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Research project:

Application of an AC Electric Field for mitigating the  
negative effects of irrigation with saline water

FINAL REPORT

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APPLICATION OF A HIGH-FREQUENCY AC ELECTRIC FIELD FOR  
MITIGATING THE NEGATIVE EFFECTS OF IRRIGATION WITH SALINE  
WATER

The problem

In many areas of this planet and also of Greece, in coastal zones in particular, the use of saline water in agriculture is unavoidable given the lack of good-quality water. In most cases the salinity of irrigation water is increased due to a high NaCl concentration. The prolonged use of saline water for irrigation in open farming results in minimization of yield and excessive accumulation of salts in the soil.

The improvement of poor-quality water may presently be achieved mainly using the method of reverse osmosis. Using this method in highly saline waters, for the production of a given quantity of clean water an equal quantity of very poor-quality water must be discarded. Furthermore, the cost of the original investment but also the cost of operation is very high.

Therefore the application of alternative low-cost methods for improving the efficiency of the brackish water used in agriculture is quite useful.

Current scientific knowledge on this question

When salinity increases above a certain limit at the root zone, the growth of plants as well as their yield decreases and such decrease is a linear function of the salt content in

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the root system (Maas, E.V. and Hoffman, G.J., 1977, Sonneveld, C. and Neiles, G.W.H. 1988, Sonneveld, C. and Van der Burg, A.M.M. 1991, Savvas, D. and Lenz, F., 1996, Sonneveld, C. and Voogt, W. 2000). The rate of accumulation of salt in the soil and the decrease in yield vary greatly among the various plant species, but is also affected by the salt-sensitivity of the variety and the environmental conditions (Helal, H.M. and Mengel, K. 1981, Sonneveld C. and Van der Burg A.M.M. 1991, Ling Li, Y. et al 2001).

In fruit vegetable crops salinity results mainly in a decrease of the size of the fruit (Shannon, M.C. et al 1987, Adams, P. and Ho, L.C. 1989, Adams, P. 1991, Xu, H.L., et al 1995, Ling Li, Y. et al 2001). Most experimental projects have shown that in fruit vegetable crops salinity affects more the size of the fruit than it does its germination (Shannon, M.C. et al 1987, Savvas, D. and Lenz, F., 1996, Katerji, N. et al 1998, Mavrogianopoulos G.N. et al 1999).

Comparative experiments establish that low and medium salinity affects the growth of the fruit more as a result of the effects of osmotic pressure and less due to the toxicity of NaCl in high concentration. This is true when the main nutrients are in abundance and in equilibrium at the root system zone (Adams, P. and Ho, L.C. 1989, Adams, P. 1991, Sonneveld, C. and Voogt, W. 2000).

The predominant mechanism associated with the NaCl tolerance of various cultivated plants is based on active blocking in conjunction with Na<sup>+</sup> retention by the lignous

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parenchyma of the roots and the stems and stalks of older leaves (Jacoby, B. 1964, Sonneveld, C. and Welles, G.W.H. 1988, Savvas, D. and Lenz, F. 2000). Thus, Na concentration in younger and photosynthetically active leaves is kept at lower levels which are non-toxic for their growth and function (Jesche, W.D. 1984, Perez-Alfocea et al 1993). There is no doubt, however, that the efficiency of such mechanism, varying between the various plant species (Bernstein, I. 1975, Brugnoli, E. and Lauteri, M. 1991), decreases with the increasing content of salts in the root system, and larger Na quantities are transported to the active young leaves (Greenway, H. and Munns, R. 1980, Jennings, D.H. 1976). Under these conditions growth and yield are largely compromised. Therefore any measure enhancing the efficiency of the mechanism of salt blocking from metabolically active tissues and leaves would increase the salt tolerance of the plant.

On the other hand, the requirements for maintaining turgor at the tissues of the plant under high osmotic pressure conditions at the root environment result in morphological and physiological changes to the plant. Physiological adaptations mainly concern changes in net assimilation (Brugnoli, E. and Lauteri, M. 1991), stomatal conductance (Xu, H.L. et al 1995), water potential at the leaf (Perez-Alfocea et al 1993) and tissue composition (Shalhevet, J. and Yaron, B. 1973, Sonneveld, C. and Welles, G.W.H. 1988, Rai, S. et al 1994, Roberts A.G. 2002).

The cost of such an adaptation is a decrease in the rate of growth and yield (Bernstein, L., 1975, Greenway, H. and Munns, R. 1980, Willumsen, J. et al 1996). Various enzymes and organic compounds are connected with such effects, including superoxide dismutase and malondialdehyde (Liang, Y. 1999), sugars (Rathert, G. 1984), proline (Greenway, H. and Munns, R. 1980), carotenoids (De Pascale S. et al 2001) etc. Therefore, every factor contributing to a greater salinity-tolerance is expected to influence one or more of such plant metabolic functions and characteristics.

A new approach to the mitigation of the negative effects of the salinity of irrigation water could be the alleviation of the harmful capacity of a specific salt concentration by modifying the properties of the solution. This could be achieved by exposing the solution to a high-frequency AC electric field before its administration to the plants. In recent papers it has been demonstrated that such an action has insignificant impact on the dissolved oxygen content balance (<0.3 mM at 20°C under regular atmospheric conditions); however it increases significantly its solubility rate (Kitazawa, K. et al 2001). Another research paper establishes that the use of water restructured through a high-frequency electromagnetic field had significant impact on the germination of fungal spores for at least a 24-hour period (Rai, S. et al 1994). Jae-Duk Moon and Hwa-Sook Chung (2000) in a scientific publication mention that the germination of tomato seed was accelerated 1.1-2.8 times when an electric and magnetic field

was applied. Furthermore, in an applied research with a hydroponic cultivation, where an electromagnetic field was applied to the nutrient solution, it was found that this enhanced salt solubility, absorptivity and the yield (Roberts A.G. 2002).

#### Scientific Purpose

The main purpose of the present research has been to investigate the effects of the AC electric field generated by the "Aqua wizard II" device, when applied to the brackish irrigation water used in the closed-system hydroponic cultivation of tomato.

In particular, the absorption of the various mineral nutrients by the plant root and transport thereof to the leaves, the growth of the root and the body, and the plant yield was investigated, as compared with the control.

#### Materials and methods

##### Tomato cultivation in a closed NFT hydroponic system

The experiment was conducted in a plastic heated greenhouse at the area of Farm Structures of the Agricultural University of Athens during the period from October 2001 until March 2002.

Tomato plants were placed in NFT channels (gullies) and 5 different interventions were applied. In the first channel the plants are irrigated with normal nutrient solution ( $2.5 \text{ dSm}^{-1}$ ) to which an AC electric field had been applied, in the second channel the plants are irrigated with normal nutrient solution

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( $2.5 \text{ dSm}^{-1}$ ) with no electric field application, in the third channel half the root of the plants is irrigated with saline nutrient solution (NaCl addition, EC =  $13 \text{ dSm}^{-1}$ ) with AC electric field being applied and the other half is irrigated with a saline nutrient solution (NaCl addition, EC =  $13 \text{ dSm}^{-1}$ ) with no electric field application, in the fourth channel plants are irrigated with a saline nutrient solution (NaCl addition, EC =  $13 \text{ dSm}^{-1}$ ) without an electric field being applied and in the fifth channel plants are irrigated with a saline nutrient solution (NaCl addition, EC =  $13 \text{ dSm}^{-1}$ ) with an electric field being applied.

[in the figure that follows:

Ηλεκτρικό Πεδίο = Electric Field

Κανονικό Θρεπτικό Διάλυμα = Normal Nutrient Solution

Αλατουχό Θρεπτικό Διάλυμα = Saline Nutrient Solution ]

There are 4 reservoirs containing nutrient solutions. One contains the recycled normal nutrient solution that goes to the first channel with application of an electric field, a second one contains the normal recycled nutrient solution that goes to the second channel without application of an electric field, the third reservoir contains the recycled saline nutrient solution that irrigates half the root of the plants of the third channel and the plants of the fourth channel, without application of an electric field, and the last reservoir contains the recycled saline nutrient solution

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irrigating the other half of the root of the plants in the third channel and the plants of the fifth channel, with application of an electric field. The mineral nutrient content in the nutrient solutions in the reservoirs was the same, except for the addition of NaCl in the reservoirs containing the saline nutrient solutions.

The electrical conductivity of the nutrient solutions in the reservoirs was corrected daily by adding concentrated nutrient solutions in volumes as required by the conductivity value, and the solutions' pH was corrected by adding acids in volumes as required by such pH value. The salinity of the saline nutrient solutions in the 2 reservoirs was due to the addition of 900 gr NaCl in 150 lt of water upon renewal of the nutrient solution in such reservoirs. On average, the electrical conductivity of the saline nutrient solutions was 13000 $\mu$ S/cm and the electrical conductivity of the non-saline nutrient solutions was 2500 $\mu$ S/cm. At regular intervals (7-10 days) the nutrient solutions in all reservoirs were renewed; i.e. reservoirs were emptied and new nutrient solutions were prepared.

Flow to the channels is continuous.

#### Measurements

##### ➤ Morphological Characteristics

7 plants have been randomly selected from each intervention; on such plants every 15 days height measurements were carried out.

##### ➤ Minerals in the nutrient solutions

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During the growth of the plants the following concentration of mineral nutrients in the main nutrient solution was applied:

$\text{NO}_3^- = 10.5 \text{ mmol/l}$ ,  $\text{H}_2\text{PO}_4^- = 1.5 \text{ mmol/l}$ ,  $\text{SO}_4^{2-} = 2.5 \text{ mmol/l}$ ,  $\text{NH}_4^+ = 0.5 \text{ mmol/l}$ ,  $\text{K}^+ = 3.0 \text{ mmol/l}$ ,  $\text{Ca}^{2+} = 3.75 \text{ mmol/l}$ ,  $\text{Mg}^{2+} = 1.0 \text{ mmol/l}$ ,  $\text{Fe} = 2.0 \text{ mg/l}$ ,  $\text{Mn} = 1.0 \text{ mg/l}$ ,  $\text{Zn} = 0.25 \text{ mg/l}$ ,  $\text{B} = 0.2 \text{ mg/l}$ ,  $\text{Cu} = 0.03 \text{ mg/l}$ ,  $\text{Mo} = 0.05 \text{ mg/l}$ .

Upon renewal of the nutrient solutions, samples were taken before emptying the reservoirs and after the new solutions were prepared. Furthermore, one week every month samples of solutions from all reservoirs were taken from the new solutions prepared, for five consecutive days. The samples of the nutrient solutions were analyzed for the following elements:  $\text{Na}^+$ ,  $\text{Cl}^-$ ,  $\text{HCO}_3^-$ ,  $\text{P}$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ .

➤ Minerals in the leaves and the root

At regular time intervals (15 days) 3 samples of leaves and 3 samples of root were taken from each different intervention and they were analyzed as to their content in the following elements:  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{P}$ .

➤ Fruit yield

In 7 randomly selected plants from each intervention, their production was measured every 15 days.

➤ Measurement methods:

Measurement	Method
pH	A glass electrode with a WTW pH 320 H-meter
Dissolved oxygen	WTW OXI 320 portable oximeter (ISO5814)
$\text{NH}_4^+$	Colorimetric method (Keeney & Nelson, 1982)
$\text{NO}_3^-$	Colorimetric method (Keeney & Nelson, 1982)

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N Kjeldal                    Standard analytic method (ISO 7890-1)

P<sub>2</sub>O<sub>5</sub>                    Colorimetric method (Olsen & Sommers, 1982)

K<sub>2</sub>O                    NaOAc method (Rhoades, 1982)

*Results*

Changes in the minerals of the nutrient solutions

No statistically significant changes in the mineral nutrients' content of the nutrient solution, as a result of the application of the AC electric field, were observed.

Concentration of minerals in leaves

Table 1: Mean concentrations in the leaves

TREATMENT	MEAN VALUES, ppm (Statistical analysis - Duncan test)				
	Na <sup>+</sup>	K <sup>+</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>	P
Nutrient solution (1)	67.4 <sup>a</sup>	1497.6 <sup>a</sup>	1306.1 <sup>a</sup>	269.7 <sup>a</sup>	346.9 <sup>b</sup>
Nutrient solution with electric field application (2)	62.7 <sup>a</sup>	1241.6 <sup>b</sup>	918.8 <sup>bc</sup>	256.5 <sup>ab</sup>	292.2 <sup>c</sup>
Saline nutrient solution (3)	2350.4 <sup>c</sup>	822.1 <sup>c</sup>	801.9 <sup>c</sup>	219.3 <sup>bc</sup>	305.3 <sup>c</sup>
Saline nutrient solution with electric field application (4)	1321.5 <sup>b</sup>	1332.7 <sup>ab</sup>	1014.9 <sup>b</sup>	233.8 <sup>b</sup>	379.4 <sup>a</sup>
Saline nutrient solution for the divided root (5)	1551.1 <sup>b</sup>	875.0 <sup>c</sup>	830.6 <sup>bc</sup>	202.1 <sup>b</sup>	305.9 <sup>c</sup>

As shown in Fig. 1 and Table 1, Na<sup>+</sup> concentration in the leaves

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of the plants that grew on the saline nutrient solution which had been subjected to an AC electric field is about 56% of the concentration in the plants that grew on saline solution not subjected to an electric field. In the plants where the root system was divided, Na<sup>+</sup> concentration in the leaves is 66% of the concentration of plants that grew on saline solution not subjected to an electric field.

[In Figures 1-5 that follow:

- blue ♦ Nutrient solution - electric field applied
- red ■ Saline nutrient solution
- yellow ▲ Saline nutrient solution for the divided root
- light blue ✕ Saline nutrient solution - electric field applied
- green • Nutrient solution

Fig.1 : Na<sup>+</sup> concentration in leaves

Fig.2 : K<sup>+</sup> concentration in leaves

Fig.3 : Ca<sup>2+</sup> concentration in leaves

Fig.4 : Mg<sup>2+</sup> concentration in leaves

Fig.5 : P concentration in leaves ]

In accordance with Table 1, see also Fig.1, K<sup>+</sup> concentration in the leaves of the plants that grew on saline nutrient solution to which an electric field was applied, over the entire period, presents no statistically significant difference as compared to the K<sup>+</sup> concentration of the plants that grew on normal nutrient solution without NaCl addition. In the last measurements a relative decrease is noted, which

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is probably due to the very quick growth of fruit. On the contrary, K<sup>+</sup> concentration in the leaves of the plants that grew on saline nutrient solution without the electric field effect was considerably lower.

Ca<sup>2+</sup> concentration in leaves, as can be seen in table 1 and fig.3, was the highest in the plants that grew on normal nutrient solution without an electric field being applied, and after that in the plants that grew on the saline nutrient solution where an electric field was applied. The lowest concentration was in the plants that grew on the saline nutrient solution where no electric field was applied.

Mg<sup>2+</sup> concentration in leaves, as can be seen in table 1 and fig.4, was the highest in the plants that grew on normal nutrient solution without an electric field being applied, and after that in the plants that grew on saline nutrient solution where an electric field was applied; it was lowest in the plants that grew on saline nutrient solution where no electric field was applied and in the plants for which the root was divided.

The highest P concentration in leaves, as can be seen in table 1 and fig.5, was observed in the plants that grew on the saline nutrient solution where an electric field was applied.

Table 1: Concentration of minerals at the root

TREATMENT	MEAN VALUES, ppm (STATISTICAL ANALYSIS Duncan test)				
	K <sup>+</sup>	Na <sup>+</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>	P
Nutrient solution (1)	1168.8 <sup>a</sup>	43.8 <sup>a</sup>	271.0 <sup>b</sup>	171.8 <sup>a</sup>	434.7 <sup>a</sup>
Nutrient solution with electric field application (2)	668.5 <sup>b</sup>	53.4 <sup>a</sup>	330.4 <sup>ab</sup>	125.8 <sup>b</sup>	417.3 <sup>a</sup>
Saline nutrient solution (3)	461.9 <sup>bc</sup>	706.3 <sup>c</sup>	356.8 <sup>a</sup>	74.2 <sup>b</sup>	422.8 <sup>a</sup>
Saline nutrient solution with electric field application (4)	347.3 <sup>c</sup>	567.4 <sup>b</sup>	242.6 <sup>bc</sup>	86.4 <sup>bc</sup>	405.9 <sup>a</sup>
Half root in saline nutrient solution (5)	659.3 <sup>b</sup>	1084.0 <sup>d</sup>	307.4 <sup>ab</sup>	104.5 <sup>bc</sup>	477.7 <sup>a</sup>
Half root in saline nutrient solution with electric field application (6)	426.2 <sup>c</sup>	609.6 <sup>bc</sup>	216.0 <sup>c</sup>	88.4 <sup>bc</sup>	463.9 <sup>a</sup>

[In Figures 6-10 that follow:

- blue ♦ Nutrient solution - electric field applied
- yellow ■ Half root / saline solution
- red ▲ Saline nutrient solution
- red ✕ Half root/saline solution, electric field applied
- light blue ▨ Saline nutrient solution, electric field applied
- green • Nutrient solution

Fig.6 : Na<sup>+</sup> concentration at the root

Fig.7 : K<sup>+</sup> concentration at the root

Fig.8 : Ca<sup>2+</sup> concentration at the root

Fig.9 : Mg<sup>2+</sup> concentration at the root

Fig.10: P concentration at the root ]

The highest  $\text{Na}^+$  concentration at the root, as shown in table 2 and fig. 6, is observed in the plants grown on saline nutrient solution without electric field being applied.

$\text{K}^+$  concentration at the root, as per table 2 and fig. 7, is highest in the plant that grew on normal nutrient solution. In the saline nutrient solution with AC electric field being applied, even though a lower mean value is noted, no statistically significant difference was observed as compared with the saline nutrient solution without application of AC electric field.

As shown in table 2 and in fig. 8,  $\text{Ca}^{2+}$  concentration at the root, in the case of the plants that grew on saline nutrient solution without the effect of the electric field presents no statistically significant difference as compared with the  $\text{Ca}^{2+}$  concentration at the root of the plants that grew on normal, non-saline environment. The lowest concentration with a statistically significant difference from the other treatments is noted in the plants that grew on saline nutrient solution with electric field application.

As shown in table 2 and in fig. 9,  $\text{Mg}^{2+}$  at the root has its highest concentrations in the plants that grew with normal nutrient solution. The statistically significant highest concentration is observed in the plants that grew on normal nutrient solution without an electric field being applied. There are no statistically significant differences between the treatments with saline nutrient solution.

Finally, as shown in table 2 and in fig. 10, P

concentration at the root presents no statistically significant difference among the plants of the various treatments.

*Photo 1.* Root of tomato plants divided in two parts. Both parts are supplied with a nutrient solution in which NaCl has been added ( $EC = 13 \text{ ds m}^{-3}$ ).

At the upper part, the saline nutrient solution is exposed to high-frequency AC electric field. At the lower part, a nutrient solution of the same chemical composition without any influence.

*Photo 2.* Tomato plants growing in a closed hydroponic system (NFT). NaCl has been added to the nutrient solution ( $EC = 13 \text{ ds m}^{-3}$ ). To the right, the saline nutrient solution is exposed to a high-frequency AC electric field. To the left, a nutrient solution of the same chemical composition without any influence.

#### Height of the Plants

As shown in fig. 11, no difference was noted in the height of the plants that grew on normal nutrient solution as compared with the height of those that grew on saline nutrient solution where AC electric field was applied. The plants having the smallest height were those that grew on saline nutrient solution without AC electric field application. In saline-treated plants in which the root was divided the height had a

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value is between:

[Fig. 11: Plant height

- ~~blue~~ ♦ Nutrient solution - electric field applied
- ~~red~~ ■ Saline nutrient solution
- yellow ▲ Saline nutrient solution for the divided root
- light blue ✕ Saline nutrient solution - electric field applied
- green ■ Nutrient solution ]

Table 3. Average plant height

INTERVENTION	Average Plant Height (12.2.2002) cm
NUTRIENT SOLUTION (1)	224.43 <sup>a</sup>
NUTRIENT SOLUTION WITH ELECTRIC FIELD APPLICATION (2)	221.00 <sup>a</sup>
SALINE NUTRIENT SOLUTION (3)	126.50 <sup>b</sup>
SALINE NUTRIENT SOLUTION WITH ELECTRIC FIELD APPLICATION (4)	200.14 <sup>ab</sup>
SALINE NUTRIENT SOLUTION FOR THE DIVIDED ROOT (5)	182.14 <sup>b</sup>

(STATISTICAL ANALYSIS Duncan test)

Yield

As shown in table 4 and fig. 12 the total yield of the plants (in both interventions) that grew on normal nutrient solution was higher than that of the others. The plants that grew on the normal solution which was subjected to the effect of the AC electric field showed a tendency for higher total yield

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which however was not statistically significant. The total yield of the plants that grew on saline nutrient solution where the AC electric field was applied, as well as of those in the saline treatment in which the root was divided, was nearly twice the yield of the plants that grew on saline nutrient solution without application of the AC electric field.

[Fig. 12: Yield of measured tomato plants

- blue ♦ Nutrient solution - electric field applied
- red ■ Saline nutrient solution
- yellow ▲ Saline nutrient solution for the divided root
- light blue ✕ Saline nutrient solution - electric field applied
- green • Nutrient solution ]

Table 4. Fruit yield from 18.1.2002 until 3.4.2002

INTERVENTION	Average Fruit Weight (12.2.2002) g/plant
NUTRIENT SOLUTION (1)	2461.6 <sup>a</sup>
NUTRIENT SOLUTION WITH ELECTRIC FIELD APPLICATION (2)	2655.4 <sup>a</sup>
SALINE NUTRIENT SOLUTION (3)	654.5 <sup>b</sup>
SALINE NUTRIENT SOLUTION WITH ELECTRIC FIELD APPLICATION (4)	1391.3 <sup>b</sup>
SALINE NUTRIENT SOLUTION FOR THE DIVIDED ROOT (5)	1778.0 <sup>b</sup>

(STATISTICAL ANALYSIS Duncan test)

*Conclusions*

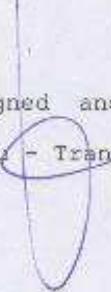
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The comparative application of the system elaborated in this laboratory on tomato plants growing in a closed hydroponic system has shown that the exposure of the nutrient solution, which had a high NaCl content ( $13 \text{ dS m}^{-1}$ ), to a high-frequency AC electric field before it reaches the plant roots resulted in a much greater salinity tolerance of the plants, so that the phenological features of the growing plants closely resemble the plants cultivated on a non-saline nutrient solution and their yield be much higher than that of the plants which were growing on saline nutrient solution to which no AC electric field was applied.

*Further research*

Further research is required in order to confirm the results on other plant species and under different cultivation conditions as well. It is also necessary to interpret such action by investigating possible changes in the physiological functions of the plants.

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