Strategies to Manage Chemical Water Quality Related Problems in Closed Hydroponic Systems

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Keywords: Na, Cl, accumulation, discharge, uptake concentration, uptake capacity

Abstract

In the Netherlands since the late nineties reuse of drainage water is obligatory for all soil less growing systems, to reduce the environmental pollution. However, this strategy has some important bottlenecks. Apart from technical and phytopathological aspects, accumulation of Na, Cl or other residual ions could be a problem. Accumulation will occur if the uptake rates are lower than the concentrations in the input. Recently a database was established with the maximum acceptable concentrations in the root environment and water sources, for a number of crops. In all cases Na showed to be the bottleneck element. A high tolerance for Na not necessarily means a high uptake rate for this ion, as was found for sweet pepper. Water sources differ highly in Na concentrations. In general, for completely closed growing systems only rainwater or desalinated water is suitable. For some crops (rose, chrysanthemum, sweet pepper) the natural background concentrations of Na in rainwater is sometimes even higher than the uptake rate. Accumulation above the maximum acceptable concentrations inevitably should be followed by discharge of a fraction of the nutrient solution to prevent yield reduction or decline in produce quality. This will result in lower water and nutrient use efficiencies than required. However, the water and nutrient losses depend highly on water management strategies accomplished by the grower. Smart strategies were developed for discharge of drainage water as low as possible for N and P. These are based on the uptake dynamics of Na and Cl and minimal required N and P levels observed with different crops. These strategies have been tested for rose and resulted in significant reduction in the nutrient losses.

INTRODUCTION

Soon after soilless culture was well established in the early 1980s the easy leaching of nutrients from this growing system was a concern in the Netherlands. Therefore reuse of drainage water was promoted and closed systems were developed (Van Os, 1994). From the 1990s the Dutch government stimulated this development and eventually, from 1995 the reuse of drainage water became obligatory (Roos-Schalij et al., 1994). However the quality of the surface waters in concentrated greenhouse areas did not improve as expected. This was caused by the fact that despite the regulations on reuse of drainage water, many growers discharge the circulating solution partly periodically (Baltus and Volkers-Verboom, 2005).

In interviews with growers, several reasons for the frequent discharges were mentioned, most frequently problems related to the root environment. These problems were specified as growth retardation, or supposed problems with soil borne diseases. Occasionally disordered nutrient solution or salinity problems are mentioned. The problems with growth retardation are mainly the excuse to discharge. So far the cause of this phenomenon could not have been established. In the meantime however, exceeding target values for Na or Cl in the circulating nutrient solution are the only legal permitted grounds for discharge. Regarding the European water framework directive and new regulations for Dutch growers, discharge has to be further reduced, aiming at emission targets instead of input targets which were effective until 2010 (Agentschap NL, 2010). This paper focuses on the issue of salinity and the strategies that can be used to minimize the discharge determined by NaCl accumulation.

Proc. XXVIIIth IHC – IS on Greenhouse 2010 and Soilless Cultivation
Ed.: N. Castilla
Acta Hort. 927, ISHS 2012

WATER SOURCES

Soilless culture inevitably means growing in a restricted root volume, so the risk of salt accumulation is rather high and will easily occur. Water of the highest quality standards is a primary requirement. For this reason, rainwater is the major water source in the Netherlands, since surface water and groundwater have too high salt contents in the main greenhouses areas. However Na and Cl will be present also in rainwater, especially along the coastal zone, but also more inland affecting the rainwater in the major greenhouse areas (Voogt and Sonneveld, 1996). Precipitation in the Netherlands is usually sufficient to cover the total crop demand, but not evenly distributed over the growing season, so storage and buffering is needed to bridge dry spells. However the storage capacity at individual holdings is limited by economic constraints, as result of the availability and the price of plots for building buffer tanks, especially in concentrated greenhouse areas. Moreover, to bridge dry years, compared to the costs a disproportionate large storage buffer is needed and for intensive cropping systems the yearly average precipitation sum is lower than the demand. Therefore secondary sources are required, to supplement in dry periods. Reverse osmosis treatment of saline groundwater is commonly used, as it is a flexible, reliable and relatively cheap alternative. However, in the near future the injection of brine to the groundwater will be strongly regulated, which will make future use of reverse osmosis unsure. Alternatively growers use tap water or surface water as secondary source, however both sources have a too high content of residual salts.

NA ACCUMULATION AND UPTAKE CAPACITY

Accumulation of residuals salts like Na and Cl in the root environment cause increase of the EC value, which will affect negatively the yield or quality of the produce (Sonneveld, 2000) Since EC in the root environment is controlled more or less automatically and kept at a certain set point, Na or Cl accumulation eventually cause reduction in the nutrient concentrations (Voogt and Sonneveld 1996). For many crops maximum acceptable Na and Cl concentrations are established ($R_{Na\text{-}max}$, $R_{Cl\text{-}max}$), based on the threshold values for these ions. In a closed growing system, the input of ions should match the crop need, or in other words for non essential elements, the uptake capacity of a crop (Voogt and Sonneveld, 1996). An important parameter in this context is the Na and Cl uptake concentration, which is the total uptake of an ion divided by the total water uptake, expressed in mmol L^{-1} (U_{Na}, U_{Cl}). Accumulation occurs when the input concentration is higher than the uptake concentration. For a number of crops the uptake concentration of Na and Cl were derived from experiments in closed systems with series of Na and Cl treatments (Baas et al., 1994; De Kreij and Van den Berg, 1990; Sonneveld and Voogt, 1983; Sonneveld and Van den Burg, 1991; Sonneveld et al., 1999) and is summarized in Table 1. The data clearly shows the great variety in uptake concentrations of different crops, which implies for instance that cucumber can be grown in closed systems without discharge better than roses. Without exception U_{Na} is lower than U_{Cl}, so consequently Na will be the bottleneck element. These uptake concentrations could be used as parameter for judging the suitability of water sources for closed growing systems. In view of this the formulation of a new term will be useful: the uptake capacity (U^{cap}_{Na}) as indicator for the ability of crops to deal with certain concentrations in the input water sources without concessions on yield or quality in closed growing systems. Mathematically it is the uptake concentration at the maximum acceptable concentration in the root environment:

$$U^{cap}_{Na} = U_{Na} \text{ at } R_{Na\text{-}max} \tag{1}$$

The data in Table 2 as such might give the impressions that the uptake of Na and Cl is static, however this is not the case. The uptake concentration appears to be strongly related with the existing concentration in the root environment (R_{Na}, R_{Cl}). Plotting the data of experiments mentioned previously clearly show high linear correlations between R_{Na} and I_{Na} , except for tomato, where a power function gives the best fit. For Cl power functions fit best, except for aster where a linear function fits best. The different behavior of both elements could be caused by the fact that Cl is required in low quantities by many plants and the uptake is even metabolically controlled, which cause a preferred uptake at low levels in the root environment (Mengel and Kirkby, 1987). Quite striking are the extreme low uptake rates for Na for Rose and Bouvardia. For sweet pepper serious differences in the Na uptake were observed between the vegetative stage and periods with heavy fruit load.

DYNAMIC FLUCTUATION

With the uptake capacities of Na and Cl and the concentrations of these ions in the input sources, the required discharge can be estimated, using the simple equation (2) given by Sonneveld (2000).

$$LF = (I_{Na} - U_{Na}) / (R_{Na\text{-}max} - U_{Na}) \qquad (2)$$

In which
LF = leaching fraction
I_{Na} = concentration of Na from inputs (water fertilizers)
U_{Na} = uptake concentration
$R_{Na\text{-}max}$ = maximum acceptable Na in root environment

However, the uptake depends highly on the present Na and Cl concentration. Moreover, in practice the use of the various water sources fluctuates according to the demand (evapotranspiration) and the availability. Consequently the Na and Cl input and so the accumulation rate will fluctuate dynamically during the growing cycle. At the same time, the water fluxes in the growing system fluctuate connected with changes in weather (radiation, VPD (vapour pressure deficit), temp) and crop development. The water fluxes can be described by the model WATERSTROMEN (Bezemer and Voogt, 2008). By linking the Na and Cl concentrations to the input water fluxes and implementing the Na and Cl uptake functions, the accumulation rate in the root environment of both ions can be described. This results in a more accurate estimation of the required discharge than the linear equation (2). With the simulated discharge quantity, estimation is possible of the total N loss, based on the average NO_3 and NH_4 concentrations in the root environment.

DISCHARGE STRATEGIES

Given the facts that in many situations, rainwater will not cover the water demand completely and many supplemental water sources contain Na and Cl, moreover, depending on the location, even rainwater contains higher Na than the uptake capacity of some crops, periodic discharge of circulating nutrient solution is inevitable. In order to keep the water use efficiency as high as possible and at the same time trying to achieve the lowest nutrient emission, several nutrient management and discharge strategies are worked out.

Reduction of Nutrients

The main problem of discharge is the emission of nutrients to the environment, next to that of plant protection chemicals. Reduction of the concentrations of N and P in the water to be discharged would diminish the problem. Experiments with tomato and rose showed that the N concentration in the root environment can be lowered quite significantly and to some extent, without yield effects, in case of tomato even with some positive effects on fruit quality (Voogt and Sonneveld, 2004; Voogt et al., 2006). For rose this was elaborated successfully in some treatments allowing the nutrient solution to deplete for N to almost zero intermittently, which moments could be used for discharge. For P it obviously will work out in the same way, since plants can deplete P to even lower concentrations than N. So both for N and P the concentration in the root environment is less important rather an adequate supply of a required quantity. However management practices based on this principle can be carried out successfully only if on-line monitoring of nutrients becomes possible, which is not feasible at the moment.

Maximize Na Uptakes

Obviously the accumulation rate of Na in the system depends highly on U_{Na}. Since the uptake is linearly related with the existing concentration in the root environment (R_{Na}), the higher R_{Na} the higher the uptake. R_{Na-max} is defined as the threshold value for yield reduction (Sonneveld, 2000). The authorities based their legal target levels for permitted discharge on these values, but these targets are sometimes considerably lower than R_{Na-max}. Secondly, the values of R_{Na-max} are a combination of the current EC and Na concentration. The EC itself is a parameter resembling the osmotic pressure and this parameter is used in growth control. The optimum value for a crop is described as the target value for EC (EC_{ss}) (Sonneveld, 2000). Besides it also resembles the sum of the required nutrients concentrations (EC_{ss-nu}). These two aspects of EC do not necessarily run parallel. The sum of the minimum required nutrient concentrations can be defined as the minimum required EC value (EC_{ss-nu}) for optimum crop development. Evidently EC_{ss} at least will be more or less equal to EC_{ss-nu} for very salt sensitive crops and significantly higher for salt tolerant crops. The difference between the EC_{ss} and EC_{ss-nu} can be defined as EC_{ss-re} available for Na accumulation if subjected to cations or for Cl in case of anions. The Na concentration derived from EC_{ss-re} is much higher than R_{Na-max} in many cases, allowing Na to accumulate much more, with higher uptake and less necessary discharge than in case of the legal targets. Simulation runs with WATERSTROMEN using higher targets levels for Na shown a strong decrease in the required discharge (Fig. 1). However, it is yet unclear whether stimulating high Na absorption is safe for the crop. In case of Aster and Bouvardia, the regrowth after the first harvest was poor and probably linked to Na accumulation in the tissue (Sonneveld et al., 1999).

Discharge Strategies

In current practice, among growers several discharge strategies are in use. There is no agreement on the best strategy. I order to estimate the effect of different strategies; several scenarios were simulated with WATERSTROMEN:

a) *Discharge Drain Collection Tanks.* In this case the total volume of the present drain water collection tanks is discharged once R_{Na-max} is reached. This is repeated several times, resembling the growers practice.
b) *Continuously x % Discharge.* During the period of supplemental water input (i.e. tap water), a certain % of the irrigation water is discharged. The % depends on the Na level in the water source.
c) *"Smart" Discharge.* The quantity of discharge water is proportional with the daily Na accumulation.
d) *Total Drainage Volume.* During the period of supplemental water input, the total of the daily drainage water produced is discharged.

Simulations were carried out for a tomato and a rose crop, the greenhouse climate and weather dataset for a specific year were used (1996). The primary water source was rainwater with Na 0.2 mmol L^{-1}, supplemental tap water with Na 1.5 mmol L^{-1}. Simulation runs were carried out with R_{Na-max} from 3 to 10 and 4 to 12 for rose and tomato respectively, rainwater collection between 500 and 3500 $m^3 ha^{-1}$. The simulation(s) result clearly showed that next to R_{Na-max}, the discharge quantity is obviously strongly affected by the volume of the rainwater collection tank, but with increasing R_{Na-max}, the differences becomes smaller (Fig. 1). This is likely due to the increasing insignificance of the Na concentration in the supplemented water relative to the R_{Na-max}. The different discharge strategies result in more or less the same discharge quantity in all situations, with the "smart" strategy the lowest. However the calculated N emission in the discharge is significantly lower in the "smart "strategy than in the others (Fig. 2). This can be explained by the fact that with the smart strategy, the Na and also the Cl concentrations are on average the highest in the drainage water , compared to the other three strategies. This causes lower NO_3 concentrations in the drainage water too, resulting in lower N emission.

CONCLUSION

For closed growing systems, currently the problems with crop growth attributed to recirculation are of main concern. However, after these problems are solved, salinity is still a serious bottleneck. Na accumulation will occur even in case of rainwater, since some crops, like rose and sweet pepper hardly are able to absorb Na. Periodic discharge of a part of the circulating solution is therefore unavoidable. This will be a serious constraint for the target of zero emission. The lowest discharge will be achieved if the $R_{Na\text{-}max}$ for a certain crop is maximized, which level match with the minimum required concentration for nutrients, $EC_{ss\text{-}nu}$. It is therefore to be recommended to work out alternative target values for $R_{Na\text{-}max}$ for each crop. Since for many crops this $EC_{ss\text{-}nu}$ is unknown yet, research should be performed on this issue. The chosen discharge strategies in this study did not yield much difference, nevertheless it is recommendable to use a smart strategy proportional to the current Na increase, since in that case the N an P emission are the lowest.

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Tables

Table 1. Uptake concentrations I_{Na} and I_{Cl} at a low and a high level in the root environement (R_{Na}, R_{Cl}) for some soilless grown greenhouse crops, expressed in mmol L^{-1}.

Crop	I_{Na}		I_{Cl}	
	R_{Na} <5 mmol/L	R_{Na} 10 mmol/L	R_{Cl} <5 mmol/L	R_{Cl} 10 mmol/L
Gerbera	0.2	0.8	1.7	2.4
Carnation	0.1	0.3	0.5	0.8
Chrysanthemum	0.2	0.5	-	-
Lily	0.4	1.0	0.6	0.9
Aster	0.2	1.5	0.4	2.0
Rose	0.0	< 0.1	0.1	0.2
Bouvardia	<0.1	0.1	0.2	0.3
Tomato	0.4	0.8	0.6	1.0
Cucumber	0.3	1.0	0.3	1.5
Sweet pepper vegetative stage	0.2	0.6	0.3	0.7
Sweet pepper heavy fruit load	<0.1	0.3	0.3	0.7

Data after Baas et al., 1991, 1994; Sonneveld et al., 1983, 1991,1999, 2003.

Table 2. Correlation equations and coefficients of the relationship between Na and Cl in the root (x) environment and the Na and Cl uptake concentrations (y).

	Na		Cl	
		R^2		R^2
Gerbera	$y = 0.0738\ x$	0.752	$y = 0.9755x^{0.3491}$	0.990
Carnation	$y = 0.0285\ x$	0.910	$y = 0.4494x^{0.221}$	0.914
Chrysanthemum	$y = 0.0490\ x$	0.970		
Lily	$y = 0.1033\ x$	0.942	$y = 0.5389x^{0.2048}$	0.987
Aster	$y = 0.1733\ x$	0.926	$y = 0.1945x$	0.966
Rose	$y = 0.0010\ x$	0.987	$y = 0.1067x^{0.1874}$	0.860
Bouvardia	$y = 0.0096\ x$	0.756	$y = 0.1524x^{0.2833}$	0.901
Tomato	$y = 0.1720\ x^{0.6548}$	0.945	$y = 0.5037x^{0.3466}$	0.734
Cucumber	$y = 0.1118\ x$	0.871	$y = 0.1105x^{1.1164}$	0.945
Sweet pepper vegetative stage	$y = 0.0253\ x$	0.793	$y = 0.1742x^{0.6377}$	
Sweet pepper heavy fruit load	$y = 0.0097\ x$	0.411		0.967

Data after Baas et al., 1991, 1994; Sonneveld et al., 1983, 1991,1999, 2003.

Figures

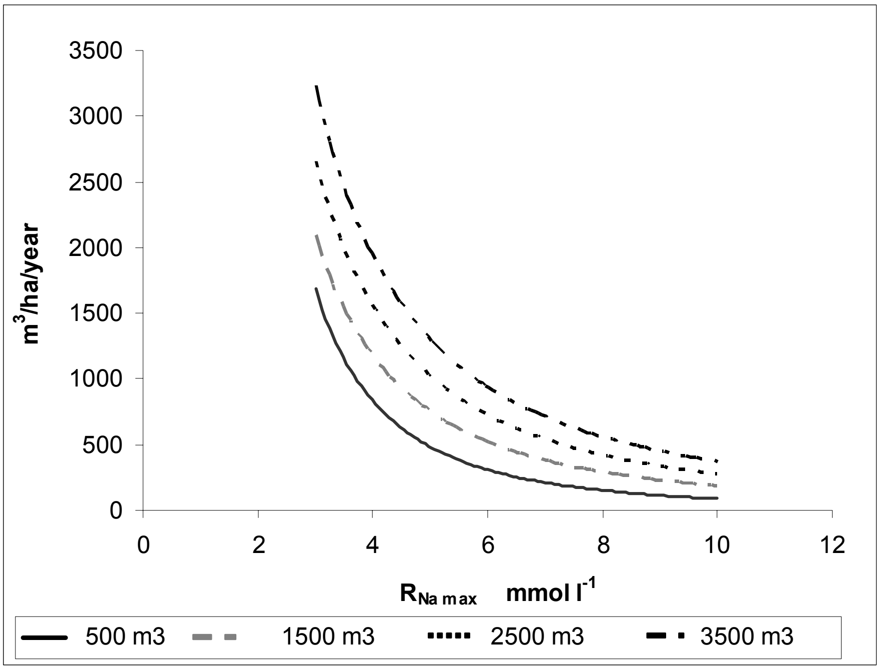

Fig. 1. The required discharge of the circulating nutrient solution in relation to $R_{Na\text{-}max}$ and the rainwater storage capacity in $m^3\ ha^{-1}$ as simulated for a year round rose crop in a dry year with supplemental tap water containing Na 1.5 $mmol^{-1}$.

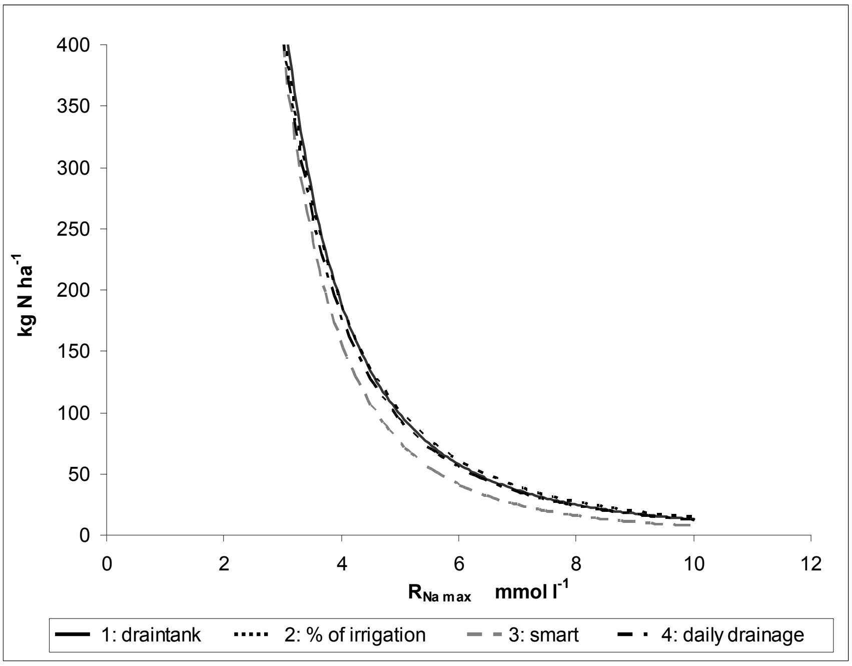

Fig. 2. The estimated N emission in the discharge in relation to $R_{Na\text{-}max}$ as simulated for a year round rose crop for the four described discharge strategies, in a dry year and supplemental tap water with Na 1.5 $mmol^{-1}$.