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# Strategy to minimise nitrogen load to finish a zero discharge cultivation

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***Abstract***

**The Dutch authorities established a plan for the reduction of water emissions from the greenhouse sector to become zero by 2027, to enforce the European Union Water Framework Directive. At the end of the cultivation period, a considerable amount of nitrate and phosphate is still present in solution in substrate slabs and in the irrigation system. The left over nutrient solution is generally discharged into the sewage system or surface water. The end of cultivation strategy was developed to use the plant uptake to reduce this nitrate and phosphate in the last 5 weeks of the cultivation period. This reduction should be realised without affecting the production or quality of the last fruits to be harvested. The strategy consisted of a gradual decrease over the last five weeks of the cultivation of nitrate, phosphate and water quantity supplied to the plant. Chloride was used to replace nitrate in the supply water. The anion-shift allowed maintaining a sufficient quantity of cations in the root environment to meet the plant's needs and to avoid production loss. A progressive shift from nitrate-nitrogen to ammonium-nitrogen was realised. The nitrogen-shift acidified the substrate slabs to release precipitated phosphate. A double irrigation cycle at the start of the day was implemented during the strategy to anticipate nutrient accumulation in the root environment. In 2016, the strategy was applied to a sweet-pepper cultivation. The water volume in the substrate slabs was reduced from 6 to 3.5 L m$^{-2}$. Nitrate quantity was reduced from 109 to 55 mmol m$^{-2}$. Phosphate quantity was reduced from 0.5 to 0.2 mmol m$^{-2}$. In 2017, the strategy was applied to a cucumber cultivation. The average water volume was reduced from 8 to 5.3 L m$^{-2}$. Average nitrate quantity was reduced from 113 to 45 mmol m$^{-2}$ and average phosphate quantity from 4.5 to 1.65 mmol m$^{-2}$.**

**Keywords:** water use efficiency, phosphate, emissions

## INTRODUCTION

The Dutch authorities established a plan for the reduction of water emissions from the greenhouse sector to zero by 2027 to enforce the European Union Water Framework Directive (WFD; EU, 2000). The WFD states that European member states must achieve a "chemical and ecological sound quality" of their surface water by 2015 with a possible extension period to 2027. Next to that, the Dutch authorities require from January 1, 2018 that greenhouse sector water emissions are free of pesticide residues (W.J. Mansveld, 2015, pers. commun.). Four legal solutions are advised to prevent pesticide emission. Individual, mobile or collective approved purification installations are the first three solutions (Van Ruijven et al., 2020). The fourth solution is a framework for zero water discharge cultivation.

The zero discharge cultivation is considered more ideal than purification of water on the long-term, because synthetic organic chemicals are not the only threat to water quality. Nitrate and phosphate emissions from greenhouse industry are responsible for water eutrophication (Massa et al., 2010). Nitrate, phosphate and other nutrients are not removed by classic purification techniques (Beerling et al., 2014). The removal of nutrients is one of the reasons why zero-discharge is considered as a goal by 2027 for the Dutch greenhouse sector.

This article describes the results of a project that aims for delivering a zero discharge solution for the end-of-cultivation. At the end of the cultivation period, a considerable amount of nitrate and phosphate is still present in solution in substrate slabs and in the irrigation system (Le Bot et al., 2001). The left-over nutrient solution is generally discharged into the sewage system or surface water. The end-of-cultivation strategy makes use of the nutrient plant uptake to reduce the nitrate and phosphate content in substrate solution and indirectly water content, in the last 5 weeks of the cultivation period. Such precise control strategies require automated decisions (Katsoulas et al., 2014). The study presents the control strategies and the result of two years of application.

## MATERIAL AND METHODS

### Cultivation

The end-of-cultivation strategy was repeated in 2016 and 2017 at the greenhouse research facilities of Wageningen University & Research in Bleiswijk, the Netherlands. The strategy was realised to end a zero discharge cultivation realised on a whole cultivation period in two greenhouse compartments of 120 $m^2$. In 2016 the strategy was run in one of the two compartments with sweet pepper, *Capsicum annuum* 'Maranello', grown on rockwool cultivation slabs from Grodan. The sweet peppers were cultivated from January until October with 2.5 plants $m^{-2}$ and 2 stems $plant^{-1}$. In 2017, cucumbers, *Cucumis sativus* were cultivated from May until October with 1.5 plants $m^{-2}$ and 2 stems $plant^{-1}$. The cucumbers were grown on coir cultivation slabs from Dutch Plantin in two compartments (120 $m^2$).

### Irrigation system

The two compartments used for the zero discharge cultivation had an identical, but completely separated, irrigation system. Drain water was collected in a drain pit and through a filter (compartment 1: band filter, 35 µm; compartment 2: fibre filter, 3 µm) pumped to the dirty drain tank. The fibre filter was rinsed with drain water, rinsing water could settle and was filtered again after settling. Drain water of both compartments was batchwise disinfected with ozone, by one disinfection unit. To prevent exchange of water masses, the ozone reaction vessel and pipelines were flushed between batches of the different compartments. Flush water of the ozone disinfection unit was discharged, but not accounted for in the closed growing system, since the flushing event was specially added to avoid mixing drain form both compartments and will not take place at a commercial nursery. Treated water was stored in a treated drain tank.

If enough treated drain water was available, 30%-v/v drain water was added to fresh water. Fresh water, treated drain water and concentrated fertilizer were mixed in a mixing tank. Concentrated fertilizer (from A and B storage tanks) was automatically added by a Venturi system until a fixed electrical conductivity (EC) setpoint was reached, based on continuous measurement. Mixing took place with all water in the irrigation system, by circulation of the nutrient solution in the looped irrigation lines (16 mm) with low pressure, before each irrigation event. Pumping pressure was increased at the start of the irrigation event, so that pressure compensated drippers (3 L $h^{-1}$) opened. Irrigation volume was 2 mL $m^{-2}$ for each 200 J of irradiation, with a maximum drain percentage of 30%-v/v. No drain water was discharged during the cropping season.

### Strategy

Target values were determined for the concentration of nutrients in the substrate slab at the end of the cultivation season (Table 1 for 2016; Table 2 for 2017). The end of cultivation strategy began 5 weeks before the cultivation was ended and the strategy was applied until the end of the cultivation. Back-casting determined weekly target values for nutrients (nitrogen and phosphorus), water volume and EC in the substrate slab. The target EC of the slabs solution was used as an estimation of the general concentration of nutrients.

Indicative schemes of irrigation setpoints were predetermined to achieve these target values in the substrate slab solution. The irrigation setpoints were corrected twice a week based on analysis of the water in the substrate slab to get as close as possible to the target values. The water, nitrate and phosphorus supply were sharply reduced during the five weeks of the strategy application.

Table 3 (2016) and Table 4 (2017) show the schemes of irrigation setpoints for the nutrient solution. The schemes included the supply concentration of nitrate and phosphorus, the supply of water per unit of radiation. A theoretical uptake of 1.5 mL $J^{-1}$ $m^{-2}$ was assumed.

Table 1. Target values for the slab nutrient concentration and water content in 2016. The target values are established for 3 moments, starting 5 weeks before the end of the cultivation and ending the last week of cultivation. The values of week 0 are the theoretical optimum.

| Parameter | Unit | Week 5 | Week 3 | Week 1 | Week 0 |
|---|---|---|---|---|---|
| Nitrate | mmol $L^{-1}$ | 20 | 10 | 5 | 0 |
| Phosphorus | mmol $L^{-1}$ | 3 | 0 | 0 | 0 |
| EC | dS $m^{-1}$ | 3.5 | 4 | ? | ? |
| Water content | %-v/v | 65 | 50 | 30 | 20 |

Table 2. Target values for the slab nutrient concentration and water content in 2017. The target values are established for 3 times starting five weeks before the end of the cultivation and ending the last week of cultivation. The values of week 0 are the theoretical optimum.

| Parameter | Unit | Week 5 | Week 3 | Week 1 | Week 0 |
|---|---|---|---|---|---|
| Nitrate | mmol $L^{-1}$ | 20 | 10 | 5 | ? |
| Phosphorus | mmol $L^{-1}$ | 0.5 | 0.1 | 0.1 | 0 |
| EC | dS $m^{-1}$ | 3 | 3 | 4 | ? |
| Water content | %-v/v | 70 | 60 | 40 | 30 |

Table 3. Irrigation setpoints scheme for the supplied nutrient solution in 2016. The schemes were established for 3 times, starting 5 weeks before the end of the cultivation season and ending the last week of cultivation. The values of week 0 are the theoretical optimum.

| Parameter | Unit | Week 5 | Week 3 | Week 1 | Week 0 |
|---|---|---|---|---|---|
| Nitrate | mmol $L^{-1}$ | 15 | 5 | 1 | 0 |
| Phosphorus | mmol $L^{-1}$ | 0 | 0 | 0 | 0 |
| EC | dS $m^{-1}$ | 2.5 | 1.5 | 1.0 | 0 |
| Water supply | mL $J^{-1}$ $m^{-2}$ | 3 | 2 | 1 | 0 |
| Ammonium | mmol $L^{-1}$ | 1.5 | 1.5 | 1.5 | 0 |
| $NH_4$-N/$NO_3$-N | %-N/N | 10 | 25 | 60 | |

Table 4. Irrigation setpoints scheme for the supplied nutrient solution in 2017. The schemes were established for 3 times starting five weeks before the end of the cultivation and ending the last week of cultivation. The values of week 0 are the theoretical optimum.

| Parameter | Unit | Week 5 | Week 3 | Week 1 | Week 0 |
|---|---|---|---|---|---|
| Nitrate | mmol $L^{-1}$ | 15 | 10 | 7 | 0 |
| Phosphorus | mmol $L^{-1}$ | 1 | 0.5 | 0.5 | 0 |
| EC | dS $m^{-1}$ | 2.5 | 1.5 | 0 | 0 |
| Water supply | mL $J^{-1}$ $m^{-2}$ | 3 | 2 | 1 | 0 |
| Ammonium | mmol $L^{-1}$ | 1.5 | 1.5 | 1.5 | 0 |
| $NH_4$-N/$NO_3$-N | %-N/N | 10 | 15 | 20 | |

A variety of adaptations were applied to the standard fertigation recipe to reach the target values without affecting productivity and product quality. Chloride was used to replace other anions (mainly nitrate) in the supply water. The concentration of chloride should directly compensate for the nitrate (mmol $L^{-1}$) reduction in the supply. This anion-shift allowed maintaining a sufficient quantity of cations in the root environment to meet the plant's needs and to avoid production loss.

pH in the root zone was reduced by increasing ammonium supply. The pH reduction increased the solubility of trace elements and prevented precipitation of calcium-phosphate in the root zone.

At the end of the cultivation period, ammonium also contributed to the total nitrogen supply. The sharp reduction in nitrate supply was pushed ahead by means of the shift in nitrogen source from nitrate to ammonium. The progressive increase of the ammonium/nitrate ratio resulted from the nitrogen source shift.

A double irrigation cycle at the start of the day was implemented during the last five weeks of the cropping season, to anticipate nutrients accumulation in the root environment. The double irrigation cycle was implemented until week 2. After week 2, the volume of solution supplied was reduced to the uptake level minus the volume of water left in the cultivation slabs above 30%-v/v. The volume supplied was divided over the time left. No drain water was produced during the last week of cultivation.

The concentrated nutrient solution was prepared every week for each compartment. The recipe adaptation was based on both a fertigation guideline and a specific estimation of the crop nutrient uptake done by an independent laboratory for each compartment, based on samples of feed and drain water. The recipe was adapted to realise the nitrate, ammonium and phosphorus set point. The concentrated solution to be prepared was calculated by taking account of the remaining solutions in the A and B containers. Salts were diluted to the remaining concentrated solution to maintain the desired nutrient balance of the nutrient solution. The volume of concentrated solution supplied was compensated by adding fresh water to the A and B containers once every week.

**Control measurements**

The nutrient solution in the substrate slabs and the supply solution were sampled 2 times a week. In 2016, the slab solution was directly sampled on the rock wool with a syringe. In 2017, the drain was gathered at the beginning of the day in the drain pit from each compartment. The drain sample was used as an estimation for the slab solution estimation.

The electric conductivity was measured directly on the sample with a portable EC meter. The pH was measured directly on the sample with a portable pH meter. The nutrient concentrations were measured the next day by atomic mass spectrometry by an independent laboratory. The elements measured were potassium, calcium, ammonium, sodium, magnesium, nitrate, sulphate, carbonate, phosphate, iron, copper, zinc, boron, manganese and molybdenum.

The water content of the substrate slab was measured with a calibrated frequency difference reflectometry sensor. The water supply and drain amount were measured by use of two volumetric buckets per compartment. A first bucket was placed under an irrigation dripper, a second bucket was placed under the collection point of an isolated gutter with a single slab from which drain could be collected. The water volumes collected were measured daily and the buckets were emptied in the drain system.

**Correctional actions**

The irrigation setpoints were adapted twice a week based on the analyses. The corrections took place the day after the control measurement. If the substrate slab solution measurement deviated more than 25% from the target value, the set point for the supply was corrected 25% in the opposite direction. For example, if the measurement of the substrate slab solution showed 15 mmol $L^{-1}$ nitrate instead of the targeted 10 mmol $L^{-1}$ nitrate, the measure was more than 25% above the target value and the supply concentration was corrected from 10 mmol $L^{-1}$ nitrate supply to 7.5 mmol $L^{-1}$ nitrate, due to a 25% reduction of the set point.

**RESULTS**

The end-of-cultivation strategy reduced slab nitrate concentration by 51%-w/w in 2016 (Figure 1). In 2017, the slab nitrate content was reduced by 63%-w/w in compartment 1 (C1) and 57%-w/w in compartment 2 (Figure 2). Slab phosphorus was reduced by 9%-w/w in 2016 (Figure 3). In 2017, the slab phosphorus content reduced by 53%-w/w in compartment 1 and 73%-w/w in compartment 2 (Figure 4). The water volume reduced by 41%-v/v in the slab and of 100%-v/v in the drain containers in 2016 (Figure 5). In 2017, the slab water volume reduced by 37%-v/v in compartment 1 and 31%-v/v in compartment 2 (Figure 6), the drain containers were completely consumed in both compartments.


Figure 1. Set points and measured slab nitrate quantity during the last 5 weeks of the cultivation in 2016 in compartment 1 (C1). The *x*-axis is a decreasing time line from the beginning to the end of the strategy. The *x*- and *y*-axis cross on the right in 0.

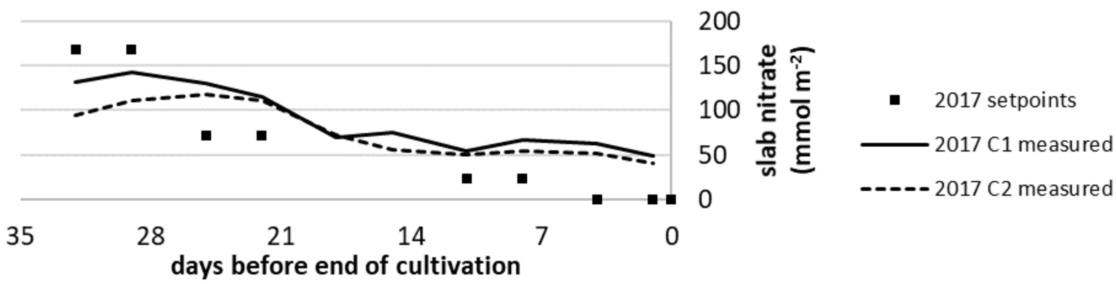


Figure 2. Set points and measured slab nitrate quantity during the last 5 weeks of the cultivation in 2017 in compartment 1 (C1) and compartment 2 (C2). The quantity is reported for two greenhouses compartments. The *x*-axis is a decreasing time line form the beginning to the end of the strategy. The *x*- and *y*-axis cross on the right in 0.

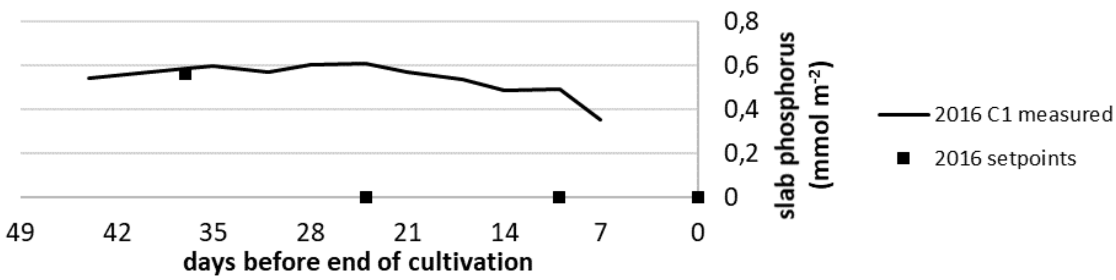


Figure 3. Set points and measured slab phosphorus quantity during the last 5 weeks of the cultivation in 2016 in compartment 1 (C1). The *x*-axis is a decreasing time line from the beginning to the end of the strategy. The *x*- and *y*-axis cross on the right in 0.

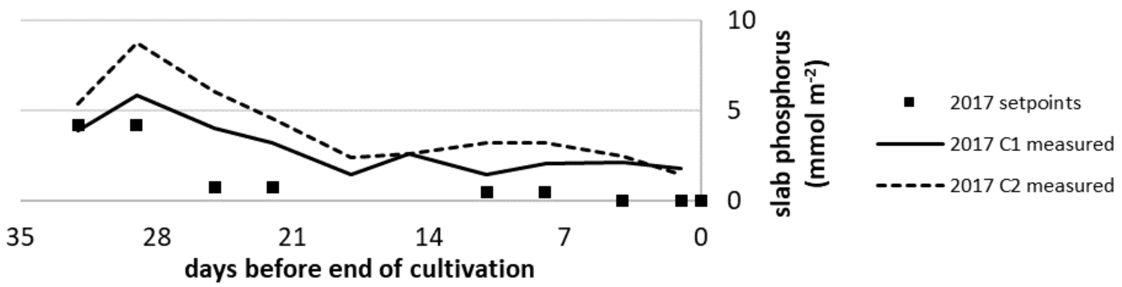


Figure 4. Set points and measured slab phosphorus quantity during the last 5 weeks of the cultivation in 2017 in compartment 1 (C1) and compartment 2 (C2). The quantity is reported for two greenhouses compartments (C1, C2). The *x*-axis is a decreasing time line form the beginning to the end of the strategy. The *x*- and *y*-axis cross on the right in 0.

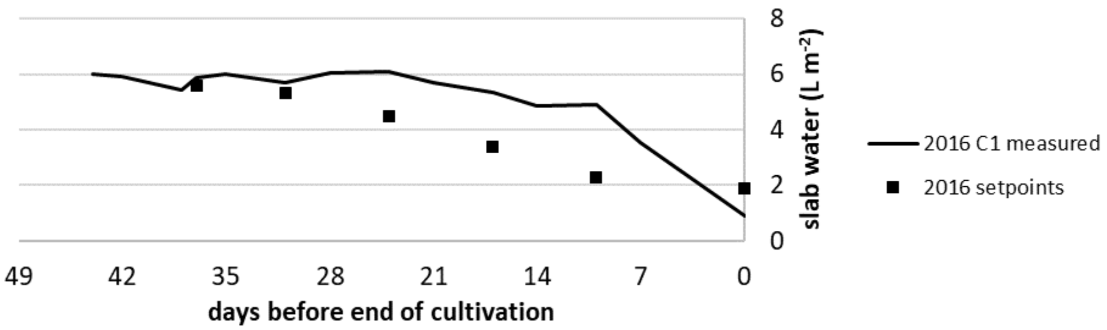


Figure 5. Set points and measured volume of solution in the slabs in 2016 in compartment 1 (C1). The *x*-axis is a decreasing time line from the beginning to the end of the strategy. The *x*- and *y*-axis cross on the right in 0.

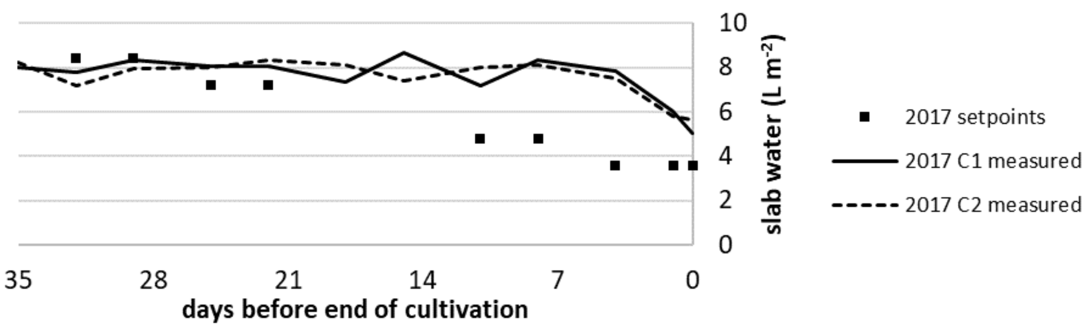


Figure 6. Set points and measured volume of solution in the slabs in 2017 in compartment 1 (C1) and compartment 2 (C2). The *x*-axis is a decreasing time line form the beginning to the end of the strategy. The *x*- and *y*-axis cross on the right in 0.

To increase phosphorus availability pH should be decreased. In 2016, the pH decreased from 7 to 5.5. The pH reduction went along with the reduction of the carbonate buffer in rock wool. The solubility of trace elements and phosphate increased because of the lower pH during the strategy than during the whole cultivation period. In 2017, it appeared to be more difficult to control pH. The pH raised from 6.3 to 7 during the two first weeks because of ammonium removal from the supplied concentrated solution. The ammonium was removed because the pH was to low the week before the beginning of the strategy in both compartments. During week 3, the pH decreased to 4 because of the ammonium supply.

However, the decrease was too strong and ammonium was removed again. The pH was raised to 5.5 with potassium carbonate in the treated drain as a consequence and a pH of 6 in the drain during week 3 and 4. The last week, the supply solution pH was not corrected and ammonium was supplied. The pH of the drain solution decreased to 4.

The EC in the drain solution increased in 2016 from 2.6 to 4.5 dS $m^{-1}$ during the end-of-cultivation strategy. In 2017, the drain EC increased towards the end from 2.4 to 3.7 dS $m^{-1}$ and 2.6 to 3.4 dS $m^{-1}$ in compartment 1 and 2, respectively. The drain EC increased because the quantity of nutrient in the slabs decreased slower than the slab water content decreased.

The plant produced in 2016 0.9 kg $m^{-2}$ of sweet pepper per week during the cultivation and 0.7 kg $m^{-2}$ of sweet pepper per week during the end of cultivation strategy. The plant produced in 2017 2.6 and 2.8 kg $m^{-2}$ of cucumber per week during the cultivation for compartment 1 and compartment 2, respectively. During the end of cultivation strategy, the cucumber yield was 2.0 and 2.2 kg $m^{-2}$ of cucumber per week for compartment 1 and compartment 2, respectively. The average daily solar radiation was also measured during the whole cultivation and the end of cultivation periods by the local weather station. The average daily radiation during the whole cultivation was 1521 J $m^{-2}$ in 2016 and 1332 J $m^{-2}$ in 2017. The average daily radiation at the end of the crop was 1090 J $m^{-2}$ in 2016 and 724 J $m^{-2}$ in 2017.

## DISCUSSION

The water volume and nitrate and phosphate quantity were reduced less than planned. This could be explained by an opposite dynamic between the nutrient reduction and the water volume reduction. It was planned to be simultaneously reduced, however, practice revealed this was hardly achievable. The strategy should rather be thought of as two related steps. The first step implied the reduction of the absolute quantity and concentration of nitrate and phosphate. The second step implied the reduction of the water volume. The removal of the absolute quantity of nitrate and phosphate decreased when the water content in the cultivation slabs and the drain percentage started to decrease faster. When the water content in the cultivation slabs decreases below 30%-v/v, the water in the pores is no longer sufficiently connected and the mobility of nutrients to the roots is no longer satisfying to meet the plant needs (Blok et al., 2017). A sufficient volume of drain, around 30%-v/v of the supply, was necessary to flush accumulated nutrient and prevent their precipitation, and so immobilisation (Raaphorst et al., 2014). The reduction of nutrients was faster before the reduction of the water volume in the slab. If the substrate slab nutrient quantity was not decreased before the water volume start decreasing, the concentrations increase as well as the electric conductivity. Early rising EC would be damageable to the fruit production before the end-of-cultivation. The water reduction should be achieved after the nutrient quantity reduction. The reduction of the water volume could only be efficient in the absence of drainage. It was not possible to decrease the overall slab water content while still creating some drain and flushing in the unique irrigation cycle.

The difference between phosphorus removal in 2016 (9%-w/w) and 2017 (63%-w/w) may be explained by the average pH during the end of cultivation. The lower pH during the end-of-cultivation in 2016 than in the whole cultivation was responsible for the dilution of phosphorus precipitated during the cultivation. The higher pH in 2017 than in 2016 may be responsible for the precipitation of some phosphate created an artefact in the measure of available phosphorus. The substitution of potassium nitrate by ammonium nitrate could not be realised in 2017 due to the low pH buffer of coir. The use of ammonium led to a direct reduction of the pH under 4 (Horchani et al., 2010). Yields become significantly reduced under pH of 4.5 (Sonneveld and Voogt, 2009) and such risk could not be taken.

The substitution of anions by chloride was very effective. Chloride did not accumulate. The response to chlorine supply was immediate. Chloride uptake did not affect the nitrate uptake. The cation/anion balance could be maintained in the system despite the reduction of the nitrate quantity (Curtin and Wen, 2004).

## CONCLUSIONS

The five week end-of-cultivation strategy allows reducing about 30-40%-v/v of the water volume held in the cultivation slabs and 100%-v/v of the water volume held in the drain buffer. The strategy allows reducing the nitrate emission per square meter by 50-60%-w/w. The reduction of the phosphate emission depends on the pH reduction realized. The strategy can be achieved without reduction of the fruit quality. It is possible to follow a pre-established schedule, which can be implemented by cultivation advisors without specific training.


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