, canopy ground cover was determined using a digital camera and image analysis software (Klassen et al., 2003). Plants were subirrigated with a fertilizer solution (20N–4.4P–16.6K general purpose water soluble fertilizer diluted to 7.1 mM N or 100 mg·L^{-1} N; The Scotts Co., Marysville, Ohio) when needed.

One month after transplanting the plugs into the market packs, two plants were destructively subsampled from each cell pack, with the remaining plants arranged again to maintain the original spacing generated by the cell packs. The roots on these subsampled plants were brushed until no further media could be wiped from them, then photographed and scored visually side by side for root quality on a scale of 1 to 5 with 1 = poor quality, stunted roots without branching and somewhat discolored appearance, and 5 = excellent, well developed roots with many root hairs. The shoots of the harvested plants were separated from the roots, dried, and weighed for dry mass. Root dry mass was not measured.

After the two plants were harvested from each cell pack, the remaining plants were subirrigated with the same formulation of a fertilizer solution at the first visual appearance of wilting.

Pansy cell pack: Expt. 3. Experiment 3 was performed from 4 May to 22 June 2004. Seeds ('Bingo Clear White') were germinated in foam cubes (15 × 15 × 30 mm each; LC1-type, Smithers-Oasis North America, Kent, Ohio) and transplanted after 3 weeks into the 88 cm^3 cell packs containing the same peat:perlite mixture, described in Expt. 2, plus polyacrylamide hydrogel added at 0%, 9.1%, 16.7%, 23.1%, and 37.5% by hydrated volume (0 L, 1:11 L, 1:7 L, 3:13 L, 3:8 L hydrogel–peat mix). In this experiment, cell packs were arranged in a completely randomized design containing 12 replicate containers per treatment for a total of 60 cell packs. Cell packs were irrigated with the previously described fertilizer solution based on the mass of the cell pack and plant appearance before wilting. When it was determined that some cell packs needed irrigation, all cell packs in the experiment were subirrigated. Canopy ground cover was recorded daily with a digital camera and analyzed with image analysis software.

One month after transplanting, two cell packs were destructively subsampled and data were collected as described in Expt. 2. At the end of the second month, flowers were tagged daily for 2 weeks. Small, hanging tags containing the treatment and date were placed around the flower stalk when the flower completely opened; tags were removed when the flower petals began to fall from the flower, and the date of removal was recorded.

Linear regression was used to determine trends in flower number, flower longevity, and shoot dry mass. If a significant trend was found in these parameters, ANOVA was used to determine differences in treatment means. Statistical analyses were performed with SigmaPlot and SigmaStat (version 6.0 and 2.0, respectively; Jandel Scientific, San Rafael, Calif.). Canopy ground cover data were analyzed with a two-way repeated-measures ANOVA.

New guinea impatiens hanging baskets: Expts. 4 and 5. Experiment 4 was conducted from 28 Nov. 2003 to 24 Mar. 2004 and Expt. 5 was conducted from 12 June to 10 Sept. 2004. Rooted cuttings of new guinea impatiens ('Pure Beauty Purple' and 'Electric Orange' for Expt. 4 and 'Pure Beauty Light Pink' and 'Paradise Bright Red' for Expt. 5; Paul Ecke Ranch, Calif.) were transplanted into 50 250-mm-diameter (4000-cm^3) hanging baskets at a planting density of four plants per basket. The same peat–perlite mixture was further amended with RO-hydrated PAM to make 0%, 16.7%, 28.6%, 37.5%, and 44.4% of the final volume (0, 1:6, 2:7 L, 3:8 L, 4:9 L hydrogel–peat mix). In Expt. 4, the plants were placed in a greenhouse with a mixture (1 lamp–1 lamp) of supplemental lighting from high pressure sodium and metal halide lamps providing about 200 µmol·m^{-2}·s^{-1} on a 16-h photoperiod. Experiment 5 did not use supplemental lighting. The environment was maintained between 22 and 28 °C days and 15 to 20 °C nights with relative humidity ranging from 20% to 50%.

In Expt. 4, the plants were established for 20 d by irrigating all plants at the same time with a modified Hoagland's nutrient solution (Hoagland and Arnon, 1950) containing 7.5 mM N, 1 mM P, 3.5 mM K, 2.5 mM Ca, 2 mM Mg, 2 mM S, 71 µM Fe, 9 µM Mn, 1.5 µM Cu, 1.5 µM Zn, 45 µM B, 0.1 µM Mo, 24 µM Cl, 0.2 µM Na using KH_2PO_4, KNO_3, $Ca(NO_3)_2$, $MgSO_4$, Fe-DTPA, $MnCl_2$, $CuCl_2$, $ZnCl_2$, H_3BO_3, and $Na_2{\bullet}2MoO_4$. After day 20, media water content was measured daily with a soil moisture time domain reflectometry probe (Theta Probe, Delta-T Devices, Cambridge, U.K.) in 8 of the 10 pots for each treatment. The mV output for the moisture probes was converted with the factory calibration, third-order equation for

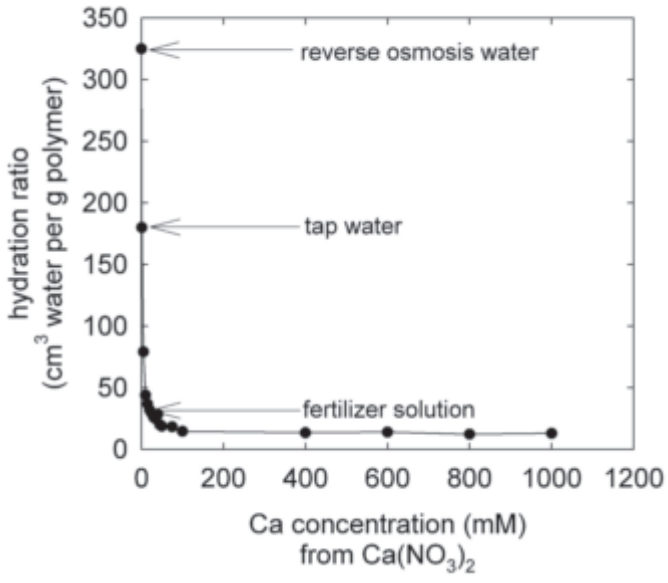

Fig. 1. Effect of water quality and $Ca(NO_3)_2$ on hydration properties of polyacrylamide hydrogel.

organic soil: $y = -0.03234 + (8.34 \times 10^{-4})\ mV + (-8.6 \times 10^{-7})\ mV^2 + (6.47 \times 10^{-10})\ mV^3$.

When the mean water content of the pots within a treatment dropped to between 13% to 15% volumetric water content, the treatment was irrigated to runoff three times during one hour to provide complete wetting of the media with the previously described fertilizer solution. Irrigation events were recorded for each treatment.

Based on the soil moisture probe results from Expt. 4, we determined that there was little variability in soil moisture between replications within each treatment. We, therefore, buried one moisture probe in a representative pot of each treatment to about 30 mm below the media surface and measured the moisture content every 10 min for Expt. 5. The data were stored in a datalogger (model DL6; Delta-T Devices, Cambridge, U.K.) and downloaded as needed. The treatment was irrigated as in Expt. 4 and recorded. Due to errors in fertigation timing for the new guinea impatiens plants containing 16.7% hydrogel, data from this treatment in Expt. 5 were discarded for all analyses.

In Expt. 4, one basket from each cultivar in each treatment was photographed daily until flowering. Photographs were analyzed for canopy coverage in image analysis software.

Plants were maintained vegetatively (flowers removed) for 100 d in Expt. 4 and 75 d in Expt. 5. At that time, the plants were allowed to flower, and the flowers were tagged for 20 d after the first flower appeared. When the final tag was removed, all the plants from all treatments were harvested and dried.

In Expts. 4 and 5, each hanging basket was considered a single replicate and were arranged in a completely randomized design containing five replications per treatment per cultivar for a total of 50 hanging baskets per experiment. Linear regression was used to determine trends in shoot dry mass, media characteristics, flower number, and flower longevity. Statistical analyses were performed with SigmaPlot.

Media physical properties. At the start of Expt. 5, the media height inside the hanging basket was marked in all treatments. After the experiment, the decrease in height was used to calculate the reduction in media volume. At this point, the drainage holes were blocked and water was added until a thin film of water was visible on the surface of the media. The saturated container was weighed, and allowed to drain. The difference in saturated weight and drained media weight was the air capacity of the media at field capacity. The media was then oven dried for 72 h at 75 °C to determine the dry weight of the media, which was used to determine the media water holding capacity. Air capacity and media water holding capacity as well as bulk densities can then be used to calculate total porosity.

Results

Physical properties of polyacrylamide hydrogel: Expt. 1. Hydration of PAM was influenced by water type (Fig. 1). With RO water, the hydration ratio was about 325 cm^3 water per g polymer. The hydration ratio for tap water was 180 cm^3 water per gram polymer, or a reduction of 45%. A reduction of 90% occurred when PAM was hydrated in a solution of RO water and $Ca(NO_3)_2$ with any concentration between 0.1 and 1.0 M $Ca(NO_3)_2$. The water holding capacity of PAM was not influenced by hydration cycles if RO water was used, but was significantly decreased with hydration cycles when tap water was used at each hydration cycle (Fig. 2A). The reduction in hydration capacity is only minimally reversible. After four hydration cycles with RO water, polyacrylamide that had been originally hydrated with 0.1 M $Ca(NO_3)_2$ only had a hydration ratio of 83 (Fig. 2B).

Analysis of PAM samples in the SEM revealed differences in the size of the honeycomb-like polymer framework depending on the solution used to hydrate the material. In 0.1 M $Ca(NO_3)_2$, the polymer walls were thick and the polymer framework was about 12 µm at their widest points (Fig. 3A). When the polymer was hydrated with 0.05 M $Ca(NO_3)_2$, the polymer walls were still thick, but the distance between the walls was up to 18 nm (Fig. 3B). In tap and RO water, the polymer walls were thin and the structure had large gaps between the walls (about 45 µm, Fig. 3C and D). PAM hydrated with tap water appeared to have areas that were damaged (cell edges in Fig. 3C).

Expanded hydrogel at higher magnification revealed further differences in structure. Those samples hydrated with $Ca(NO_3)_2$ had areas that appeared to not have expanded as indicated

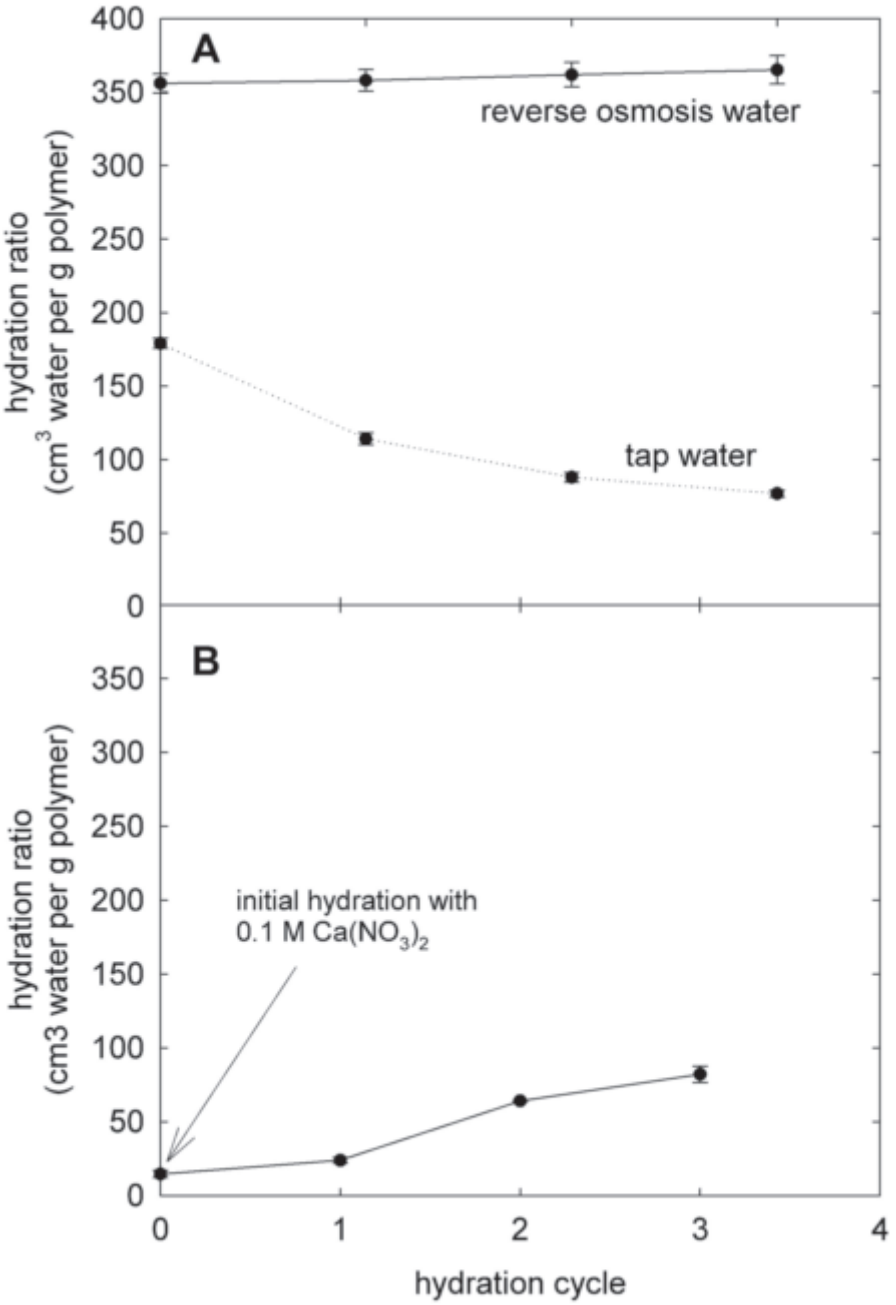

Fig. 2. Effect of multiple hydration cycles on the hydration properties of polyacrylamide hydrogel (**A**). Ca^{2+} content of the tap water used in this study was 1.3 mM. Recovery of hydration capacity after initial hydration with 0.1 M $Ca(NO_3)_2$ and subsequent rehydration with reverse osmosis water (**B**). Error bars represent standard deviations of means. Some error bars are smaller than the symbols. There was a significant difference among hydration ratios of each hydration cycle, based on Tukey's test of means.

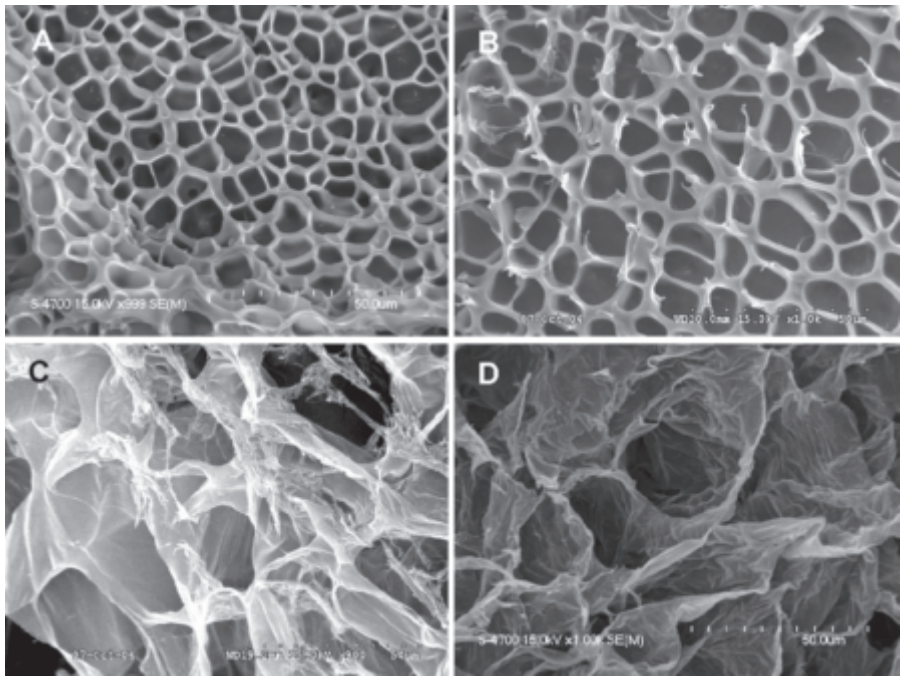

Fig. 3. Hydrated structure of polyacrylamide hydrogel in 0.1 M $Ca(NO_3)_2$ (**A**), 0.05 M $Ca(NO_3)_2$ (**B**), tap water (**C**), and reverse osmosis water (**D**). Scale in the lower right of each picture indicates 50 µm. All images were taken with a scanning electron microscope at a magnification of between 900 and 1000× with an accelerating voltage of 15.0 kV.

by the smaller polymer framework at higher magnification (Fig. 4A). Higher magnification of RO-hydrated PAM appeared to be completely expanded and did not reveal any reduction in polymer frame size (Fig. 4B).

Pansy cell pack studies: Expts. 2 and 3. In Expt. 2, the roots in the control were discolored and averaged a score of 1.91 ± 1.1 (SD), which was significantly different ($P < 0.05$) from the treatments containing 16.7% and 28.8% polymer (3.45 ± 1.4 and 4.5 ± 0.8, respectively; Table 1). In Expt. 3, all roots appeared healthy, but the roots of the control plants did not extend to the bottom of the cell pack. The pansy plants grown in polymer-amended media had higher root quality scores; the two highest polymer treatments (23.1% and 37.5%) had higher root quality scores than the control (Table 1).

In Expt. 2, there was a significant effect of amount of polymer on final shoot dry mass per pack with the pansies grown in the media containing the highest polymer fraction being significantly larger than the other two treatments ($y = 2.58 + 0.0197x$, $r^2 = 0.32$, $P = 0.0012$; Fig. 5A), but the magnitude of increase was fairly small (about 2% increase in size per percentage increase in PAM media content). The effect was not observed in Expt. 3.

Flower longevity was not influenced by the use of PAM (data not shown). Flower number was enhanced with incorporation of PAM in the media based on linear regression ($y = 7.9 + 0.0603x$, $r^2 = 0.081$, $P = 0.451$; Fig. 5B). Pansies grown with >40% PAM had an additional flower or two per cell pack. There was no effect of PAM on percent groundcover in Expt. 2, but the plants grown with PAM had greater canopy ground cover after a few weeks of growth (Fig. 6).

New guinea impatiens hanging basket studies: Expts. 4 and 5. Initially, polymer incorporated into the media allowed for more time between irrigations (Table 2). Gradually, that advantage was lost until the end of the 100-d growth period where the treatments with the most PAM (37.5% and 44.4%) actually required more frequent irrigations. Growth was similar in all PAM treatments based on image analysis of subsampled plants (data not shown). Final shoot dry mass tended to decrease with more PAM (average regression equation: $y = 36.9 - 0.153x$, $r^2 = 0.241$, $P < 0.0001$), but there was no significant difference among treatment means (Fig. 7).

The rate of water loss, as indicated by the decrease in volumetric water content, was not different between treatments ($P = 0.344$; Table 3). There was a tendency ($P < 0.0001$) to have increased maximum hydrated volumetric water content with more PAM amended in the media indicating more water is held in the root-zone when PAM is incorporated. This is not to imply greater plant available water necessarily, only greater water content in the root zone. Interestingly, the maximum volumetric water content increased through the production period (data not shown), and more so with more polymer amended in the media, suggesting that there was a greater capacity to hold water as the plants grew. This increase coincided with changing substrate properties from the beginning of the trial to the end. Total media volume, air capacity, and porosity decreased more with higher PAM amounts (Fig. 8A).

Flower tagging indicated more flowers developed on plants grown in media with little to no PAM ($y = 18.7 - 0.23x$, $r^2 = 0.24$, $P = 0.0132$; Fig. 8B). Flower longevity increased with intermediate amounts of PAM in 'Electric Orange', but was not affected by polymer in the 'Pure Beauty' lines (Fig. 8C).

Discussion

The polymer's expansion characteristics and structural changes observed with the SEM likely explain much of the observed decreases in porosity and substrate volume during production. This also explains why many of the benefits of PAM incorporation are only observed in short-term studies or early in production. The structural changes observed in the SEM were similar to the findings of Johnson and Veltkamp (1985), but in that study, the water quality used to hydrate the polymer was not reported and no differences between hydration properties between polymers hydrated in different solutions was not reported.

Pansy canopy coverage was larger and had slightly larger plants at the end of the study, suggesting they can grow faster in PAM-containing media. If they grow more rapidly, however, the benefit of reduced irrigations is lost, so the benefit becomes more rapid plant production. The growth enhancement was not observed with new guinea impatiens, and in fact, plants grown in PAM-containing media were smaller at the end of the experiments.

Potential for irrigation saving: Production. It is difficult to estimate the water use for growing plants throughout the growth cycle in a greenhouse, but as a rule of thumb, Nelson (1998) and Reed (1996) assume 20 $L \cdot m^{-2}$ is needed for irrigations under typical environmental conditions. For the purposes of these calculations, we will assume a range of 5 to 20 $L \cdot m^{-2} \cdot d^{-1}$ is needed. Under a best-case scenario of packing 25-cm hanging baskets pot to pot,

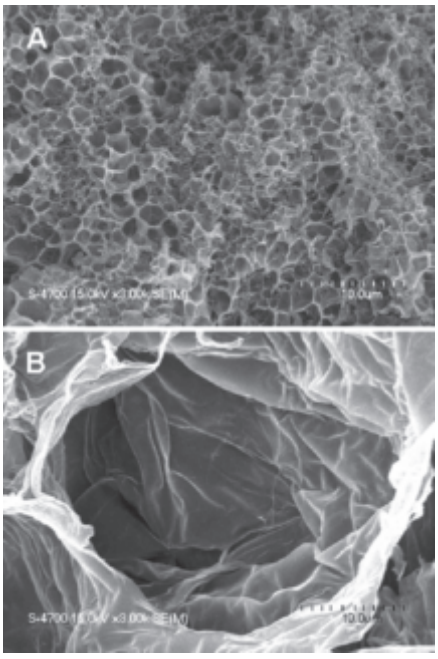

Fig. 4. Hydrated structure of polyacrylamide hydrogel in 0.1 M $Ca(NO_3)_2$ (**A**) and reverse osmosis water (**B**). Images reveal areas of the polymer that is inhibited from expansion if exposed to salt solutions, whereas the sample hydrated with reverse osmosis water appears to be completely expanded. Scale in the lower right of each picture indicates a length of 10 µm. Both images were taken with a scanning electron microscope at a magnification of 3000× with an accelerating voltage of 15.0 kV.

Table 1. Pansy root index with standard deviations after 1 month of growth (a score of 1 = poor growth and 5 = excellent growth). In both experiments, pansy root growth in six-cell market packs was enhanced after one month by growth in media amended with polyacrylamide hydrogel.

	Root index (score of 1 to 5) based on polymer in media (% by vol hydrated media)				
Experiment	0	9.1	16.7	23.1	37.5
2	1.91 ± 1.1 a[z]	---	3.45 ± 1.4 b	4.5 ± 0.8 b	---
3	1.42 ± 0.67a	2.5 ± 1.09ab	2.58 ± 1.0ab	2.83 ± 0.83bc	4.33 ± 0.89c

[z]Means followed by different letters in a row indicate significant difference ($P < 0.05$) based on one-way ANOVA and Tukey's test of means.

there is a total of about 15 pots m^{-2}. Each pot can hold a volume of 5.6 L. Peat can hold up to 8 times its own mass in water depending on its grade (Handreck and Black, 2002), with a 7 water : 1 peat mass ratio being a useful assumption for a broad range of peat qualities. If there was between 70% and 90% peat in each pot, each pot could hold a maximum of 3.2 L of water or 48 $L \cdot m^{-2}$. If 75% of this water is available, that water would be consumed in between 1.8 and 7.2 d.

If media consisted of 50% hydrated polymer, with the remaining 50% consisting of a typical peat–perlite mixture, there would be an additional 1.2 L of water per pot, assuming all the water in the polymer is available. The water would then be consumed in 2.7 to 10.8 d or up to 3.6 d longer than without polymer. Our study suggests that over time, all the water held by the polymer is not available, compression of media results in less media volume available to hold water (about 25% reduction), the PAM shrinks over time with irrigations because of the salts in fertilizer solutions (about 90% reduction), and there typically isn't that much PAM incorporated into the media (40% less is typical), which results in an improvement of much less than 1 day for hanging baskets. Other pot types (for example, six-cell market packs) have additional limitations due to their smaller root zone volumes, so a reduction in air capacity would be critical for those container sizes.

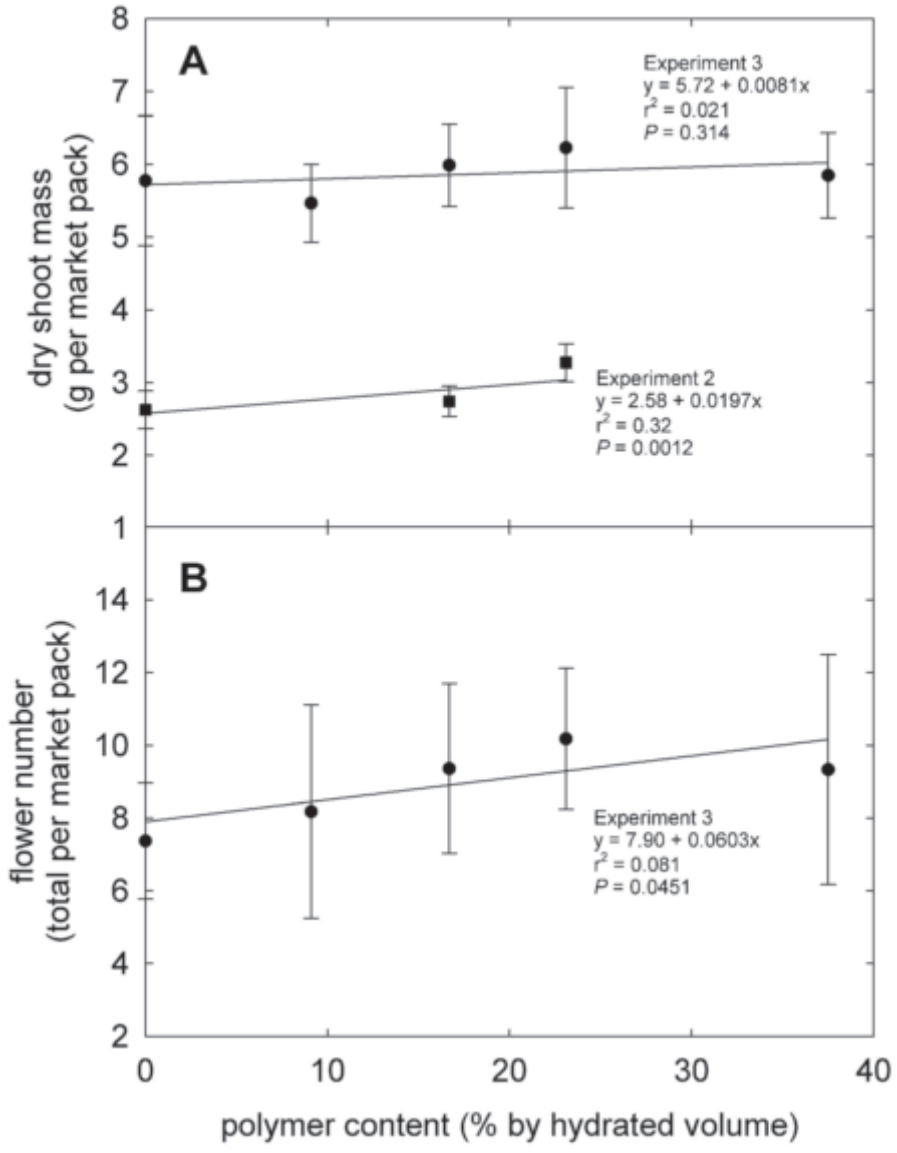

Fig. 5. Influence of polymer content in the media on final shoot mass in Expts. 2 and 3 (**A**) and total flower number (**B**) of pansy in Expt. 3. In Expt. 2, final shoot dry mass was calculated from six-cell packs, each with four plants, and in Expt. 2, final shoot mass was calculated from ten-cell packs, each with six plants. Flower number was calculated from ten-cell packs, each containing six plants.

Potential for irrigation savings: Consumers. Consumers purchase the plants when the plants are large, (after the polymer physical properties have been negatively influenced by periodic dehydration and hydration, and the substrate has shrunk) and typically place the product in higher light and lower humidity environments, which increases their water use. Typical C3 plants have water use efficiencies of at least 300 g of water used per gram biomass formed. Assuming CO_2 is not elevated and temperature is within some typical ranges (20 to 30 °C), some estimates of average water demand can be derived, based on the energy cascade modeling approach (Volk et al., 1995). Assuming an average of 30 $mol \cdot m^{-2} \cdot d^{-1}$ photons × radiation capture (assume a value of 90% for these finished, mature plants) × photosynthetic or quantum efficiency of 0.04 mol C fixed/mol photons (Lal and Edwards, 1995; Long, 1991) = 1.08 mol C fixed per $m^{-2} \cdot d^{-1}$. Assuming that plants are composed primarily of carbohydrates, this translates to 32.4 g of biomass per $m^{-2} \cdot d^{-1}$ (dry weight). To achieve this, 5.8 L of water was needed per pot per day (32.4 × 300 cm^3 H_2O/g biomass, plant area of 0.6 m^2; 1 g H_2O = 1 cm^3 H_2O). This is far more water than is available with a media mix that consists of 85% peat, and after the media volume and hydration capacity of PAM is decreased throughout production, is far greater than that available with a media mix containing substantial PAM. It is not likely, therefore, that the consumer will derive any benefit from purchasing a hanging basket amended with PAM.

Overall, the use of PAM may be beneficial to growers desiring less frequent irrigations for their plants, especially early in plant establishment. If used, watering techniques must change to accommodate slower rewetting time. Incorporating PAM into growing media will likely minimally decrease flower number, decrease some plant species' size, decrease media porosity with time, and lose its effectiveness after the initial 3 weeks of plant production.

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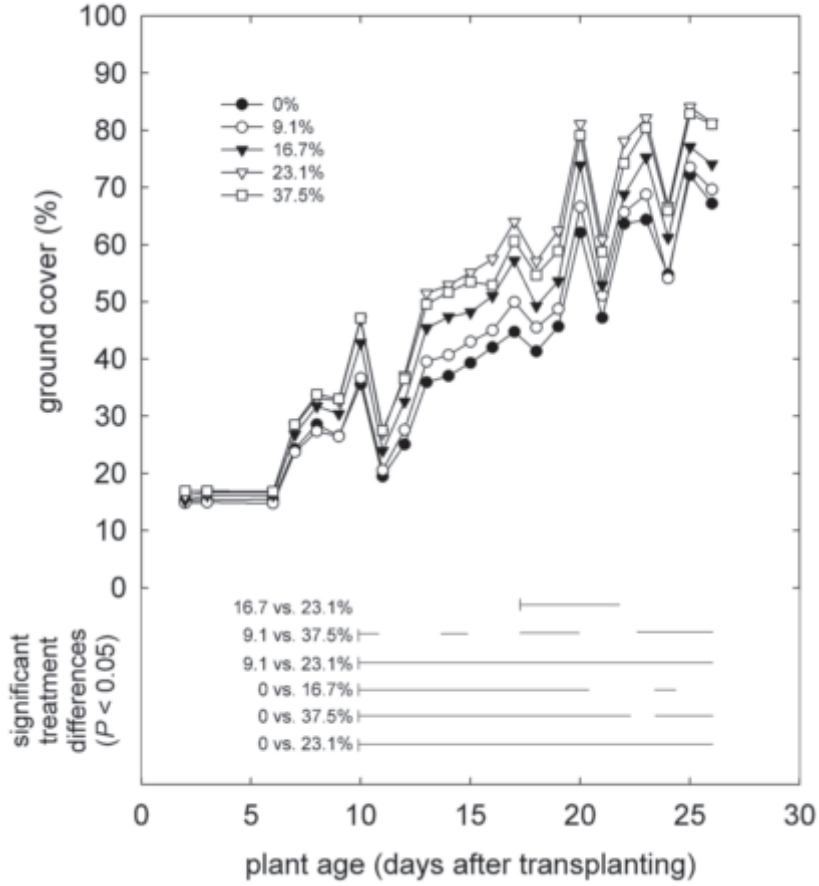

Fig. 6. Influence of polymer content on ground cover canopy expansion in the initial 30 d of growth of pansy in market packs. Each data point is an average of 10 plants. Lines and broken lines at the bottom of the figure indicate significant differences ($P < 0.05$) between the treatments, based on Tukey's multiple comparison test of means, listed next to the lines during the time period covered by the lines.

Table 2. Days between irrigation events for the new guinea impatiens hanging baskets that contained different amounts of hydrated polyacrylamide hydrogel in Expt. 4, and the total number of irrigations for the 100-d growing period.

Polymer content	Irrigation event					Total
(% hydrated volume)	1st	3rd	5th	7th	9th	irrigations
0	4	8	8	6	6	13
16.7	8	7	7	6	6	12
28.6	13	9	9	7	4	10
37.5	14	10	10	8	4	10
44.4	15	9	9	7	4	10

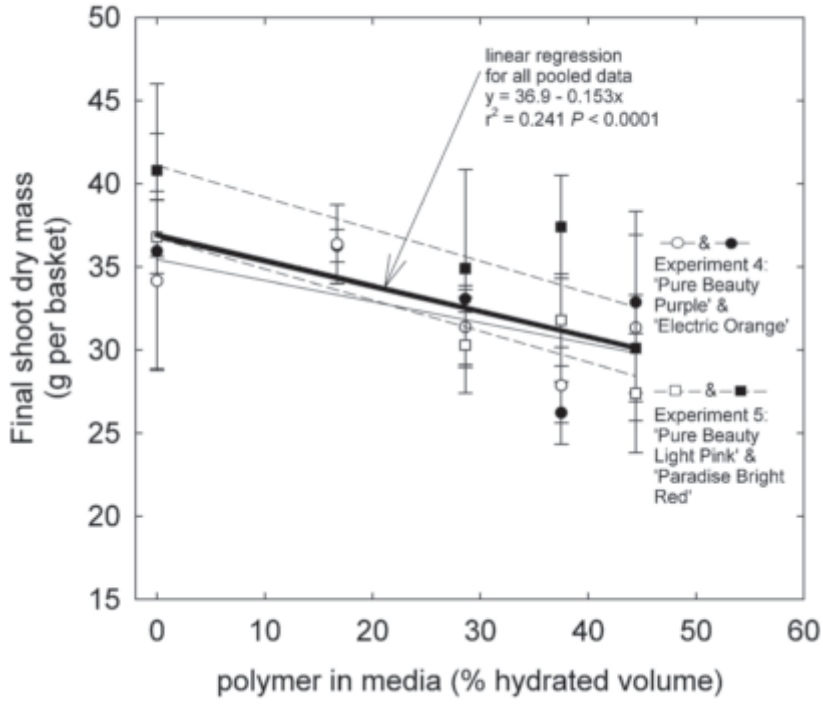

Fig. 7. Final dry mass of four cultivars of new guinea impatiens in two separate experiments (Expts. 4 and 5). The thick line represents the regression line if all data from the 4 cultivars were pooled. The regression equations from the cultivars used in Expt. 4 are y = 36.7 -0.15x, $r^2 = 0.21$, $P = 0.0203$ and y = 34.2 – 0.10x, $r^2 = 0.16$, $P = 0.0493$ and for Expt. 5 are 41.1 – 0.19x, $r^2 = 0.33$, $P = 0.008$ and y = 36.7 – 0.19x, $r^2 = 0.54$, $P = 0.0002$.

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Table 3. Mean soil moisture properties of media during initial 3 weeks of new guinea impatiens growth in 25-cm hanging baskets containing different amounts of polyacrylamide hydrogel.

Polymer in media (% hydrated vol)	Rate of volumetric water loss (%/d)	Max volumetric water content (%)
0	–4.28 a[z]	41.8 ± 0.061 a
28.8	–4.28 a	42.1 ± 0.044 a
37.5	–3.92 a	43.8 ± 0.031 a
44.4	–5.35 a	53.6 ± 0.012 b

[z]Means followed by different letters indicate significant differences based on Dunn's method of pair-wise multiple comparison procedures.

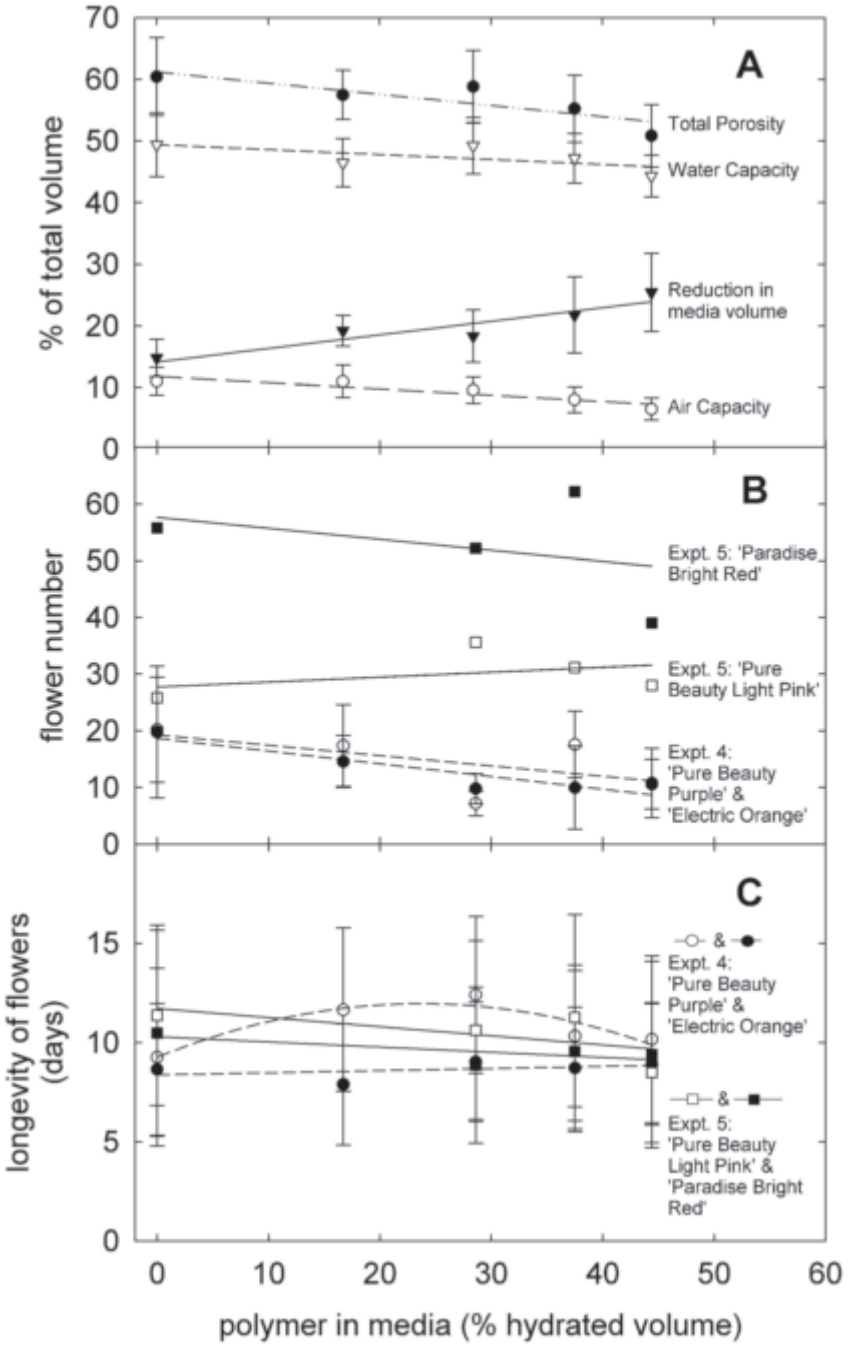

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Fig. 8. Polymer content had a significant influence on media properities (**A**) including total porosity ($y = 61.2 – 0.18x$, $r^2 = 0.22$, $P = 0.0007$), water holding capacity ($y = 14.1 – 0.22x$, $r^2 = 0.31$, $P = 0.0002$), reduction in media volume ($y = 49.4 – 0.081x$, $r^2 = 0.081$, $P = 0.048$), air space ($y = 11.8 – 0.10x$, $r^2 = 0.35$, $P < 0.0001$). Each data point represents five hanging baskets. Flower number (**B**) for both cultivars was also influenced in Expt. 4 ($y = 19.3 – 0.18x$, $r^2 = 0.14$, $P = 0.063$; $y = 18.7 – 0.23x$, $r^2 = 0.24$, $P = 0.0132$). Each data point in Expt. 4 represents five hanging baskets. Flower number in Expt. 5 were pooled so data represent the average of five hanging baskets. Flower number (**C**) increased with intermediate polymer concentrations in one cultivar in Expt. 4 ($y = 9.3 + 0.23x – 0.0048x2$, $r^2 = 0.06$, $P < 0.0001$), had no effect in the other cultivar ($y = 8.4 + 0.008x$, $r^2 = 0.002$, $P = 0.40$), and decreased significantly for both cultivars in Expt. 5 ($y = 11.7 – 0.05x$, $r^2 = 0.025$, $P = 0.0001$; $y = 10.3 – 0.03x$, $r^2 = 0.0095$, $P = 0.0016$). A total of 2,362 flowers were monitored for their longevity in the two experiments.