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NaCl Accumulation in a Cucumber Crop Grown in a Completely Closed Hydroponic System as Influenced by NaCl Concentration in Irrigation Water

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Summary

Four different NaCl concentrations in the irrigation water, 0.8, 5, 10 and 15 mM, were applied as experimental treatments to cucumber (*Cucumis sativus* L.) grown in a closed hydroponic system. These treatments were attained by automatically injecting the required amounts of NaCl into irrigation water containing 0.8 mM NaCl, whenever water was mixed with fertilizers and drainage solution to prepare fresh irrigation solution. Initially, the Na^+ and Cl^- concentrations increased rapidly in both the fresh nutrient solution supplied to the crop and the drainage water, but they were stabilized to maximal levels depending on the treatment 45–55 days after initiation of solution recycling. It was concluded that the Na^+ and Cl^- concentrations in the root zone were maximized as soon as the Na/water and Cl/water uptake ratios reached equal levels with the NaCl concentration in the irrigation water. Based on these data, relationships between the Na/water or Cl/water uptake ratios and the NaCl concentration in the root zone were established. The leaf Na^+ and Cl^- concentrations were influenced by both the external Na^+ and Cl^- concentrations and the season. The Cl:Na uptake ratio (mol basis) was higher than 1 at low external NaCl concentrations but decreased below 1 as salinity increased, thereby indicating a more rapid decline in the ability of the plant to exclude Na^+ from the leaves as compared to that for Cl^-.

Zusammenfassung

NaCl-Anreicherung beim Gurkenanbau in geschlossenen Hydrokultursystemen in Abhängigkeit von der NaCl-Konzentration im Bewässerungswasser. In einem Gewächshausversuch mit Gurken, die in geschlossenen Hydrokultursystemen angebaut wurden, enthielt das mit der Sickernährlösungen gemischte Bewässerungswasser 0,8, 5, 10 oder 15 mM NaCl. Die vier obengenanten Behandlungen wurden durch automatischen Zusatz der benötigten Mengen von NaCl zu Wasser mit einem Gehalt von 0,8 mM NaCl erzielt. Die Na^+- und Cl^--Konzentrationen erhöhten sich bald nach Aktivierung der geschlossenen Systeme sowohl in der Frisch- als auch in der Sickernährlösung drastisch. Nach einer anfänglichen Steigungsphase reduzierten sich aber die Na^+- und Cl^--Anreicherungsraten in allen Nährlösungen stufenweise bis auf Null. Dies führte 45–55 Tage nach Aktivierung der geschlossenen Systeme zur Stabilisierung der Na^+- und Cl^--Konzentrationen in allen Frisch- und Sickernährlösungen auf bestimmten Höchstniveaus, deren Höhe von den Behandlungen abhängig war. Die fortlaufende Anreicherung von Na^+ und Cl^- in den geschlossenen Systemen wurde auf die Angleichung der Na/Wasser- und Cl/Wasser-Verhältnisse mit der entsprechenden NaCl-Konzentration im Bewässerungswasser zurückgeführt. Die gemessenen Höchstwerte der Na^+- und Cl^--Konzentrationen in den Sickernährlösungen und die entsprechenden NaCl-Konzentrationen im Wasser ergaben mittels Regressionsanalyse ein Model, das die Schätzung der Na^+- und Cl^--Aufnahmeraten von Gurken in Abhängigkeit von der NaCl-Konzentration im Wurzelraum ermöglicht. Die Na^+- und Cl^--Blattkonzentrationen wurden sowohl bei Änderungen in der NaCl-Konzentration im Wurzelraum, als auch von der Jahreszeit beeinflusst. Das Cl:Na-Aufnahmeverhältnis, bezogen auf Mol, das bei verhältnismäßig geringen NaCl-Konzentration im Wurzelraum höher als 1 war, unterschritt diesen Grenzwert sobald die Salzkonzentration im Wurzelraum über ein bestimmtes Niveau anstieg. Dieses Ergebnis weist auf eine schneller abnehmende Ausschlussfähigkeit der Gurkenpflanze für Na^+ als für Cl^- bei steigenden NaCl-Konzentrationen im Nährmedium hin.

Key words. *Cucumis sativus* – electrical conductivity – salinity – salt stress – soilless culture

Introduction

Closed hydroponic systems are considered environment-friendly, because they eliminate the use of methyl bromide and other toxic chemicals to sterilize the soil, and reduce the contamination of groundwater due to fertilizer residues by collecting and recycling the fertigation effluents (VAN OS et al. 2001). However, the presence of NaCl in the irrigation water may result in undesirably high Na^+ and Cl^- concentrations in the root environment, if their supply rate via the water is higher than their uptake rate and the nutrient solution effluents are recycled (RAVIV et al. 1998; SAVVAS 2002a). The adverse effects of salinity on horticultural crops grown hydroponically have been extensively studied and quantified (SONNEVELD 2000; SAVVAS 2001; ADAMS 2002). Nevertheless, in most studies involving plant responses to salt exposure in hydroponics, constant salinity levels were tested. Even when physiological mechanisms underlying salinity effects were studied, constant salinity levels were commonly applied, since they enable a better interpretation of the results (GREENWAY and MUNNS 1980; MUNNS 2002). However, plants grown under commercial conditions in closed hydroponic systems are exposed to progressive salt accumulation rather than constant salinity levels. It is, therefore, important to understand the pattern of salt accumulation in completely closed hydroponic systems.

The effects of a progressive salinity build-up on growth and yield of plants grown in closed hydroponic systems have been studied for certain crop species (RAVIV et al. 1998; BAR-YOSEF et al. 1999, 2000). However, there is little information regarding the rate of salt accumulation in long-term greenhouse crops grown hydroponically, when all the drainage solution is recycled. In the latter case, the volume of water input is essentially equal to that of water removal via transpiration. Hence, the rate of Na^+ and Cl^- accumulation depends on the Na/water and Cl/water ratios at both input and output levels. The former corresponds to the Na^+ and Cl^- concentrations in the irrigation water used to replenish the recycled drainage solution. The latter is mainly influenced by the ability of a given plant species to exclude salts at each particular NaCl concentration in the root zone and is expressed in terms of uptake concentration (SONNEVELD et al. 1999; SONNEVELD 2000). SILBERBUSH and BEN-ASHER (2001) have proposed a theoretical model to simulate nutrient uptake by soilless grown plants under saline conditions. This model enables a better understanding of the complex relationships involved in salt accumulation in closed hydroponic systems. However, an investigation conducted under commercial growing conditions that might enable a quantification of the relationship between rate of accumulation and NaCl concentration in the irrigation water is still lacking. Therefore, this study was designed to provide a model-based quantification of Na^+ and Cl^- accumulation in a cucumber crop grown in a completely closed hydroponic system as a relationship of the NaCl concentration in the irrigation water.

Materials and Methods

The experiment was conducted in a glasshouse located at the Faculty of Agricultural Technology in Arta (lat. 39 ° 7 'N, long. 20 ° 56 'E), Greece. Cucumber (*Cucumis sativus* L. cv. 'Camaron') seedlings grown in peat cubes (4×4×4 cm) were transferred to porous polyurethane slabs (100×20×6 cm) as soon as the third true leaf had expanded. The plants were distributed over 12 independently operating hydroponic systems (experimental units). Each experimental unit consisted of two channels, 5 m in length, accommodating 20 plants (10 plants per channel). Crop density was 1.6 plants per m^2. The plants were pruned according to the umbrella training system (KLIEBER et al. 1993). The high summer temperatures were controlled by passive ventilation and automatically operated shading screens. Trickle irrigation was automatically applied at intervals depending on solar radiation intensity, which was monitored using a solar energy sensor (Volmatic, SC 21B). Water evaporation was negligible because all channels were covered with polyethylene sheets.

Four different nutrient solution treatments were established in a randomized block design, with three blocks. In all treatments, the entire quantity of drainage water after each application of nutrient solution (irrigation cycle) was captured and recycled in the next watering cycle. Recycling was performed by means of a computer-controlled installation and a model based on the concept of drainage solution plus fresh water (SAVVAS 2002b). The replenishment of the drainage solution with nutrients and fresh water before recycling was based on identical set points in all treatments for the part of electrical conductivity (EC) arising from nutrients (2.1 dS m^{-1}), pH (5.6), macronutrient ratios on equivalent basis (0.35:0.45:0.2 for K:Ca:Mg, 0.075 for H_2PO_4:(SO_4+NO_3+H_2PO_4), 2.4 for N:K, 0.08 for NH_4-N:total-N), and micronutrient concentrations (25 μM Fe, 15 μM Mn, 4 μM Zn, 0.75 μM Cu, 25 μM B, 0.5 μM Mo). However, the NaCl concentration in the irrigation water, which was mixed with drainage solution and fertilizers when preparing fresh nutrient solution, was different in each treatment (0.8, 5, 10 and 15 mM NaCl, respectively). As a result, the total EC of the fresh nutrient solution supplied to the crop (E_{tb}) was also different in each treatment. Specifically, E_{tb} was 2.2, 2.7, 3.3 and 3.9 dS m^{-1} before recycling initiation. To allow for the accumulation of Na^+ and Cl^- after recycling initiation, thereby ensuring identical nutrient feed in all treatments, the actual EC of the nutrient solution supplied to the plants, henceforth denoted by E_{ta} (dS m^{-1}) was variable at each irrigation cycle, depending on the rate of NaCl accumulation. Since the latter could not be continuously monitored, E_{ta} was automatically estimated at each irrigation application using the equation

$$E_{ta} = E_{tb} + a(E_{ra} - E_{rb}), \qquad (1)$$

where a was the fraction of the drainage to be recycled at each irrigation application (0–1), E_{rb} was the EC (dS m^{-1}) of the drainage solution at the date of recycling initiation and E_{ra} was the actual EC (dS m^{-1}) of the drainage solution at each irrigation application, measured automatically in real time. The variable a was also estimated in real time, since it is by definition the volume ratio between the recycled drainage solution (measured on-line) and the solution supplied to the crop (preset constant). Hence, the target EC of the fresh nutrient solution, that was used for the automatic calculation and injection of fertilizers and water to the recycled drainage (Savvas 2002b), was E_{ta} as calculated by (1).

The concentration of NaCl in the irrigation water was 0.8 mM. To obtain irrigation water containing 5, 10 and 15 mM NaCl, stock solution of NaCl was automatically injected whenever fresh nutrient solution was prepared. Since the recycled drainage fraction (a) was a variable at each irrigation application, the volume of added water, and thus the required amount of NaCl, was also variable and was automatically calculated in real time as a function of a. The required NaCl stock solution was dispensed by means of a peristaltic pump (SEKO, Italia S.p.A, type SE 57BT) having a constant injection rate (J in l s^{-1}). The injection time (T in s) was automatically calculated at each irrigation cycle, using the equation

$$T = \frac{MV(1-a)(C_i - C_w)}{DJ} \qquad (2)$$

where M denotes the molecular weight (g) of NaCl, V the volume (m^3) of the prepared fresh nutrient solution, C_i the concentration of NaCl in the irrigation water of each treatment (mM), C_w the natural concentration of NaCl in the irrigation water (0.8 mM), and D the NaCl concentration in the NaCl stock solution (kg m^{-3}).

The cucumber seedlings were planted on 13 June and immediately supplied with nutrient solution differing in the NaCl concentration according to the irrigation water used in each treatment. Recycling of the drainage solution was initiated on 18 June and the experiment was terminated on 16 October. Samples of drainage solution and fresh nutrient solution supplied to the crop were collected 0, 8, 22, 38, 56, 78, 100, and 120 days after treatment initiation and analysed to determine their Na^+ and Cl^- concentrations. The nutrient concentrations were also measured regularly and adjusted to ensure adequate and similar nutrient supply in all treatments. Samples of young leaves (5^{th} leaf from the apex) were collected 8, 22, 38, 78, 100, and 120 days after treatment initiation. In addition, portions of the basal part of the stem (15 cm) were obtained at the end of the experiment. The concentrations of Cl and Na were determined in all the tissue samples.

All leaf and stem samples were dried at 80 °C to constant weight and ground. Sodium was extracted from the ground tissue material using 1 N HCl after dry ashing at 550 °C for 5 hours. The Na^+ concentrations in both the plant tissue extracts and the nutrient solutions were measured by atomic absorption spectrophotometry (GBC 932 A/A). Chloride was extracted from the ground plant tissue using water at 85 °C. The determination of Cl^- in both the plant tissue extracts and the nutrient solutions was performed by titration with $AgNO_3$ in the presence of K_2CrO_4 (Eaton et al. 1995). The nutrient concentrations aimed at monitoring the nutrient supply were measured as described previously (Savvas and Gizas 2002).

Results and Discussion

The accumulation of Na^+ in the drainage solution exhibited a sigmoid pattern with time in the three high salinity treatments, with a slow rate during the initial 10–15 days after onset of recycling, followed by a rapid build-up of Na^+ during the subsequent 35–40 days (Fig. 1). Thereafter, the Na^+ concentration in the drain-

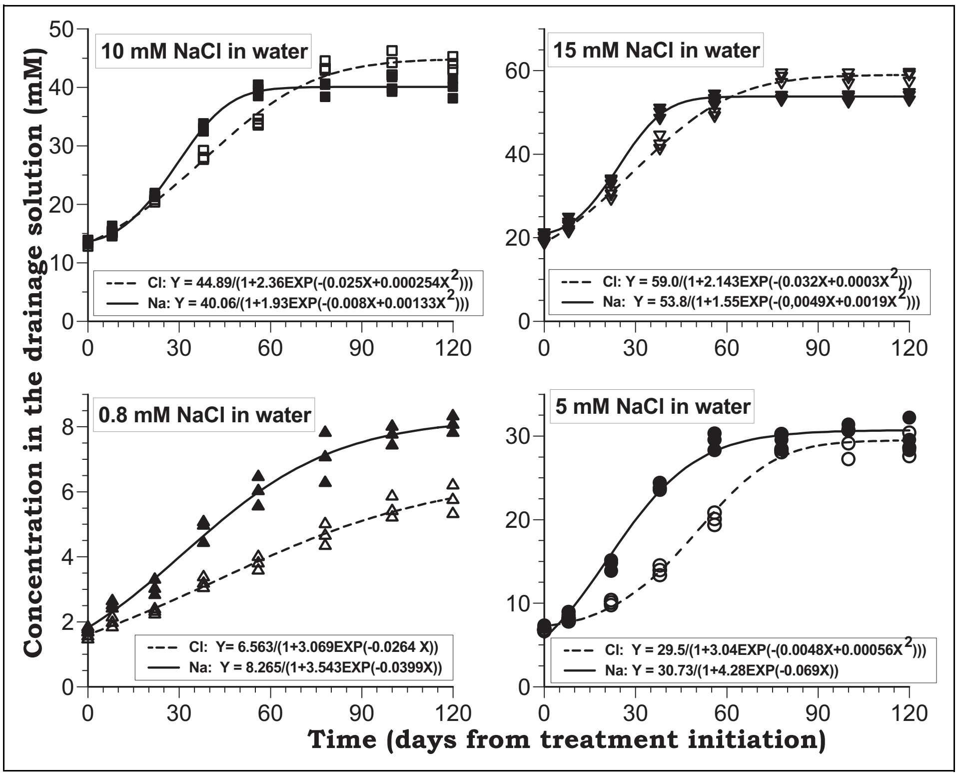

Fig. 1. Concentrations of Na^+ and Cl^- in the drainage solution that was captured and recycled in a cucumber crop grown in a closed hydroponic system as influenced by different NaCl concentrations in the irrigation water used to compensate for transpiration losses. Closed and open symbols indicate measured values for Na^+ and Cl^-, respectively.

age water remained constant until the end of the experiment. In the treatment with low NaCl concentration in the irrigation water (0.8 mM) the accumulation of Na^+ was slower and led to a nearly constant Na^+ concentration in the drainage water 100 days after recycling initiation. In all treatments, the accumulation of $Cl^–$ in the drainage solution exhibited a similar pattern with that of Na^+, but the rates were slower, and maximal $Cl^–$ levels were reached later. In the two highest NaCl treatments, the ultimate $Cl^–$ concentrations in the drainage solution were higher than those of Na^+. The accumulation of Na^+ and $Cl^–$ in the drainage solution even at low external NaCl concentrations indicates that the primary physiological mechanism involved in the salt tolerance of cucumber is the exclusion of salt ions from the photosynthetically active leaves, which is common in glycophytes (Shannon 1984; Savvas and Lenz 1996; Munns 2002).

If all the drainage solution is recycled, the volume of irrigation water introduced into the system when preparing fresh nutrient solution is equal to the volume of water removed via transpiration. Hence, Na^+ and $Cl^–$ will accumulate as long as the Na/water and Cl/water uptake ratios (uptake concentrations) are lower than the NaCl concentration in the irrigation water used to compensate for transpiration losses (input rate). However, the accumulation of Na^+ and $Cl^–$ in the external solution imposes corresponding increases in the uptake concentrations, since the latter are functions of the external NaCl concentration (Sonneveld et al. 1999). As a result, the accumulation of Na^+ and $Cl^–$ will cease as soon as the uptake concentrations reach equal levels with the NaCl concentration in the irrigation water. This consideration is in agreement with our results, which revealed a rapid initial increase followed by stabilization of Na^+ and $Cl^–$ concentrations at maximal levels depending on their concentrations in the irrigation water. A similar approach is indicated also by the model of Silberbush and Ben-Asher (2001).

The Na^+ and $Cl^–$ concentrations in the fresh nutrient solution supplied to the crop also increased during the experiment in all treatments, but the increase was much lower than in the drainage solution (Fig. 2). The $Cl^–$ concentration in the fresh nutrient solution was invariably lower than that of Na^+ when the NaCl concentration in the irrigation water was low (0.8 and 5 mM) but increased to values higher that that of Na^+, 62 and 56 days after treatment initiation with 10 and 15 mM NaCl in the irrigation water, respectively. In closed systems, the fresh nutrient solution is prepared by mixing drainage solution with irrigation water and nutrients. Assuming that the Na^+ and $Cl^–$ input via fertilizer impurities is negligible, the Na^+ and $Cl^–$ concentrations in the fresh solution (C_{ti}) are functions of the drainage fraction (a) and their concentrations in drainage solution (C_{ri}) and irrigation water (C_{wi}), as described by equation

$$C_{ti} = aC_{ri} + (1 - a)C_{wi} \qquad (3)$$

where i denotes Na^+ or $Cl^–$. Equation (3) indicates that a restriction of a in a closed hydroponic system depresses C_{ti} and vice versa. Relating the irrigation frequency to solar energy is a means to approach a desired drainage fraction (Sonneveld 1995; Sigrimis et al. 2001). In our experiment, a was maintained close to 0.4 (±0.05), when C_{ri} was stabilized at a maximal level, by irrigating at intervals depending on real-time measurement of solar energy. As a result, the fluctuations of Na^+ and $Cl^–$ in the fresh irrigation solution (C_{ti}) were minimized after stabilization of C_{ri} at a maximal level.

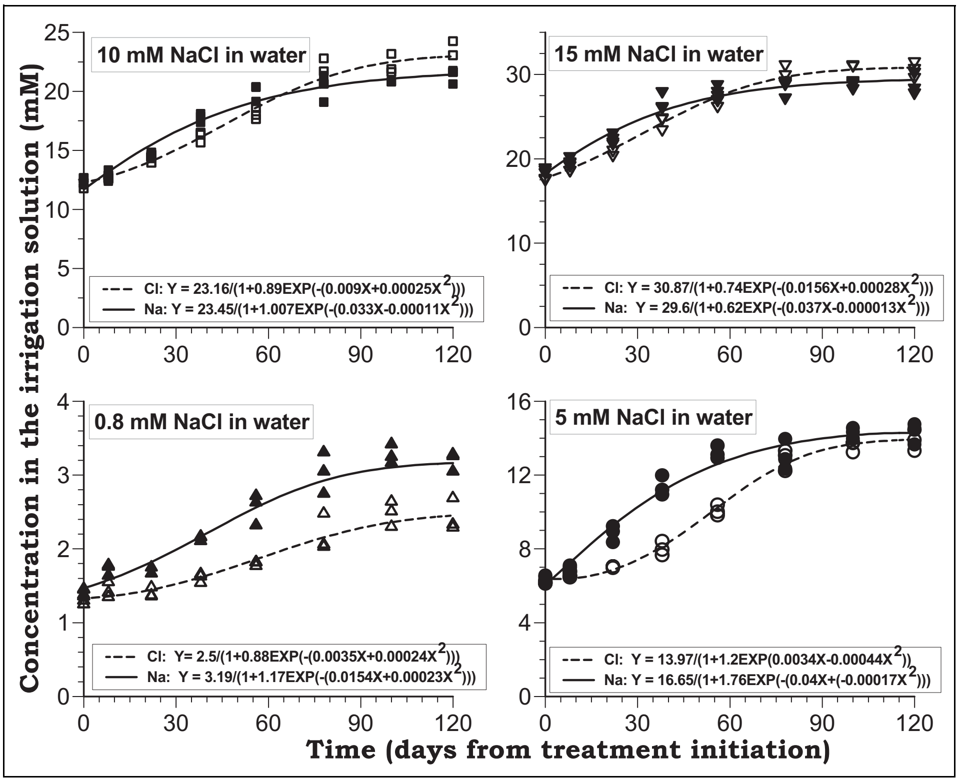

Fig. 2. Concentrations of Na^+ and $Cl^–$ in the fresh nutrient solution supplied to a cucumber crop grown in a closed hydroponic system as influenced by different NaCl concentrations in the irrigation water used to compensate for transpiration losses. Closed and open symbols indicate measured values for Na^+ and $Cl^–$, respectively.

As previously stated, the maximal Na^+ and Cl^- levels established in the drainage solution (Fig. 1), imposed as high Na^+ and Cl^- uptake concentrations as the NaCl concentration in the irrigation water of the particular treatment. These pairs of values may be used to establish mathematical relationships between the Na^+ and Cl^- concentrations in the root zone and their respective uptake concentrations by regression analysis. According to SONNEVELD et al. (1999) the relationships between the Na^+ or Cl^- concentration in the root zone (X), and the uptake concentrations of Na^+ or Cl^- (Y), may be described by the exponential model

$$Y = bX^c \qquad (4)$$

where b and c are constants. To obtain a better fit, we used the generalized form of this model

$$Y = bX^c + d \qquad (5)$$

which includes d as a constant. The obtained equations for our cucumber crop and the best fit curves corresponding to equation (5) are presented in Fig. 3.

SONNEVELD and VAN DER BURG (1991) found uptake concentrations for Na between 0.2–0.4 mmol l–1 when the NaCl concentration in the root environment was less than 5 mM, increasing to 1.2–1.4 and 2.0–3.2 mmol l–1 as the external NaCl concentration was raised to 12.5 and 25 mM NaCl, respectively. The corresponding uptake concentrations for Cl– in the above study were 0.2, 2.1 and 5 mmol l–1 at external NaCl concentrations of <5, 12.5 and 25 mM NaCl, respectively. These values are similar to those predicted by the equations shown in Fig. 3. Comparison of our results with those of SONNEVELD and VAN DER BURG (1991) and Sonneveld et al. (1999) concerning various vegetables and ornamental plants reveals similar Na+ and Cl– uptake rates at low NaCl concentrations in the root environment but much more rapidly increasing rates with rising external NaCl concentrations in cucumber. An exception is aster (*Aster novi-belgii* L.), which also exhibited rapidly increasing Na+ and Cl– uptake concentrations with rising external NaCl levels (SONNEVELD et al. 1999).

Under Mediterranean summer conditions, a maximal acceptable salinity value of 3 dS m^{-1} was calculated for cucumber (SAVVAS et al. 2004). According to Sonneveld and VAN DER BURG (1991), to maintain an EC value of 3.0 dS m^{-1} without to suppress any nutrient concentrations below adequacy levels, the Na^+ and Cl^- concentrations in the root zone, should not exceed 12 mM. Concentrations of 12 mM Na^+ and Cl^- in the root environment roughly correspond to uptake concentrations of 2 mM (Fig. 3). Hence, to recycle consistently all the drainage solution occurring in hydroponically grown cucumber crops, a maximal NaCl concentration in the irrigation water of approximately 2 mM is acceptable under Mediterranean summer conditions.

The accumulation of Na^+ and Cl^- in the root zone led to an appreciable increase of the Na^+ and Cl^- concentrations in the leaf of cucumber (Fig. 4). The inhibi-

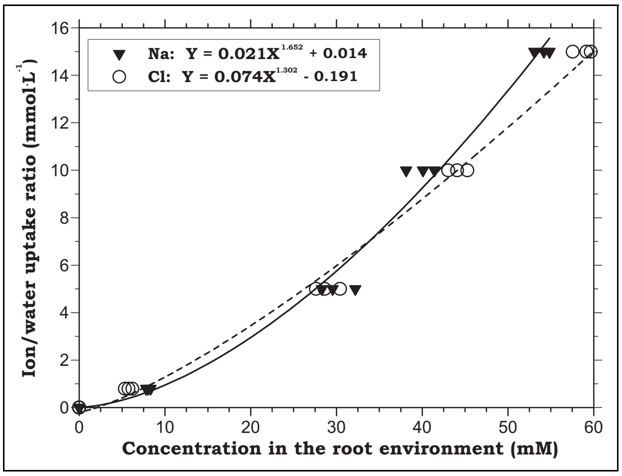

Fig. 3. Relationships between Na^+ and Cl^- concentrations in the root zone, as measured in the drainage solution, and ion/water ratios at which Na^+ and Cl^- are taken up (uptake concentrations) by cucumber grown in a closed hydroponic system. Symbols indicate measured values for Na^+ and Cl^-, respectively (solid line = Na^+, dotted line = Cl^-).

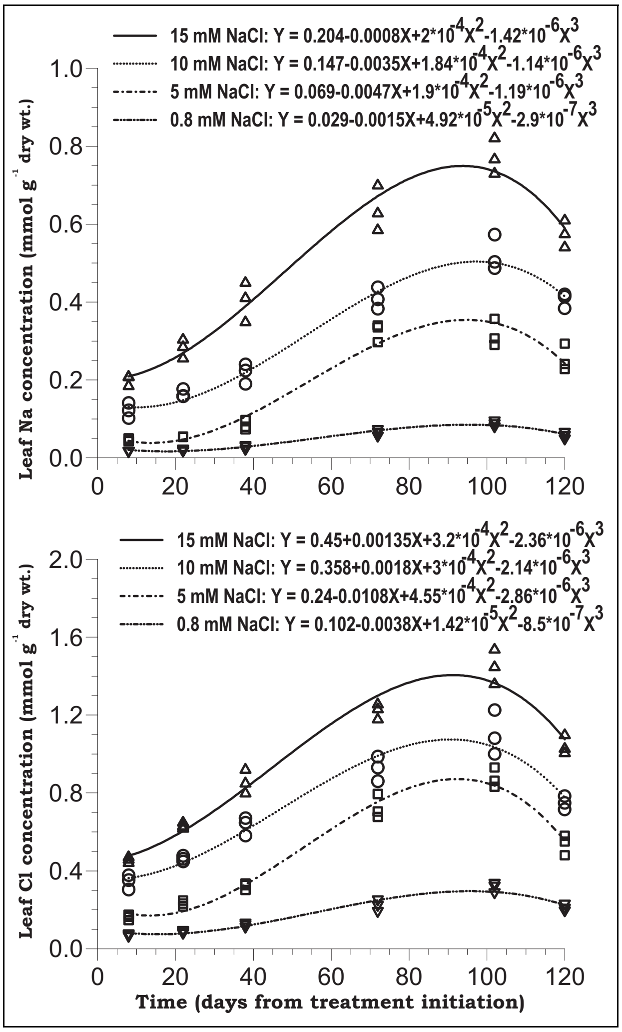

Fig. 4. Concentrations of Na^+ and Cl^- in the fifth leaf of cucumber grown in closed hydroponic systems with different NaCl concentrations in the irrigation water used to compensate for transpiration losses. Symbols indicate measured values.

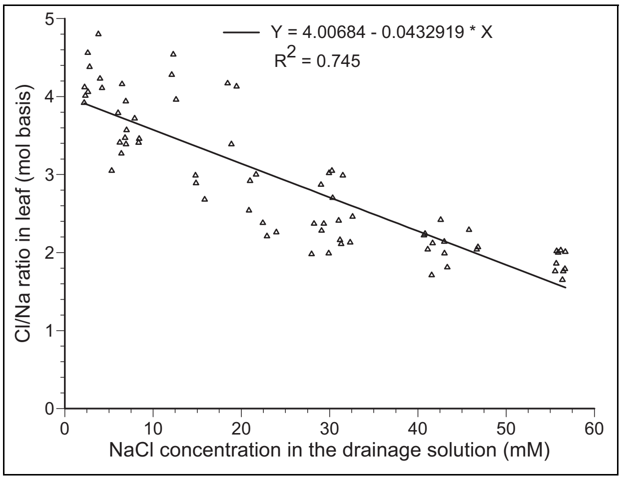

Fig. 5. Relationships between Cl:Na ratio in the leaf of cucumber grown in closed hydroponic systems and the external NaCl concentration as measured in the drainage solution. Symbols indicate measured values.

tion of photosynthesis in cucumber seems to result mainly from restricted chloroplast activity and is much more severe than in the salt sensitive bean (Drew et al. 1990). Hence, a causal relationship between the high Na^+ or Cl^- uptake ratio by cucumber and its high salt sensitivity (Jones et al. 1989; Drew et al. 1990) is indicated. The maximal Na^+ and Cl^- accumulation in the fifth leaf occurred in all salinity treatments later than in the drainage solution. However, on day 120 (16 October), the leaf Na^+ and Cl^- concentrations declined in all treatments. This was presumably a seasonal effect, originating from reduced solar radiation due to the advent of autumn, which suppressed the transpiration rate. Indeed, reducing the transpiration rates while maintaining constant external Na^+ and Cl^- concentrations may effectively suppress the leaf Na^+ and Cl^- concentrations (Greenway and Munns 1980; Levitt 1980).

The Cl:Na uptake ratio dropped to values below 1 when the NaCl concentration exceeded 35 mM in the root zone (Fig. 3), which implies that, above this threshold, Na^+ was taken up more rapidly than Cl^-. However, the Cl:Na ratio in the leaf of cucumber was always higher than 1 (Fig. 5). Hence, we assumed that the Cl:Na ratio was lower than 1 in some other parts of cucumber, e.g. roots and stem, due to deposition of Na^+ to the xylem parenchyma. Indeed, chemical analysis revealed higher Na^+ concentrations than those of Cl^- in the basal part of the stem in all treatments, and thus Cl:Na ratios lower than 1 (Table 1).

The Cl:Na ratio in the leaf of cucumber decreased with increasing NaCl concentrations in the root environment (Fig. 5). Unlike in the leaf, the Cl:Na ratios in the basal region of cucumber stem were not significantly different between treatments (Table 1). Decreasing Cl:Na ratios as the external NaCl concentration increases were found also by Lessani and Marschner (1978) in the leaf of many moderately tolerant and sensitive species to salinity. A decreasing Cl:Na ratio in the leaf of salt sensitive plants as the external NaCl concentration increases, indicates a more rapid breakdown of the ability of these plants to exclude Na from the photosynthetically active leaves in comparison to Cl^-. This implies that the adverse effects of NaCl salinity on these plants may originate primarily from a progressive impairment of their ability to exclude Na from the photosynthetically active leaves. In agreement with this view, the leaf Cl^- concentration differs much less between plant species compared with that of Na^+ (Lessani and Marschner 1978). It seems that compartmentation of Cl^- in leaf cells is highly regulated by most cultivated plants (Xu et al. 2000), in contrast to Na^+ (Mennen et al. 1990). Nevertheless, further research is needed to discriminate the deleterious effects of Na^+ from those of Cl^- on cucumber, when this plant species is exposed to salinity.

Table 1. Na^+, Cl^- concentrations and Cl:Na ratio (mol basis) in the basal region of the stem of cucumber grown in a completely closed hydroponic system for 120 days, as influenced by the concentration of NaCl in the irrigation water. In each column, values followed by the same letter do not differ significantly ($P \leq 0.05$).

NaCl concentration in water (mM)	Na^+ (mmol g^{-1} dry wt)	Cl^- (mmol g^{-1} dry wt)	Cl:Na ratio (mol basis)
0.8	0.42 a	0.29 a	0.68 a
5.0	1.19 b	0.79 b	0.66 a
10.0	1.41 c	0.98 c	0.69 a
15.0	1.78 d	1.22 d	0.69 a

Conclusions

In cucumber crops grown in closed hydroponic systems, Na^+ and Cl^- originating from the water used to compensate for transpiration losses accumulate in a sigmoid patter in the root zone up to maximal levels depending on the NaCl concentration in the primary water supply. Under Mediterranean summer conditions, the Na/water and Cl/water uptake ratios for cucumber (Y) were related to the Na^+ and Cl^- concentrations in the drainage water (X) via the equations $Y_{Na} = 0.021X_{Na}^{1.652} + 0.014$ and $Y_{Cl} = 0.074X_{Cl}^{1.302} + 0.191$. These relationships, in combination with the Na^+ and Cl^- concentrations measured in leaf and stem, indicate that cucumber takes up both Na^+ and Cl^- at relatively high rates, but those for Na^+ increase more rapidly with rising NaCl concentrations in the root zone. At higher concentrations than approximately 2 mM NaCl in the irrigation water, a partial discharge of drainage water seems inevitable in order to prevent a build-up of Na^+ and Cl^- in the root zone at harmful levels.

Acknowledgements

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