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Abstract

Competition for freshwater resources, and legal restrictions on discharge of agrochemicals (plant protection products and fertilisers) increase pressure on agricultural practice to improve water-use-efficiency of crop production globally. Zero-discharge greenhouse crop production can be an effective solution to both problems. Preliminary results of experiments with cucumber and sweet pepper on stone wool substrate in two greenhouse compartments showed that productivity did not significantly differ in zero-discharge growing compared to standard growing strategies. In this paper we present the final evaluation of the sweet pepper trial (December 2014 – November 2015). In the reference compartment a total amount of 465 m^3 ha^{-1} y^{-1} (169.3kg N) was discharged. In the zero-discharge compartment there was no discharge during cropping. The nutrient composition of irrigation and drain water was analysed weekly (compared to two-weekly in reference) and nutrient stock composition was changed accordingly. Drain water was filtered with a flatbed filter (no rinsing water) and upon changes in fertigation, the new fertigation solution was first distributed throughout the entire irrigation system by a circulation pump, before application. An irrigation strategy was developed for the end of the cropping season, aiming to drain substrate slabs and to empty drain tanks as much as possible and reduce the amount of remaining nutrients in the slabs, without compromising productivity. Water-use-efficiency of the zero-liquid discharge strategy was lower than in de reference strategy, due to a more vegetative crop growth.

Keywords: Greenhouse horticulture, sweet pepper, emission, pesticides, plant protection products, soilless culture

INTRODUCTION

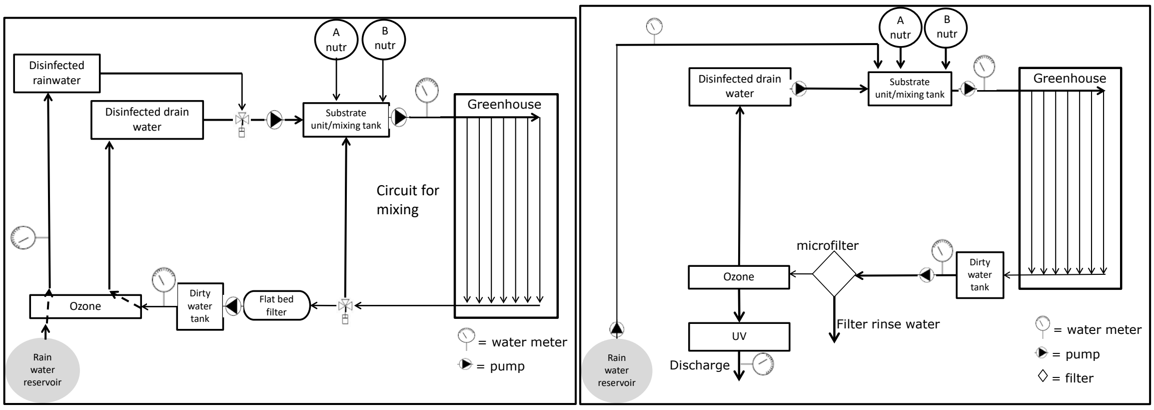
The increasing world population is challenging the agri-food sector: how to feed the world within the carrying capacity of planet earth? More efficient use of resources and increase of production is needed, or as is often rephrased: 2x more with 2x less. Presently, agriculture uses 70% of the available freshwater resources (FAO, 2014), and the environmental impact of agricultural wastes (water polluted with fertilisers and plant protection products) is significant. Greenhouse horticulture, and especially soilless cultivation, is pre-eminently capable of both improving crop yield and water-use-efficiency. For example, for the production of 1 kg tomato in a modern greenhouse (stone wool substrate, recirculation of drain water, climate control) only 15 L of water is needed, compared to 60 L for a kg tomato produced outdoors (soil grown, free-drainage, no climate control) (Van Kooten et al., 2008). Also nutrients, land and other resources are more efficiently used in high-tech greenhouses due to better control of growth parameters and therefore more efficient production.

While being highly resource use efficient compared to other agricultural systems, these water efficient high-tech greenhouses still face a (related) sustainability issue. Due to occasional discharge of nutrient solutions from the greenhouse, leaching of nutrients and plant protection products to ground and surface waters occur, thus exceeding water quality standards in greenhouse areas (PBL, 2016). In order to make the next step in improving the water footprint of greenhouse production and comply with legislation (e.g. the EU Nitrate Directive (1991), the EU Water Framework Directive (WFD, 2000), the Ontario Nutrient Feedwater Regulation (2015), the Dutch nitrogen emission standards (Ministry of Infrastructure and Environment, 2013)), the water-nutrient cycle of soilless cultivations needs to be fully closed. Beerling et al. (2014) studied the reasons for discharging nutrient solutions by commercial greenhouses, and proposed solutions to overcome this need to discharge.

In 2014 a study with cucumber and sweet pepper production was started in which all necessary solutions for a zero-liquid discharge were applied and further developed. Preliminary results are described in Beerling et al. (in press). In this paper we describe the final results of this study, in which the fully closed sweet pepper cultivation was compared to a current practice semi-closed cultivation. Our aims are to demonstrate that zero-liquid discharge is possible without compromising production and quality, and to show how this can be achieved with current technology and strategies.

MATERIALS AND METHODS

In two greenhouse compartments of nett 120 m^2 a sweet pepper crop (Maranello, Enza Seeds; December 2014 – November 2015) was grown on Grodan stone wool substrate slabs (GT Expert, 6.5 cm) in a hanging gutter system. In each compartment a different cultivation strategy was followed, using a different system setup: 1) a zero-liquid discharge strategy in which all drain water is collected and reused, and 2) a reference strategy with occasional discharge of drain water. The occasional discharge is in accordance with common practice and the Dutch nitrogen emission standard for 2015 for sweet pepper (133 kg N ha^{-1}). Both systems had separate, recirculating irrigation systems, of which the setup can be seen in Figure 1.



1. Zero-discharge cultivation 2. Reference cultivation

Figure 1. *Overview of water flows, storage tanks and technologies as applied in the two compartments.*

Sodium is an important reason for growers to discharge their drain water (taken up in legislation, Besluit Glastuinbouw, 2002), as only small amounts are taken up by the crop and high concentrations can be detrimental. Therefore, in both compartments high quality irrigation water (low sodium content, <0.1 mmol L^{-1}) is used: a mixture of rooftop collected rain water (0.1-0.2 mmol L^{-1} sodium) and ground water treated with reverse osmosis (<0.1 mmol L^{-1} sodium). This is a prerequisite for recirculating hydroponic cultivation. The fresh irrigation water was mixed with disinfected drain water and fresh nutrients in a mixing tank to the recommended EC (2.7 – 3.0 dS m^{-1}) and pH (5.5) before application to the crop (by

Infa Techniek). Small storage tanks were used to be able to quickly switch nutrient composition without the necessity of discharge. Fresh nutrients were applied from A and B stock solutions, to deliver the correct nutrient composition for closed hydroponic production of sweet pepper on stone wool (NH_4: 0.75, K: 5.75, Ca: 3.5, Mg: 1.125, NO_3: 12.75, SO_4: 1, H_2PO_4: 1 mmol L^{-1} and Fe: 15, Mn: 10, B: 25, Cu: 0.75, Mo: 0.5 µmol L^{-1}; Sonneveld and Voogt, 2009; De Kreij et al., 1999). Small A and B stock solutions were applied, as this makes it possible to change nutrient recipe easily without the need for discharge.

Drip irrigation was applied through 16 mm pipes, using 3 L h^{-1} pressure compensated drippers (Revaho). Small diameter pipes (25 mm is common practice) were used to decrease the system volume. A smaller system volume allows for quicker changes in nutrient solution. The nutrient solution was circulated with low pressure (no opening of drippers) through the entire irrigation system in the ZLD compartment to be sure all plants get the same nutrient solution. This is especially important when applying for example changes in nutrient composition or plant protection products, as this ensures simultaneous application of these changes to all plants in the greenhouse.

Drain water is collected separately for both compartments. In the reference greenhouse the water is stored in a dirty drain water tank, to be filtered with a 40 µm microfilter before disinfection with ozone. The rinsing water was discharged. In the zero-discharge compartment, the drain water was filtered with a flatbed gravity filter (Fiber Filtration) equipped with a 40 µm cloth (no rinsing water, thus no discharge), before storage in the dirty drain water tank and disinfection (Figure 1). Both filters were applied for the removal of solid particles from the drain water.

The filtered water of both compartments was disinfected with ozone (Agrozone; 2.1 mg L^{-1} min^{-1}) to reach an oxidation reduction potential (ORP) value of 600 mV, with a post-treatment of 0.5 min. Ozone is an effective disinfector for recirculating systems (Van Ruijven et al., 2016) since it does not bring in any components that cannot be taken up by the crop. In the ZLD strategy, also the fresh irrigation water is disinfected with ozone up to an ORP value of 900 mV before application. As this is not common practice in sweet pepper production, in the reference compartment rainwater was not disinfected. At forehand discharge was planned (Table 1) to mimic the (often) subjective decisions of growers. Total amount of discharge water was planned to be 430 m^3 ha^{-1} yr^{-1}, thereby reaching 133 kg N ha^{-1} yr^{-1} (assuming 22 mmol NO_3^- L^{-1} in the drain solution).

Nutrient composition of drain and drip irrigation were analysed weekly for the ZLD compartment and biweekly for the reference. New nutrient recipes were calculated by uptake-analysis (Groen Agro Control). The nutrient uptake is the difference between applied nutrients in irrigation water and returned nutrients in drain water. An estimation of dry matter production based on light, temperature and CO_2 conditions then gave the uptake of nutrients per kg of dry matter. This is compared to target values and ratios in fruit and leaves to calculate the new nutrient recipe. Uptake values should remain between an upper and lower limit to optimise production.

Irrigation strategy was controlled by application of three Grosens sensors (Grodan) per compartment, by measuring EC, water content (WC%) and temperature directly in the stone wool slabs, and illustrating it directly in a web tool (Figure 2).

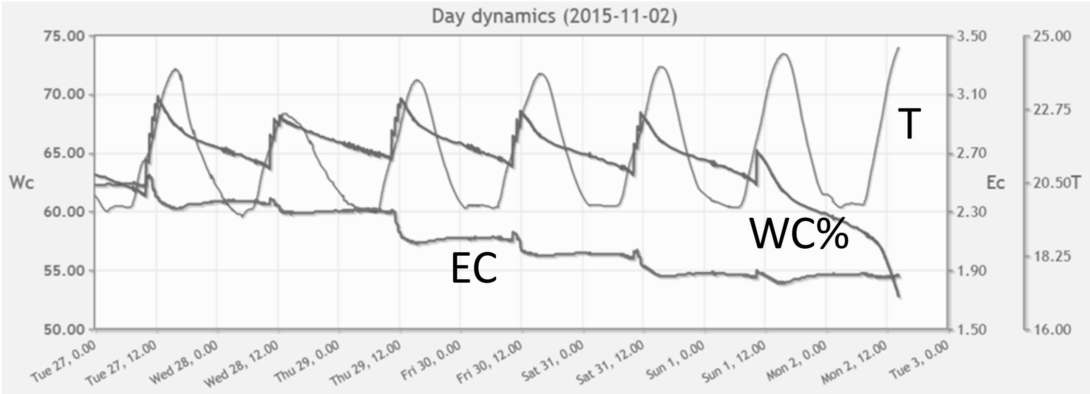


Figure 2. *Graph from Grosens measurements at the end of the cropping season in zero-discharge compartment (Temperature (T, °C), Water content (WC, %), conductivity (EC, mS cm⁻¹).*

In both compartments as much as possible the same climate conditions (VPD, radiation, temperature, CO_2) were applied (Figure 3). When necessary, conditions were adapted to maintain a similar plant growth and development for both strategies. Additional CO_2 was applied to maintain a level of 600 – 700 ppm in both compartments.

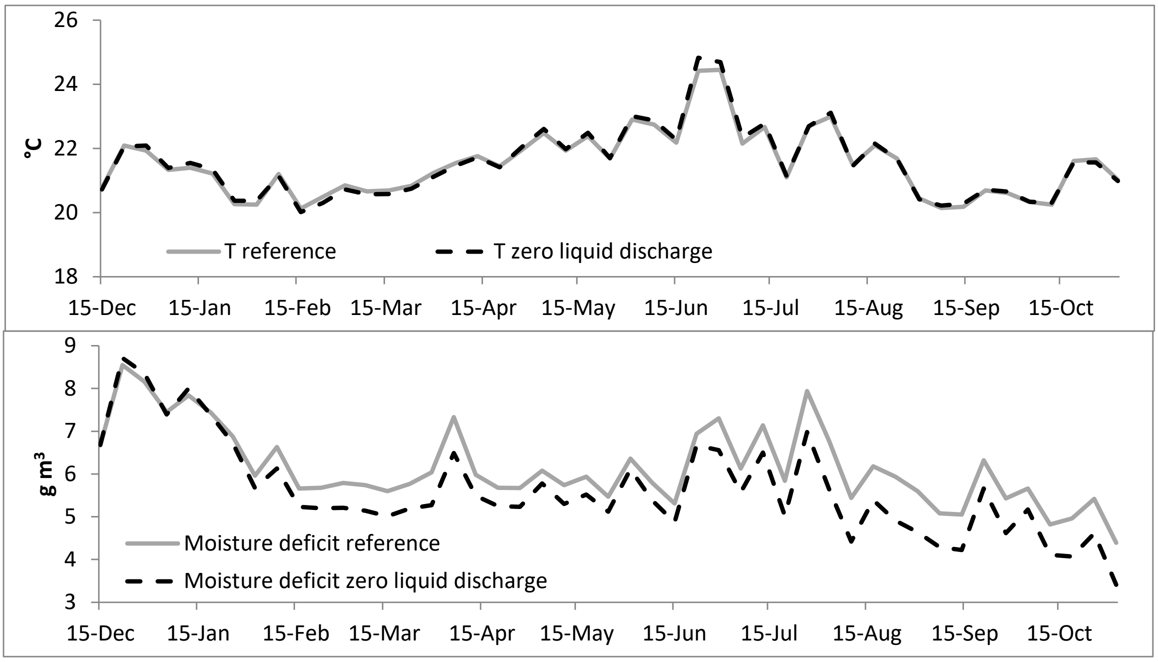


Figure 3. *Temperature (°C) and moisture deficit (g m^{-3}) of both compartments*

Weekly production was determined by counting and weighing the first class fruits from four rows in each compartment, containing 25 plants each (with three stems). Production per m^2 was an average from these 100 plants.

RESULTS AND DISCUSSION

Productivity

No significant difference was found in productivity of good quality red sweet pepper fruits of the reference greenhouse (26.3 kg m^{-2}) and the zero liquid discharge (ZLD, 27.4 kg m^{-2}) compartment (Figure 4). Also fruit load and stem thickness during the cropping season was equal in both compartments (Figure 5a and b). The small system volume (small diameter pipes, small mixing tank and small A and B stock) created a quick response time to change the nutrient solution. This showed to be, as a more stable nutrient composition was created.

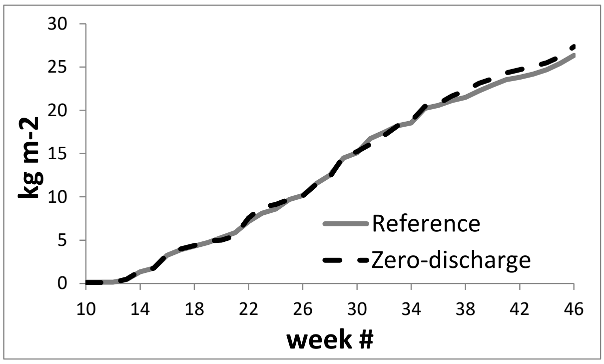


Figure 4. *Cumulative production of first quality red sweet peppers (Maranello, Enza Seeds) in reference and zero liquid discharge compartments*

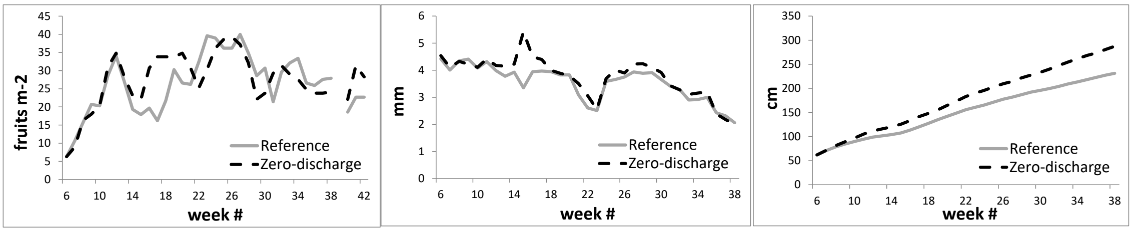


Figure 5 *a. Fruit load; b. stem thickness; and c. plant height of the crops in the reference and zero liquid discharge compartments during the cropping season*

In the ZLD compartment no water was discharged, as planned (Table 1). In the reference greenhouse 465 m^3 ha^{-1} was discharged. Nitrate levels turned out to be 26 mmol L^{-1} in practice, which decrease the allowed volume of discharge water to 365 m^3 ha^{-1} yr^{-1}. Actually nitrogen was more discharged than planned and allowed. It shows that it is crucial to monitor the discharged solution, to stay within the legal boundaries.

Table 1. *Overview of planned and realised moments and amount of discharge water for both greenhouse compartments*

Planned and realised discharge	**Reference (m^3 ha^{-1})**		**Zero liquid discharge (m^3 ha^{-1})**	
	Planned	**Realised**	**Planned**	**Realised**
First flush from slabs	40	23	0	0
No recirculation for first 6 weeks	30	15	0	0
March - April	90	117	0	0
May - August	180	220	0	0
September - November	90	100	0	0
TOTAL	**430 (= 133 kg N ha^{-1})**	**465 (= 169 kg N ha^{-1})**	**0 (= 0 kg N ha^{-1})**	**0 (= 0 kg N ha^{-1})**

Sodium accumulation

An increase in sodium concentration in irrigation water during the cropping season is one of the main reasons for discharging the nutrient solution. Common practice for sweet pepper production is to discharge before the threshold of 6 mmol Na L^{-1} (Sonneveld and Voogt, 2009) is exceeded. Therefore Na accumulation was an important factor to monitor. In Figure 6 it can be seen that sodium levels in both crops stayed below the threshold value (6 mmol L^{-1}). This means the input water and fertilisers were of sufficient quality to keep input and uptake in balance, and the sodium level was no reason for discharge in the ZLD compartment. Overall, the sodium level in the production cycle of the reference greenhouse was only 1 mmol L^{-1} lower, although 4% of the drain water was discharged.

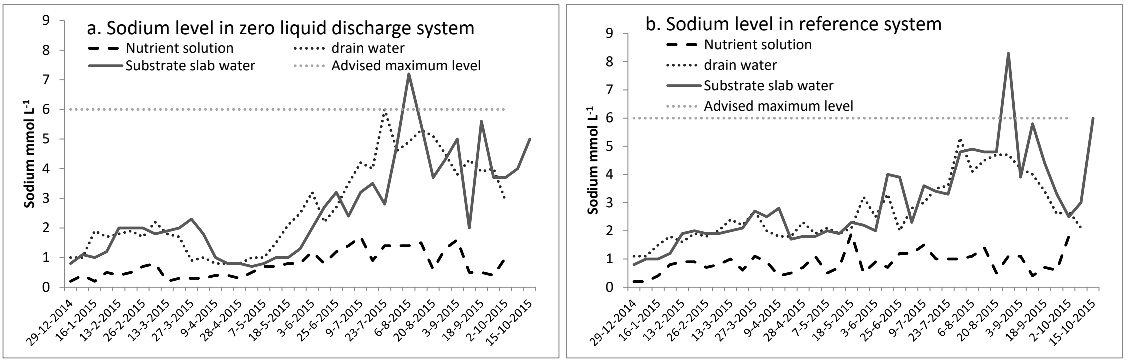


Figure 6. *Sodium levels in the a. zero liquid discharge compartment and b. the reference compartment*

End of cultivation strategy

A strategy was developed for the end of the growing season, to minimise the amount of water in storage tanks and to minimise the amount of nutrients left over in the stone wool substrate slabs when discarded. In the last five weeks of growing, irrigation was decreased, as well as the amount of nutrients applied (less NO_3^-, more Cl^-), at the same time decreasing the amount of drain water. Uptake analysis ensured that the crop received enough nutrients to maintain good quality fruits. The pH of the irrigation solution was lowered, to lower the pH in the substrate and thereby to dissolve precipitated phosphate to become available for the crop (Figure 7). With this strategy, the remaining nutrient solution in the tanks decreased drastically resulting in less sodium in the system which is of use at the start of the next growing season. Now there was no need to discharge the remaining nutrient solution as is mostly done in practice.

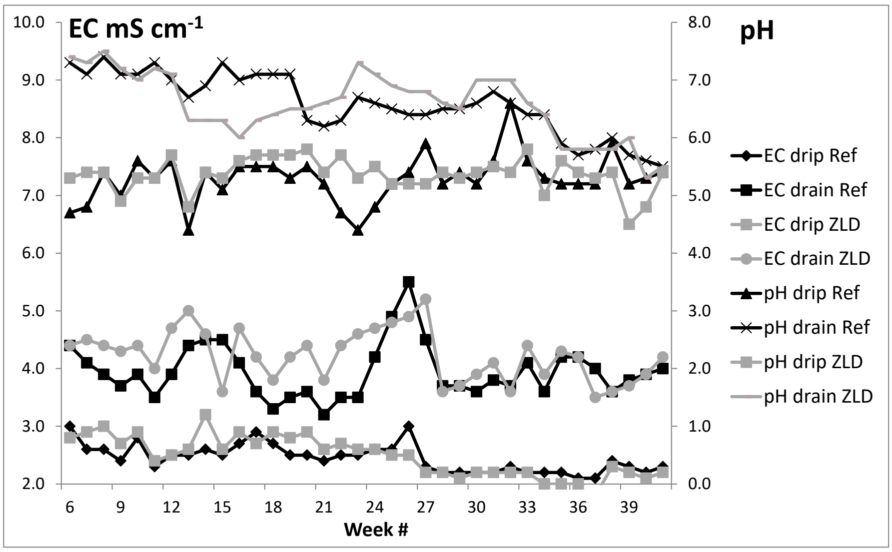


Figure 7. *Measurements of EC (mS cm^{-1}) and pH of drip and drain water for both the reference and the zero liquid discharge (ZLD) compartments.*

Water use efficiency

A significant difference was found in plant height (Figure 5c). The crop in the reference compartment received less water during the first weeks, due to an irrigation pump that was working at too low pressure. It resulted in a more generative growth and shorter plant height of the reference crop, but not in a difference in productivity.

This effect can also be seen in Figure 8, in which the total irrigation volume is shown. As the crop in the ZLD compartment had a higher plant length and hence a higher leaf area index (not measured), more irrigation was required to replete the evaporated water. This resulted in a higher water-use-efficiency in the in the reference compartment compared to the ZLD compartment. Water-use efficiency was calculated from fresh irrigation water and productivity (WUE = fresh irrigation water / productivity): 24 L kg^{-1} in zero liquid discharge and 22.5 L kg^{-1} in reference compartment. Water-use efficiency in de ZLD compartment can be further improved by steering the crop towards a more generative growth.

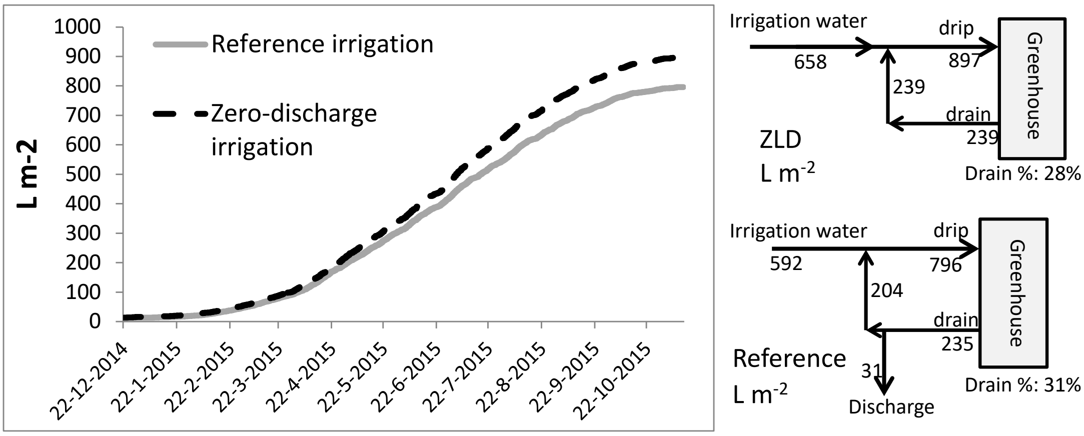


Figure 8. *Cumulative drip irrigation water (L m^{-2}) for both the reference and the zero liquid discharge (ZLD) compartment and the composition of drip water from fresh irrigation water and drain water.*

CONCLUSIONS

The effect of zero-liquid discharge (ZLD) of drain water in hydroponic cultivation was investigated in a sweet pepper cultivation on stone wool substrate slabs from December 2014 – November 2015, and compared to a reference in which drain water was discharged (within the boundaries of Dutch nitrogen emission standards for 2015). Full recycling of all drain water does not affect sweet pepper production negatively, since no difference was found in quality and numbers of fruits with the reference crop. Complete recycling was technically made possible with current technology and installation, in combination with a growing strategy aimed at 100% reuse of the nutrient solution.

To realise a zero-liquid discharge of drain water the first drain after opening the slabs and during the first weeks of cultivation should be reused, the general custom to discharge during the season can be avoided and the end of cultivation strategy should be further optimised.

In a ZLD system balance between input in the system and crop uptake is of utmost importance. During the cropping season it is therefore essential to keep all relevant elements (e.g. sodium, nutrients) within boundary concentrations for the crop to grow optimally. In the reference system there is still some room for 'mistakes', as an imbalance in input and uptake can be corrected by discharging water. All measurements used in this study were the aim to control this balance, and have proven to be effective.

Water-use-efficiency of the ZLD strategy was lower than in de reference strategy, due to a more vegetative crop growth. This can be improved by steering towards a more generative crop growth. A further step towards a water use efficient crop would be to also collect and reuse all evaporated water. A closed greenhouse in which the ventilation windows are shut and the de-humidification water is reused would be a solution, though not economically feasible at this time.

ACKNOWLEDGEMENTS

We would like to thank STOWA, Topsector Tuinbouw & Uitgangsmateriaal, EFRO/Kansen voor West and Province of South Holland for their financial contribution. Without the support and valuable input (knowledge and materials) of the project partners (Grodan, Groen Agro Control, Agrozone, Infa Techniek, Elektravon Haket, Fiber Filtration, Enza Zaden and Van der Lugt Plantenkwekerij) this project would not have been possible.

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