HortScience 41(2):437–441. 2006.

Comparative Effects of NaCl and $CaCl_2$ Salinity on Cucumber Grown in a Closed Hydroponic System

Fidanka Trajkova and Nicolas Papadantonakis
Mediterranean Agronomic Institute of Chania, P.O. Box 85, Chania 73100, Greece

Dimitrios Savvas[1]
Faculty of Agricultural Technology, T.E.I. of Epirus, P.O. Box 110, Arta 47100, Greece

Additional index words. Salt stress, ion-specific effects, osmotic effects, soilless culture, growth responses

Abstract. **The objective of this study was to discriminate among Na, Cl, and Ca salinity effects on cucumber (*Cucumis sativus* L.). Cucumber plants grown in perlite were exposed for 134 days to low and moderate levels of salinity induced by the addition of either NaCl or $CaCl_2$ at equal rates (on a chemical equivalent basis) to a standard nutrient solution for cucumber up to two target electrical conductivity (EC) levels (3.0 and 5.0 dS·m^{-1}). The experimental treatments included also a control, which was irrigated with the standard nutrient solution without additional salt. The mean EC values in the drainage solution were 2.35, 3.94, 4.2, 6.31, and 6.35 dS·m^{-1} for the control, low NaCl, low $CaCl_2$, high NaCl, and high $CaCl_2$ treatments, respectively. The fresh and dry weights of stems and leaves were reduced only under conditions of high NaCl salinity, whereas root mass was not affected. Fruit yield decreased in proportion to the increase in NaCl salinity, while $CaCl_2$ salinity reduced yield only at the high EC, to a level that corresponded to the low NaCl salinity. The suppression of yield with increasing salinity resulted mainly from a decrease in fruit size, while the number of fruit per plant was reduced to a lesser extent. These changes caused a reduction in the number of Class I fruit and an increase in nonmarketable produce. Both salinity sources enhanced the total soluble solids and the fruit chlorophyll concentration. NaCl salinity appreciably raised the concentrations of Na and Cl in young and old leaves, and suppressed the K concentration. $CaCl_2$ salinity increased leaf Cl and Ca levels and diminished Mg and K. It is concluded that cucumber is more susceptible to NaCl salinity than to equal EC levels of $CaCl_2$ salinity.**

The capture and recycling of the fertigation effluents in closed-loop hydroponic systems saves water and fertilizers, while restricting pollution of water resources by nitrates and phosphates (Carmassi et al., 2005; Savvas, 2002a). However, in many cases the available irrigation water may contain considerable amounts of salts (Sonneveld, 2002; Urrestarazu and Garcia, 2000). If the drainage solution is completely recycled, Na and Cl accumulate in the root zone thereby imposing corresponding increases in the mean Na to water and Cl to water (mmol·L^{-1}) uptake ratios (Sonneveld, 2000). However, as these ratios are gradually approaching equal levels with the NaCl to water ratio (concentration) in the irrigation water, an equilibrium between input and output of Na and Cl is established and thus the build-up of Na and Cl into the closed system ceases (Savvas et al., 2005a). In cucumber crops, a concentration of 5 mM NaCl in the irrigation water, which is common in many Mediterranean countries, may increase the Na and Cl levels in the drainage water up to a range of 30 to 35 mM (Savvas et al., 2005a, 2005b). The elevation of the Na and Cl concentrations to these levels imposes an increase in the total salt concentration equivalent to an electrical conductivity of about 5.5 dS·m^{-1}, assuming that the supply of nutrients via the nutrient solution is sufficient. Such salinity levels are detrimental to cucumber growth and yield (Drew et al., 1990; Jones et al., 1989).

In semiarid regions such as those within the Mediterranean basin, calcium bicarbonate in the irrigation water frequently occurs at concentrations exceeding the mean ratio of Ca to water uptake by the plants. Accumulation of bicarbonates does not constitute a problem in soilless culture since this anion is removed by adding nitric acid in the process of nutrient solution preparation (Sonneveld, 2002). However, calcium may rapidly accumulate in a closed hydroponic system if its concentration in the irrigation water (Ca to water ratio) exceeds the mean Ca to water uptake ratio (Savvas, 2002b; Sonneveld, 2000). Thus, the question arises as to whether Ca accumulation is as harmful as Na to plant growth and yield. Many greenhouse-grown plant species, such as tomato and eggplant, respond to the total salt concentration rather than to the specific salts imposing salinity, providing the latter are present at only moderate levels (Adams, 1991; Savvas and Lenz, 2000; Shannon and Grieve, 1999; Sonneveld and van der Burg, 1991). However, other plant species, such as gerbera, pepper and lettuce are sensitive to particular salt ions at relatively low concentrations (Sonneveld, 1988; Sonneveld and van der Burg, 1991; Tas et al., 2005). Drew et al. (1990) stated that high NaCl concentrations (25 to 50 mM) in the rooting medium restrict cucumber growth due mainly to impairment of the photosynthetic apparatus at the chloroplast level which indicates ion specific effects. However, these authors did not arrive at a conclusion as to whether Na or Cl imposed specific effects. According to Sonneveld (2000), cucumber is specifically sensitive to NaCl. Previous research revealed a more rapid decline in the ability of cucumber to exclude Na from the leaves than Cl, which may indicate a higher susceptibility to Na than Cl (Savvas et al., 2005a). However, further research is needed to assess the relative impact of excessive Na and Cl concentrations on cucumber growth and yield.

In view of the above background, the purpose of the present study was to determine the response of cucumber plant growth and fruit yield and quality to salinity caused by Na or Ca, when the accompanying anion is Cl, and to test whether this response depends also on the level of salinity. The discrimination between specific Ca, Na, and Cl effects will provide some insight into the mechanisms responsible for the impairment of cucumber growth under saline conditions. To attain this goal, cucumber plants were grown at two salinity levels, each of which was imposed by adding either NaCl or $CaCl_2$ at the same equivalent rate to a basic nutrient solution used as a control.

Materials and Methods

The experiment was carried out in a glasshouse of the Mediterranean Agronomic Institute of Chania (24° 03' 12"), Greece. Cucumber (*Cucumis sativus* L. 'Palmera', RIJK ZWAAN) seedlings grown in peat cubes were planted on 2 Mar. 2004 in opaque, polyethylene bags containing perlite at the stage of two fully developed, true leaves. Each bag had a length of 1.2 m, a volume of 50 L and accommodated three plants. Nutrient solution was automatically prepared and supplied to the plants by means of a computer controlled device (Autonet, Athens, Greece) and a drip irrigation system. Irrigation was automatically applied by means of a suitable computer program, at intervals depending on solar radiation intensity, which was monitored using a pyranometer (Volmatic, SC 21B). Five separate fertigation ducts were connected to the control system, which enabled automated preparation, supply and recycling of five different nutrient solutions (experimental treatments). Four experimental units per treatment corresponding to four replications were established in a completely randomized experimental design. Each experimental unit was a plot of 12 cucumber plants. Plant spacing within a row was 0.4 m. The plants were trained to a single stem, according to a modification of the umbrella system described by Klieber et al. (1993), and supported by plastic twine attached 2.5 m above the plant row on a horizontal wire. During the experiment, the temperature ranged from 15 to 26 °C during the night and 17 to 33 °C during the day, while the relative humidity (RH) fluctuated from 40 to 90%. High temperatures (T) during the summer were controlled by passive ventilation (T > 25 °C), shading (spraying on the covering material with a calcium carbonate and

Received for publication 11 Oct. 2005. Accepted for publication 3 Dec. 2005. The authors wish to thank Prof. Harold-Christopher Passam from the Agricultural University of Athens for reviewing the manuscript.
[1]To whom reprint requests should be addressed; e-mail savvas@teiep.gr.

calcium oxide suspension), and an automatically operating fog system (RH < 60%).

A standard nutrient solution for cucumber (De Kreij et al., 1999) with an EC value of 2.1 $dS \cdot m^{-1}$, used as a control, was compared with four salinity treatments. The nutrient concentrations in the standard nutrient solution were as follows (mM): NH_4-N 1.25, K 8, Ca 4, Mg 1.37, NO_3-N 16, SO_4–S 1.37, H_2PO_4–P 1.25, Fe 0.015, Mn 0.01, Zn 0.005, Cu 0.0008, B 0.025, Mo 0.0005. The salinity treatments were obtained by adding either NaCl or $CaCl_2$ at identical equivalent rates (8 and 24 $meq \cdot L^{-1}$ in the low and the high salinity treatments, respectively) to the standard nutrient solution up to two target EC levels (3.0 and 5.0 $dS \cdot m^{-1}$). The treatments were initiated on the day of planting. Ten days after planting, recycling of the drainage solution was initiated according to the method of reference nutrient solution established by Savvas and Manos (1999) and Savvas (2002a). This method is based on replenishment of nutrient uptake in the closed system at constant nutrient ratios, but varying absolute doses according to the on-line measured volume and EC of the drainage solution. The nutrient ratios in the reference nutrient solution used to replenish plant uptake after recycling initiation were those suggested by De Kreij et al. (1999) for cucumber grown in closed systems, with small modifications (identical in all treatments) whenever the nutrient concentrations in the drainage solution tended to diverge from the target levels suggested for the root zone by the above authors. The pH of the solution supplied to the plants was set at 5.5. After initiation of recycling, the pH and the EC of the drainage solution were monitored daily at 10.00 a.m. throughout the experiment, while Na, Ca, and Cl were measured fortnightly in both the drainage and the irrigation nutrient solution. Based on these measurements, the ratios of NaCl and $CaCl_2$ to the other nutrients in the reference nutrient solution were properly adjusted in some cases to maintain the Na, Ca, and Cl concentrations in the irrigation nutrient solution close to the above target values. However, the changes were identical for NaCl and $CaCl_2$ in the two treatments of each salinity level. Furthermore, the concentrations of P, K, Mg, S, NO_3-N, Fe, Cu, Mn, Zn, B, and Mo in both the nutrient and the drainage solutions were determined every month to adjust the nutrient ratios in the reference nutrient solution in order to prevent nutritional imbalances in the root zone.

Harvesting was performed twice per week throughout the cropping period, starting on 21 Apr. and terminating on 14 July. At each harvest, the fruit weight, total number of harvested fruit, number of fruit graded Class I (including the 'Extra' class fruit), and number of nonmarketable fruit (too small and deformed fruit) were recorded separately for each experimental unit. Grading was based on EU standards, specifically the Commission Regulation (EEC) No 1677/88. To obtain a more comprehensive assessment of the influence of the treatments on fruit quality, fruit length, diameter and firmness, pH of the fruit sap, total soluble solids (TSS), and fruit chlorophyll concentration were assessed. Fruit length, diameter and firmness were measured once per week in all fruit of two plants per experimental unit. Total soluble solids and pH of fruit sap were measured weekly in one fruit per experimental unit. Fruit samples used for chlorophyll determination were collected six times during the whole cropping period (17, 20, and 24 May; 9 and 25 June; and 6 July 2004). Furthermore, to assess the influence of the tested salt sources and levels on plant growth, the fresh and dry weights of roots, stems and leaves of two plants per experimental unit were measured at the end of the experiment (134 d after planting).

The chlorophyll concentration in cucumber fruit was estimated according to Harborne (1990). The fruit samples were selected randomly and blended to form a homogenous paste. Subsequently, a 5 g-portion of this paste was placed in plastic flasks and mixed with 24 mL acetone and 0.1 g of $CaCO_3$. The samples were kept in the dark to minimize chlorophyll degradation and transformation. The chlorophyll concentration was measured using a spectrophotometer (Hitachi U-2001 UV/Vis) with readings of absorption spectra taken at 663 and 646 nm and a cell path length of 1 cm. A penetrometer (Bishop FT 011) was used to measure fruit firmness in Newtons (N). Firmness was tested at the basal, central and distal parts of the fruit and the final value was the average of the three measurements. The pH of fruit sap was measured by an Orion 920A pH meter following random selection and blending of one fruit per replicate. Total soluble solids were determined directly by exerting pressure on the fruit and measuring the sap obtained with a digital refractometer (Palette-Atago PR-100).

To determine the effects of NaCl and $CaCl_2$ salinity on tissue mineral concentrations, samples of old leaves (first leaf below the last mature fruit), young fully developed leaves (fifth leaf from the stem apex), roots, and fruit were randomly collected from each experimental unit. Samples of old leaves were collected once (70 d after treatment initiation), while young leaves and fruit were collected twice (young leaves on the 70th and the 120th day and fruit on the 74th and the 122nd day after treatment initiation). Root samples were collected at the end of the experiment. The roots were placed on a sieve (mesh size 4 mm), washed by tap water at low pressure in order to remove adhered perlite grains, and subsequently washed again using demineralised water. The tissue samples were placed directly into an oven at 65 °C for 48 h and then ground to pass through a 40 mesh sieve. Subsequently, 0.5 g of the ground material was used to determine the Na, Ca, Mg, K, and P concentrations by employing inductively coupled plasma atomic emission spectroscopy (ICP–AES, Leeman Labs Inc, PS 1000 AT) after dry ashing at 600 °C for 4 h and extraction by means of 2 M HCl. Chloride was extracted from 0.25 g of ground plant material using water at 85 °C, and measured by titration with 0.1 M $AgNO_3$ in the presence of K_2CrO_4 (Eaton et al., 1995). The concentration of organically bound N in leaves was determined by Kjeldahl digestion (Mills and Jones, 1996). The ICP-AES instrument was used to measure Na and nutrient concentrations in the drainage solution (except NO_3, which was measured by an ion selective electrode using a CONSORT C835 ion meter, and Cl, which was measured as described above) in order to maintain the target concentrations of each treatment (data not presented).

All data were subjected to one way analysis of variance and, when a significant F test was obtained, all possible comparisons between the five treatment means were carried out by employing Duncan's multiple range test ($P = 0.05$).

Results

The average values of the actual electrical conductivity (EC) of the nutrient solutions

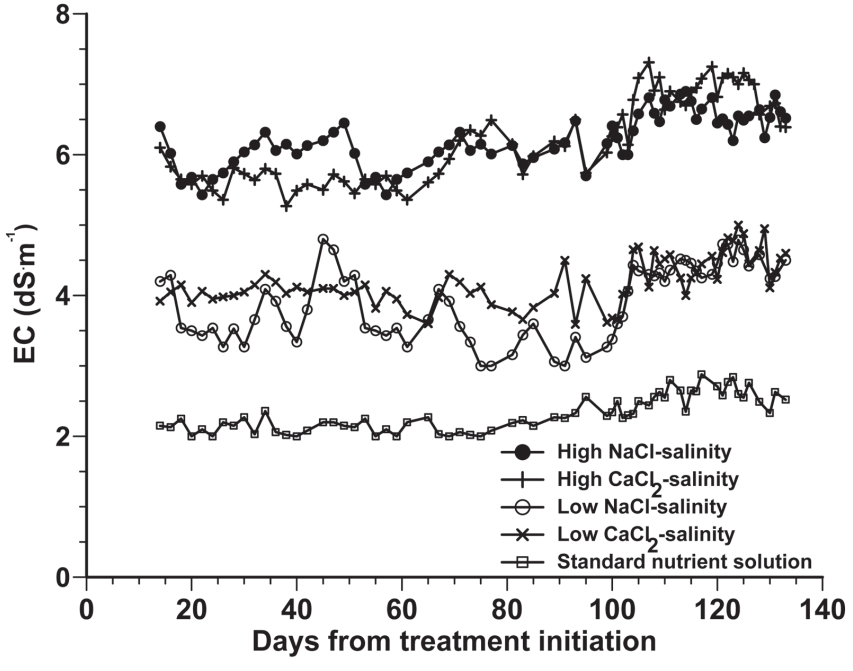

Fig. 1. Electrical conductivity (EC) in drainage solutions originating from a cucumber crop grown in closed hydroponics as influenced by different salinity treatments. Each point is the average of 4 replications, each consisting of 12 plants.

Table 1. Mean Ca, Na, and Cl concentrations in the drainage solution of each treatment.

Treatment	Concn (mM)		
	Ca	Na	Cl
Standard nutrient solution	4.23	1.23	2.7
Low NaCl salinity	5.68	16.5	17.30
Low $CaCl_2$ salinity	12.68	3.67	20.70
High NaCl salinity	5.20	31.0	42.53
High $CaCl_2$ salinity	23.51	3.74	43.51

supplied to the plants were 2.1, 3.0, 3.0, 5.0, and 4.8 $dS \cdot m^{-1}$ for the control, low NaCl, low $CaCl_2$, high NaCl, and high $CaCl_2$ treatments respectively, while the corresponding mean EC values in the drainage water were 2.35, 3.94, 4.2, 6.31, and 6.35 $dS \cdot m^{-1}$. The course of EC in the drainage solution during the cropping period is shown for all treatments in Fig. 1. The mean external Ca, Na, and Cl concentrations in each treatment are given in Table 1.

Increasing the salinity to 3.94 or 4.2 $dS \cdot m^{-1}$ in the drainage solution by adding either NaCl or $CaCl_2$ in the irrigation solution, respectively, had no influence on the vegetative growth of cucumber (Table 2). The further increase of EC to 6.3 $dS \cdot m^{-1}$ in the drainage solution due to enhanced supply of NaCl significantly reduced both the fresh and dry weight of stems and the dry weight of leaves to 55% to 60% of the values measured in the control treatment. However, a similar increase of EC in the leachate due to addition of $CaCl_2$ in the irrigation solution had only a minor impact on stem fresh weight and no effect on stem dry weight and either fresh or dry leaf weight. The NaCl salinity did not affect root dry weight, while the high level of $CaCl_2$ salinity enhanced appreciably the root dry mass.

With NaCl, total fruit yield and mean fruit weight were suppressed by both salinity levels tested, while the total number of fruit per plant decreased only at the high EC level of 6.3 $dS \cdot m^{-1}$ (Table 3). Furthermore, as the NaCl salinity increased, the total number of Class I fruit per plant decreased while that of nonmarketable fruit rose. By contrast, $CaCl_2$ salinity affected total fruit yield only at the high EC level, although both levels of $CaCl_2$ salinity reduced the mean fruit weight. Total fruit number and number of Class I fruit declined significantly while number of nonmarketable fruit increased at the high $CaCl_2$ salinity level.

Raising EC by adding NaCl restricted the mean length of fruit proportionally to the level of salinity, while the mean fruit diameter was significantly reduced only at the high salinity level (Table 4). The $CaCl_2$ salinity restricted mean fruit length and diameter only at the high EC level. Fruit firmness was lowered by both salinity sources, but at the high EC level the effect of NaCl was more marked than that of $CaCl_2$. The pH of fruit sap was slightly elevated by both salt sources and at both salinity levels. Total soluble solids (TSS) were enhanced only at the high EC level by both salinity sources, while the effect of NaCl was more profound than that of $CaCl_2$. The fruit chlorophyll concentration tended to rise with increasing salinity, but the increase was statistically significant only at the high $CaCl_2$ salinity level.

As the level of NaCl salinity in the drainage solution rose, the Na concentration in fruit, young and old leaves and roots of cucumber increased (Table 5). The highest increase was observed in the roots and the lowest in the young leaves, while the Na concentrations of the old leaves and fruit were closer to those measured in the young leaves than in the roots. The Cl concentration in the tissues increased in all salinity treatments as the external level of Cl rose. At high salinity, the $CaCl_2$ source exacerbated leaf Cl concentration increase, while in the fruit the increase in Cl was not dependent on the salinity source. The Ca concentration in old leaves fell significantly with increasing external NaCl concentrations, while in young leaves, fruit and roots there was no NaCl treatment effect on Ca concentrations (Table 5). $CaCl_2$ salinity enhanced the concentration of Ca in the young and old leaves as well as in the fruit, while the root Ca concentration was unaffected.

The K concentration in fruit, young leaves and old leaves was similarly suppressed by both salinity sources, while in the roots K was restricted only when the EC was raised by NaCl (Table 6). High NaCl salinity caused a reduction in the concentration of Mg in the old leaves and an increase in the roots, but had no effect on the young leaves and fruit (Table 6). $CaCl_2$ salinity imposed a more profound suppression of Mg concentration in comparison to equal levels of NaCl salinity, which was significant in all plant tissues except the fruit. The effects of both salinity sources on tissue concentrations of P and organically bound N were small and inconsistent (data not presented).

Discussion

Our results revealed a higher susceptibility of both vegetative growth and fruit yield of cucumber to NaCl compared to $CaCl_2$ salinity. These findings indicate that the suppressive effects of salinity on plant growth and yield had, at least partly, an ion-specific origin and were not depending exclusively on the level of salinity, regardless of salt source. Previous research has pointed out a specific susceptibility of cucumber to NaCl salinity (Sonneveld and Van der Burg, 1991), which was earlier attributed by Drew et al. (1990) to inefficient exclusion of Na and Cl from the photosynthetically active leaves. Savvas et al. (2005a) found that the ability of cucumber

Table 2. Effect of salinity level and source (NaCl and $CaCl_2$) on total dry weight of roots and total fresh and dry weight of stem and leaves at crop termination in a cucumber crop grown for 134 d in a closed hydroponic system. Values are means of four measurements.

Treatment	Root (g/plant)	Stem (g/plant)		Leaf (g/plant)	
	Dry wt	Fresh wt	Dry wt	Fresh wt	Dry wt
Standard nutrient solution	4.15 b[z]	421.7 a	68.73 a	158.6 ab	33.37 a
Low NaCl salinity	5.68 b	417.3 a	68.51 a	170.4 a	34.81 a
Low $CaCl_2$ salinity	5.63 b	436.0 a	73.39 a	173.8 a	35.87 a
High NaCl salinity	6.20 b	241.5 c	38.08 b	94.7 b	18.16 b
High $CaCl_2$ salinity	12.33 a	356.1 b	63.91 a	112.7 ab	24.23 ab

[z]Mean separation in columns by Duncan's multiple range test. In each column, values followed by the same letter do not differ significantly at $P \leq 0.05$.

Table 3. Influence of salinity level and source (NaCl and $CaCl_2$) on total fruit fresh weight yield, mean fruit fresh weight, and grade of cucumbers grown for 134 d in a closed hydroponic system. Values are means of four measurements.

Treatment	Total yield (kg/plant)	Mean fruit wt (g)	No. fruit[z]/plant		
			Total	Class I	Nonmarketable
Standard nutrient solution	6.85 a[y]	326 a	19.5 a	9.9 a	2.5 c
Low NaCl salinity	5.19 b	288 b	18.5 a	6.7 b	2.8 c
Low $CaCl_2$ salinity	6.37 a	294 b	20.7 a	8.9 a	2.6 c
High NaCl salinity	3.87 c	239 d	15.8 b	3.6 c	6.0 a
High $CaCl_2$ salinity	4.86 b	263 c	15.3 b	5.6 b	4.4 b

[z]Quality grading according to EU standards.
[y]Mean separation in columns by Duncan's multiple range test. In each column, values followed by the same letter do not differ significantly at $P \leq 0.05$.

Table 4. Influence of salinity level and source (NaCl and $CaCl_2$) on fruit quality characteristics of cucumber grown in a closed hydroponic system. Values are means of four measurements.

Treatment	Mean length (cm)	Mean diam (cm)	Firmness (N)	pH	TSS[z] (% fresh wt)	Chlorophyll ($\mu g \cdot g^{-1}$ fresh wt)
Standard nutrient solution	35.7 a[y]	3.74 a	45.7 a	5.49 c	3.32 c	4.89 b
Low NaCl salinity	34.1 b	3.55 ab	45.2 ab	5.60 b	3.48 bc	5.46 ab
Low $CaCl_2$ salinity	34.7 ab	3.80 a	44.6 bc	5.65 a	3.43 bc	5.29 ab
High NaCl salinity	29.7 d	3.28 b	43.2 d	5.64 ab	3.81 a	5.79 ab
High $CaCl_2$ salinity	32.6 c	3.52 b	44.2 c	5.62 ab	3.54 b	6.12 a

[z]TSS = total soluble solids.
[y]Mean separation in columns by Duncan's multiple range test. In each column, values followed by the same letter do not differ significantly at $P \leq 0.05$.

to exclude Na from photosynthetically active leaves decreased more rapidly than that of Cl as the external NaCl concentration increased, which indicated a Na-related rather than a Cl-related sensitivity of this plant species to salinity. The present results provide convincing evidence that external Na concentrations specifically affect the growth of cucumber to a much greater level than that caused by a similar increase of salinity in the root environment due to enhanced Ca concentration, when the accompanying ion is in both cases chloride. Many plant species exposed to relatively low salinity levels, such as those commonly encountered in commercial greenhouse crops, respond mainly to the total salt concentration in the root zone rather than to the concentration of specific ions (Adams, 1991; Munns, 2002; Savvas and Lenz, 2000; Sonneveld, 2000). However, in other cases, specific ion effects have been demonstrated when plants were exposed to salinity. For example, most crops seem to be specifically susceptible to sodium bicarbonate, while cucumber is more severely affected by salinity originating from excessive NaCl or Mg levels than by isosmotic concentrations of a salt mixture (Sonneveld, 1988). A higher sensitivity to NaCl was also observed in barley (Termaat and Munns, 1986) and bean (Montero et al., 1998) when exposed to isosmotic salinity levels imposed either by NaCl or by various salt combinations. Furthermore, it seems that the adverse effects of moderate salinity levels on romaine type lettuce are mainly Na-specific (Tas et al., 2005).

In the present study, both salinity sources affected the fruit yield of cucumber more severely than the vegetative growth, although at the high level of NaCl salinity the differences were small. This result agrees with those previously derived from experiments involving long-term exposure of cucumber to NaCl salinity (Chartzoulakis, 1992; Savvas et al., 2005a, 2005c). However, Ho and Adams (1994) reported a greater reduction in the dry matter of shoots than in that of fruit following exposure of young cucumber plants for 27 d to NaCl salinity (5.5 and 8 dS·m^{-1}) in the recirculating nutrient solution. Presumably, a strong suppression of vegetative growth during the early stages of development restricts the potential of the plant for subsequent fruit production, thereby modifying the dry matter partitioning between vegetative shoot and fruit in long-term crops.

The suppression of fruit yield with increasing salinity was due to a restriction of both mean fruit weight and the number of fruit per plant. However, the suppression of mean fruit weight rather than fruit number per plant was primarily responsible for yield reduction at high salinity levels, irrespective of the salt used to increase the EC of the nutrient solution. Previous reports regarding the relative contribution of fruit number per plant and mean fruit weight to yield decline in cucumber plants exposed to salinity are contradictory. Thus, Drew et al. (1990), in agreement with the present results, found that increasing salinity up to 50 mM NaCl in the nutrient solution supplied to cucumbers in sand culture caused a reduction in cucumber yield solely as a result of smaller fruit size, while the number of fruit per plant was not affected. However, Chartzoulakis (1992), Jones et al. (1989), and Savvas et al. (2005c) found that NaCl salinity reduced fruit yield mainly through the formation of fewer fruit per plant, while mean fruit weight was less severely affected. Presumably, these discrepancies originate mainly from the timing of salinization, while genotypic differences between the cultivars used in each case may also be involved, as suggested by Drew et al. (1990). Indeed, Drew et al. (1990) started the NaCl treatment 35 d after sowing, while Savvas et al. (2005c) gradually exposed their plants to salinity for a period of 50 to 60 d after treatment initiation. In contrast, in the present experiment, as well as in those of Chartzoulakis (1992) and Jones et al. (1989), exposure to salinity was initiated at the early stage of two fully developed true leaves.

The effects of both salinity sources on quality grading and external fruit quality (length, and diameter) were comparable with those for mean fruit weight. This was anticipated, since the length and diameter of a fruit are intimately related to its weight, while differences in fruit size may shift the grading percentages, as also reported by Savvas and Lenz (2000) for eggplant. The increase in total soluble solids is a well known effect of salinity on fruit of vegetable plants (Del Amor et al., 1999; Mizrahi and Pasternak, 1985; Schnitzler and Gruda, 2002), which seems mainly to result from the osmotic potential of the nutrient solution in the root environment rather than the salt source, since this trend was similar with both NaCl and $CaCl_2$ salinity. However, fruit chlorophyll concentration was enhanced only by high $CaCl_2$ salinity. Sonneveld and Van der Burg (1991) observed an enhancement in the color index of cucumber fruit with increasing salinity following the addition of either NaCl or extra major nutrients. Although the color index may relate to the fruit chlorophyll concentration, their results are not directly comparable with ours. The slight but significant increase in pH in fruit sap and the decrease of cucumber fruit firmness with rising salinity are in disagreement with the responses of these quality parameters to salinity in tomato (Petersen et al., 1998; Sonneveld and van der Burg, 1991). However, at high salinity levels, the fruit firmness of melon significantly decreased (Del Amor et al., 1999). It seems that the pH of fruit sap and the fruit firmness are not similarly influenced by salinity in different plant species.

Both salinity sources brought about comparable increases in the tissue Cl concentrations, while NaCl salinity was much more harmful to cucumber growth. These results provide convincing evidence that the increase of NaCl salinity affects growth and yield of cucumber much earlier than the occurrence of harmful Cl levels in the plant tissues. The same is valid for the decrease in K uptake, which was similar with both salinity sources, although the suppression of growth was much more profound with

Table 5. Effect of salinity level and source (NaCl and $CaCl_2$) on the Na, Cl and Ca concentrations (mmol·g^{-1}) in various tissues of cucumber grown in a closed hydroponic system. Values are means of eight measurements in young leaves and fruit and four measurements in old leaves and roots.

	Fruit			Young leaves[z]			Old leaves[y]			Roots	
Treatment	Na	Cl	Ca	Na	Cl	Ca	Na	Cl	Ca	Na	Ca
Standard nutrient solution	0.08 c[x]	0.06 c	0.12 bc	0.06 c	0.11 d	0.47 c	0.10 c	0.11 e	1.71 c	0.13 c	0.38 a
Low NaCl salinity	0.20 b	0.17 b	0.13 bc	0.15 b	0.17 c	0.45 c	0.31 b	0.50 c	1.52 d	0.28 b	0.31 a
Low $CaCl_2$ salinity	0.08 c	0.14 b	0.14 b	0.06 c	0.18 c	0.57 b	0.09 cd	0.38 d	1.89 b	0.13 c	0.29 a
High NaCl salinity	0.42 a	0.27 a	0.11 c	0.24 a	0.37 b	0.41 c	0.48 a	0.67 b	1.21 e	0.93 a	0.29 a
High $CaCl_2$ salinity	0.11 c	0.30 a	0.19 a	0.05 c	0.46 a	0.75 a	0.07 d	0.88 a	2.63 a	0.14 c	0.28 a

[z]First leaf below the last mature fruit.
[y]Fifth leaf from the stem apex.
[x]Mean separation in columns by Duncan's multiple range test. In each column, values followed by the same letter do not differ significantly at $P \leq 0.05$.

Table 6. Effect of salinity level and source (NaCl and $CaCl_2$) on K and Mg concentrations (mmol·g^{-1}) in various tissues of cucumber grown in a closed hydroponic system. Values are the means of eight measurements in young leaves and fruit and four measurements in old leaves.[z]

	Fruit		Young leaves[z]		Old leaves[y]		Roots	
Treatment	K	Mg	K	Mg	K	Mg	K	Mg
Standard nutrient solution	1.02 a[x]	0.13 a	0.62 a	0.20 a	0.69 a	0.37 a	0.53 a	0.10 b
Low NaCl salinity	0.92 ab	0.13 a	0.54 b	0.20 a	0.52 b	0.37 a	0.24 c	0.10 b
Low $CaCl_2$ salinity	0.92 ab	0.12 a	0.57 b	0.17 b	0.65 a	0.23 b	0.43 abc	0.07 bc
High NaCl salinity	0.81 b	0.12 a	0.47 c	0.21 a	0.49 bc	0.25 b	0.31 bc	0.14 a
High $CaCl_2$ salinity	0.88 b	0.11 a	0.47 c	0.16 b	0.44 c	0.18 c	0.46 ab	0.05 c

[z]First leaf below the last mature fruit.
[y]Fifth leaf from the stem apex.
[x]Mean separation in columns by Duncan's multiple range test. In each column, values followed by the same letter do not differ significantly at $P \leq 0.05$.

NaCl. Na suppression of K in all plant tissues and of Ca and Mg mainly in the older leaves, as well as Ca restriction of K and Mg uptake, are well known effects of ion competition during exposure to salinity, and have been discussed elsewhere (Grattan and Grieve, 1999; Savvas et al., 2005b). The appreciable enhancement of the leaf Ca concentration by $CaCl_2$ salinity was presumably due to the increased Ca to (Ca+Mg+K) ratio in the root zone, since an increase of the Ca level by maintaining the same Ca to Mg to K ratio has no effect (Savvas and Lenz, 2000) or even diminishes (Adams, 1991) the leaf Ca concentration. The leaf Ca level was enhanced also in lettuce when the $CaCl_2$ concentration in the root zone was increased (Tas et al., 2005).

Consideration of the data of tables 5 and 6 reveals that the increase of tissue Na concentration with increasing NaCl salinity was offset by a concomitant decrease in the K concentration of the young leaves and fruit, and the K, Ca, and Mg levels of the old leaves. As can be calculated from the data of Table 1, the dry to fresh weight ratio in the leaf, which is an inverse measure of the leaf water content, ranged between 0.192 (high NaCl salinity) and 0.215 (high $CaCl_2$ salinity). Statistical analysis revealed that the differences of dry to fresh weight ratios between the treatments were insignificant. Since salinity did not reduce the leaf water content, indicating that leaf dehydration did not occur, we assume that the restriction of growth at high salinity was not due to a lack of osmotic adjustment. Furthermore, the lack of leaf dehydration rules out the possibility of salt accumulation in the cell walls of the leaves, as suggested by Flowers et al. (1991) for rice and Tas et al. (2005) for lettuce.

The susceptibility of cucumber to high external NaCl concentrations was attributed by Drew et al. (1990) to high toxicity of Na or Cl at an intracellular level. The higher susceptibility to increased NaCl concentrations, as opposed to equally high $CaCl_2$ levels, indicates that Na rather than Cl is the primary cause of salt damage in cucumber. To avoid Na toxicity, the plants are forced to exclude Na from the leaves and produce compatible organic solutes at the expense of growth so as to maintain the necessary driving force for water transport and avoid stomata closure (Munns, 2002). However, as the NaCl salinity increases, a progressive break-down of Na-exclusion occurs in cucumber (Savvas et al., 2005a), and thus net photosynthesis is affected at the chloroplast level due to inefficient Na compartmentation within the protoplast (Drew et al., 1990), thereby additionally suppressing growth and yield. In contrast, although Ca is maintained at relatively low levels within the cytoplasm, an increased intracellular Ca concentration may be less harmful than that of Na, presumably due to the involvement of calmodulin in combination with more efficient compartmentation of Ca in the vacuole and other cell compartments, such as the mitochondria (Garciadeblas et al., 2001; Marmé, 1984; Marschner, 1995). Nevertheless, the huge increase in root mass at the high $CaCl_2$ level may have also contributed to the higher tolerance of cucumber to this salinity source, presumably by improving the efficiency of the plants to take up water.

In conclusion, an increase of the electrical conductivity up to about 4 $dS \cdot m^{-1}$ due to accumulation of Ca in cucumber crops grown in closed hydroponic systems should not affect total yield and fruit quality, although mean fruit weight and fruit firmness may be slightly reduced, providing a balance nutrient supply. Cucumber is more susceptible to NaCl than to $CaCl_2$, which points to Na-specific salinity effects. This may be attributed to inefficient comparmentation of Na within the cell, which forces the plant to exclude Na from the leaf. To exclude Na, the plant must expend energy for osmotic adjustment. When Na-exclusion breaks down, the plant suffers directly from Na toxicity at a biochemical level.

Literature Cited

Adams, P. 1991. Effects of increasing the salinity of the nutrient solution with major nutrients or sodium chloride on the yield, quality and composition of tomatoes grown in rockwool. J. Hort. Sci. 66:201–207.

Carmassi, G., L. Incrocci, R. Maggini, F. Malorgio, F. Tognoni, and A. Pardossi. 2005. Modeling salinity build-up in recirculating nutrient solution culture. J. Plant Nutr. 28:431–445.

Chartzoulakis, K.S. 1992. Effects of NaCl salinity on germination, growth and yield of greenhouse cucumber. J. Hort. Sci. 67:115–119.

Commission Regulation (EEC) No 1677/88 of 15 June 1988 laying down quality standards for cucumbers. Official J. L 150, 16/06/1988, p. 0021–0025.

De Kreij C., W. Voogt, and R. Baas. 1999. Nutrient solutions and water quality for soilless cultures. Brochure 196. Res. Sta. Floricult. Glasshouse Veg. (PBG), Naaldwijk, The Netherlands.

Del Amor, F.M., V. Martinez, and A. Cerdá. 1999. Salinity duration and concentration affect fruit yield and quality, and growth and mineral composition of melon plants grown in perlite. HortScience 34:1234–1237.

Drew, M.C., P.S. Hole, and G.A. Picchioni. 1990. Inhibition by NaCl of net CO_2 fixation and yield of cucumber. J. Amer. Soc. Hort. Sci. 115:472–477.

Eaton, A.D, L.S. Clesceri, and A.E. Greenberg (eds.). 1995. Standard methods for the examination of water and wastewater. 19th ed. Amer. Public Health Assn. Wash., D.C.

Flowers, T.J., M.A. Hajibagheri, and A.R. Yeo. 1991. Ion accumulation in the cell walls of rice plants growing under saline conditions: Evidence for the Oertli hypothesis. Plant Cell Environ. 14:319–325.

Garciadeblas, B., B. Benito, and A. Rodríguez-Navarro. 2001. Plant cells express several stress calcium ATPases but apparently no sodium ATPase. Plant Soil 235:181–192.

Grattan, S.R. and C.M. Grieve. 1999. Salinity-mineral nutrient relations in horticultural crops. Sci. Hort. 78:127–157.

Harborne, J.B. 1990. Phytochemical methods: A guide to moderntechniques of plant analysis, p. 214–218. 2nd ed. Chapman and Hall, London.

Ho, L.C. and P. Adams. 1994. Regulation of the partitioning of dry matter and calcium in cucumber in relation to fruit growth and salinity. Ann. Bot. 73:539–545.

Jones, Jr., R.W., L.M. Pike, and L.F. Yourman. 1989. Salinity influences cucumber growth and yield. J. Amer. Soc. Hort. Sci. 114:547–551.

Klieber, A., W.C. Lin, P.A. Jolliffe, and J.W. Hall. 1993. Training systems affect canopy light exposure and shelf life of long English cucumber. J. Amer. Soc. Hort. Sci. 118:786–790.

Marmé, D. 1984. Calcium transport and function, p. 599–625. In: A. Läuchli and R.L. Bieleski (eds.). Encyclopedia of plant physiology. New Ser. vol. 15A. Springer Verlag, Berlin, New York.

Marschner, H. 1995. Mineral nutrition of higher plants. 2nd ed. Academic Press, London.

Mills, H.A. and J. Jones, Jr. 1996. Plant analysis handbook II. MicroMacro Publ., Inc., Athens, Ga.

Montero, E., C. Cabot, C.H. Poschenrieder, and J. Barcelo. 1998. Relative importance of osmotic-stress and ion-specific effects on ABA mediated inhibition of leaf expansion growth in *Phaseolus vulgaris*. Plant Cell Environ. 21:54–62.

Mizrahi, Y. and D. Pasternak. 1985. Effects of salinity on quality of various agricultural crops. Plant Soil 89:301–307.

Munns, R. 2002. Comparative physiology of salt and water stress. Plant Cell Environ. 25:239–250.

Petersen, K.K., J. Willumsen, and K. Kaack. 1998. Composition and taste of tomatoes as affected by increased salinity and different salinity sources. J. Hort. Sci. 73:205–215.

Savvas, D. 2002a. Nutrient solution recycling, p. 299–343. In: D. Savvas and H.C. Passam (eds.). Hydroponic production of vegetables and ornamentals. Embryo Publ., Athens, Greece.

Savvas, D. 2002b. Automated replenishment of recycled greenhouse effluents with individual nutrients in hydroponics by means of two alternative models. Biosyst. Eng. 83:225–236.

Savvas, D. and F. Lenz. 2000. Effects of NaCl or nutrient-induced salinity on growth, yield, and composition of eggplants grown in rockwool. Sci. Hort. 84:37–47.

Savvas, D. and G. Manos. 1999. Automated composition control of nutrient solution in closed soilless culture systems. J. Agr. Eng. Res. 74:28–33.

Savvas, D., V.A. Pappa, G. Gizas, and A. Kotsiras. 2005a. NaCl accumulation in a cucumber crop grown in a completely closed hydroponic system as influenced by NaCl concentration in irrigation water. Euro. J. Hort. Sci. 70:217–223.

Savvas, D., A. Kotsiras, G. Meletiou, S. Margariti, and I. Tsirogiannis. 2005b. Modeling the relationship between water uptake by cucumber and NaCl accumulation in a closed hydroponic system. HortScience 40:802–807.

Savvas, D., V.A. Pappa, G. Gizas, and L. Maglaras. 2005c. Influence of NaCl concentration in the irrigation water on salt accumulation in the root zone and yield in a cucumber crop grown in a closed hydroponic system. Proc. Intl. Symp. Soilless Culture and Hydroponics. 14–19 Nov. 2004, Almeria, Spain (in press).

Schnizler, W.H. and N.S. Gruda. 2002. Hydroponics and product quality, p. 373–411. In: D. Savvas and H.C. Passam (eds.). Hydroponic production of vegetables and ornamentals. Embryo Publ., Athens, Greece.

Shannon, M.C. and C.M Grieve. 1999. Tolerance of vegetable crops to salinity. Scientia Hort. 78:5–38.

Sonneveld, C. 1988. The salt tolerance of greenhouse crops. Neth. J. Agr. Sci. 36:63–73.

Sonneveld, C. 2000. Effects of salinity on substrate grown vegetables and ornamentals in greenhouse horticulture. PhD diss. Univ. Wageningen, The Netherlands.

Sonneveld, C. 2002. Composition of nutrient solutions, p. 179–210. In: D. Savvas and H.C. Passam (eds.). Hydroponic production of vegetables and ornamentals. Embryo Publ., Athens, Greece.

Sonneveld, C. and A.M.M. Van der Burg. 1991. Sodium chloride salinity in fruit vegetable crops in soilless culture. Neth. J. Agr. Sci. 39:115–122.

Tas, G., N. Papadandonakis, and D. Savvas. 2005. Responses of lettuce (*Lactuca sativa* L. var. *longifolia*) grown in a closed hydroponic system to NaCl or $CaCl_2$ salinity. J. Appl. Bot. Food Qual. 79:136–140.

Termaat, A. and R. Munns. 1986. Use of concentrated macronutrient solutions to separate osmotic from NaCl-specific effects on plant growth. Austral. J. Plant Physiol. 13: 509–522.

Urrestarazu, M. and M. Garcia. 2000. Modeling electrical conductivity management in a recirculating nutrient solution under semi-arid conditions. J. Plant Nutr. 23:457–468.