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Macronutrient cycling in hydroponic lettuce cultivation

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ABSTRACT

In order to address issues of limited resources and contamination by fertilizers, nutrient solutions may be reused in hydroponics as an alternative to their disposal in the environment. This work evaluated the feasibility of nutrient replacement for the nutrient solutions reused during lettuce hydroponic cultivation. The experiment was carried out in an agricultural greenhouse in an NFT hydroponic system using the "Milena" lettuce cultivar. The experiment was divided into two stages: 1) monitoring and data collection and proposition of nutrient replacement management; and 2) validation of the proposed replacement management. Monitoring the consumption of the crop's nutritional solution in the first stage served as the basis for the proposed nutritional replacement management. Management was validated in the second stage through the evaluation of fresh and dry mass, crop nutritional status, and the amount of the fertilizer applied in the treatments: T1 - nutrient replacement with nutrient solution reuse; and T2 - nutrient replacement without nutrient solution reuse. The fresh and dry mass data and the amount of nutrients absorbed by the plants were submitted to the t-test at 5% probability, showing no significant difference between the treatments, making it possible to conclude that the nutrient solution reuse provided nutrient replacement during the lettuce crop cultivation.

Keywords: hydroponic system, *Lactuca sativa* L., macronutrient rational use.

Ciclagem de macronutrientes no cultivo de alface hidropônica

RESUMO

O reúso de soluções nutritivas em hidroponia se torna alternativa ao descarte de água e nutrientes no ambiente, já que a escassez desses recursos e a contaminação do solo por fertilizantes são problemas, tanto econômicos quanto ambientais. Este trabalho avaliou a viabilidade da reposição de nutrientes para o reúso das soluções nutritivas descarte durante o desenvolvimento da cultura da alface em hidroponia. O experimento foi realizado em estufa agrícola, em sistema hidropônico NFT utilizando a cultivar de alface Milena. O experimento foi dividido em duas etapas, sendo a primeira: monitoramento e coleta de dados e proposição de manejo da reposição de nutrientes e a segunda: validação do manejo de reposição proposto. O monitoramento do consumo da solução nutricional da cultura, na primeira etapa, serviu como base para o manejo de reposição nutricional proposto. O manejo foi validado na segunda etapa através da avaliação das massas fresca e seca, o estado nutricional da cultura e a quantidade de fertilizantes aplicados nos tratamentos, T1 - reposição de nutrientes com reaproveitamento da solução nutritiva e T2 - reposição de nutrientes sem reaproveitamento da solução nutritiva. Os dados de massa fresca e seca e a quantidade de nutrientes absorvidos pelas plantas foram submetidos ao teste estatístico T ao nível de 5% de significância, mostrando não haver diferença significativa entre os tratamentos, sendo possível concluir que a reposição de nutrientes proporcionou o reúso da solução nutritiva durante o desenvolvimento da cultura da alface.

Palavras-chave: hidroponia, *Lactuca sativa* L., uso racional de macronutrientes.

1. INTRODUCTION

In recent decades, population growth and agriculture modernization have led to increased consumption of resources. One of these is water, the consumption of which has brought environmental problems such as contamination and scarcity. In this sense, to meet growing food demand with minimal impact on the environment, agriculture must be managed rationally.

Water scarcity and soil contamination are problems felt worldwide, leading the productive sectors to more rigorous management of water resources, such as considering water reuse, controlling losses and waste, and reducing consumption and residue production (Barros *et al.*, 2015). In this scenario, the protected cultivation of vegetables, which has been developed on a large scale under the hydroponic system, represents an alternative for producers looking for cultivation technologies that guarantee their production with less environmental impact.

The number of establishments that produce lettuce in Brazil is 108,603 units (approximately 80,000 hectares), which have a total of 908,186 tons per year (IBGE, 2017). It is estimated that the hydroponic cultivation of leafy vegetables in Brazil is approximately 2,000 hectares, with a growth trend for the coming decades (Lima *et al.*, 2018). The adoption of new cultivation technologies has been increasing in recent years, such as the cultivation of lettuce in a hydroponic system of the NFT (Nutrient Film Technique) under protected cultivation (Sala, 2019).

The NFT (Nutrient Film Technique) system is a hydroponic cultivation technique that makes nutrients available to plants through a thin film of nutrient solution adequate to meet the requirements of each plant species (Bezerra Neto and Paes, 2011). It has shown significant growth in the last decades because of its advantages over soil cultivation, such as the potential for efficient use of water and nutrients (Santos *et al.*, 2013), less exposure to climate factors and phytosanitary problems, higher yield, and added value to the product, precocity, and better plant quality (Bezerra Neto, 2016). In addition to the efficient use of water, as it reduces losses by evaporation, NFT hydroponics can also reduce the environmental risks associated with salt accumulation in the environment (Alves *et al.*, 2011).

However, some producers who use NFT hydroponics have discarded nutrient solutions after partial nutrient consumption by plants or due to disease occurrence (Badgery-Parker, 2002). Such disposal is often done after a period of use since producers still do not have a fast and cheap method to quantify nutrient contents in the solution to provide an appropriate nutritional balance by replacing missing nutrients. Thus, the disposal and non-reuse of nutrient solutions from hydroponic systems have been environmental and economic concerns but little discussed in the literature. Nutrient replacement can be done in NTF cultivations by nutrient solution reuse for several crop cycles without impacting productivity (Backes *et al.*, 2003). Therefore, nutrient solution disposal can be reduced and/or eliminated by periodic adjustments in its composition throughout plant growth and development cycles (Gimenez *et al.*, 2008).

Furthermore, in 2020, Brazil imported more than 80% of the fertilizers used in agriculture (SAE, 2020). For this reason, nutrient solution reuse becomes a good alternative as it enables savings of these inputs. Another advantage of such a practice is mitigating environmental impacts by not releasing salts into the environment. In Brazil, lettuce is the main species and represents 80% of the vegetables grown under the NFT hydroponic system (Furlani, 1999; Sala and Costa, 2012). Moreover, this vegetable is among the five most marketed in Brazilian supply centers (CONAB, 2020).

Since producers need practical information for the rational use of nutrients and water, this study evaluated the feasibility of nutrient replacement with nutrient solution reuse during the lettuce development in hydroponics.

2. MATERIAL AND METHODS

The study was carried out in the Department of Natural Resources and Environmental Protection (DRNPA) of the Center for Agricultural Sciences (CCA), Federal University of São Carlos (UFSCar), Campus of Araras, São Paulo State, Brazil. The area lies at the UTM coordinate: 7531348 N; 254144 E; datum WGS 84, and Zone 23K. According to Köppen's classification, the local climate is classified as *Cwa*, which is characterized by two well-defined seasons, one dry with mild temperatures (April to September) and another rainy with higher temperatures (October to March). Annual temperature and rainfall averages are 21°C and 1400 mm, respectively (Valadares *et al.*, 2008).

The experiment was carried out in an arched-roof greenhouse (commercially known as Poly House). It measured 6.4 x 20.0 x 3.5 m (width x length x height) and was enveloped with a transparent UV-treated polyethylene sheet and white shade screen on the sides. The crisp lettuce cultivar Milena was used under NFT hydroponic cultivation.

The experimental area consisted of eight benches containing four polypropylene channels (75 mm wide x 3.0 m long). The channels were spaced at 0.30 m, the plants at 0.25 m, and the benches at 0.70 m to facilitate handling. Each bench had 44 plants, 11 per channel, with a useful plot covering the 18 central plants (Figure 1). The experiments were carried out in a completely randomized block design, with three replications in the first stage and one in the second.

The hydroponic solutions were supplied by two 500-L reservoirs, a pumping system, cultivation benches, a system for returning the nutrient solution to the reservoir by gravity, and an aerator. Nutrient solutions were supplied to each channel at an average flow rate of 1.5 L min^{-1} (Martinez and Silva Filho, 2004). In addition, the pump timer was set to 15 minutes for every half-hour during the daytime and 15 minutes for every hour during the nighttime, providing an intermittent nutrient solution flow to the plants (Cuba *et al.*, 2015).

The experiment was divided into two stages: 1) monitoring and data collection and proposition of nutrient replacement management; and 2) validation of the proposed replacement management. Monitoring the consumption of the crop's nutritional solution in the first stage served as the basis for the proposed nutritional replacement management.

2.1. Nutrient solutions

Nutrient solutions for Stages 1 and 2 were prepared according to the lettuce crops recommendations adapted from Furlani *et al.* (1999), Table 1.

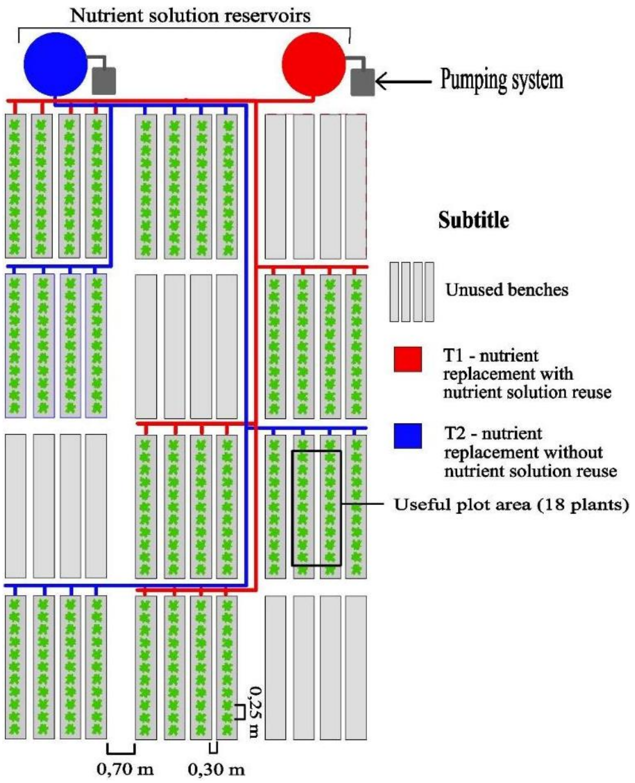

Figure 1. Schematic of the hydroponic system structure and treatment distribution.

Table 1. Lettuce nutrient recommendation used, which results in a nutrient solution with a pH - 6.3 and an electrical conductivity - 1.6 dS m^{-1}.

Fertilizer	**Concentration (g 1000 L^{-1})**
Calcium nitrate	500
Potassium nitrate	500
Magnesium sulfate	350
Monoammonium Phosphate	100
Conmicros Standard	20

Nutrient solution pH and electrical conductivity (EC) were monitored daily to maintain a suitable environment for lettuce growth (Martinez, 2002).

2.2. Stage 1 – Nutrient solution monitoring and crop data collection

The nutrient solution was prepared and made available on the same day plants were transplanted to the hydroponic channels (0 days after transplanting – DAT) and discarded at 7 DAT. Moreover, solution preparation, disposal, and collection were performed weekly until 28 DAT (the end of the lettuce cycle). The macronutrients present in the nutrient solution were analyzed weekly. The nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) contents were determined to use these results in the following experiment stage. Solution samples were collected in triplicates, and the contents of N were determined by TOC-LCPN development; P by the vanadomolybdophosphoric acid method with a wave reading of 440 nm in length; K in a Digimed flame spectrophotometer (Model DM-62); Ca in an atomic absorption spectrophotometer and Mg in an Iris-HI801 model spectrophotometer - HANNA Instruments.

Plants were also sampled weekly to characterize nutrient contents and build a lettuce shoot absorption curve. Leaves were dried in a forced-air circulation oven at 70°C until reaching a constant weight (Silva, 2009), with macronutrients (N, P, K, Ca, and Mg) being quantified (Carmo *et al.*, 2000).

Lettuce shoot fresh (FM) and dry (DM) masses were determined using the same plants sampled weekly for leaf analysis. These plants were weighed on an analytical scale right after being collected from benches (FM) and after drying (DM). At 28 DAT, yield per square meter was obtained, and the useful plot area and border comprised 1.8 m^2 each.

The experimental design consisted of entirely randomized blocks, with 44 plants per bench and 176 plants per reservoir, totaling 528 plants in three replications.

Statistical analyzes were performed using the EXCEL software. The results of absorbed nutrient content from the nutrient solution (three replicates) were t-tested at 5% significance, and no significant differences were found between treatments.

2.3. Stage 2 – Nutrient replacement proposal validation

In Stage 2, two treatments were carried out in the same structure as in Stage 1, T1 - nutrient replacement with nutrient solution reuse and T2 - nutrient replacement without nutrient solution reuse.

Macronutrient consumption data were validated, and fertilizer replacement in T1 was based on the difference between nutrient contents in the initial and discarded nutritional solutions, thus obtaining the amount of nutrients absorbed by plants. The values were obtained in nutrient concentration (mg L^{-1}) and transformed into amounts of salts (calcium nitrate, potassium nitrate, magnesium sulfate, mono-ammonium phosphate, potassium sulfate, urea, and ConMicros). The entire solution volume was considered to adjust nutrients, considering the amount remaining in the reservoir and evapotranspiration. Mean micronutrient consumptions were calculated to be used as a basis for replacement. The nutrient solution in T2 was according to the procedure performed in Stage 1. Nutrient solution pH and electrical conductivity (EC) were monitored daily.

The experimental design consisted of completely randomized blocks. For leaf fresh and dry mass measurements, the useful area of each bench was divided into two subplots for plant sampling (9 subsamples), totaling 72 samples per treatment at the end of the crop cycle (30 DAT).

T1 and T2 were compared for plant-absorbed nutrient contents and plant fresh and dry weights. In addition, data were subjected to analysis of variance to verify the differences for the studied variables.

Water consumption was measured weekly based on reservoirs' water balance, so the Water Use Efficiency (WUE) (estimated in kg m^{-3}) was obtained by dividing the production (kg) by the water consumed volume (m^{-3}) of each treatment applied during the lettuce crop cycle.

3. RESULTS AND DISCUSSION

3.1. Stage – 1

As expected, nutrient solution pH varied throughout the experiment since solutions have no buffering capacity (Backes *et al.*, 2004). However, the values were maintained from 5.45 to 6.75 for the best plant growth (Castellane and Araújo, 1995).

Average electrical conductivity (EC) was within the recommended range for hydroponic lettuce cultivation, from 1.5 to 1.8 dS m^{-1}. These values corroborate the recommendation of Castellane and Araújo (1995), who reported a range from 1.5 to 2.5 dS m^{-1}, a reference for EC monitoring. EC remained virtually constant between 0 and 7 days after transplanting (DAT), and nutrient solution absorption was low compared to other plant growth stages. Such low absorption is due to the reduced size of lettuce plants at the beginning of the cycle. Yet, from 7 to 21 DAT, EC increased by 9.2% due to higher plant water demands and the absence of water replacement in the reservoir between nutrient solution changes, thus concentrating the nutrients. In the last week of evaluation (21 and 28 DAT), EC showed an inverse behavior, decreasing by 4.0% from the optimal value. This reduction is due to plants' increased demand for water and nutrients at the end of the cycle.

3.1.1. Nutrient solution chemical analysis

Nitrogen exports were constant throughout the crop cycle, and this nutrient was consumed (159.47 mg L^{-1}) at 28 DAT. As to Heinen *et al.* (1991), differences between nutrient solution N reductions and plant-absorbed N contents are significant, which can be explained by N denitrification and/or immobilization. Up to 21 DAT, nutrient solution P concentrations decreased, while its consumption by plants increased (6.75 mg L^{-1} between 0 and 7 DAT; 19.58 mg L^{-1} between 7 and 14 DAT; and 38.78 mg L^{-1} between 14 and 21 DAT); however, its concentrations remained practically constant from 21 to 28 DAT (34.88 mg L^{-1}). Potassium was the most exported nutrient from the nutrient solution, with the highest expression between 21 and 28 DAT (224.36 mg L^{-1}), followed by 14 to 21 DAT (187.13 mg L^{-1}). However, Ca was less exported between 7 and 14 DAT (15.35 mg L^{-1}), with a marked increase between 14 and 21 DAT (39.79 mg L^{-1}) and 21 and 28 DAT (84.48 mg L^{-1}). Up to 21 DAT, Mg exports remained constant, which were 4.84 mg L^{-1} between 0 and 7 DAT, 7.40 mg L^{-1} between 7 and 14 DAT, and 8.60 mg L^{-1} between 14 and 21 DAT, but increased from 21 to 28 DAT (26.48 mg L^{-1}) (Figure 2).

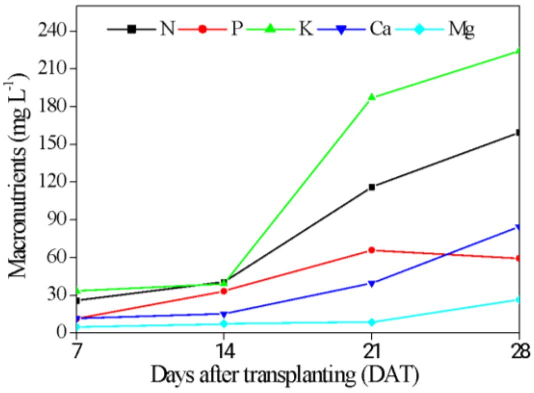

Figure 2. Averages of macronutrient contents from nutrient solution at 7, 14, 21, and 28 days after transplanting (DAT).

3.1.2. Nutrient absorption curve and agronomic evaluation of lettuce cv. Milena

Average leaf analysis results (Figure 3) were compared to the optimal ranges for macronutrients by Raij *et al.* (1997). All of them were within their respective suggested content, and no visual symptoms of nutrient deficiency or toxicity were observed in plants.

Leaf analysis showed that K was the nutrient most absorbed by plants, followed by N, Ca, P, and Mg. This result corroborates the findings on lettuce plants of Fernandes *et al.* (2002) on the cultivars Regina, Babá de Verão (butterhead), and Grandes Lagos (iceberg), and those of Gondim *et al.* (2010) on the cultivar Brasil 303 (butterhead), both in experiments with the hydroponic system in autumn. Our findings also agree with Benini *et al.* (2005) on the cultivar Verônica (loose-leaf) under hydroponic and conventional approaches in the autumn/winter.

Fresh shoot mass accumulation was slow until 14 DAT, representing 1.4% of the total accumulated from 0 to 7 DAT and 6% from 7 to 14 DAT. Then, fresh mass accumulation increased from 14 to 21 DAT, reaching 22.4% of the total. The highest expansion was 69.6%, achieved in the last week (21 to 28 DAT). At harvest time (28 DAT), plants had an average of

226.2 g total fresh weight. These values are higher than Vaz, Junqueira (1998), and Benini *et al.* (2005) on cv. Verônica (207.8 g, 183.4 g, and 124.5 g, respectively). When researching the performance of lettuce seedlings cv. Vanda in trays with different cell volumes, Lima *et al.* (2018) reported an average of 246 g plant^{-1} at 29 DAT.

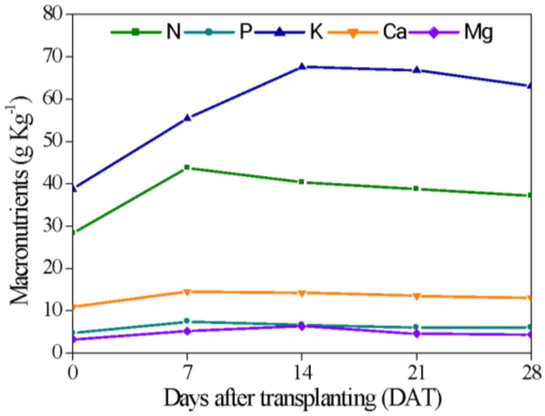

Figure 3. Macronutrient concentrations in dry shoot matter of lettuce cv. Milena at 0, 7, 14, 21, and 28 days after transplanting (DAT).

At 28 DAT, total water consumption averaged 4.1 L (Figure 4), around 144.5 mL plant^{-1} day^{-1}. According to Furlani *et al.* (2009), water absorption by hydroponic lettuce is, on average, between 75 and 100 mL plant^{-1} day^{-1}. High consumption may be related to production system failures, such as water loss due to leakages and evaporation from uncapped holes after plant sampling.

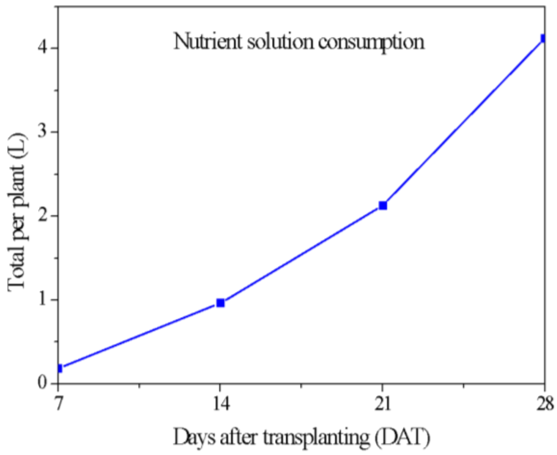

Figure 4. Nutrient solution consumption throughout the cycle of the lettuce cv. Milena.

The yield of the lettuce cv. Milena reached, on average, 2.75 kg m^{-2}, similar to that found by Lima *et al.* (2018) (2.51 kg m^{-2}).

Shoot dry mass (SDM) accumulation was, on average, 13.04 g plant^{-1} at 28 DAT, which is similar to that obtained by Lima *et al.* (2018) of 12.42 g plant^{-1}.

3.2. Stage 2

Nutrient solution pH ranged from 5.8 to 6.7 in T1 and 6.0 to 6.7 in T2. To reduce pH, phosphoric acid was added to the solution, as Martinez (2006) recommended.

Average electrical conductivity (EC) ranged from 1.69 to 2.33 dS m^{-1} in T1 and from 1.60 to 2.00 dS m^{-1} in T2. These values were within the range from 1.5 to 2.5 dS m^{-1} recommended by Castellane and Araújo (1995).

Table 2 describes the amounts of salts used in T1 and T2. Since the nutrient solution of T1 was not discarded, the parts of salts used could be reduced compared to T2 without damaging fresh mass production. In the third week of cultivation, besides the salts already used, potassium sulfate and urea were used to avoid adding some nutrients in excess.

Table 2. Total contents of fertilizers used during the crop cycle in T1 and T2 are expressed in salts and individual nutrients for a total volume of 512.5 L for T1 and 1400 L for T2.

Fertilizer	The total amount of salts		The total amount of nutrients	
	T1 (g)	T2 (g)	T1 (g)	T2 (g)
Calcium nitrate	407.7	700	N – 142.45	N – 240.5
Potassium nitrate	423.5	700	P – 49.46	P – 216
Magnesium sulfate	249.4	490	K – 190.57	K – 315
Monoammonium phosphate (MAP)	91.6	140	Ca – 77.46	Ca – 133
ConMicros Standard	15.2	28	Mg – 22.45	Mg – 45
Potassium sulfate	18.9	–		
Urea	8.3	–		

During Stage 2, plants of both treatments showed no visual symptoms of nutrient deficiency. Therefore, the leaf analysis results of T1 and T2 were compared to the optimal ranges of macronutrients recommended by Raij *et al.* (1997), which are: N = 30–50 g kg^{-1}, P = 4–7 g kg^{-1}, K = 50–80 g kg^{-1}, Ca = 15–25 g kg^{-1}, and Mg = 4–6 g kg^{-1}. The results for T1 were 45 g N kg^{-1}, 8.32 g P kg^{-1}, 69.25 g K kg^{-1}, 7.70 g Ca kg^{-1}, and 2.78 g Mg kg^{-1}, while those of T2 were 46.50 g N kg^{-1}, 9.23 g P kg^{-1}, 56.12 g K kg^{-1}, 7.06 g Ca kg^{-1}, and 2.61 g Mg kg^{-1}.

The order of nutrient absorption found in the leaf analysis was K > N > P > Ca > Mg. Grangeiro *et al.* (2006) found a similar result in field cultivation.

The contents of N and K were within the range considered adequate for lettuce (Raij *et al.*, 1997). Otherwise, P content was above the optimal range in both T1 and T2; however, plants showed no visual toxicity symptoms. According to Malavolta (2006), excess P toxicity is not commonly seen in plants; yet, it can cause micronutrient deficiencies (e.g., copper, iron, manganese, and zinc), leading to reduced biomass. Such excess may be related to the addition of phosphoric acid to decrease nutrient solution pH, thus increasing P contents and hence luxury consumption by plants.

Both treatments showed Ca and Mg contents below the optimal range for lettuce growth. It may be related to high K contents in nutrient solutions. Potassium excess decreases Ca and Mg contents in the medium (Rosolem, 2005) since these ions compete for the same absorption sites. Despite the low levels, no deficiency symptoms of these nutrients were observed. This may have occurred because the cultivar Milena has a high tolerance to lack of Ca and is slow-growing (late cultivar), thus masking the symptoms.

At 30 DAT, total shoot fresh mass accumulation reached 156.7 g $plant^{-1}$ in T1 and 156.3 g $plant^{-1}$ in T2. These values are close to those of Vaz and Junqueira (1998) and Benini *et al.* (2005). They obtained 183.4 g and 124.5 g of fresh biomass per plant for the cultivar Verônica, respectively. On the other hand, Ceccherini *et al.* (2020) studied a different number of tray cells for lettuce production under conventional and hydroponic systems for summer cultivation. They obtained a fresh mass of about 280 g $plant^{-1}$. In our study, the low mass yields achieved in both treatments may be related to the K effect on Ca and Mg absorption, which was below the range recommended (Raij *et al.*, 1997). In addition, high K contents in nutrient solutions may impair plant growth or production (Rosolem, 2005).

Total water consumption per plant for T1 and T2 at 30 DAT was, on average, 2.0 L (Figure

5), about 66 mL per plant^{-1} day^{-1}. Milder temperatures and high relative humidity decrease water consumption by plants.

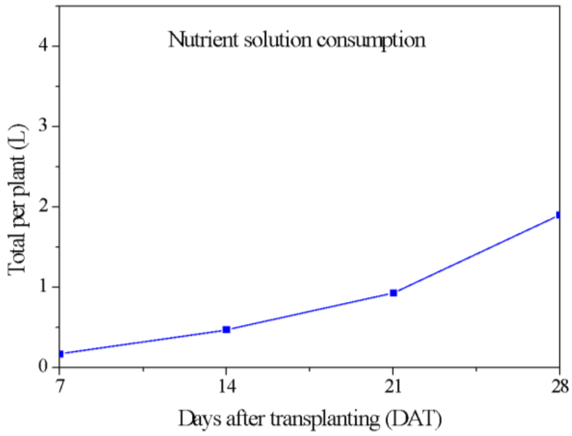

Figure 5. Nutrient solution consumption throughout the cycle of the lettuce cv. Milena.

At 30 DAT, the total shoot dry mass accumulated reached 6.53 g plant^{-1} for T1 and 6.43 g plant^{-1} for T2, with no difference between these treatments ($p \leq 0.05$) and a *p*-value of 0.3185976. The total water volume used in Stage 2 was 512.5 L for T1 and 1400 L for T2.

The WUE for T1 and T2 were, respectively, 53.81 kg m^{-3} and 19.65 kg m^{-3}. These results show that T1 increased the WUE with the solution reuse during the crop cycle. However, the fresh mass production was equal, T1 – 27.580 kg and T2 – 27.508 kg.

4. CONCLUSION

Under this study, we concluded that nutrient solution reuse provided replacement of nutrients during the lettuce crop cultivation.

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