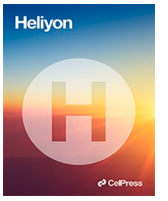
Heliyon 10 (2024) e32316

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon



Research article

Dynamics of micro and macronutrients in a hydroponic nutrient film technique system under lettuce cultivation

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ARTICLE INFO

Keywords:
Water quality
Electrical conductivity
Uptake efficiency

ABSTRACT

While hydroponics is considered an efficient vegetable production system, there is a compelling need to investigate the efficiency of the current generic nutrient dosing recommendation primarily based on electrical conductivity (EC) measurements. Such information is critical to fine-tune and optimize the current hydroponic management practices for improved nutrient uptake efficiency. This study investigated the dynamics of some micro and macronutrients (N, P, Ca, Mg, K, Fe, and Mn) in a recirculating nutrient film technique (NFT) hydroponic system under lettuce cultivation. The research was conducted in an indoor controlled environment growth chamber with lettuce grown in different EC levels (1.2 and 1.6 dS m^{-1}). Each treatment had four hydroponic cultivation units, each one with 24 plants. Nutrient solution and tissue samples were collected two to three times per week. Nutrient dynamics, including nutrient uptake efficiencies and environmental losses, were calculated using a mass balance approach. The effects of EC level on fresh and dry lettuce biomass and nutrient uptake were insignificant. Observed variations in nutrient solution composition during lettuce cultivation included the almost complete removal of ammonia nitrogen, nitrate decreases towards the end of the experiment, consistent increases in aqueous Ca concentration, and corresponding decreases in K and Mn. Average N losses ranged between 27 and 40 %, presumably through denitrification, while 10–14 % of N was assimilated into the plant biomass. The remaining N in the recirculating nutrient solution was estimated to be between 50 and 59 %. The average P loss was 11–35 %, likely due to precipitation, while 52–77 % remained in the nutrient solution. Nutrient uptake efficiencies averaged 19–31 % K, 12–21 % P, 9–16 % Mn, 4–6 % Ca, 3–4 % Mg, and 2–4 % Fe. These results suggest that elevated nutrient concentrations in recirculating nutrient solutions led to losses and underutilization. Findings from this study provide a comprehensive dataset critical to improving hydroponic nutrient management beyond N and P. Hydroponic nutrient management should target providing essential nutrients needed by plants at the correct proportions considering the plant growth stage.

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https://doi.org/10.1016/j.heliyon.2024.e32316
Received 5 February 2024; Received in revised form 31 May 2024; Accepted 31 May 2024
Available online 1 June 2024

1. Introduction

Conventional agricultural practices often involve inefficient chemical fertilizer use and generate waste, contributing to resource limitations and environmental degradation. Furthermore, decreases in per capita land availability, poor soil fertility, and extreme weather events challenge food productivity demands, motivating alternative crop production methods [1–3]. Hydroponic farming is becoming a viable food production alternative due to the improved nutrient and water use efficiency by growing crops in balanced nutrient solutions. Soilless cultivation, directly in nutrient solutions or substrates, replaces soil, allowing crop production in areas with limited land and unsuitable soil conditions [4].

Recirculating of hydroponic nutrient solutions reduces water and nutrient waste by capturing and reusing the drainage, ideally using only 5 % of the water needed for an equivalent amount of production in conventional agriculture [5]. Drainage nutrient solution recycling allows for a 33–40 % reduction in potable water and a 35–54 % reduction in nutrients used compared to drain-to-waste hydroponic systems [6,7]. However, hydroponic systems rely heavily on standard, pre-mixed inorganic fertilizers, and mostly, growers use 20–30 % more nutrients than the plants require due to variable plant uptake, equipment limitations employed in monitoring nutrient solutions, or to overcome losses due to precipitation [8–10]. Increased nutrient concentrations could also cause nutrient imbalances, salt accumulation, and reduced nutrient uptake efficiency [11–14], as well as pathogen risks and phytotoxicity [15].

As a result, replacing the hydroponic nutrient solution is a more common practice than closed-system continuous recirculation [16]. Based on electrical conductivity (EC) measurement, nutrient solution replacement may occur weekly or after a cultivation cycle. For instance, at the end of one cultivation cycle, the nutrient solution was reused in the next cycle by adding nutrients. However, in situations where the solution is not reused, there is a resource loss, which could contribute to surface and groundwater pollution if not properly managed [17–19]. Hydroponic cultivation heavily relies on nitrogen (N) and phosphorus (P) fertilizer inputs. Concentrated phosphate (30–100 mg L^{-1}) and nitrate (200–300 mg L^{-1}) were reported in greenhouse hydroponic nutrient wastewater from strawberry, tomato, and capsicum cultivation, although discharge concentrations for lettuce production are under-undocumented [20–22]. Concentrations of other nutrients with environmental and public health concerns in hydroponic wastewater are less documented. Therefore, optimizing hydroponics to ensure a balanced nutrient supply may reduce pollution risks.

Standard laboratory analysis can be employed in determining nutrient contents in hydroponic solutions; however, cost and time constraints lead hydroponic growers to use relatively simple equipment for EC measurements [23]. Electrical conductivity relates to the total dissolved ions and does not provide the concentration of individual nutrients; thus, nutrient imbalances, organic buildup, and microbial growth may limit the accuracy [24]. Nutrient solution composition may strongly influence the plant uptake and microbial activity, with effects on yield and resource use efficiency [25–27].

Often, hydroponic nutrient management follows the same recommendation for most vegetables, including lettuce (*Lactuca sativa* L.). The recommendation for hydroponic lettuce cultivation primarily focuses on maintaining EC at 0.8–1.2 dS m^{-1} during germination, then 1.2–1.8 dS m^{-1} for final production [28–32]. Furthermore, environmental conditions, such as EC, pH, dissolved oxygen, and temperature, can impact nutrient dynamics, plant growth, and nutrient uptake [33–35].

Limited studies have characterized the dynamic nutrient solution quality changes in recirculating nutrient film technique (NFT) hydroponic systems. Observed accumulations of unwanted compounds and nutrient imbalances in recycled nutrient solutions maintained through EC-based replenishment emphasize the need to understand nutrient solution composition changes [11]. Beyond N

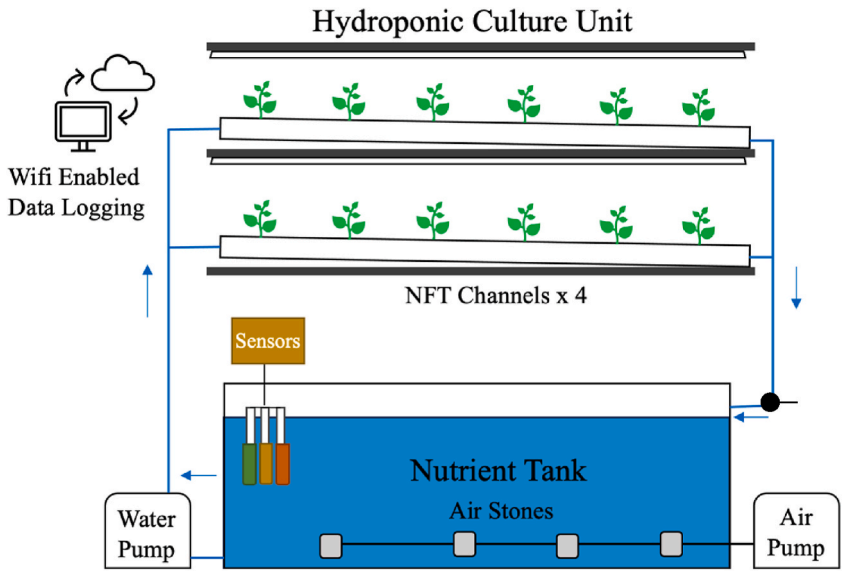

Fig. 1. NFT hydroponic system cross-section schematic.

and P budgets and maximizing crop yield, few studies included other macronutrients (K, Ca, and Mg) or micronutrients when considering nutrient uptake efficiency [12,17]. There is a critical need to improve understanding of recirculating hydroponic nutrient solution composition dynamics under different growing conditions to fine-tune nutrient application and replenishment.

Therefore, the objective of the present study was to evaluate the dynamics and fate of critical micro and macronutrients (N, P, Ca, Mg, K, Fe, and Mn) in a recirculating NFT hydroponic system with nutrient replacement after 35 days of lettuce production. Results from this study will provide critical information on nutrient solution dynamics that could be used to optimize nutrient management in recirculating NFT systems, thereby promoting the environmental and economic sustainability of hydroponic systems.

2. Materials and methods

2.1. Study site, experimental design, and growth conditions

This study was conducted with lettuce (*Lactuca sativa* L.) in an indoor controlled environment growth chamber in the Agricultural and Biological Engineering Department at the University of Florida, Gainesville (29.6°N, 82.3°W), USA. Lettuce was cultivated in a recirculating nutrient film technique (NFT) hydroponic system with nutrient solution recirculation without replacement by 35 days, in two cultivation cycles: one from August to September 2022 and other from April to May 2023.

Each hydroponic culture unit consisted of four NFT cultivation channels made from food-grade polyvinyl chloride (PVC) (1.2 m length × 11.2 cm width × 4.0 cm height) (Crop King, Lodi, OH, USA) (Fig. 1). The plants were arranged in 0.025 m holes and spaced at 0.203 m. Each unit also included a 102-L capacity rectangular tank to store the nutrient solution (Project Source, Commander, USA) from which the 40 L volume of solution was adjusted. From a FS-2500 submersible pump (Freesea, Athens, Greece), the nutrient solution was pumped into the hydroponic channels at a flow rate of 0.5 L min^{-1}. By gravity, the solution returned to the reservoir. Air stones attached to an air pump provided aeration in the nutrient tanks (Carefree, 2" Air stones).

The photoperiod was set as 16.5 h (between 6:00 a.m. and 9:30 p.m.) and was maintained solely by supplemental lighting from SIERA LEDs (HelioSpectra, Chicago, IL, USA). The light photosynthetic photon flux (PPF) was measured using an Apogee MG-500 full-spectrum quantum light sensor (Apogee, Logan, UT, USA), with a mean of 250 μmol m^{-2} s^{-1}. The daily light integral was 15 mol m^{-2} d^{-1}. The carbon dioxide (CO_2) was maintained above 600 ppm using the Vaisala CARBOCAP® Carbon Dioxide Probe GMP252 (Vaisala, Vantaa, Finland). The air temperature, airflow, and relative humidity (60 %) were maintained using a thermostat within the chamber HVAC system (Environmental Grow Chambers, TC2). The average air temperature was maintained at 24 and 19 °C during the day and night, respectively, while the average nutrient solution temperature was 22.7 °C.

The study investigated two electrical conductivity (EC) levels of the nutrient solutions (1.2 and 1.6 dS m^{-1}) in a randomized experimental design with four replications per treatment. Three lettuce cultivars ('Rex', 'Skyphos', and 'Muir') were grown under 1.2 dS m^{-1} EC, while under 1.6 dS m^{-1} EC only the cultivar 'Rex' was used. The seeds were obtained from a commercial source (Paramount Seeds Inc., Stuart, FL, USA) and sown in rockwool (Crop King, Lodi, OH, USA). The seeds received deionized water for the first day, then once germinated, were irrigated with a dilute nutrient solution at 0.8 dS m^{-1} EC in a single ebb-and-flood system for seven days to ensure uniform seedling size at the time of transplant. Flooding events occurred for 15 min every 6 h during this period. Uniform healthy seedlings were randomly selected for transplant into the NFT system (the cultivars were randomly planted so that an equal number was in each channel, with 24 plants per channel), and the full-strength nutrient solution was applied once the seedlings developed between two and three true leaves [28]. Deionized water, stock nutrient solution, and acid additions occurred periodically to maintain the nutrient solution, EC, and pH levels. Each experiment had four NFT systems, with four channels each, operated independently inside the growth chamber.

A two-part nutrient solution was mixed with deionized water and used to fill and regularly replenish the reservoirs. Part A contained a commercial solid nutrient mixture, lettuce formula (8-15-36), combined with magnesium sulfate ($MgSO_4$), while part B consisted only of calcium nitrate ($Ca(NO_3)_2$) (ChemGro, Colorado Springs, CO, USA). The composition of the complete nutrient solution is described in Table 1. Automatic dosing of concentrated nutrient solution at a 1:50 dilution rate was employed to maintain EC levels at 1.2 and 1.6 dS m^{-1}.

Between each cultivation cycle, the nutrient solution was replaced, and the composition of the deionized water and initial nutrient solution were analyzed. The daily nutrient replenishment was also recorded over the study period (Table 2). Adjustments for evapotranspiration losses occurred through periodic additions of deionized water based on float switch water-level sensor model

Table 1
Compositions of micro and macronutrients of the nutrient solution formulation used at the start of the experiment.

Macronutrient (mg L^{-1})			Micronutrient (mg L^{-1})		
	1.2 dS m^{-1}	1.6 dS m^{-1}		1.2 dS m^{-1}	1.6 dS m^{-1}
NO_3–N	93.1	123.6	B	1.05	1.40
NH_4–N	2.6	3.5	Cu	0.10	0.14
P_2O_5–P	34.5	46.1	Fe	2.09	2.79
K_2O–K	152.5	203.5	Mn	1.05	1.40
SO_4–S	139.1	185.7	Mo	0.05	0.07
Ca	76.1	100.6	Zn	0.26	0.35
Mg	104.6	139.6	Cl	10.46	13.96

Table 2
Average nutrient concentration in deionized water, initial concentration of the nutrient solution (IC_{ns}), and daily nutrient replenishment rate (ADRR).

Nutrient	Deionized water (mg L^{-1})	IC_{ns} (mg L^{-1})		ADRR (mg L^{-1} d^{-1})	
		1.2 dS m^{-1}	1.2 dS m^{-1}	1.2 dS m^{-1}	1.2 dS m^{-1}
NO_3–N	0.075	110 ± 2.1	130 ± 2.7	2.9 ± 1.1	6.6 ± 1.7
NH_4–N	–	6.9 ± 0.55	8.7 ± 0.86	0.083 ± 0.030	0.19 ± 0.048
P	0.098	30 ± 0.83	51 ± 0.62	1.1 ± 0.40	2.5 ± 0.62
K	0.20	190 ± 5.7	260 ± 5.8	4.9 ± 1.8	7.0 ± 2.8
Ca	0.68	98 ± 11	93 ± 13	2.4 ± 0.89	5.5 ± 1.4
Mg	0.31	34 ± 1.0	70 ± 6.5	3.3 ± 1.2	7.5 ± 1.5
Fe	–	0.65 ± 0.010	0.90 ± 0.11	0.066 ± 0.024	0.15 ± 0.038
Mn	–	1.1 ± 0.12	1.3 ± 0.23	0.033 ± 0.012	0.0749 ± 0.019

The daily replenishment rates and initial concentration values were averages of four replicate samples over two cultivation cycles.

Anndason DP3500 and using EZO™-PMP peristaltic pumps (Atlas Scientific, Jacksonville, FL, USA). A base solution of 1 M KOH was added manually to the nutrient tanks to adjust the initial pH. Then, automatic acid dosing (1 M HNO_3) was implemented with real-time recording and data transfer to an online database. Baseline nutrient solution parameters (EC, pH, DO, and temperature) were measured using lab-grade sensor probes and their corresponding EZO™ embedded circuits (Atlas Scientific, Jacksonville, FL, USA). The nutrient solution in each reservoir was maintained with DO concentrations greater than 6.0 mg L^{-1} and pH values of 5.9 ± 0.1 [28].

2.2. Evaluations

2.2.1. Nutrient solution sampling and analysis

Nutrient solution samples were collected from the hydroponic channel directly after contact with the plants every two to three days, with a total of 12 evaluations during each cultivation cycle. The samples were immediately stored at 4 °C, then analyzed for total ammonia nitrogen (TAN), nitrate/nitrite (NO_3-/NO_2–N), total nitrogen (TN), phosphate (PO_4–P), calcium (Ca), magnesium (Mg), and micronutrients (iron – Fe and manganese – Mn) using reaction kits (HACH® Co. Ltd., Loveland, CO, USA) and a DR 3900 spectrophotometer (HACH®, Loveland, CO, USA). Specific methods used include HACH® 10031 (ammonia-salicylate), 10242 (s-TKN), 8190 (Total-PhosVer), 10293 (Ca and Mg), IR-20 (Fe and Mn). Nutrient solution samples were also analyzed in the University of Florida Institute of Food and Agricultural Sciences (UF/IFAS) Analytical Research Laboratory using the EPA (Environmental Protection Agency) methods 350.1 (NH_4–N), 353.2 (NO_x-N), 351.2 (TKN), 365.1 (total phosphorous), and 200.7 (Fe and Mn).

2.2.2. Tissue sampling and analysis

After transplanting, destructive tissue samples were collected and plant growth parameters were recorded regularly, including fresh and dry weight and nutrient content. An analytical balance was used for weight measurements. Plant roots and shoots (stems and leaves) were separated and individually weighed to determine root fresh weight (RFW) (g) and shoot fresh weight (ShFW = stem fresh weight - SFW + leaf fresh weight - LFW) (g). Total fresh weight (TFW) (g) was obtained by the sum of ShFW and RFW. Total dry weight (g) (root dry weight - RDW + shoot dry weight - ShDW) was determined by drying each sample in a Heratherm OGS750 forced-air oven at 60 °C (Thermo Scientific, Langenselbold, HE, Germany) for 48 h. Dried lettuce samples were then ground in a cyclone sample mill (UDY Corporation, Fort Collins, CO, USA) with a 10-mesh (2 mm) sieve and further analyzed for nutrient elements (N, P, K, Ca, Mg, Fe, and Mn) by an elemental analyzer at the UF/IFAS Analytical Research Lab. Plant tissue analytical methods include EPA method 353.2 (NO_x-N), 350.1 (NH_4–N), 351.2 (TKN), 200.7 (total P), and ICP-EPA method 200.7 (total metals).

2.3. Nutrient mass balance

A mass balance was calculated for each nutrient (N, P, K, Ca, Mg, Fe, and Mn) for each replicated hydroponic channel and EC level. The mass of each nutrient input to the system was determined from the initial nutrient solution and daily additions of stock nutrient solution, water, acid (HNO_3), and base (KOH). After the initial set-up, nutrient inputs came only from the stock nutrient and pH adjustment solutions. The volume of stock nutrient and pH solutions entering the hydroponic unit was measured using a sensor-based dosing system and then totaled each day. The total volume of the stock solution added was multiplied by the known concentration of each nutrient species to calculate the mass: N (TAN, NO_3–N, NO_2–N), P (P_2O_5–P), K (K_2O–K, KOH–K), Ca ($Ca(NO_3)_2$–Ca) Mg ($MgSO_4$–Mg), Fe (Fe-DTPA), and Mn ($MnSO_4$–Mn).

Plant nutrient uptake or assimilation was calculated by multiplying the measured shoot and root dry mass by nutrient concentration from tissue analysis. The mass of nutrients remaining in the nutrient solution was determined based on nutrient solution composition measurements. The nutrient concentration was multiplied by the nutrient solution volume in the reservoir. Finally, the mass of nutrients lost to the environment, potentially due to dentification, precipitation, or biofilm formation, was calculated by subtracting the mass of nutrients taken up by the plant and in the hydroponic nutrient solution, from the total amount of nutrients added to the system. For a given sampling interval during the experiment, the nutrient mass lost (X_{lost}, g) and percent lost (X_{lost}, %) for each nutrient were calculated using Eq. (1) [17]. The mass balance of nutrient X in hydroponics:

$$C_{X,added} V_C = C_{X,water} V + C_{X,plant} M_{plant} + X_{lost} \quad (1)$$

Percent loss of X in hydroponics:

$$X_{lost}(\%) = \left[\left(C_{X,added}V_C - C_{X,water}V - C_{X,plant}M_{plant}\right) \ / \ C_{X,added}V_C\right] \times 100 \quad (2)$$

where X is the individual nutrient for a given sample period, and $C_{X,\ added}$ is the concentration of the particular nutrient in the stock, acid, and base solution, combined in a single term (mg-X L^{-1}); V_C is the total volume of the stock solutions added (L-X); $C_{X,water}$ is the concentration of the individual nutrient in recirculating water (mg-X L^{-1}); V is the volume of recirculating water (L); $C_{X,plant}$ is the concentration of nutrient X assimilated in the plants at harvest (%, mg-X kg^{-1}); M_{plant} is the average dry mass of the plant (g-X); and X_{lost} is the mass of nutrient lost to the environment via denitrification, precipitation, or biofilm generation (g-X, %). In this study, X_{lost} was unknown and was calculated by subtracting the chemical fertilizer term (left side of Eq. (1)) from the rest of the known nutrient products (right side of Eq. (2)). A dynamic equilibrium was assumed during each sampling interval, and average nutrient concentration values were used for each element. The mass balance, thus, assumes steady-state conditions in the production system [17].

2.4. Nutrient uptake efficiency

Nutrient uptake efficiency (NUE, mg-X g^{-1} X_i) was calculated as the ratio of the nutrient uptake in the plant (X_{plant}) and the amount of nutrient added [36].

$$NUE_X = C_{X,plant}M_{plant} \ / \ \left(C_{X,added}V_C \times T\right) \quad (3)$$

where C_x is the concentration of the nutrient in the stock nutrient and pH adjustment solutions (g-X L^{-1}); V_C is the rate of nutrient addition (L day^{-1}); T is the production duration (days); $C_{X,plant}$ is concentration of nutrient X assimilated in the plants at harvest (%, mg-X kg^{-1}); M_{plant} is the average dry mass of the plant (g-X). The initial nutrient concentrations were assumed to be zero because the dry mass of the whole plant upon transplanting was less than 1 g [17].

2.5. Data analysis

Data was checked for outliers and consistency. Since the study involved repeated measurements of nutrient solution and plant tissue samples that violate the independence assumption of parametric tests, statistical analysis was conducted using mass balance data at the end of the experiment. In addition, while the effect of cultivars in nutrient dynamics was assumed to be minimal compared to the

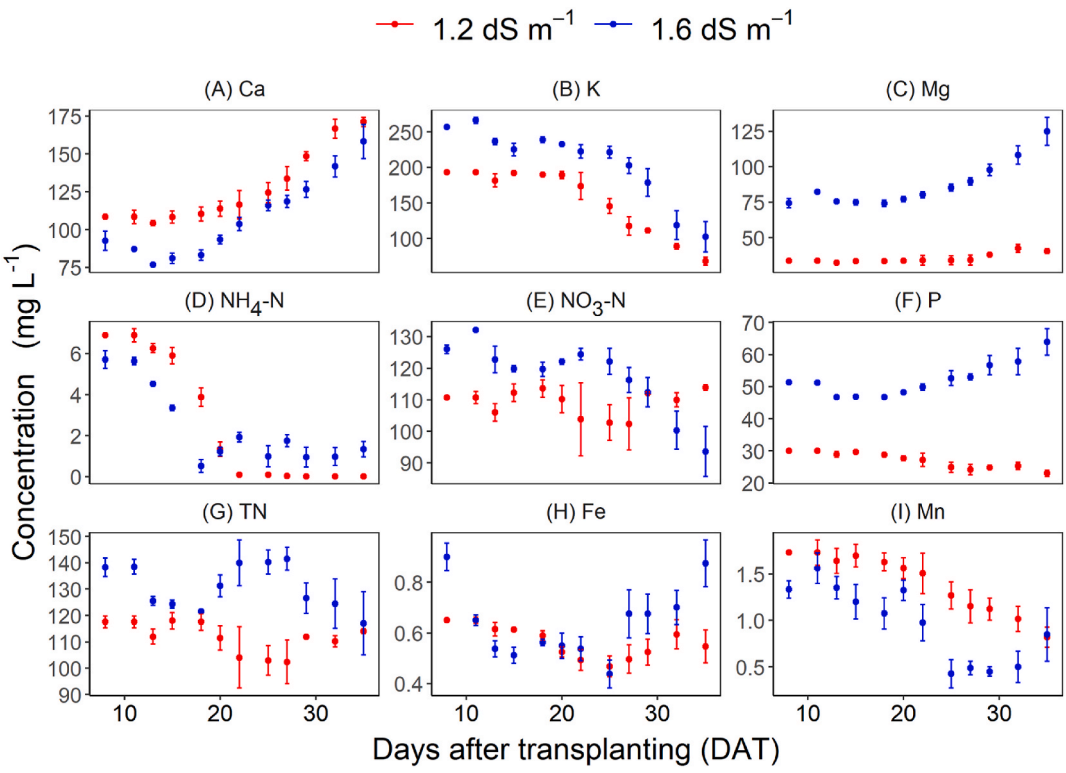

Fig. 2. Dynamics of micro and macronutrients in recirculating hydroponic nutrient solution under electrical conductivity levels of 1.2 and 1.6 dS m^{-1} during 35-d lettuce growth period. The error bars represent the standard error.

effect of EC level, there were differences in cultivar types in each treatment, for instance, under cultivation with 1.2 dS m^{-1} EC consisted of three cultivars ('Rex,' 'Skyphos,' and 'Muir'), while under 1.6 dS m^{-1} EC consisted of one cultivar ('Rex'). A single-factor analysis of variance (ANOVA) test was conducted to assess the effect of EC on nutrient concentration, nutrient uptake, and loss at the end of the experiment. The R programming language was used for data analysis and preparation of graphics.

3. 3. Results and discussion

3.1. Hydroponic nutrient solution dynamics

Results showed that K, Mg, and P concentrations in the recirculating hydroponic nutrient solution were consistently higher throughout the lettuce growth period for the electrical conductivity (EC) level of 1.6 dS m^{-1} than for 1.2 dS m^{-1} EC (Fig. 2B–C, F). In contrast, Ca and Mn concentrations were higher under 1.2 dS m^{-1} EC in relation to EC level of 1.6 dS m^{-1} (Fig. 2A–I). This was against the expectation that the higher EC setpoint for 1.6 dS m^{-1} would increase the concentrations of all elements due to the higher daily average replenishment rates with fixed proportions of nutrient stock solution. Mixed results were observed for the remaining elements, with no clear and consistent differences in nutrient concentrations between the two EC treatments. The K concentration in the stock solution was the highest (11.2 % w w^{-1}), followed by Mg and Ca (7.69 and 5.54 %, respectively), while Mn concentration was the least of all elements considered in this study. Overall, nutrient concentrations in the recirculating water varied over time for all elements, except for Mg and P for the EC level of 1.6 dS m^{-1}, which showed relatively no change throughout the 35-d experiment. Water parameters, such as DO, temperature, and pH, were the same for both treatments. This confirms that differences in nutrient concentrations were not due to environmental factors.

Steady increases in Ca concentrations were observed for both treatments. Percent Ca increases reached 72.8 and 53.5 % between 8 and 35 DAT for EC levels of 1.2 and 1.6 dS m^{-1}, respectively (Fig. 2A). The increasing concentration trend of Ca under both treatments suggests a potential over-application or under-utilization of the element, which competes with other cations at the plant root and contributes to total dissolved ion readings [37]. In contrast, K (Fig. 2B) and Mn (Fig. 2I) concentrations decreased by 60.4–81.5 % and 54.7–81.7 %, respectively, while Fe concentrations remained low, around 0.4–0.9 mg L^{-1} (Fig. 2H). A potential negative dynamic between Ca, K, Mn, and Fe was observed. A similar accumulation of Ca in NFT recirculating nutrient solution was reported in previous studies, alluding to competitive impairment between Ca, K, Mg, and metallic micronutrients [38]. On the other hand, in deep-water culture (DWC) hydroponics, Ca and K were previously reported as relatively stable, around 300 and 150 mg L^{-1}, respectively [12]. Compared to DWC, stock nutrient additions, CO_2 supplementation, and hydroponic system design may cause differences between

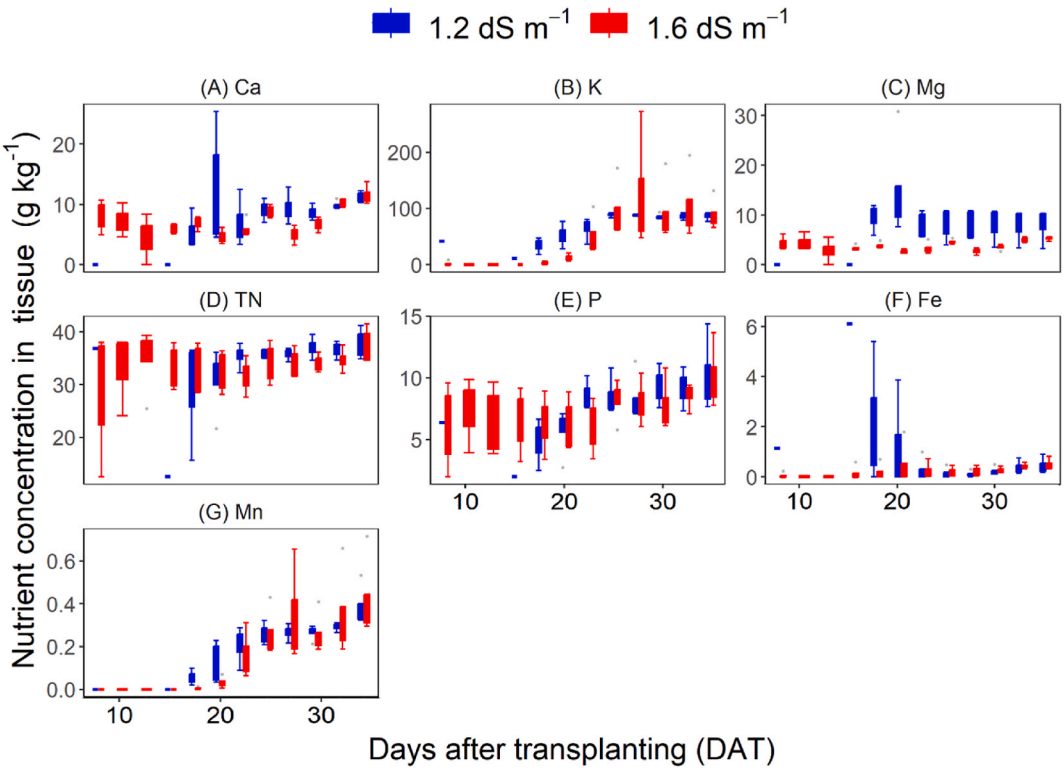

Fig. 3. Nutrient concentration in dry tissue samples throughout the 35 days of production under electrical conductivity setpoints of 1.2 and 1.6 dS m^{-1}. The error bars represent the standard error.

reported studies.

Despite their essential role in plant development, there is a lack of information about Fe and Mn dynamics in NFT systems [39]. While Fe concentration was constant, Mn showed a steady decrease with the progression of the study. Studies show that Fe and Mn availability in recirculating nutrient solutions depends on the pH (increasing availability with decreasing pH) and uptake concentration [40]. The pH in this study was constant at the optimal range (5.5–6.0); other factors such as water uptake, plant age, and nutrient supply may have influenced changes in Mn concentration dynamics.

The concentration of NH_4–N was initially high but showed a rapid drop under both treatments during the first 20 days to nearly 0–1 mg L^{-1} for the remainder of the lettuce growth period (Fig. 2D), suggesting nitrification and other changes in the water chemical environment within the first 20 days. Assimilation of NH_4–N into lettuce plants was previously reported to be less than 2 % of the total NH_4–N removed from the nutrient solution, while the remainder of the NH_4–N removal was reported to be through oxidation to nitrate [41]. Nitrate nitrogen (NO_3–N) (Fig. 2E) and total N (Fig. 2G) did not show a consistent trend. At the end of the study, the average nitrate concentrations were 109 and 117 mg L^{-1} for the EC levels of 1.2 and 1.6 dS m^{-1}, respectively, and were within the recommended range of 100–150 mg L^{-1} [42].

Phosphorus increased slightly under 1.6 dS m^{-1} EC but remained constant under 1.2 dS m^{-1} EC (Fig. 2F). However, P concentrations in recirculating hydroponic lettuce may not significantly influence N, K, Ca, and Mg concentrations [43]. Overall, observed results of NO_3–N, NH_4–N, P, Fe, and Mn dynamics for 35 days were consistent with existing previous studies [12,17,38,41]; however, limited information exists characterizing macro and micronutrient composition in completely recirculating nutrient solutions for hydroponic NFT lettuce production systems.

3.2. *Nutrient content in tissue and biomass accumulation in lettuce plants*

Nutrient content results consistently showed that EC treatments did not affect nutrient uptake, except Mn, which showed slight differences between the two treatments between days 25 and 35 (Fig. 3). However, nutrient content in lettuce tissue showed exponential increases with the progression of the lettuce growth period. Moreover, fresh (Fig. 4A) and dry (Fig. 4B) biomass accumulation of lettuce plants was not significantly affected by EC level. Throughout the lettuce growth period, biomass accumulation showed a steady and consistent increase, which reached about 300 g of fresh biomass per lettuce plant. The slight variation under the high EC (1.6 dS m^{-1}) treatment confirms that the effects of cultivar and EC on fresh and dry biomass accumulation are minimal.

These results underscore, while EC offers an inexpensive, rapid assessment of nutrient solution quality and an NFT nutrient dosing recommendation [32], observed nutrient accumulation and depletion, specifically in the cases of Ca, K, Mn, and NH_4–N, indicates the opportunity for improved operating methods and sensing tools to enable continuous nutrient solution reuse. Understanding plant nutrient uptake at different phases of development and nutrient interactions within the growing season would allow growers to fine-tune observed nutrient accumulation and depletion, specifically in the cases of Ca, K, Mn, and NH_4–N, indicating their nutrient blends and individual nutrient application rates. A current one-size-fit nutrient dosing recommendation based on the EC setpoint of 1.6 dS m^{-1} was less effective in overall nutrient use efficiency. Under cultivation of lettuce in NFT hydroponics by 25 days [44], the EC decreased by 16 % at the end of the cultivation cycle. This variation depends on the species and season of the year in which cultivation

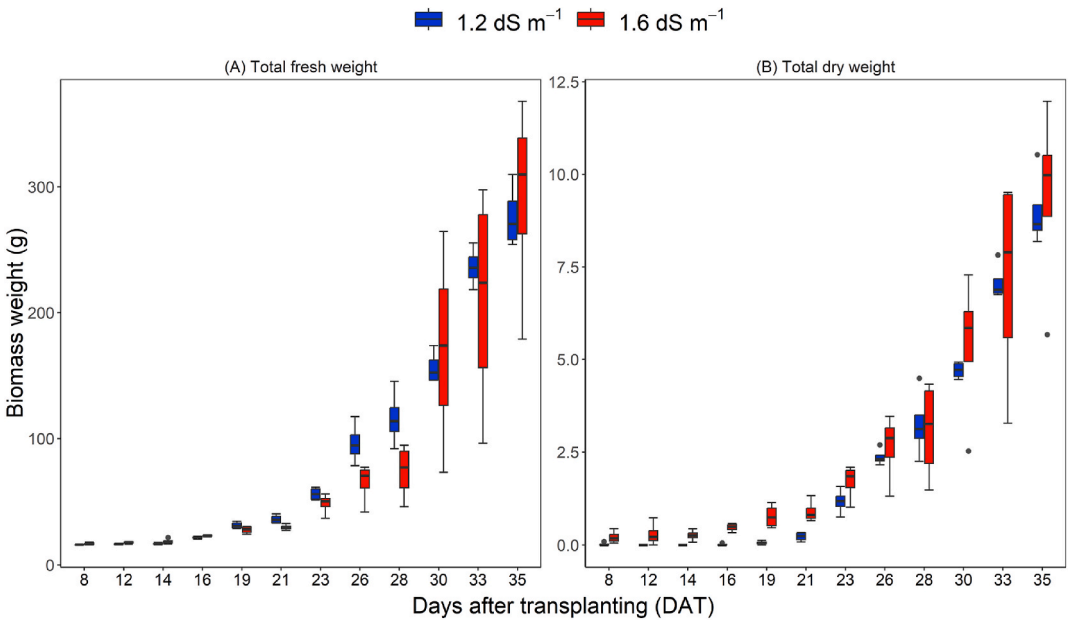

Fig. 4. Fresh and dry biomass accumulation for a single lettuce plant under electrical conductivity setpoints of 1.2 and 1.6 dS m^{-1} over 35 days of lettuce production. The error bars represent the standard error.

is practiced. For instance, under cultivation of coriander also in NFT hydroponics by 25 days [45], the EC levels decreased by 13 and 14 % at the end of the cultivation cycle in summer and spring.

3.3. Nutrient mass balance and nutrient uptake efficiency

Results showed that EC treatment effects were more pronounced on the proportion of nutrients lost to the environment and available in hydroponic nutrient solution (Table 3, Fig. 5). In contrast, the treatment effect on nutrient uptake (assimilation) was consistently non-significant relative to nutrient type (Table 3). Nutrient uptake efficiency (NUE) indicates the proportion of added nutrients absorbed by the plants. As the experiment and lettuce growth progressed, NUE consistently increased, though variations in the magnitude of increase were observed among different nutrients.

Regardless of EC level, K exhibited the highest uptake, while Fe and Mn showed the least (Table 3, Fig. 5B–F-G). Results showed that NUE ranged between 10 and 14 % N, 12–13 % P, 19–22 % K, 4–6 % Ca, 3 % Mg, 2–3 % Fe, and 10–11 % Mn (Table 3). The lowest observed nutrient uptake efficiency for Ca, Mg, and Fe suggests potential focus areas for future research to optimize hydroponic nutrient efficiencies. Over the 35-day lettuce growth period, nitrogen losses to the environment were relatively constant but were more than plant uptake under both treatments; only 50–62 % of the N remained in the nutrient solution, while only 10–14 % was taken up by the plants (Table 3, Fig. 5E).

The lettuce biomass N concentration averaged 28–37 g N per kg of dry mass (DM) of lettuce (Fig. 3D), which was comparable with reports from previous studies. Hydroponic systems reported similar lettuce N contents, averaging 2–5 % N of DM (autumn) [31,42,46], 1.3–3.1 % N of DM (spring) [42], and 0.548–0.916 g-N per plant lettuce N content [47]. Recent hydroponic studies reported similar trends, where the mass of N taken up by the plants was less than the N remaining in the water and lost to the environment. In NFT hydroponics, N uptake tended to increase over time, with 9–33 % of total N uptake occurring 14 days after transplanting (DAT) and 54–88 % at 28 DAT [42]. Furthermore, deep-water culture (DWC) hydroponics reported similar plant N assimilation (14–24 %) but comparably higher N losses (76–87 %) [17]. A lower percent N loss in the indoor NFT suggests improved efficiency over DWC, possibly from smaller reservoir nutrient solution volumes or the thin nutrient solution film around the root zone. Precisely controlled environmental and lighting conditions in indoor grow rooms versus greenhouses may also lower nutrient losses [48]. Lighting conditions may also influence N uptake, and lettuce tissue N contents were found to increase 16–17 % under red/blue LED lights compared to white lights [49]. Furthermore, N overapplication during the early plant stages and heterotrophic microbial communities may contribute to denitrification and nitrous oxide (N_2O) emissions [50]. Excess N in the aerated reservoirs and shallow channels may undergo denitrification, leading to total N loss.

Phosphorus losses averaged between 11 and 35 % under the EC levels of 1.2 and 1.6 dS m^{-1}, respectively. The EC level effect on P loss was significant ($p < 0.05$) (Table 3). A lower EC may have a more significant P loss because lettuce P uptake may increase with EC [51,52]. Most P (52–77 %) remained in the hydroponic nutrient solution (Table 3). The lettuce tissue P content, 0.39–1.01 % of DM, was within the reported range of 0.4–1.05 % [31,46–48]. Previous studies stated comparable P assimilation (11–21 %) and losses (15–27 %) [17], indicating excess P application to the recirculating nutrient media than the plants require. Fish culture coupled with NFT hydroponics also had similar P assimilation (29.4 %) and losses (13.1 %), presumably to suspended solids and precipitate [53].

As shown in Fig. 6, the rise in N and P uptake at 21 DAT, the start of rapid lettuce growth, was comparable to a reported 80 and 59 % increase in N and P absorption between 20 and 30 DAT [54]. P inputs that remained in the nutrient solution or were lost decreased over time, suggesting that P use and uptake efficiency increased with decreasing P inputs to a limit [43,54,55].

Despite losses averaging 16–27 % for the entire growth period, potassium had the highest plant uptake, 19–21 % (Table 3), indicating a greater nutrient uptake efficiency (Fig. 6B). K uptake notably increased over time, and results were comparable with other studies that reported 46–63 % K uptake by 28 DAT [56]. Absorption of K was the highest between 23 and 35 DAT, corresponding with reported increases of 48 % during the final ten days of harvest [54]. K content, averaging 3.7–10.8 % of DM, was proportionally the largest, followed by N, Ca, P, and Mg [31,46–48,57,58].

Similarly, Ca had the smallest losses at 14–19 % of the total added, with no significant differences between EC levels (Table 3). Compared with the other macronutrients, Ca existed primarily in the recirculating nutrient solution (76–80 %), with a small percent of the inputs (5–6 %) taken up by the plant on average during the growth period (Table 3, Fig. 5A). In contrast, Mg, Fe, and Mn losses were the highest, ranging between 29 and 62 %, 55–67 %, and 14–35 %, respectively (Table 3). These nutrients had the lowest percentages of assimilation, 3–4 % (Mg), 2–4 % (Fe), and 9–16 % (Mn) of inputs, suggesting a comparably lower uptake (Fig. 6C–F, G). Plant

Table 3
Summary of nutrient mass balance as a percentage of nutrients lost, assimilated, and remaining in the nutrient solution at the end of each experiment.

Status	EC	N	P	K	Ca	Mg	Fe	Mn
	(dS m^{-1})	(%)						
Lost	1.2	40.0 ± 5.06	34.8 ± 3.91	27.1 ± 3.97	19.2 ± 3.26	62.1 ± 4.31	67.0 ± 4.03	13.6 ± 6.40
	1.6	26.7 ± 3.75	11.0 ± 3.19	15.7 ± 2.54	14.0 ± 3.51	29.2 ± 2.34	55.7 ± 2.13	35.3 ± 4.74
Assimilated	1.2	10.3 ± 0.84	13.4 ± 1.14	21.5 ± 1.15	4.51 ± 0.29	2.91 ± 0.26	2.30 ± 0.19	11.1 ± 0.58
	1.6	14.0 ± 1.29	11.8 ± 1.57	19.2 ± 2.60	6.09 ± 0.80	2.83 ± 0.35	2.76 ± 0.54	9.58 ± 1.33
Nutrient	1.2	49.8 ± 4.36	51.8 ± 3.04	51.4 ± 3.01	76.3 ± 3.07	35.0 ± 4.09	30.7 ± 3.95	75.3 ± 5.95
Solution	1.6	59.4 ± 3.47	77.2 ± 1.79	65.1 ± 1.35	79.9 ± 2.99	68.0 ± 2.11	41.5 ± 1.75	55.1 ± 3.98

Each value represents an average of four data points with the standard error.

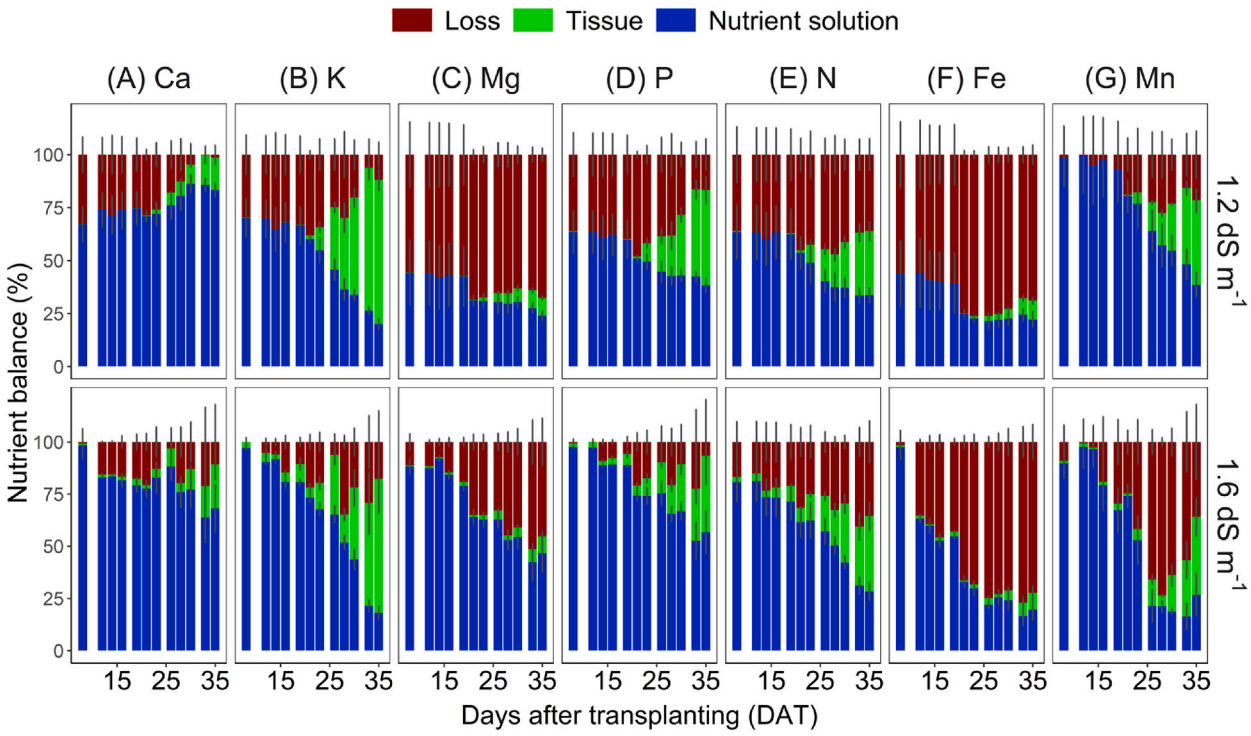

Fig. 5. Nutrient mass balance components in different forms (assimilated in lettuce tissue, remaining in nutrient solution, and unaccounted for) as a percentage of nutrients added under EC levels of 1.2 and 1.6 dS m^{-1}.

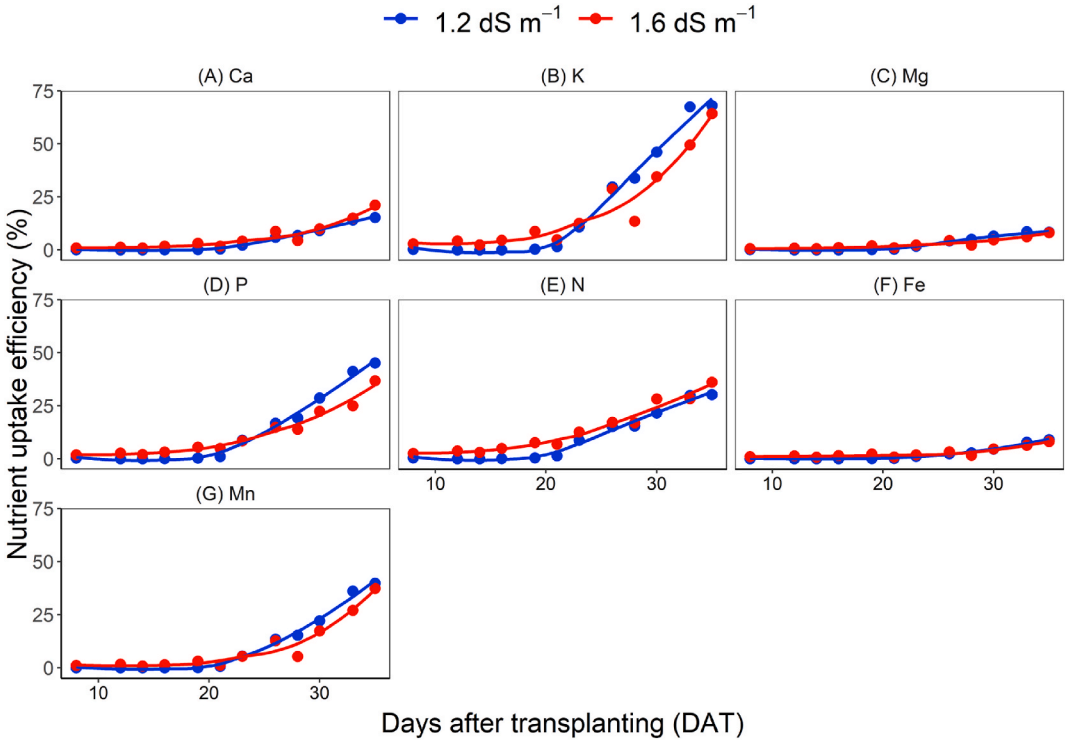

Fig. 6. Nutrient uptake efficiency (NUE) of lettuce plants under 1.2 and 1.6 dS m^{-1} EC treatments.

nutrient contents, 0.35–1.53 % (Ca), 0.17–0.65 % (Mg), 0.0047–0.0141 % (Fe), and 0.0098–0.483 % (Mn) of DM, were within ranges that were reported by other studies [31,46,48,57,58]. It is worth noting that Fe had the highest losses for the two EC levels; however, limited information exists on iron loss mechanisms in hydroponics. Aeration can change the iron species and remove iron through oxidation [59,60].

High N and P concentrations in the recirculating nutrient solution indicate more N and P were added than the plants require, resulting in losses most likely due to denitrification (N) and precipitation (P). This suggests that hydroponic growers could reduce P inputs into continuously NFT recirculating system without compromising yield [55]. Nutrient management methods based on maintaining a high EC through the addition of pre-mixed nutrient blends and weekly nutrient solution replacement resulted in similar tissue N and P contents [49]. Early stages of lettuce production in NFT systems were characterized by high nutrient concentrations remaining in the nutrient solution but increases in lettuce growth over time led to increased nutrient and water demand, reducing nutrient and water losses [49]. Sensors-based approaches may provide a tool for managing N concentrations in recirculating nutrient solutions; however, lower EC setpoints at early lettuce stages and incremental EC adjustments based on biomass increases and corresponding nutrient uptake increases may improve hydroponic NFT efficiency.

Furthermore, steady increases of Ca in the recirculating water suggest more Ca was added than the plants required, leading to accumulation. Studies show that Ca, Mg, and K in nutrient solutions compete in the cation exchange capacity (CEC); therefore, their concentrations and ionic ratios impact nutrient uptake and elemental composition of lettuce leaves [61]. In this regard, Ca accumulation may decrease the availability of other nutrient cations as these ions compete for active sites on the root [54]. An elevated Ca could reduce Mg uptake; therefore, monitoring the ratios of K, Ca, and Mg is necessary [62]. Nutrient uptake efficiency may not be a linear function of concentration in the nutrient solution, and Mg uptake could be more highly affected by nutrient concentration compared with the Ca and K ratio [63].

Overall, observed dynamics in nutrient concentrations in the hydroponic nutrient solution and lettuce tissue during the study suggest that the practice of maintaining a constant EC by adding high concentrations of nutrients requires revisions. Revisions should consider the plant growth stage and corresponding nutrient uptake to reduce losses. Incremental increases in the EC to consider increasing lettuce biomass may fine-tune nutrient application at early growth stages. Hydroponic nutrient management should continuously adjust to meet plant nutrient needs and optimize nutrient use efficiency.

4. Conclusion

This study provides comprehensive insights into the dynamics of recirculating nutrient solution, nutrient uptake efficiencies (N, P, Ca, Mg, K, Fe, and Mn), and nutrient losses in hydroponic NFT lettuce production systems. Nutrient imbalances compounded as the nutrient solution recirculated without replacement over the duration of lettuce production. Nutrient uptake efficiencies remained low for most elements, challenging the reliability of the recommended nutrient dosing based on maintaining constant electrical conductivity (EC). The findings also consistently reveal inefficiencies in current hydroponic nutrient dosing and management practices, which result in significant nutrient loss and under-utilization.

Nutrient dosing guidelines may consider updating measurement techniques and implementing operational changes in addition to EC monitoring. Nutrient management should also target providing critical nutrients plants need at the correct proportions at each growth stage. Findings from this study provide a comprehensive dataset critical to improving hydroponic nutrient management beyond N and P; however, further research is needed to explore methods to increase hydroponic nutrient uptake efficiency and consider nutrient dynamics at different plant growth stages for resource optimization.

Funding sources

This work was supported by a UF IFAS ABE Pathfinders Fellowship and a UF Global Food Systems Institute Graduate Fellowship.

Data availability

Data will be made available upon request.

CRediT authorship contribution statement

Kelsey Vought: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Haimanote Bayabil:** Writing – review & editing, Visualization, Supervision, Funding acquisition, Formal analysis. **Jean Pompeo:** Visualization, Investigation. **Daniel Crawford:** Investigation. **Ying Zhang:** Supervision, Resources, Conceptualization. **Melanie Correll:** Supervision, Resources, Conceptualization. **Ana Martin-Ryals:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors thank Stephen Lantin and Anna Langley for their contribution to data collection and UF IFAS Analytical Research Lab for their contribution to sample processing.

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