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Magnetic treatment of irrigation water: Its effects on vegetable crop yield and water productivity

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ABSTRACT

This study examines whether there are any beneficial effects of magnetic treatment of different irrigation water types on water productivity and yield of snow pea, celery and pea plants. Replicated pot experiments involving magnetically treated and non-magnetically treated potable water (tap water), recycled water and saline water (500 ppm and 1000 ppm NaCl for snow peas; 1500 ppm and 3000 ppm for celery and peas) were conducted in glasshouse under controlled environmental conditions during April 2007 to December 2008 period at University of Western Sydney, Richmond Campus (Australia). A magnetic treatment device with its magnetic field in the range of 3.5–136 mT was used for the magnetic treatment of irrigation water. The analysis of the data collected during the study suggests that the effects of magnetic treatment varied with plant type and the type of irrigation water used, and there were statistically significant increases in plant yield and water productivity (kg of fresh or dry produce per kL of water used). In particular, the magnetic treatment of recycled water and 3000 ppm saline water respectively increased celery yield by 12% and 23% and water productivity by 12% and 24%. For snow peas, there were 7.8%, 5.9% and 6.0% increases in pod yield with magnetically treated potable water, recycled water and 1000 ppm saline water, respectively. The water productivity of snow peas increased by 12%, 7.5% and 13% respectively for magnetically treated potable water, recycled water and 1000 ppm saline water. On the other hand, there was no beneficial effect of magnetically treated irrigation water on the yield and water productivity of peas. There was also non-significant effect of magnetic treatment of water on the total water used by any of the three types of vegetable plants tested in this study. As to soil properties after plant harvest, the use of magnetically treated irrigation water reduced soil pH but increased soil EC and available P in celery and snow pea. Overall, the results indicate some beneficial effect of magnetically treated irrigation water, particularly for saline water and recycled water, on the yield and water productivity of celery and snow pea plants under controlled environmental conditions. While the findings of this glasshouse study are interesting, the potential of the magnetic treatment of irrigation water for crop production needs to be further tested under field conditions to demonstrate clearly its beneficial effects on the yield and water productivity.

1. Introduction

Long spell of drought and competing water demands in most parts of Australia have put enormous pressure on water resources. Steps need to be taken to conserve both the quantity and quality of water and appropriate strategies will have to be developed to avoid risk to future water supplies. The main efficiency gains must come from the dominant user, irrigation, accounting for over 70% of the total water use in Australia (ANRA, 2008).

One of the ways by which we can reduce the total water used for irrigation is to employ practices that improve crop yield per unit volume of water used (i.e., water productivity). There have been some claims made that the magnetic treatment of irrigation water can improve water productivity (Duarte Diaz et al., 1997). If those claims are valid, there is scope for magnetic treatment of water to save water supplies and assist in coping with the future water scarcity.

There is hardly any study reported, with valid scientific experiments, on the effects of magnetic treatment of water on crop yield and water productivity. However, some closely related studies have reported on some beneficial effects of magnetic field in a number of other farming situations. For example, Lin and

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Yotvat (1990) reported an increase in water productivity in both crop and livestock production with magnetically treated water. Some studies have shown that there is an increase in number of flowers, earliness and total fruit yield of strawberry and tomatoes by the application of magnetic fields (Esitken and Turan, 2004; Danilov et al., 1994). An increase in nutrient uptake by magnetic treatment was also observed in tomatoes by Duarte Diaz et al. (1997). Amaya et al. (1996) and Podleoeny et al. (2004) have shown that an optimal external electromagnetic field accelerates the plant growth, especially seed germination percentage and speed of emergence.

Podleoeny et al. (2004) studied the effects of magnetic treatment by exposing the broad bean seeds to variable magnetic strengths before sowing and observed marked beneficial effects on seed germination, emergence rate and seed yield. Plant emergence was more regular after the use of the magnetic treatment and the emergence occurred 2–3 days earlier in comparison with the control treatment. They attributed the higher number of pods per plant and the fewer plant losses per unit area for broad bean during the growing season and consequently the yield increase to the pre-sowing treatment of seeds with magnetic field.

Magnetic fields can also influence the root growth of various plant species (Belyavskaya, 2001, 2004; Muraji et al., 1992, 1998; Turker et al., 2007). Muraji et al. (1992) demonstrated an enhancement in root growth of maize (*Zea mays*) by exposing the maize seedling to 5 mT magnetic fields at alternating frequencies of 40–160 Hz. However, there was a reduction in primary root growth of maize plants grown in a magnetic field alternating at 240–320 Hz. Highest growth rate of maize roots was achieved in a magnetic field of 5 mT at 10 Hz (Muraji et al., 1998). Turker et al. (2007) reported an inhibitory effect of static magnetic field on root dry weight of maize plants, but there was a beneficial effect of magnetic field on root dry weight of sunflower plants.

Belyavskaya (2004) and Turker et al. (2007) reported that weak magnetic field had inhibitory effect on growth of primary roots during early growth. The proliferative activity and cell reproduction in meristem in plant roots are reduced in weak magnetic field (Belyavskaya, 2004). Cell reproductive cycle slows down due to the expansion of G1 phase in many plant species and G2 phase in flax and lentil roots. There was a decrease in the functional activity of genome at early pre-replicate period in plant cells exposed to weak magnetic field. In general, these studies conclude that weak magnetic field caused intensification of protein synthesis and disintegration in plant roots. Mitochondria were also found to be very sensitive to magnetic field. The size and relative volume of mitochondria in cells increased due to a very weak magnetic field (Belyavskaya, 2001, 2004). Cells of plant roots exposed to weak magnetic field showed calcium over-saturation in all the organelles in cytoplasm (Belyavskaya, 2004). Belyavskaya (2001) reported disruptions in different metabolic systems including Ca^{2+} homeostasis in root cells due to low magnetic field.

Impact of heat stress at 40 °C, 42 °C and 45 °C for 40 min in cress seedlings (*Lepidium sativum*) was reduced by exposing plants to extremely low-frequency magnetic field (50 Hz, 100 μT) (Ruzic and Jerman, 2002). Magnetic field probably acts on the same cellular metabolic pathways as temperature stress, and as such, the study suggested that magnetic field act as a protective factor against heat stress.

In general, the literature review reveals that there are possibly some beneficial effects of magnetic field or treatment on plant growth and other related parameters. However, there is no clarity as to the extent of these effects and mechanisms operating behind these effects. Furthermore, there is not much research carried out on the effects of magnetic treatment of irrigation water on plant growth and crop and water productivity.

In this study, therefore, we investigate the effects of magnetically treated potable water, recycled water and saline water on plant yield and water productivity under controlled environmental conditions in glasshouse. The main objectives of the study are:

- To examine the performance of magnetically treated potable water, recycled water and saline water on plant growth, yield and produce nutrient composition of selected plant types,
- to quantify water productivity and water saving potential of magnetically treated irrigation water, and
- to determine the changes in soil properties due to irrigation with magnetically treated water from different sources.

2. Materials and methods

2.1. Location, plant material and growing conditions

The project involved glasshouse experiments and laboratory analysis of soil and plant properties. The glasshouse experiments were conducted to examine the effects of magnetic treatment of potable water, recycled water and saline water on plant yield, the total water use, water productivity, soil properties and nutrient composition of snow peas, celery and peas. The study was conducted under controlled environmental conditions with day and night temperature of 20 °C and 15 °C respectively in the glasshouse.

Glasshouse experiments were conducted with celery, snow pea and pea plants. There were two factors in the study: type of irrigation water and magnetic treatment of water. The following three types of irrigation waters were selected for the study:

- Potable water,
- recycled water, and
- saline water.

The potable water used was the normal drinking water supplied by the Sydney Water Corporation in the area, while the recycled water was the treated effluent sourced from the Richmond Sewage Treatment Plant. The saline water used in the study was prepared by adding measured amounts of NaCl salt to potable water to achieve required salinity levels.

To understand the impact of salinity levels on magnetically treated water, two salinity levels were used for each plant type. The salinity levels were 500 ppm and 1000 ppm for snow peas and 1500 ppm and 3000 ppm for celery and peas. The salinity levels of irrigation water selected for snow peas were lower due to a higher sensitivity of snow pea plants to salts when compared to celery and pea plants. By having two salinity levels in the study for each plant type, in effect, we had a total of four irrigation water types, i.e., potable water, recycled water and two variants of saline water. Snow pea, pea and celery seeds were initially sown in seeding mixture on 16th April 2007, 16th April 2007 and 2nd July 2007 respectively, and normal potable water was used for establishing the seedlings. Once seedlings achieved required growth, healthy seedlings were selected for planting in the study. Pea, celery and snow pea seedlings were transplanted on 4th May 2007, 9th May 2007 and 17th July 2007, respectively. Two uniform size plants per pot were transplanted in celery and pea pots, while four plants per pot were transplanted in snow pea pots. The experiments for snow pea, pea and celery were conducted in separate areas within the glasshouse, and there were 48 pots for each plant type studied. The pea, celery and snow pea plants were harvested on 26th June 2007, 24th October 2007 and 22nd November 2007, respectively.

For achieving statistically valid and unbiased estimates of treatment means, treatment differences and experimental error, we used statistical principle of local control, replication and randomisation in these experiments. Completely randomised design was used in the study and each treatment had four replications.

2.2. Magnetic treatment

The irrigation water of different types was treated with a magnetic device before applying to the plants. The mean values of pH, EC, N, P and K values of different irrigation water types before and after magnetic treatment are presented in Table 1. Magnetic treatment of water tends to reduce slightly the water pH, while there is no apparent trend for EC values. The values of N, P and K content of different water types were not affected by magnetic treatment of water. Recycled water had greater N, P and K content compared with tap water and saline water (Table 1).

Magnetic treatment device, supplied by Omni Environment Group Pty Ltd. (a Sydney based Australian company), with its magnetic field in the range of 3.5–136 mT was used for the magnetic treatment of irrigation water. The device comprised of a 100 mm pipe section with its internal diameter 22 mm. The device contains two magnets, and the arrangement of their north and south poles and the direction of magnetic field generated are shown in Fig. 1. For the magnetic treatment of irrigation water, it was passed twice through the magnetic treatment device at the flow rate of 10 ml/s, providing the water magnetic field exposure of about 3 s.

The intensity of magnetic field generated by the two magnets was measured along the longitudinal and cross-sectional directions of the pipe by Sypris Model 5070 Gauss/Tesla Meter^{TM}. The values of the magnetic field varied from 3.5 mT to 93 mT along the axis of the pipe (centre line). In this case, there was a trend of increasing values at the beginning of the pipe length, reaching peak values at the middle section of the pipe (between 30 mm and 70 mm distance from the beginning of the pipe length) and the trend of decreasing values towards the end of the pipe length.

Depending upon the distance along the pipe length, the values of the magnetic field also varied across the pipe diameter, varying from 3.3 to 136 mT, 3.2 to 94 mT, 3.2 to 97 mT and 1.8 to 118 mT at 5 mm, 10 mm, 15 mm and 20 mm distances from the one end of the pipe wall to the other. The peak values of the magnetic field in this case were observed for the pipe section between 30 mm and 70 mm distances from the beginning of the pipe length.

2.3. Soil properties and planting of seedlings

Soil for the study was obtained from a local garden supplier and was sieved to remove any pebbles or non-soil material. The soil for peas and celery was loamy sand in texture and had the value of $pH_{1:5(soil:water)}$ 6.3, $EC_{1:5(soil:water)}$ 655 μS/cm, available P (Olson-P) 22.2 mg/kg, NO_3–N 1.52 mg/kg and extractable K (0.05 M HCL) 780 mg/kg. The soil used for snow peas was also loamy sand in texture but had the value of $pH_{1:5(soil:water)}$ 6.4, $EC_{1:5(soil:water)}$ 220 μS/cm, available P (Olson-P) 19 mg/kg, NO_3–N 0.85 mg/kg and extractable K (0.05 M HCL) 530 mg/kg. Results indicate that the soils had low available N, moderate available P and adequate K.

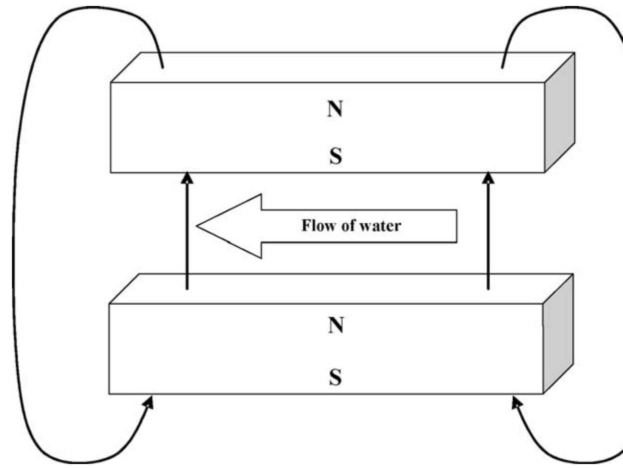

Fig. 1. Schematic of magnetic fields and direction of water flow during the magnetic treatment.

Before planting the seedlings, each pot was filled with air dried soil to a constant weight of 14 kg. For celery and peas, two uniform seedlings of similar size and vigour were transplanted in each pot, while for snow peas four seedlings were transplanted in each pot.

2.4. Irrigation scheduling

The main irrigation scheduling strategy used in the study was to apply enough water to bring the soil back to field capacity at the end of each irrigation. The plants were irrigated alternate days and the volume of irrigation water applied was determined by knowing the change in pot weight due to evapotranspiration since the last irrigation. The volume of water applied varied with treatments and the stage of crop growth and was recorded for each application.

In celery and peas, initially normal potable water (no magnetic treatment) was applied to pots for the first 10 days, irrespective of the experimental treatments, to avoid any salt injury effects on young seedlings. Thereafter, irrigation water of different types as described earlier was used for the control and treatments involving celery, snow pea and pea plants. Over the total growing period, magnetically treated water was used for 42 days in peas, 158 days in celery, and 143 days in snow peas. Pea plants matured relatively quickly, and for this reason the duration of water application for peas was shorter when compared with those for celery and snow peas.

2.5. Data collection and analysis

The volumes of water applied at each irrigation were recorded to determine the total water used in the three types of plants. Water productivity was calculated, based on both fresh and dry weights of produce in celery (kg of celery shoots per kL of water used) and snow peas and peas (kg of pods per kL of water used).

Celery was harvested at physiological maturity and the whole mass of produce was considered as yield. Both fresh weight and

Table 1
Effects of magnetic treatment on mean values of pH, EC and N, P and K concentrations in different types of irrigation waters.

Irrigation water type	pH		EC (mS/m at 25 °C)		N (mg/l)		P (mg/l)		K (mg/l)	
	Control	Magnetic treatment	Control	Magnetic treatment	Control	Magnetic treatment	Control	Magnetic treatment	Control	Magnetic treatment
Potable water	8.15	8.13	0.254	0.255	0.254	0.257	0.044	0.045	2.28	2.19
Recycled water	9.08	9.09	0.943	0.940	1.475	1.465	0.062	0.062	19.32	19.32
500 ppm saline water	8.38	8.35	1.241	1.230	0.276	0.280	0.047	0.046	2.34	2.40
1000 ppm saline water	8.42	8.37	2.187	2.192	0.275	0.277	0.047	0.048	2.43	2.43
1500 ppm saline water	8.40	8.36	3.07	3.10	0.284	0.286	0.049	0.049	2.49	2.49
3000 ppm saline water	8.41	8.36	5.83	5.80	0.303	0.300	0.050	0.050	2.79	2.79

oven dry weight of celery were measured and are reported in Section 3. Pea and snow pea pods were harvested at physiological maturity every week to determine the influence of different treatments on plant yield. These pods were oven dried at 65 °C to determine the dry weight of pods under different treatments. Whole shoots of the plants were harvested at maturity and were also oven dried at 65 °C to determine the dry weight of shoots.

Oven dried samples of snow pea pods as well as shoots and roots of both snow peas and celery were analysed by ICP (inductively coupled plasma), a method described by Zarcinas et al. (1987) to determine the Ca, Mg, Na, P and K concentrations in the harvest of both snow pea and celery plants. Soil samples after the harvest of snow pea and celery plants were also collected and analysed to determine the impact of magnetic treatments and different sources of water on soil $pH_{1:5(soil:water)}$, $EC_{1:5}$, available N (NO_3–N) and available P (Olson-P) and extractable K (0.05 M HCl). It should be noted that, in Section 3, we have presented the results only for the elements that were significantly affected by magnetic treatment.

It should also be noted that the initial statistical analysis of glasshouse data for pea plants indicated that there is no significant effect of magnetic treatment of irrigation water on plant yield, total water used and water productivity. For this reason, further plant and soil analysis for pea experiments was not carried out to save time and resources.

The data relating to plant yield, dry matter weight, water use, plant nutrient composition and soil properties were tabulated and statistically analysed to understand the treatment effects on plant yield, water productivity and soil properties. All data were subjected to the analysis of variance (ANOVA), including separation of main effects of irrigation water types and magnetic treatment and their interaction effects. The least significant difference (LSD at $P = 0.05$) was used to assess the differences among pairs of treatment means and the F values of the ANOVA indicated the significance.

The effects of magnetic treatment in relation to different plant and irrigation water types are presented in tabular form. Hereafter, a change in parameter value indicated to be significant means the value is statistically significant at 95% confidence level when compared with the control treatment. In addition, we have referred the treatment effect differential when the interaction between magnetic treatment and irrigation water type was significant for some experimental treatments and not for others. For example, the treatment effect is referred to differential when there was a non-significant effect of magnetic treatment of a particular water type (e.g., potable water) and a significant effect for another water type (e.g., saline water).

3. Results and discussion

3.1. Plant yield

3.1.1. Celery

There were differential effects of magnetic treatments of different irrigation water types on yield based on both celery fresh weight and shoot dry weight (Table 2). The interaction effects between magnetic treatment and different irrigation water types indicate significant increase in yield due to the magnetic treatment of recycled water and 3000 ppm saline water. Irrigation with magnetically treated 3000 ppm saline water and recycled water respectively resulted in 23% and 12% increase in plant yield on fresh weight basis. Similarly, magnetically treated 3000 ppm saline water and recycled water treatment respectively resulted in 26% and 12% increase in shoot dry weight. However, there was no statistically significant increase in the yield or shoot dry weight by irrigating celery with magnetically treated potable water and 1500 ppm saline water.

It is interesting to note that, the irrigation with recycled and 3000 ppm saline waters (no magnetic treatment) resulted in 8% and 74% reduction in celery yield when compared to irrigation with potable water. However, the magnetic treatment of these waters completely eliminated the yield reduction in recycled water and changed the yield reduction from 74% to 68% in 3000 ppm saline water.

3.1.2. Snow peas

Similar to celery plants, the magnetic treatment of different irrigation water types had differential effect on snow pea yield based on fresh and dry weights of pods (Table 2). Effects of magnetic treatment of potable water, recycled water and 1000 ppm saline water were significant and respectively resulted in 7.8%, 5.9% and 6.0% increase in snow pea yield when compared with control treatments. Similarly, magnetically treated potable water, recycled water and 1000 ppm saline water respectively resulted in 8.5%, 7.0% and 8.2% increase in dry weight of pods. However, there was no significant effect of magnetically treated irrigation water on snow pea yield for 500 ppm saline water.

The magnetic treatment of irrigation water resulted in significant increase (6.1%) in number of snow pea pods per pot. The magnetic treatment also resulted in increasing trend for the number of pods for individual irrigation water types, but it was not significant. Unlike celery, the magnetic treatment had no significant effect on shoot dry weight for snow peas. The increase in number of snow pea pods per pot also contributed to the significant increase in the fresh and dry weights of pods in snow pea plants. This finding in the current study is similar to the ones of Esitken and Turan (2004) and Danilov et al. (1994) who reported increased fruit yield of strawberry and tomatoes by magnetic fields.

3.2. Water productivity

3.2.1. Celery

Similar to plant yield, there was differential impact of magnetic treatment of different irrigation water types on water productivity (kg of fresh or dry weight produced per kL of water used) based on both fresh and dry weights of celery (Table 2). In particular, there was significant increase in water productivity based on fresh weight by applying magnetically treated 3000 ppm saline water (24%), 1500 ppm saline water (11%) and recycled water (12%) when compared with the controls. Similar trends were also observed for the water productivity based on dry weight, but the increase for 1500 ppm saline water was not significant.

3.2.2. Snow peas

The magnetic treatment of different water types also had differential impact on the water productivity based on both fresh and dry weights of snow pea pods (Table 2). For water productivity based on fresh weight basis, the effects of the magnetic treatment were significant for potable water, recycled water and 1000 ppm saline water but non-significant for 500 ppm saline water. There was 12%, 7.5% and 13% increase in water productivity based on fresh pod weight by respectively applying magnetically treated potable water, recycled water and 1000 ppm saline water when compared with the control treatments. Similar trends were also observed for water productivity based on dry weight basis, but the effect of magnetic treatment was non-significant for recycled water.

3.3. Total plant water use

The total water used by celery, snow pea and pea plants during the growing period varied considerably with the type of irrigation water used. However, the magnetic treatment of the water did not have significant effect on the total water used by the three plant types during the growing period for any of the irrigation water types (Table 2). It is an important finding from this study, particularly indicating that the magnetic treatment has no direct effect on evaporation from soil surface and transpiration from plants.

3.4. Dry weight of roots

Except 3000 ppm saline water in case of celery, the magnetic treatment did not have significant effect on the root dry weight (Table 2) of celery and snow peas. Irrigating celery with magnetically treated 3000 ppm saline water had a significant increase (15%) in celery root dry weight when compared with the control.

3.5. Nutrient and elemental composition of produce

Overall, irrigating celery with magnetically treated water significantly increased the Ca and P concentrations of celery

Table 2

Effects of magnetic treatment of irrigation waters on mean values of plant yield parameters, water use and water productivity (based on fresh weight) of (a) celery, (b) snow peas and (c) peas.

(a) Celery

Water source	Yield – fresh weight (g)	Yield – dry weight (g)	Shoot dry weight (g)	Root dry weight (g)	Water use (ml)	Water productivity (kg/kL water)
Control						
Potable water	414.3	54.9	54.9	123.5	37,933	10.94
Recycled water	377.3	51.0	51.0	121.8	35,596	10.60
1500 ppm saline water	181.0	28.0	28.0	49.4	23,945	7.56
3000 ppm saline water	108.5	16.0	16.0	23.8	20,568	5.28
Magnetic treatment						
Potable water	414.5	53.8	53.8	119.5	36,307	11.42
Recycled water	424.0	57.1	57.1	125.3	35,822	11.84
1500 ppm saline water	198.3	29.2	29.2	49.2	23,597	8.40
3000 ppm saline water	133.3	20.3	20.3	27.3	20,405	6.53
$LSD_{0.05}$						
$LSD_{0.05}$ water	13.4	2.9	2.9	2.8	907	0.45
$LSD_{0.05}$ magnetic	9.5	2.1	2.1	NS	NS	0.32
$LSD_{0.05}$ water × magnetic	18.9	3.8	3.8	4.0	NS	0.64

(b) Snow peas

Water source	Mean yield – fresh weight (g)	Mean yield – dry weight (g)	Mean shoot dry weight (g)	Mean root dry weight (g)	Water use (ml)	Water productivity (kg/kL water)
Control						
Potable water	216	30.93	46.0	4.35	19,279	11.22
Recycled water	198	28.66	44.5	3.84	18,154	10.95
500 ppm saline water	186	27.95	44.6	3.36	17,084	10.88
1000 ppm saline water	164	24.68	34.5	2.89	16,159	10.14
Magnetic treatment						
Potable water	233	33.56	46.2	4.19	18,546	12.58
Recycled water	210	30.65	44.7	3.72	17,901	11.77
500 ppm saline water	188	28.44	44.4	3.50	17,032	10.87
1000 ppm saline water	174	26.71	35.4	3.14	15,214	11.42
$LSD_{0.05}$						
$LSD_{0.05}$ water	6.8	2.51	1.95	0.16	691	0.40
$LSD_{0.05}$ magnetic	4.8	1.77	NS	NS	NS	0.29
$LSD_{0.05}$ water × magnetic	9.6	NS	NS	0.23	NS	0.57

(c) Peas

Water source	Mean yield – fresh weight (g)	Mean yield – dry weight (g)	Water use (ml)	Water productivity (kg/kL water)
Control				
Potable water	1.60	1.24	4263	0.38
Recycled water	1.23	0.93	4160	0.30
1500 ppm saline water	1.05	1.04	3788	0.28
3000 ppm saline water	0.88	1.05	3695	0.24
Magnetic treatment				
Potable water	1.62	1.24	4058	0.40
Recycled water	1.33	1.02	4166	0.32
1500 ppm saline water	1.03	1.02	3704	0.28
3000 ppm saline water	0.93	1.10	3617	0.25
$LSD_{0.05}$				
$LSD_{0.05}$ water	0.12	0.13	208	0.03
$LSD_{0.05}$ magnetic	NS	NS	NS	NS
$LSD_{0.05}$ water × magnetic	NS	NS	NS	NS

Table 3
Effects of magnetic treatment of irrigation water types on mean values of Ca and P concentrations of celery shoots.

Water source	Ca concentration (mg/kg dry matter)			P concentration (mg/kg dry matter)		
	Control	Magnetic treatment	Mean	Control	Magnetic treatment	Mean
Potable water	10,500	10,500	10,500	2867	2933	2900
Recycled water	10,900	11,767	11,333	2733	2967	2850
1500 ppm saline water	10,167	12,867	11,517	2203	2500	2352
3000 ppm saline water	11,500	13,400	12,450	2373	2667	2520
Mean	10,767	12,133	11,450	2544	2767	2655
$LSD_{0.05}$ water		1517			295	
$LSD_{0.05}$ magnetic		1072			209	
$LSD_{0.05}$ water × magnetic		NS			NS	

shoots (Table 3). However, the interaction effects between magnetic treatment and irrigation water types were not significant for any of the elements measured in celery shoots.

For snow peas, overall, the magnetically treated water had significant effects on Ca, Mg and Na concentrations in pods (Table 4). As to the individual water sources, there was a significant increase in Ca and Mg concentration in snow pea pods when the plants were irrigated with magnetically treated recycled water and 1000 ppm saline water. However, there was a decrease in Mg concentration of pods when the plants were irrigated with magnetically treated potable water and 500 ppm saline water. Irrigating snow pea plants with magnetically treated 1000 ppm saline water resulted in significantly reduced Na concentration in pods.

3.6. *Soil properties after plant harvest*

3.6.1. *Soil $EC_{1:5}$*

Except for 3000 ppm saline water, the magnetic treatment of irrigation water had no significant effect on $EC_{1:5}$ values after the harvest of celery plants (Tables 5 and 6). On the other hand, overall, the magnetic treatment resulted in significant effects on $EC_{1:5}$ value after harvest for snow pea plants when compared with the control treatment. In particular, the magnetically treated potable water, recycled water and 1000 ppm saline water resulted in significant increase in soil $EC_{1:5}$ values after the harvest of snow pea plants.

3.6.2. *Soil $pH_{1:5}$*

For both celery and snow pea plants, the magnetic treatment of irrigation water types varied significantly and affected soil pH after the harvest (Tables 5 and 6). Irrigating the two plant types with magnetically treated potable water and recycled water significantly decreased soil $pH_{1:5}$ after the harvest when compared with the control treatments. For snow peas, irrigation with magnetically treated 1000 ppm saline water also decreased the soil pH.

3.6.3. *Available soil P and extractable soil K*

For celery, the magnetic treatment of recycled water and 1500 ppm and 3000 ppm saline water significantly increased the available soil P and extractable soil K when compared with the controls (Tables 5 and 6). However, the magnetic treatment of potable water had non-significant effect on the values for the two elements. On the other hand, for snow pea plants, the significant

Table 4
Effects of magnetic treatment of irrigation water types on mean values of Ca, Mg and Na concentrations of snow pea pods.

Water source	Ca concentration (mg/kg dry matter)			Mg concentration (mg/kg dry matter)			Na concentration (mg/kg dry matter)		
	Control	Magnetic treatment	Mean	Control	Magnetic treatment	Mean	Control	Magnetic treatment	Mean
Potable water	3733	3633	3683	2200	2100	2150	25	35	30.0
Recycled water	3700	4100	3900	2100	2200	2150	45	44	44.5
500 ppm saline water	4233	4167	4200	1983	1930	1956	147	166	156.5
1000 ppm saline water	4200	5000	4600	1817	1933	1875	866	517	691.5
Mean	3967	4225	4096	2025	2041	2033	271	190	230.5
$LSD_{0.05}$ water		102.74			15.28			14	
$LSD_{0.05}$ magnetic		72.65			10.80			10	
$LSD_{0.05}$ water × magnetic		145.30			21.60			19	

Table 5
Effects of magnetic treatment of irrigation water types on mean value of soil $EC_{1:5}$, $pH_{1:5}$ and available P after snow pea harvest.

Water source	$EC_{1:5}$ (μS/cm at 25 °C)			$pH_{1:5}$			Available P (Olson-P)		
	Control	Magnetic treatment	Mean	Control	Magnetic treatment	Mean	Control	Magnetic treatment	Mean
Potable water	178	191	185	6.23	6.20	6.22	17.10	19.05	18.08
Recycled water	240	269	255	6.26	6.22	6.24	18.55	19.12	18.84
500 ppm saline water	375	382	379	6.11	6.13	6.12	18.25	18.34	18.30
1000 ppm saline water	523	563	543	6.15	6.10	6.13	17.71	17.74	17.73
Mean	329	351	340	6.19	6.16	6.18	17.90	18.56	18.23
$LSD_{0.05}$ water		7.39			0.02			0.52	
$LSD_{0.05}$ magnetic		5.23			0.02			0.37	
$LSD_{0.05}$ water × magnetic		10.45			0.03			0.74	

Table 6
Effects of magnetic treatment of irrigation water types on mean values of soil $EC_{1:5}$, $pH_{1:5}$, available P and extractable K after celery harvest.

Water source	Soil $EC_{1:5}$ (μS/cm at 25 °C)			Soil $pH_{1:5}$			Available P (mg/kg soil)			Extractable soil K		
	Control	Magnetic treatment	Mean	Control	Magnetic treatment	Mean	Control	Magnetic treatment	Mean	Control	Magnetic treatment	Mean
Potable water	482	468	475	6.14	5.98	6.06	19.43	19.29	19.36	697.4	695.9	696.7
Recycled water	619	686	653	6.15	5.98	6.07	20.7	22.35	21.53	725.3	740.2	732.7
1500 ppm saline water	1556	1541	1549	5.91	5.97	5.94	20.17	24.55	22.36	723.9	735.5	729.7
3000 ppm saline water	2163	2297	2230	5.94	5.94	5.94	22.03	26.44	24.24	724.5	753.6	739.0
Mean	1205	1248	1227	6.04	5.97	6.00	20.58	23.16	21.87	717.8	731.3	724.5
$LSD_{0.05}$ water		66			0.08			0.68			7.24	
$LSD_{0.05}$ magnetic		NS			0.06			0.48			5.12	
$LSD_{0.05}$ water × magnetic		93			0.11			0.96			10.24	

effect of the magnetic treatment was limited to the available soil P only, and this effect was observed through irrigation with potable water.

3.7. Influence of magnetic treatment on soil properties, and other attributes

In the current study, an increase in soil available P and extractable K, particularly under magnetically treated recycled water and saline water irrigation, appears to have played some role in improving yield and water productivity of celery plants. Magnetic treatment of water may be influencing desorption of P and K from soil adsorbed P on colloidal complex, and thus increasing its availability to plants, and thus resulting in an improved plant growth and productivity. Noran et al. (1996) observed (under drip irrigation system) differences in the concentrations of K, N, P, Na and Ca + Mg in soils irrigated with magnetically treated water when compared those with normal water. They argued that magnetic treatment of water slows down the movement of minerals, probably due to the effect of acceleration of the crystallisations and precipitation processes of the solute minerals.

In the current study, we also observed a decrease in soil pH after harvest of celery and snow peas under magnetically treated water treatment. It is speculated that there may be a relatively greater soil acidification due to the release of greater organic acids with in the rhizosphere by celery and snow pea plants irrigated with magnetically treated water compared with plants irrigated with water without magnetic treatment. Organic acids released in rhizosphere may be responsible for desorption of P and K, and thus making these nutrients more available to plants.

Increased Ca and P concentrations in celery shoots and Ca and Mg concentration in snow pea pods under magnetically treated water in current study also suggest an improved availability, uptake, assimilation and mobilization of these nutrients within plant system and may have contributed in improving the productivity of celery and snow pea plants with magnetic treatment of water. Duarte Diaz et al. (1997) reported an increase in nutrient uptake by magnetic treatment in tomatoes. A marked increase in P content of citrus leaves by magnetically treated water was also reported by Hilal et al. (2002).

Our results of reduced Na concentration in snow pea pods irrigated with magnetically treated saline water (1000 ppm NaCl) suggest restricted Na loading into snow pea pods. Magnetic treatment may be assisting to reduce the Na toxicity at cell level by detoxification of Na, either by restricting the entry of Na at membrane level or by reduced absorption of Na by plant roots. Alternatively, the reduction of Na concentration in snow pea pods may be associated with dilution effect of increased yield when snow peas were irrigated with magnetically treated saline water.

Although Na is required in some plants, particularly halophytes (Glenn et al., 1999), high Na concentration is a limiting factor for plant growth in most crops (François et al., 1994; Munns, 2002; Muranaka et al., 2002). Excessive Na has detrimental effects on electron transport and photosynthesis, and it also affects through stomatal closure (Muranaka et al., 2002) which reduces assimilates supply. Excessive Na may also disrupt the cell wall and increase the permeability of the cell membrane, leading to increased solute leakage from leaves at high salt concentration. It is also interesting to note that the apparently reduced accumulation of Na in plants with magnetically treated saline water in the current study may have helped the plants to continue their growth with less detrimental effects on plant yield.

The beneficial effects of magnetic treatment of some water types in the current study may be due to some alterations within plant system at biochemical level and their possible effects at cell level. External electric and magnetic fields have been reported to influence both the activation of ions and polarisation of dipoles in living cells (Moon and Chung, 2000). Electromagnetic fields (EMFs) can alter the plasma membrane structure and function (Paradisi et al., 1993; Blank, 1995). Goodman et al. (1983) reported an alteration of the level of some mRNA after exposure to EMFs. Increased concentration of gibberellic acid-equivalents (GAs), indole-3-acetic acid (IAA) and trans zeatin were reported in sunflower plants under field up application of magnetic field, whereas concentrations of these hormones decreased in magnetic field of the opposite direction (Turker et al., 2007). The above statements further suggest that the magnetic treatment of water probably alters something in water, makes the water more functional within plant system and therefore probably influences the plant growth at cell level. Magnetic treatment of water may also affect phyto-hormone production leading to improved cell activity and plant growth.

3.8. Practical implications and future research needs

Results of the glasshouse experiments reveal differential beneficial effects of magnetically treated potable water, recycled water and saline water irrigation on the yield and water productivity of celery, snow pea and pea plants. The effects of magnetic treatment of recycled water and 3000 ppm saline water were significant on plant yield and water productivity (kg of fresh or dry produce per kL of water used) of celery, but the effects of magnetic treatment of potable water and 1500 ppm saline water were non-significant. In snow peas, there were significant effects of magnetic treatment of potable water, recycled water and 1000 ppm saline water, but there was non-significant effect of 500 ppm saline water. On the other hand, in pea plants, the effects of magnetic treatments were non-significant for all the water types. In pea plants, their short growing period to harvest and salt injury effects probably confounded the treatment effects, leading to very little effect of magnetic treatment of water. These results raise some interesting but critical questions that need further explanation, research and experimentation. For example, one key question is that why magnetic treatment failed to have any effect on yield under potable water and 1500 ppm saline water treatment in celery plants and 500 ppm saline water treatment in snow pea plants.

Improved water productivity with magnetic treatment of water in the current study could help in the sustainability of water resources, particularly in the use of recycled and saline waters for irrigation. As water productivity is based on the amount of yield and water required to produce this yield, the increased yield of both celery and snow peas under magnetically treated water irrigation mainly contributed to the increase in the water productivity of the two plant types in the current study.

The results of the current study demonstrate some significant effects of magnetically treated irrigation water on water productivity, yield and nutrient composition of snow pea and celery plants under some conditions. However, the study has raised some important questions that must be answered before any unequivocal conclusion could be reached as to the usefulness of the magnetic treatment in improving crop yield and water productivity at farmer's field. In particular, the questions are: (a) why did the magnetic treatment improve the plant yield and water productivity in some instances and not in others? (b) how does the magnetic treatment affect water, soil and plant? and (c) will the magnetic treatment of irrigation water have significant benefits under field conditions?

4. Conclusions

- The magnetic treatment of irrigation water resulted in statistically significant increases in the yield and water productivity for celery and snow pea plants in some instances. However, it had no significant effect on the yield and water productivity for pea plant. This means, before this technology can be recommended to farmers, it will be critical to clearly understand the mechanisms and processes that affect plant yield and water productivity through the magnetic treatment, the conditions under which it will work and the extent of its effectiveness under field situations.
- The effect of magnetic treatment of irrigation water on the total water used for any of the plant types included was not significant in this study.
- Under some circumstances, when compared with the control treatment, the magnetic treatment of irrigation water tends to change soil pH, EC, available P and extractable K measured at the crop harvest.
- Overall, the data collected in this preliminary study under controlled conditions in glasshouse situation suggest that there are possibly some beneficial effects of the magnetic treatment of irrigation water for the plant yield and water productivity. As such, the results need to be further tested under field conditions to assess the usefulness of magnetic treatment of irrigation water in crop production.

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