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

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Abstract
The effects of four different NaCl concentrations in the irrigation water used to replenish the transpiration losses in a cucumber (Cucumis sativus L.) crop grown in a closed hydroponic system were investigated for 4 months in a glasshouse experiment. Four different NaCl concentrations in the irrigation water, particularly 0.8, 5, 10 and 15 mM, were compared. These were obtained by automatically injecting the required amounts of NaCl to irrigation water containing 0.8 mM NaCl. During the experiment, no drainage solution was discharged. Initially, the electrical conductivity (EC) increased rapidly in the root environment, as indicated by the values measured in the drainage solution. However, 6-7 weeks after recycling initiation the EC of the drainage water approached asymptotically a maximal level depending on the treatment. The concentration of some macronutrients showed also an increasing tendency with time, but this increase was relatively small and could not account for the observed rise of EC. Hence, this pattern of EC increase was ascribed to accumulation of Na and Cl, which was initially rapid but tended to be minimized as uptake concentrations of Na and Cl were approaching the corresponding concentrations in the irrigation water used to compensate for the transpiration losses. The yield was suppressed by the progressive increase of EC at a rate of 12.3% per unit of EC increase above 3.02 dS m⁻¹. The yield suppression was due to decrease of both the mean fruit weight and the number of fruits per plant. The mean length of the cucumber fruit was also affected by the progressively increasing salinity.

INTRODUCTION
A major problem in closed hydroponic systems is the accumulation of salt ions occurring in the irrigation water at concentrations exceeding the corresponding ratios of ion to water uptake by the plants (Sonneveld, 2000; Savvas, 2002a). Sodium chloride is the most frequently accumulating salt in closed hydroponic systems. Lately, some models have been proposed to predict the rate of salt accumulation in closed hydroponic systems (Silberbush and Ben-Asher, 2001; Pardossi et al., 2004; Savvas et al., 2004a). The accumulation of NaCl originating from the irrigation water in closed hydroponic systems may force the growers to regularly discharge a part of the drainage solution (Raviv et al., 1998). This practice restrict the efficiency of closed hydroponic systems to prevent groundwater contamination with nitrates and phosphates. An efficient management of drainage solution discharge may effectively restrict groundwater pollution while minimizing or even avoiding yield losses. However, to efficiently manage the drainage solution in closed hydroponic systems, a good understanding of the responses of the plants to increasing and not to constant salinity levels is required.

The effects of progressively increasing salinity in closed hydroponic systems on plant growth and yield have been studied for some crop species (Bar-Yosef et al., 1999, 2000; Raviv et al., 1998). However, there is no information on the effects of a progressively increase of salinity in the root zone due to recycling of the drainage solution on the yield of cucumber. Therefore, in the present paper we address also the impact of NaCl accumulation in a closed system on the yield of cucumber.
MATERIALS AND METHODS

Cucumber (Cucumis sativus L. cv. ‘Camaron’) plants were grown in a glasshouse for 4 months in a closed hydroponic system. The experiment was conducted in a glasshouse located in Arta (lat. 39°7’N, long. 20°56’E), Greece. There were four different treatments corresponding to four different NaCl concentrations in the irrigation water used to compensate for transpiration losses, particularly 0.8, 5, 10 and 15 mM. These concentrations were obtained by automatically injecting the required amounts of NaCl to irrigation water containing 0.8 mM NaCl when it was mixed with drainage solution and nutrients to prepare fresh nutrient solution. At each watering cycle, the entire volume of drainage solution selected after the previous watering application was recycled. Hence, the recycled drainage fraction (a) was a variable at each irrigation application. As a result, the volume of the replenished water, and thus the amount of NaCl required to establish each treatment, were also variables, which were automatically calculated in real time as functions of a. The required amounts of NaCl stock solution were dispensed by means of a peristaltic pump having a constant injection rate. The injection time (T in s) was automatically calculated in each irrigation cycle, using equation

\[ T = \frac{MV(1-a)(C_i - C_w)}{DJ} \]

where \( M \) denotes the molecular weight of NaCl, \( V \) the volume (m³) 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), \( D \) the concentration of NaCl in the NaCl stock solution (kg·m⁻³) and \( J \) injection rate of the peristaltic pump (L·s⁻¹).

Recycling was based on a previously developed model, which ensured adequate supply of all nutrients, despite the increasing concentrations of Na and Cl in the closed system (Savvas, 2002b). The electrical conductivity (EC) and the concentrations of Na, Cl and major nutrients in both the irrigation solution and the drainage water were measured at 8 sampling dates. At three sampling dates, the micronutrient status in the root zone was also checked to confirm that their supply was adequate (data not shown).

The experiment was established by transplanting cucumber seedlings grown in peat cubes (4×4×4 cm) at the stage of the third true leaf into channels connected to 12 fully automated hydroponic installations, which constituted the experimental units. Each experimental unit consisted of two channels, 5 m in length, and accommodated 20 plants (10 plants/channel). Porous polyurethane slabs (100×20×6 cm) were used as growing media. A crop density of 1.6 plants per m² was employed. The plants were automatically supplied with nutrient solution via a trickle irrigation system at intervals depending on solar radiation intensity. All channels were covered with polyethylene sheets to prevent water evaporation. The cucumber seedlings were planted on 13 June, the recycling of the drainage solution was initiated five days later, and the experiment was terminated on 15 October.

The electrical conductivity in the nutrient solution samples was measured automatically by means of a GLMU-020 instrument. The concentrations of Ca, Mg and K in the same samples were measured by atomic absorption spectrophotometry (GBC 932 A/A), while that of NH₄ was determined colorimetrically at 640 nm by the phenate method using a “Continuous Flow Analyzer”, type San++ of SKALAR (Eaton et al., 1996).

RESULTS AND DISCUSSION

In Figure 1, the best fit curves illustrating the changes in the electrical conductivity (EC) of both the irrigation solution and the drainage water with time are presented. Initially, the EC increased rapidly in the root environment, as indicated by the values measured in the drainage water. However, after some time, the rate of EC increase showed a constantly declining course and gradually approached asymptotically a maximal level depending on the treatment. In particular, the presence of 0.8, 5, 10 and 15 mM NaCl in the irrigation water raised the EC of the drainage solution up to 3.25, 5.80, 6.96 and 8.62 dS m⁻¹, respectively. The maximal values were approached nearly 50 days after treatment initiation.

The course of the Na and Cl concentrations with time in both the irrigation solution and the drainage water have been presented in a previous paper (Savvas et al., 2004b). As shown in Figure 2, the concentration of some macronutrient cations, particularly Ca and Mg, showed an increasing tendency with time, but this increase was relatively small and could not
account for the observed rise of EC. Hence, the increase of EC in the root zone is ascribed predominantly to the accumulation of Na and Cl. As has been shown in a previous paper (Savvas et al., 2004a), the accumulation of Na and Cl in the root zone results in corresponding increases in the uptake concentrations of these ions by the plants. Hence, as the uptake concentrations of Na and Cl were approaching their concentrations in the irrigation water used to compensate for the transpired water, their accumulation was suspended and thus the EC tended to level off.

The increase of the Ca and Mg concentrations in the drainage solution (Fig. 2) is a common phenomenon in closed systems (Sonneveld, 2002). The relatively high Ca concentration in the irrigation water (2 mM) hampered a more efficient management of its supply via the model used to compensate for Ca removal via plant uptake (Savvas, 2002a). Therefore, the level of Ca in the root zone increased more markedly than that of any other cation. In contrast, the NH₄ concentration in the drainage water was declining with time. This is ascribed to preferential uptake of N predominantly in cationic form, presumably in combination with nitrification of the NH₄ ions (Lea-Cox et al., 1996).

The yield was severely affected by the progressive increase of EC (Fig. 3a). The presence of 5, 10 and 15 mM NaCl in the irrigation water suppressed the final yield to nearly 62.7%, 47.4% and 35.6%, respectively, compared to the control treatment (0.8 mM NaCl in the irrigation water). However, the relative yield depressions were nearly constant throughout the harvesting period, despite the increasing EC during the initial 50 days. This may indicate that young cucumber plants are more sensitive to salinity than older plants and thus the lower salinity levels during the first 6-8 weeks after planting were offset by increased salt sensitivity at that growing stage.

The suppression of yield was due to both a restricted number of fruits per plant (Fig. 3b) and a reduced mean fruit weight (Fig. 3c). The suppression of the number of fruits per plant is commensurate with the restriction of the vegetative shoot mass of cucumber, which was demonstrated in another paper (Savvas et al., 2004a). The mean length of the cucumber fruit was also affected by the progressively increasing salinity but to a lesser extent than the mean weight (Fig. 3d).

The quantification of the effects of the progressively increasing salinity in the closed system according to the Maas and Hoffman (1977) model revealed a decrease in the fruit yield of cucumber at a rate of 12.3% per unit of EC increase above 3.02 dS m⁻¹ (Fig. 4). The rate of yield decrease is nearly double as high as that found by Sonneveld and Van der Burg (1991) in a rockwool grown crop with constant NaCl-salinity levels. This difference may be ascribed to the Mediterranean summer conditions prevailing in our experiment, which contrast with the mild climate prevailing in the Netherlands. As has been shown in another experiment with tomato (Sonneveld and Welles, 1988), the climatic conditions strongly influence the responses of greenhouse grown plants to salinity. The salinity threshold value (STV) of 3.02 dS m⁻¹ found in our experiment is within the range reported by Sonneveld and van der Burg (1991). These results indicate that the gradual increase of salinity during the initial 7-8 weeks after planting in our experiment had hardly any ameliorating effect on the responses of cucumber to the NaCl-salinity.

The above results indicate that even a concentration of 0.8 mM NaCl in the irrigation water may result in EC values exceeding the salinity threshold value, if no drainage water is discharged. Nevertheless, at NaCl levels not exceeding 1 mM in the irrigation water, a more efficient management of the nutrient supply might enable maintenance of the EC to levels that are not harmful for cucumber yield. However, at higher NaCl levels than 1-2 mM NaCl in the irrigation water, a partial discharge of drainage water seems inevitable in order to maintain the EC below the STV for cucumber (see also Savvas et al., 2004b). Further research is required to establish efficient models enabling minimal discharge of drainage water by minimizing yield losses in cucumber crops grown in closed soilless culture systems.

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Literature Cited
Fig. 1. Changes of electrical conductivity with time in the irrigation solution and the drainage water in a cucumber crop grown in a closed hydroponic system as influenced by the NaCl concentration in the irrigation water used to compensate for transpiration losses. Closed and open symbols indicate measured values in the irrigation solution and the drainage water, respectively.

Fig. 2. Concentrations of major nutrient cations in the drainage water in a cucumber crop grown in a closed hydroponic system as influenced by the NaCl concentration in the irrigation water used to compensate for transpiration losses.
Fig. 3. Cumulative yield (fruit weight and no of fruits) as percentages of the best treatment, mean fruit weight, and fruit length during 120 days of drainage solution recycling in a cucumber crop grown in a completely closed hydroponic system as influenced by the NaCl concentration in the irrigation water used to compensate for transpiration losses.

Fig. 4. Rate of yield reduction with increasing electrical conductivity in the drainage solution due to accumulation of NaCl in a cucumber crop grown in a closed hydroponic system.