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Nutrient solution dynamics and yield of lettuce (Lactuca sativa) in an EC-controlled recirculating hydroponic system

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Abstract

In this study, the nutrient dynamic and growth performance of lettuce in a closed recirculating hydroponic system were investigated. Lettuce was grown in three parallel nutrient film technique (NFT) units, illuminated with LED-light. A balanced standard nutrient solution (NS) was used, and the electrical conductivity (EC) and pH were adjusted regularly to constant average values of 1.16 mS cm^{-1} and 6.2 with standard deviations of ±0.12 and ±0.5, respectively. The volume of NS in each unit was kept at 20 L by adding refill solution to replace nutrient uptake and transpiration. Lettuce growth during the first six weeks in the NFT-system was normal and stable. After six weeks, a decrease in concentrations of N, P, and K was observed, with a corresponding decline in yield of lettuce. After ten weeks, lettuce weight at harvest was reduced by 56% in average compared to the control, and the concentrations of N, P and K in the NS were reduced by 54.5, 90.5 and 96.6%, respectively. Contrarily, more slowly absorbed nutrients like Ca, S, Zn, Cu, and B experienced increases by factors of 2.2, 2.9, 6.6, 4.9 and 2.5, respectively. The depletion and accumulation of nutrients in the NS were reflected in corresponding deficiency and excess levels of nutrients in leaf tissue compared to norm-values of healthy lettuce. The study showed that after six weeks, corresponding to a yield of 1 kg lettuce per 10 L tank volume of NS, the reduced growth implied that the recirculated NS should have been discharged and replaced, or a "tailor-made" refill solution should have been used to avoid depletion of some nutrients. Based on the foliar analysis and calculations of actual nutrient absorption rates, the composition of such a refill NS was suggested.

Keywords: NFT-system, recirculation, EC-control, foliar analysis, nutrient management

Introduction

Today, several leafy vegetables, including lettuce, can easily be grown in indoor and outdoor hydroponic systems. Due to several advantages over conventional farming practise, including better nutrient and water utilization, hydroponic systems can contribute to increased food production worldwide with a lower environmental impact. However, there are several possibilities to further improve the nutrient and water efficiency by increasing the lifetime of nutrient solution (NS), which is of utmost importance, since nutrients, such as phosphorus and some micronutrients, are becoming scarce resources (Chowdhury et al., 2017). Among hydroponic systems, we distinguish between open and closed cultivation systems. The closed systems utilize water and nutrient more efficiently than open systems, with substantial less discharge to the environment, thereby reduced environmental and economic costs (Bugbee, 2004). A frequently applied system is the nutrient film technique (NFT) system (Son et al., 2016).

Usually, the concentration of nutrients in the recirculating NS is controlled by electrical conductivity (EC) which is a sum parameter for all dissolved minerals in ionic form in the solution. It is difficult to keep a well-balanced NS in closed hydroponic systems for long time, because nutrients are absorbed by the plants at different rates. The actively absorbed nutrients like N, P, K, and Mn will be taken up much faster than the intermediate and passively absorbed nutrients with slower uptake rates (Tsukagoshi and Shinohara, 2016). If new NS is regularly supplied to replace transpiration, the differences in uptake rates will result in an imbalance in the recirculating NS with time, even if the EC-value is kept at a constant level. Some nutrients will accumulate, while other will be depleted. Frequently drainage and refill of new NS (one to two weeks intervals) will solve the problem, but not the cost and environmental challenges. To overcome problems with nutrient imbalance, several strategies have been proposed to determine and control nutrient requirements, including automated monitoring of nutrient concentration by ion-selective electrodes (Kim et al., 2013; Cho et al., 2018) and development of mathematical models, software and automated systems (Domingues et al., 2012; Kozai et al., 2018). However, the practical implication of these strategies is somewhat limited. Ion-selective electrodes for monitoring are still expensive, and need skills and time for calibration and operation (Son et al., 2016). The mathematical models need a lot of input parameters and need to be adapted to the current crop in order to work (Signore et al., 2016). Another novel concept to avoid nutrient imbalance is quantitative management of the NS. This implies that refill solution is made based on calculations of actual nutrient uptake rates by the plants. Uptake rates are determined by nutrient content in leaf tissue, yield, and amount of water transpired (Signore et al., 2016; Tsukagoshi and Shinohara, 2016). However, the uptake rate and leaf tissue content will vary among crops and local growth conditions, and "tailor-made" nutrient solutions are therefore needed.

In this study, we investigated the nutrient dynamic and growth performance of lettuce (Lactuca sativa L.) during a 68 days growth period from September to December 2018 in an EC-controlled closed LED-illuminated hydroponic system, without discharge of NS. Refill solution was added regularly to maintain a constant volume, and EC- and pH-values were adjusted to constant values. The aim of the study was to highlight the accumulation and depletion of individual nutrients in the recirculating NS, determine the time for growth limitation, and determine the limiting nutrients by NS and foliar analysis. Based on the actual nutrient requirements by foliar analysis, the composition of a "tailor-made" refill solution was suggested.

Materials and methods

The growth systems

The experiment was carried out in a growth room located at the University of Agder in Norway, during a 68 days period from 27th of September to the 4th of December 2018. The growth systems consisted of a seeding system and a closed grow-out nutrient film technique (NFT) system. In the seeding system, seeds of Lactuca sativa L. (Batavia-type, 'Partition') from the seed company LOG AS, Norway, were seeded in Grodan rockwool cubes (36×36×40 mm) and inserted in net pots. The cubes in net pots were placed in trays with NS and illuminated with LED-light with a wavelength peak in the blue (445 nm) spectral ranges, with a total photon flux density of 210 µmol

m^{-2} s^{-1}. After 2 weeks in the seeding system, the seedlings were transplanted to the NFT-system for additional 4 weeks growing before harvesting.

The NFT-system included three identical parallel units for triplicate experiments. Each unit consisted of a 2400 mm long rectangular PVC-pipe with dimensions 100 mm width and 50 mm height, and a 20-L nutrient tank with a submerged pump to circulate the NS to the 12 plants in each unit. The 45 mm holes for plants in net pots were separated by 200 mm. NS was supplied intermittently by the pump and a timer (30 min on/off cycles). The flow rate was 3.5 L min^{-1}. LED-lamps with wavelength peaks in the blue (445 nm) and red (660 nm) spectral ranges were suspended over the pipes producing photosynthetically active radiation (PAR) with a flux density of 220 μmol m^{-2} s^{-1}. By illumination of 18 h day-1, the total daily illuminating dose was about 15 mol m^{-2} d^{-1}. The temperature of the growth room was kept in the range of 22-24°C, CO2 concentration at 410-450 ppm, and the relative humidity at 35-40%.

Each of the three parallel units of the NFT-system was operated in a continuous production mode during the experimental period. At the starting date (27th of September 2018), 9 seedlings (2 weeks old) were collected from the seedling system and transferred to the NFT-system (3 seedlings to each of the three units). After 4 weeks, the NFT-system was fully stocked, and the first 3 lettuce heads of the total of 12 lettuces in each unit were harvested and replaced by 3 new seedlings (2 weeks old). During the 68 days experimental period from 27th September to 4th December, there were 7 harvests, with a total production of 21 lettuce heads from each unit, which gave a total of 63 lettuce heads from the 3 parallel units of the NFT-system.

Nutrient solution

The NS used in the NFT-system was prepared from two commercial stock solutions, Nutri-A and Nutri-B, from Panponic Biosystems AS, Norway. The profile of the applied NS at the start of the experimental period is shown in Table 1. Every second day throughout the experimental period, pH- and EC-values were adjusted to maintain a pH value of approximately 6 and an EC value of approximately 1.1 mS cm^{-1} by adding new NS to compensate for nutrient uptake and transpiration losses, up to the initial volume of 20 L. A diluted nitric acid solution was used to adjust the pH. NS was never discarded throughout the experimental period.

Table 1. Soluble nutrient content of the applied NS in this study and suggestion for composition of an alternative refill-solution calculated from the actual nutrient uptake in healthy leaves in this study.

	Soluble concentration (mg L^{-1})											
	N[a]	P	K	Ca	Mg	S	Zn	B	Cu	Fe	Mn	Mo
Applied NS	111	23	140	94	23	23	0.26	0.19	0.07	1.7	0.42	0.04
Alternative refill NS	262	32	247	74	17	13	0.25	0.11	0.03	0.6	0.71	0.01

[a]N – 96% of the nitrogen in the applied NS was as NO_3-N, only 4% as NH_4-N.

Physical and chemical analysis

At every harvest, the fresh weights of all the lettuces were measured. After 40 days (the 6th of November) and after 68 days (end of the experimental period), leaf tissue from the harvested lettuces of the three parallel units were collected and analyzed for macro- and micronutrient content by the Eurofins laboratory, Norway. Leaf tissue was collected from different parts of the lettuces to avoid biases due to uneven nutrient distribution within the plants. The nutrients were dissolved by nitric acid microwave extraction and analyzed by inductively coupled plasma atomic emission spectrometry (ICP-OES) according to European Standards (DIN EN ISO 11885).

The pH value and the EC of the nutrient solution in the three units were monitored before and after adjustment every second day by using a calibrated Jenway 3150 instrument and a calibrated Hach HQ40d instrument, respectively. Samples of the NS for macro- and micronutrient analysis were collected from the three parallel units at day 0, after 34 days, and after 68 days (end of the experimental period) and sent to the LMI laboratory, Sweden, for analysis by ICP-OES according to European Standards. Before analysis, the samples were filtered through Whatman GF/C membrane filters with pore openings of 0.45 μm.

Statistics

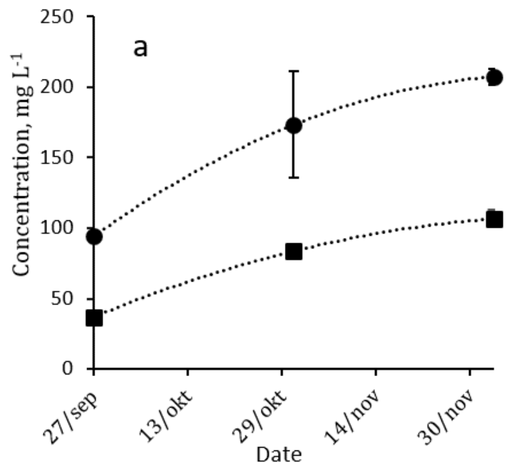
Mean values and standard deviations of individual nutrient concentrations (n=3), leaf tissue contents (n=3) and lettuce weights (n=9) are presented on the graphs. Where standard deviation bars are not observable, they do not extend beyond the dimensions of the symbols. Statistical differences in means of individual nutrient concentrations between dates during the experimental period, and differences in lettuce weights, were tested using one-way analysis of variance (ANOVA). All tests were performed using a significance level of $P<0.05$.

Results and discussion

Nutrient dynamic of the recycled solution

The chemical composition of the applied NS at the beginning of the growth period of the NFT-system is shown in Table 1. The measured mean pH value of the NS of the three hydroponic units throughout the experimental period was 6.2 with a standard deviation of±0.5. Adjustment of the pH with diluted nitric acid was required because the pH-values tended to increase during the period. As pointed out by other researchers, the ratio of NH_4^+ to NO_3^- in the NS is an important factor regarding pH development in hydroponic systems (Libia and Gómez-Merino, 2012). pH increase will prevail where nitrate is the dominating nitrogen compound, which was the case for the NS used in this study, where 96% of the N-content was present as NO_3^--N. The EC of the recycled NS varied to some extent during the growth period as a result of nutrient uptake in plants and supplementation of refill solution. The measured mean value of the three units throughout the experimental period was 1.16 mS cm^{-1} with a standard deviation of ±0.12.

The fate of macro- and micronutrients during the growth period is shown in Figures 1 and 2. As indicated, the variations among individual nutrients were pronounced, even though the EC values in the three units were maintained at approximately constant levels (mean of 1.16 mS cm^{-1}) throughout the period. Significant decreases ($P<0.05$) in the concentration of NO_3-N, P, and K were observed to final concentrations of 47.4, 2.2 and 4.7 mg L^{-1}, respectively, after 68 days (Figure 1b). Compared to the initial concentrations, NO_3-N, P and K were reduced by 55.7, 90.5, and 96.6%, respectively. As indicated, and also pointed out by other authors, these elements are rapidly absorbed by the plants, and may also be subjected to luxury absorption when present in high concentrations, thereby creating an imbalance in the NS (Bugbee, 2004; Signore et al., 2016). The decreases in concentration of these elements were observed. On the other hand, macronutrients with passive uptake experienced accumulations in the recirculated NS, e.g. Ca and S which increased by factors of 2.2 and 2.9, to concentrations of 207.3 and 106.7 mg L^{-1}, respectively (Figure 1a).



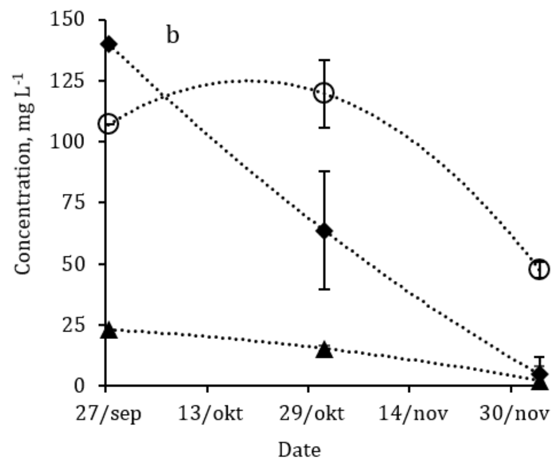


Figure 1. Concentrations of macronutrient in the recirculating solution from the start (27th of September) to the end (4th of December) of the 68 days growth period. a) ●; Ca, █ ; S. b) ◯; NO3-N, ◆; K, ▲; P.

Among the micronutrients, increased NS concentrations were recorded for Si, Fe, Zn, and Cu (Figure 2). Si was the element with the highest gain, with a factor of 5.5, to a final concentration of 6.1 mg L^{-1}. Zn and Cu increased with time by factors of 2.2 and 2.9. The only micronutrient with a significant decrease was Mn which was reduced by 73.8%, to a final concentration of 0.11 mg L^{-1}. As expected, the data show that an imbalance in concentrations in the recirculated NS developed over time when refill solution was added to replace nutrient uptake and transpiration, to a constant EC-value and constant tank volume of 20 L.

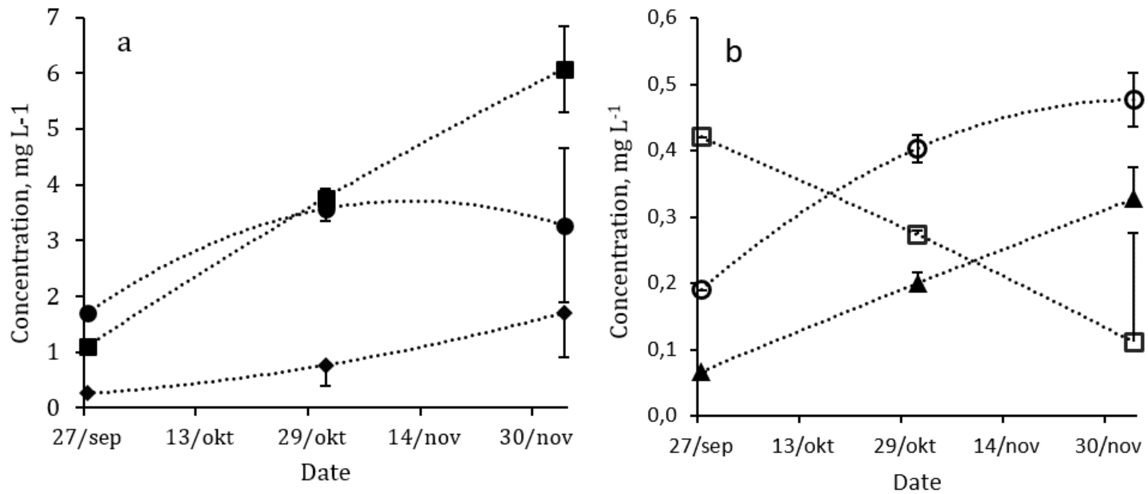


Figure 2. Concentrations of micronutrient in the recirculating solution from the start (27th of September) to the end (4th of December) of the 68 days growth period. a) ■; Si, ●; Fe, ◆; Zn. b) ◯; B, □; Mn, ▲; Cu.

Nutrients content in lettuce leaves

Leaf macro- and micronutrient concentrations in harvested lettuce after 40 days (on the 6th of November) and at the end of the growth period of 68 days (on the 4th December) compared to the norm of leaf tissue concentrations in healthy Lactuca sativa L. are shown in Figures 3 and 4 (Hartz et al., 2007). It should be noted that the leaf content of some nutrient, especially K, Ca, and Mg, may differ considerable between studies dependent on local environmental conditions (Hartz et al. 2007). The foliar analysis of the macronutrients shows that the elements with the highest accumulation in leaf tissue were N, followed by K, Ca, P, Mg and S (Figure 3), which is a composition in lettuce leaf tissue also experienced by others (Zhang, 2016), but deviates from the norm-values of Hartz et al. (2007) by a higher N-value than K-value. Generally, plants require more N and K than other elements.

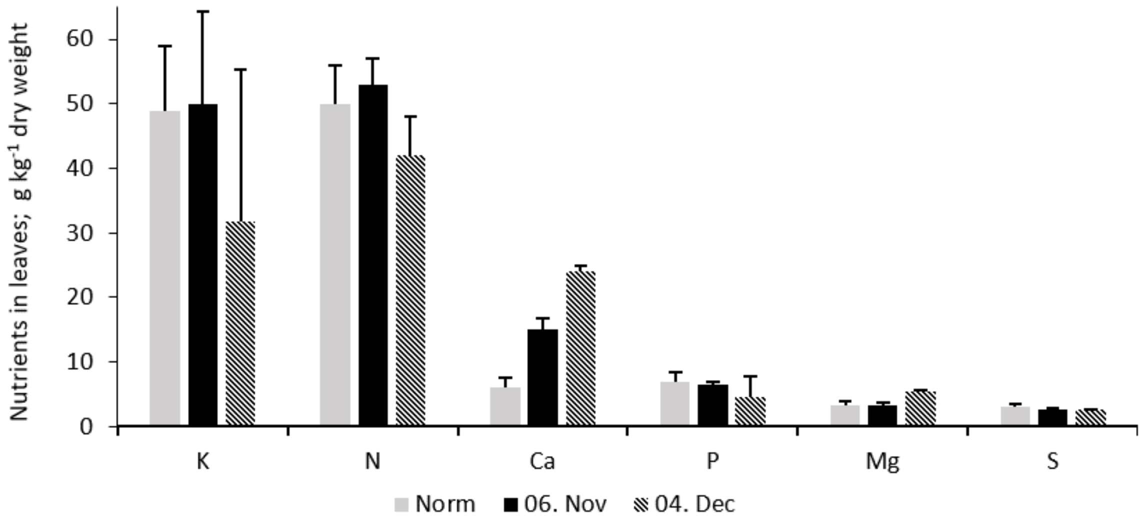


Figure 3. Leaf macronutrient concentrations in harvested lettuce on the 6^{th} November (40 days after start-up) and on the 4th December (end of the 68 days growth period) compared to the norm of leaf tissue content in healthy *Lactuca sativa* L. (Hartz et al., 2007).

The depletion and accumulation of various elements in the NS as shown in Figures 1 and 2 were reflected in leaf tissue content (Figures 3 and 4). The two macronutrients that deviated most from the norm by Hartz et al. (2007) were K and Ca, which also were pointed out as the nutrients with highest variations between studies. The leaf tissue content of K was only 59% of the norm at the end of the growth period (4th December), while Ca content was 2.8 times higher than the normal value (Figure 3). The deficiency of K in leaf tissue corresponded to the low concentration of K found in the recirculating NS, while the elevated Ca content in the leaves corresponded to the elevated Ca concentration in the solution. This suggests that foliar analysis can be an indicator of the availability of nutrients in the recirculated NS, and that absorption to some extent is proportional to the concentration of nutrient in the recirculated NS, as also pointed out by Domingues et al. (2012). However, among the other macronutrients, there were no large deviation from the norm-values, even for elements low in nutrient concentration in the recirculated solution, e.g. N and P. The sufficient N and P levels in leaf tissue indicate that plants may utilize low nutrient solution concentrations, here 47.4 mg L^{-1} as NO_3-N and 2.2 mg L^{-1} P at the end of the growth period, and that they also have the ability to store nutrients in roots and stems and remobilise them when required to avoid leaf deficiencies (Bugbee, 2004).

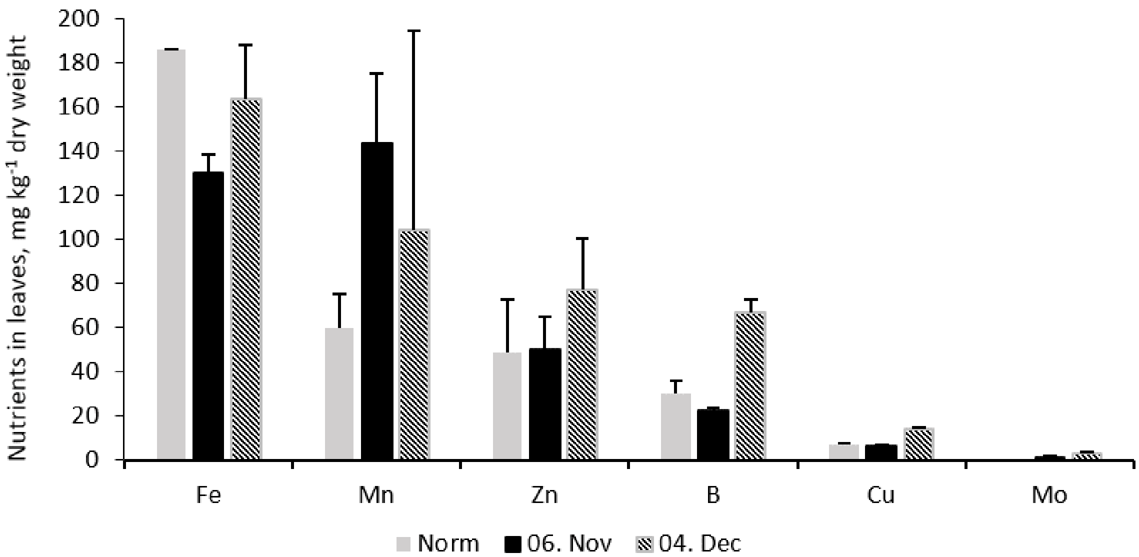


Figure 4. Leaf micronutrient concentrations in harvested lettuce on the 6th November (40 days after start-up) and on the 4th December (end of the 68 days growth period) compared to the norm of leaf tissue content in healthy *Lactuca sativa* L. (Hartz et al., 2007).

Of the micronutrient, Fe and Mn showed the highest accumulation in leaf tissue (Figure 4). Compared to the norm-value, the Fe content was low at the 6th of November, but increased toward the end of the growth period, which also corresponded to the observed increase of Fe in the NS (Figure 2a). Mn was 2.4 times higher than the norm-value on the 6th of November but was reduced to 1.7 times the norm-value after 68 days (end of the growth period), in accordance with decreased Mn concentration in solution (Figure 2b). Zn, B and Cu all accumulated in the NS, to concentrations 2.6, 2.2, and 2.1 times the norm-values after 68 days, respectively, which again was reflected in high nutrient concentrations in solution (Figure 2).

Lettuce growth and yield

The first harvest of lettuce was conducted on 25th of October, 4 weeks after the start-up of the NFT-system (27th of September). The average fresh weights of lettuce per head from the NFT-system (three parallel units) are shown in Figure 5. As indicated, the weights were more or less stable during the first three harvests (235-250 g per head). After the third harvest on the 6th of November (6 weeks after the start of the NFT-system), the weight per head declined steadily to 104 g in average at the end of the growth period (4th of December), which was only 44% of the weight of the first harvest and significantly lower (P<0.05). The reduced growth toward the end of the growth period corresponded to the depletion of macronutrients like K, P and N in the recirculated NS. Since there were no pronounced deficiencies of N and P in leaf tissue, the results may suggest that the deficiency of K in the NS toward the end of the growth period, with the resulting deficiency of K in leaf tissue, was the main reason for the reduced growth rate and yield of lettuce as shown in Figure 5. There was a strong linear correlation between the concentrations of K in the NS and weight of lettuces, with a coefficient of determination (R2) of 0.91. Accumulation of elements to toxic levels can be a problem in closed systems, but the elevated level of e.g. Ca in our study was probably not growth limiting. Ca is regarded as nontoxic, even at high tissue concentration (Bugbee, 2004).

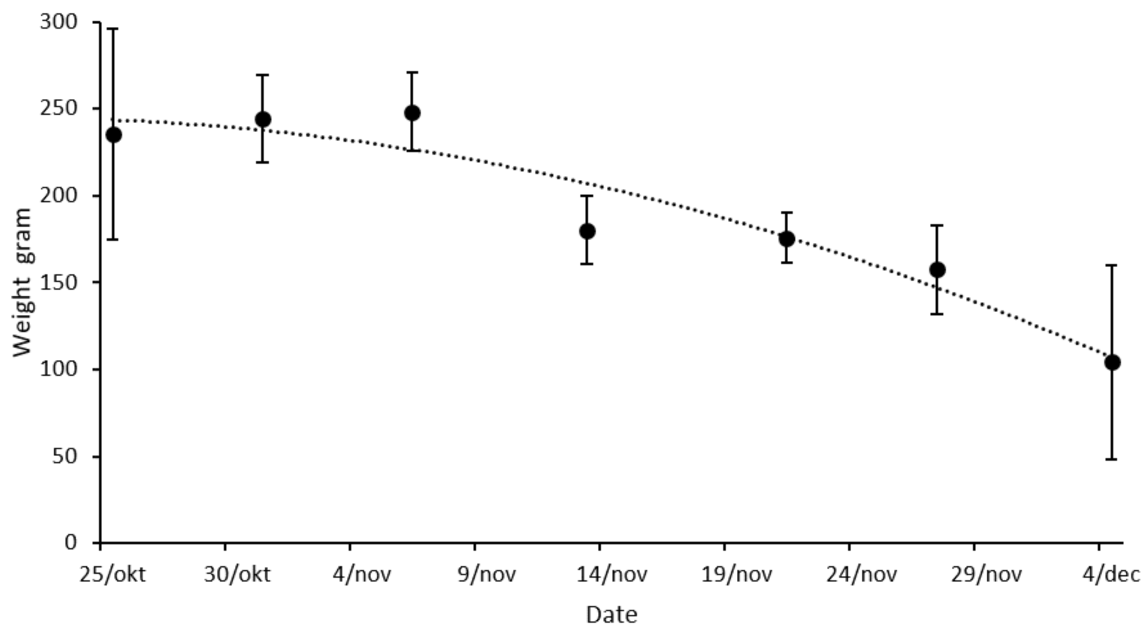


Figure 5. The average fresh weights of 6 week grown lettuces per head from the three parallel NFT-systems during the growth period from 27th September (first harvest on 25th October) to 4th of December.

The reduced lettuce growth toward the end of the period implies that the recirculated NS should have been discharged and replaced by new solution after approximately 6 weeks of operation, or a better balanced refill solution should have been applied during the growth period to avoid depletion of some elements. Bugbee (2004) suggested to use 1/3 strength of Hoagland solution for refilling. This may reduce or eliminate accumulation of elements like Ca and S but will not solve the problem with depletion of actively absorbed elements. Another strategy is to calculate the actual uptake of elements based on the leaf nutrient content per kg of plant dry weight and the amount of water used for transpiration, and then calculate the concentration of the refill solution (Bugbee, 2004; Signore et al., 2016). In our study, a total of 56 L of NS was refilled to the three parallel units of the NFT-system to replace transpiration during the period of high productivity (27th September to 6th of November). During this 6-week period with high yield, there were three harvests (9 lettuce heads per harvest, a total of 27 lettuce heads) with a total fresh weight of 6549 g with an average dry matter (DM) content of 4.2%. Based on the nutrient content in leaf tissue on the 6th of November shown in Figures 3 and 4 and the volume of refill solution applied during the period (56 L), the calculation of actual nutrient absorption rates were conducted, and the required strength of an alternative refill NS was estimated as shown in Table 1. The alternative solution shows higher concentrations of the nutrients which were depleted in the recirculated NS (N, P, K, and Mn), and lower concentrations of those accumulated (Ca, Mg, S, B, Cu, Fe, and Mo), which will supply the lettuce with nutrient amounts according to the requirements.

If discharge and refill of NS should be the strategy to avoid nutrient imbalance, the frequency will be determined by the ratio of the NS tank volume to plant growth rate. Lower volume of the recirculated NS implies more frequent discharge and refill. In our study, with a total production of 6549 g lettuce during the period of high yield (from 27th September to 6th of November), the 20 L of NS in each unit (60 L NS of the total system) should have been replaced after a fresh weight lettuce production of approximately 100 g per liters of NS, or 1 kg lettuce per 10-L tank volume of NS.

Conclusions

This study shows that NS can be reused in a closed NFT-system for several weeks without compromising yield and quality of lettuce. The only input to the system was refill of a standard nutrient solution to compensate for nutrient uptake and transpiration, while EC and pH values were kept constant. As expected, long time continuous reuse resulted in growth reduction and depletion of some nutrients and accumulation of others. After six weeks, corresponding to a yield of 1 kg lettuce per 10 L tank volume of NS, P and K concentrations in the NS were reduced to 2.2 and 4.7 mg L^{-1}, respectively. More slowly absorbed nutrients accumulated in the recirculated NS. The depletion and accumulation of nutrients in the solution were reflected in deficiency and excess levels in leaf tissue compared to norm-values of healthy lettuce. Strategies for management of recycled NS need to be implemented to avoid nutritional problems. Based on the foliar analysis and calculations of actual nutrient absorption rates in healthy lettuce, an alternative refill NS was introduced, with higher concentrations of the nutrients which were depleted (N, P, K, and Mn), and lower concentrations of those accumulated (Ca, Mg, S, B, Cu, Fe, and Mo), compared to the applied NS.

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