Food and Energy Security

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ORIGINAL ARTICLE OPEN ACCESS

Temporal Variation of Nutrient Ratios Within Hydroponic Nutrient Solutions

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Received: 2 December 2025 | **Revised:** 25 February 2026 | **Accepted:** 27 February 2026

Keywords: electrical conductivity | fertigation | hydroponics | macronutrients | micronutrients

ABSTRACT

Indoor hydroponic farming enables pesticide-free food production with significantly lower water use than conventional agriculture. However, standard practices often involve frequent replacement of nutrient solutions to manage nutrient imbalances and microbial contamination, generating large volumes of nutrient-rich waste with both environmental and economic costs. We investigated the temporal dynamics of nutrient composition under two contrasting nutrient management strategies, focusing on the impact on cost per yield and sustainability on Red Batavia lettuce production. In Treatment 1, half-strength Hoagland's solution was replaced weekly to maintain an electrical conductivity (EC) of 1.0–1.2 mS/cm^{-1} as per typical industry practice to maintain target nutrient ratios. In Treatment 2, nutrient solution was not replaced, and instead topped up only to maintain sump tank volume, irrespective of EC. Macro and micronutrient concentrations were monitored across both treatments to evaluate EC as a proxy for nutrient availability. While Treatment 1 achieved significantly higher yields (> 20%; $p < 0.05$), the cost per gram of fresh and dry weight was substantially higher than in Treatment 2, by 63% and 66%, respectively. Nutrient depletion accelerated at later growth stages, particularly in Treatment 2, suggesting increased uptake efficiency under limited availability. Over both treatments, EC was found to be a poor proxy for actual nutrient changes. These findings highlight a trade-off between yield maximisation and nutrient-use efficiency, emphasising the need for more strategic nutrient management. Our results support the advancement of circular, resource-efficient hydroponic systems aligned with long-term sustainability goals. Specifically, the integration of solution reuse, targeted nutrient dosing, and non-disruptive pathogen control could improve environmental performance and economic viability in indoor food production.

1 | Introduction

If greenhouse gas (GHG) emissions continue at the present rate, a 2°C rise in global temperature above pre-industrial levels is likely by the late 2020s (Bevacqua et al. 2025; McCulloch et al. 2024). Agriculture is a major contributor to this trajectory, accounting for 13.5% of global greenhouse gas emissions while consuming 70% of freshwater resources (Pomoni et al. 2023). Feeding a global population of 8.1 billion under current practices would further amplify environmental degradation, particularly if expansion into remaining natural habitats continues, in contrast to intensifying land already under cultivation (Adegbeye et al. 2020; Venter et al. 2016).

Sustainable intensification combines traditional agricultural practices with emerging technologies to raise yields per unit area while minimising environmental costs (Xydis et al. 2020). Hydroponics represents one promising component within a broader, holistic range of sustainable agricultural practices, offering the potential for year-round cultivation with reduced

land, water, and nutrient inputs (Rajaseger et al. 2023; Sharma and Bipana 2024).

While hydroponic systems can achieve improved yield, water use efficiency, and spatial productivity under controlled conditions, their environmental footprint remains highly context dependent (Barbosa et al. 2015; Goh et al. 2023; Kozai 2018; Touliatos et al. 2016). Chief among the limitations are high energy demands and the need for regular replacement, and therefore disposal of nutrient solution, which risks contributing to point-source pollution (Ahn et al. 2021; Barbosa et al. 2015; Lee et al. 2018; Martin and Molin 2019; Son et al. 2020). These challenges underscore the importance of developing more sustainable nutrient management strategies to ensure that hydroponic systems fulfil their potential as climate-resilient agricultural solutions.

In hydroponics, plants uptake nutrients via the roots using mechanisms similar to those in soil-based environments, although these undergo metabolic and morphological adaptations in response to the soil-less environment (Lei and Engeseth 2021). As in soil, the 'essential nutrients' including nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S) are primarily absorbed in their ionic forms via diffusion, active transport and mass flow. These mechanisms are influenced by nutrient concentration, pH, the microbial makeup of the rhizosphere and other abiotic factors like temperature, humidity and light availability (Al Meselmani 2022; Baiyin et al. 2021a; Xiaochuang et al. 2015).

Although hydroponic systems remove mechanical barriers to nutrient uptake, nutrient bioavailability must be carefully managed to prevent nutrient deficiency or even toxicity in plants (Sambo et al. 2019). Due to varying rates of micro and macronutrient uptake between plants and the risk of complexation and ion precipitation associated with temperature, dissolved CO_2 concentrations, ionic strength and pH changes, as well as certain growing practises, periodic replacement of the nutrient solution is common at the commercial scale (Ahn et al. 2021; Carmassi et al. 2003; Kumar and Cho 2014; Lopez et al. 2003; Pomoni et al. 2023; de Rijck and Schrevens 1998; Sambo et al. 2019; Sharma et al. 2018).

Plants exhibit differential uptake rates not only between nutrients, resulting in the faster depletion of some ions over others, but also across developmental growth stages (Pomoni et al. 2023). While overall nutrient assimilation generally positively correlates with biomass accumulation, the relative demand for specific nutrients has been shown to vary over time. Availability of certain nutrients may therefore decline more rapidly at key growth stages to meet the physiological demands of developmental processes (Bodale et al. 2021; Gong et al. 2024; Hartz et al. 2007; Xu et al. 2004). As highlighted by Pomoni et al. (2023), monitoring these independent, dynamic nutrient fluxes poses a challenge in commercial settings, where monitoring typically relies on electrical conductivity (EC) and pH as proxies for solution quality. EC provides a rapid and cost-effective estimate of total ion concentration in nutrient solutions, but it reflects only aggregate salinity and cannot distinguish between individual nutrients (Son et al. 2020).

Optimal nutrient management involves not only monitoring EC and pH, but also understanding the chemical equilibria between ions, requiring some understanding of stoichiometry. Many growers first purify nutrient solutions, for example through reverse osmosis (RO), and by adjusting pH (Trientini et al. 2021) with the addition of an acid (usually phosphoric or citric acid) or a base (usually potassium carbonate or potassium hydroxide) undertaken either manually or using automatic dosers (Cambra et al. 2018; Singh et al. 2019; Trientini et al. 2021).

For biosecurity, disinfection methods such as UV, ozone, or fine filtration are employed. However, these methods can disrupt nutrient stoichiometry and impact yield. UV and ozone treatments deplete Fe^{2+} and Mn^{2+} by up to 90% and 35%, respectively, and can induce phytotoxicity through oxidative stress (Lau and Mattson 2021; Lee and Lee 2015; Vargas et al. 2023). Slow filtration is less disruptive but reduces dissolved oxygen and has variable efficacy (Ehret et al. 2001; Mine et al. 2000). Chemical disinfectants like hydrogen peroxide and chlorine are also used, but risk phytotoxicity, deplete beneficial microbes, and alter nutrient bioavailability (Hendrickson et al. 2022; Lau and Mattson 2021; Kriem et al. 2023; Saldinger et al. 2023). pH reduction (e.g., to pH4) may combat pathogens like *Pythium aphanidermatum* (Edson) Fitzp., but reduces the solubility and availability of nutrients and can reduce biomass accumulation by up to 60% (Kudirka et al. 2023).

Evaporation is another major concern, as it concentrates salts, disturbs nutrient balance and pH, and leads to elevated EC. An EC exceeding 1.4 mS/cm^{-1} can indicate conditions that hinder calcium uptake, potentially resulting in tipburn in lettuce (Fayezizadeh et al. 2021; Savvas et al. 2005). Evaporation can also cause pH drift via ammonium volatilisation, leading to micronutrient lockout or precipitation (Jeong and Lee 2008; Sambo et al. 2019). Covering fertigation systems with opaque, light-blocking lids helps limit these effects and suppress algal growth (Conn et al. 2013; Robinson et al. 2006).

Due to the trade-offs inherent in managing hydroponic solution, growers often combine several strategies (Hosseinzadeh et al. 2019; Van Os 2001). However, as discussed by Ahn et al. (2021), the industry is still in its technological infancy, and the tools available for routine monitoring and adjustment are necessarily those that are practical, affordable, and simple to use. For many growers, these tools remain crude and inadequate for accurately assessing hydroponic solution status and correcting deviations from optimal conditions. As such, the strategy of managing this still primarily involves periodic dumping and replacement of entire nutrient solution reservoirs, with a minority of growers reusing wastewater (Langenfeld and Bugbee 2024).

This study set out to address the following hypotheses pertaining to the commercial practice of periodic (weekly) nutrient solution replacement in hydroponic growing systems:

Hypotheses:

1. Fluctuations in nutrient concentration and ratios are significantly influenced by crop developmental growth stages.
2. Periodic replacement of nutrient solution:

   2.1 Significantly improves nutrient availability.

   2.2 Significantly increases yield.

   2.3 Is significantly more economical in terms of cost per gram of saleable biomass.

3. Changes in EC reflect changes in overall nutrient concentrations.

To address these hypotheses, 384 Red Batavia lettuce plants were supplied continuously with half strength modified Hoagland's solution during 3 weeks of vegetative growth in recirculating hydroponic systems. Two dosing regimes were compared: one where the nutrient solution was periodically replaced to maintain an EC value within the range of 1–1.2 mS/cm^{-1} (Treatment 1), and another where no adjustments for EC were made, with sump tanks instead continuously topped up with nutrient solution to a predetermined level (Treatment 2). Treatment 1 most closely resembled common practice within the industry (Farhangi et al. 2023; Hosseini et al. 2021; Soufi et al. 2023).

2 | Methods

2.1 | Growing

The trial was conducted at Greens for Good (GfG), a vertical farming enterprise established in Liverpool, UK in 2019. Lettuce variety Red Batavia was selected as a model organism for several reasons. It is of significant economic importance as one of the most commonly grown hydroponic crops (Ibrahim et al. 2023; Matysiak et al. 2022; Meng and Runkle 2023; Modarelli et al. 2022; Sng et al. 2021). The leafy vegetable belonging to the *Asteraceae* family is commonly consumed raw in salads, and despite public perception around its low nutritional value, it is rich in vitamin C, folate, β-carotene, phenolic compounds, minerals and fibre (Kim et al. 2016; Majid et al. 2021; Sapkota et al. 2019). In addition to being an extensively researched experimental variety, the cultivar is the main crop of GfG, making the trial directly applicable to a commercial setting.

Lettuce Red Batavia seed (by CN Seeds Ltd) was sown into Cultilène rockwool plugs in three plastic cell tray inserts. Each cell insert contained 150 plugs which were soaked in tap water, purified through reverse osmosis (RO), until uniformly moist (Eshkabilov et al. 2021; Sublett et al. 2018; Yan et al. 2019). The inserts were placed into trays, and then into a germination tent in complete darkness at 90% ± 5% humidity and 23°C ± 2°C for 48 h (Kobayashi and Yamaji 2020). A film of 10 mm RO water was maintained in the bottom of each tray. Humidity was maintained using a Ram Ultrasonic Humidifier. Subsequently, they were moved to a propagation rack, and cloches placed on top, with uniform illumination from Valoya C series, 90 W, AP 673 L spectrum LEDs at 120 $\mu mol\,m^{-2}s^{-1}$ for 16 h d^{-1} (Nguyen et al. 2022; Paz et al. 2019). Temperature was maintained at 23°C ± 2°C when lights were on and 21°C ± 0.2°C when lights were off. On emergence of seedlings, samples were fertigated with a diluted ¼ strength Hoagland's solution (EC 0.6) cloches were removed, and humidity was maintained at 70% ± 10% (Lee et al. 2019; Samarakoon et al. 2020; Song et al. 2020).

At 14 days after sowing (DAS), approximately the four true leaf growth stage, uniform plants were selected and transplanted into 3 hydroponic systems comprising eight 150 cm ZipGrow towers (Lee et al. 2019). A ZipGrow tower is a plastic gutter-like structure, which stands vertically, usually adjacent to a series of others, to form a wall (see Figure 1). Before transplant into each system, the ZipGrow towers were cleaned mechanically using a jetwash, and sterilised using Isopropyl Alcohol 99.9%. The fertigation systems were sterilised, first by draining the solution, and then by recirculating H_2O_2 at a concentration of 200 ppm, double the reported concentration required to be effective in eliminating a range of antagonistic bacteria (Bosmans et al. 2016). This was then drained, and the system was recirculated with RO water to remove residue. Draining and recirculation of RO water was repeated once more before leaving to dry. Nutrient solution from an 80 L black plastic sump tank filled with half strength Hoagland's solution (full composition given in Supporting Information; Table S1) was delivered to each of these via a fertigation system consisting of rubber tubing, plastic guttering and a Jecod DCS Series DCS2000 Variable Flow Dc Aquarium Pump.

Solution was recirculated around the system at a rate of 1.5 $L\,min^{-1}$ (Baiyin et al. 2021a, 2021b; Genuncio et al. 2012). Each tower contained a plastic grow medium, Matrix Media, and a 'wicking strip': a piece of material laid down the centre of the tower, designed to intercept nutrient solution as it is dripped from above, and to absorb and retain it so that it was immediately available in the rhizosphere. Nutrient solution (half strength Hoagland's) was prepared fresh at the start of each treatment and stored in six sealed one-litre Duran bottles at room temperature. Solution was maintained at pH 6.5 ± 0.5 using H_3PO_4, and aerated using air diffuser stones connected to a compressed air supply through silicone tubing (Eshkabilov et al. 2021; Hoagland and Arnon 1950; Touliatos et al. 2016). pH and EC were monitored using meters by Essentials. To limit evaporation and algal growth in the fertigation system, every tank had a lid.

Conditions were maintained across each system, with 8 plants per tower (as per industry recommendation), producing 192 samples per treatment, grown to harvest over three and a half weeks (40 DAS) (ZipGrow 2023). The photoperiod was maintained at 16 h d^{-1}, and the Photosynthetically Active Radiation (PAR) was increased to a uniform spread of 200 $\mu mol\,m^{-2}s^{-1}$ using Valoya C series, 90 W, AP 673 L spectrum LEDs (Liu et al. 2023). These were calibrated using a Skye PAR Sensor. Ambient light was entirely blotted out using a blackout sheet. Temperature was maintained at 23°C ± 2°C when lights were on and 21°C ± 0.2°C when lights were off (Ahmed et al. 2020). Environmental conditions were monitored using Gravity light sensors, DHT22 Temperature and humidity sensors, and Analog Infrared sensors for CO_2.

For Treatment 1, nutrient solution was replaced on a weekly basis, maintaining the EC within a suitable range (1–1.2 mS/cm^{-1}) throughout (Hosseini et al. 2021; Touliatos et al. 2016). On 21 DAS, 28 DAS and 35 DAS, the contents of the entire sump tanks were removed, and the whole fertigation systems drained. The sump tanks were cleaned using RO water and isopropyl alcohol before being dried and replaced. The tanks were then refilled with 70 L of fresh half strength Hoagland's solution. This process was undertaken within a 15-min window, whilst LEDs were off, to minimise the impact on live samples. Cultilène rockwool plugs and grow media within the system retained their moisture throughout.

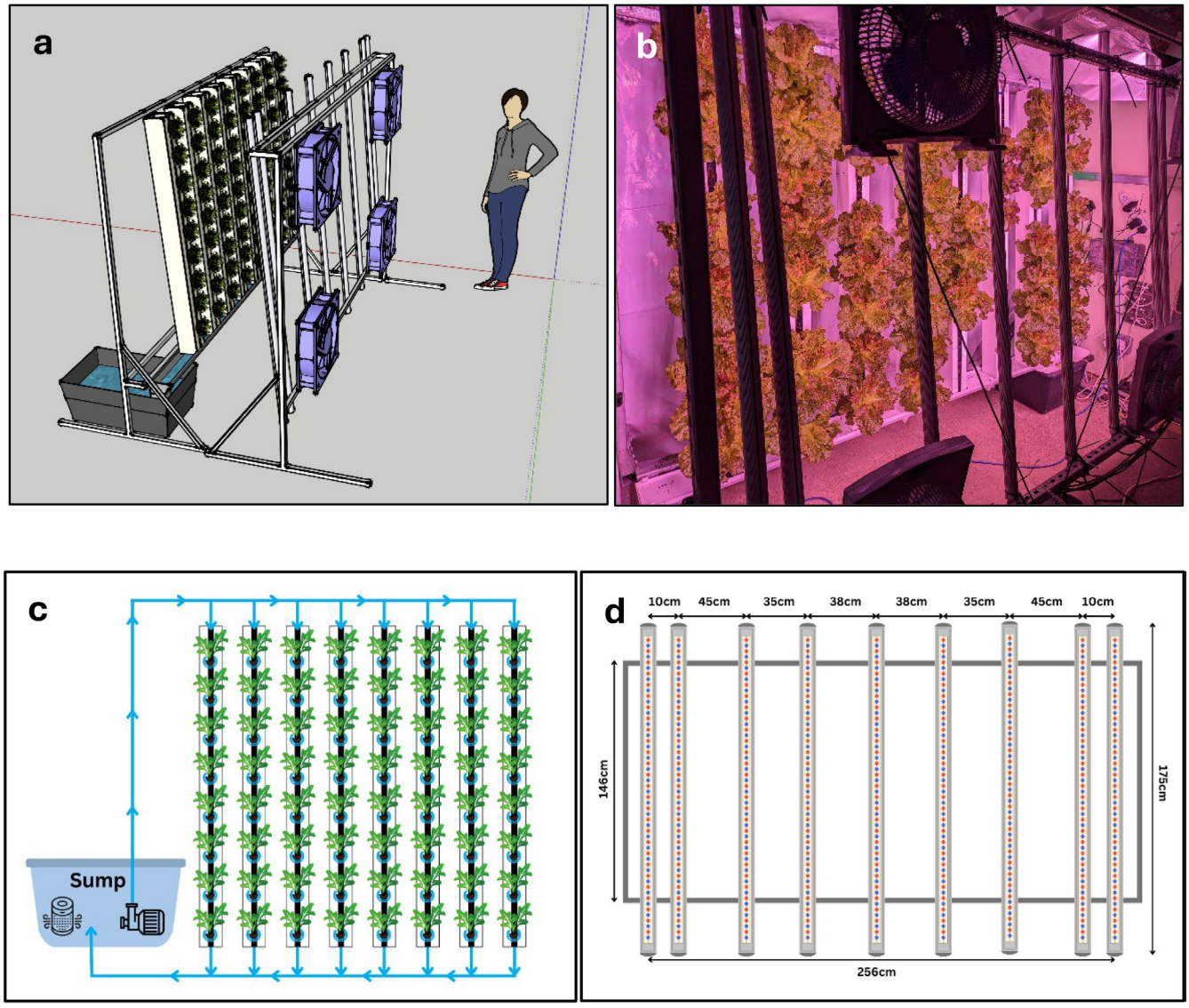

FIGURE 1 | 3D model of one of three grow systems (a) and actual setup at GfG (b). 2D model of fertigation system with sump tank containing an air stone and submersible pump (c). ZipGrow towers were connected via rubber tubing and dripper systems. LED lighting rig, positioned 60.5 cm away from the grow area to provide an even spread of 200 μmol m^{-2}s^{-1} when angled congruently with the angle of the ZipGrow towers, at 43.2° (d).

Alongside Treatment 1, half strength Hoagland's solution was recirculated in a fourth Control system in the absence of any biological components. Solution samples were taken on the same dates as in the treatment group.

For Treatment 2, half strength Hoagland's solution was recirculated to the same number of samples, grown and configured in exactly the same way as in Treatment 1 with the exception of periodically replacing the nutrient solution. Instead, for Treatment 2 the solution volume was maintained at a predetermined level (70 L volume) in the sump tank, topping up as required with 10 L of nutrient solution whenever the sump volume fell to 60 L. At no stage was solution dumped or replaced.

2.2 | Solution Sampling

For nutrient analyses, 100 mL samples of nutrient solution were taken from each sump tank immediately before and 30 min after replacing (in Treatment 1) and topping up (in Treatment 2). These were frozen in plastic bottles and kept in a −20°C freezer until they were fully thawed and processed (Yang and Kim 2020). Samples were analysed using a Hanna HI-83300-02 Multi-Parameter Benchtop Photometer & pH Meter and respective test kits for macro and micronutrients. Protocols for each of these tests were derived from the HI83300 Multiparameter Photometer for Water & Wastewater Instruction Manual by Hanna Instruments. Samples were diluted with RO water to accommodate for the concentration ranges where necessary.

2.3 | Destructive Harvest

On 40 DAS, 26 days after transplanting, all samples were harvested. A random subset of 10 samples was selected for each treatment, and the whole leaf area of these was scanned using a Canon LiDE 300 Colour Flatbed Scanner. Leaf area

index was then recorded using ImageJ, by setting the scale using known dimensions of the scanner (36.7 × 25 cm), setting image to 8-Bit, and measuring with the ROI manager tool (mm^2) (Albrechtová et al. 2019; Sapkota et al. 2019; Sauceda et al. 2017).

For all 384 plants across both treatments, the leaf number, length of the longest leaf, width of the widest leaf and rosette width at widest point were recorded. Following this, the fresh weight of above ground biomass of all plants was recorded, and plants were subsequently placed in loose brown paper bags for drying at 70°C until a constant weight was reached. After approximately 4 days, the dry weights of these samples were recorded (Kotsiras et al. 2016; Lei and Engeseth 2021; Sapkota et al. 2019). Root harvest was not undertaken due to the mesh design of the Media which rendered this impossible without physically damaging the grow system. Deployment of high-resolution 3D root imaging equipment was beyond the scope of this project.

2.4 | Statistical Analysis

All statistical analyses were conducted using R version 4.3.2 within the RStudio integrated development environment (Posit Software, PBC, 2023). Changes in micronutrient and macronutrient concentrations, as well as EC, were analysed across vegetative growth stages following transplant. The 26-day period was segmented into four intervals: 14–20 DAS, 21–27 DAS, 28–34 DAS, and 35–40 DAS. Percentage change for each parameter was calculated within each interval, also accounting for the shorter duration of the final period (35–40 DAS).

Because these interval data represented repeated observations from the same replicate systems, repeated-measures analyses were employed. For each Treatment × Nutrient combination, replicate systems were treated as subjects with interval as the within-subject factor. Data were first checked for normality (Shapiro–Wilk) and homogeneity of variance (Levene's test). Where assumptions were satisfied, repeated-measures ANOVA was used to test for differences in mean percentage change between intervals (Chandnani and Roy 2024). Post hoc comparisons were conducted with paired *t*-tests and Benjamini–Hochberg (B-H) adjustment for multiple testing. Where assumptions were not met, the non-parametric Friedman test was applied, with Wilcoxon signed-rank tests for pairwise contrasts under the same correction procedure.

In parallel, similar analyses were undertaken between treatments, but within each time period, allowing direct comparison of the rate of nutrient depletion under different dosing regimes at given growth stages. These between-treatment comparisons employed one-way ANOVA where assumptions were met, followed by Tukey's Honest Significant Difference (HSD) test, or the Kruskal–Wallis H test with appropriate post hoc alternatives where assumptions were violated (Birlanga et al. 2021; Eriksen et al. 2016). To analyse total nutrient loss from each system, the same framework was applied, using ANOVA or robust non-parametric alternatives depending on distributional assumptions.

Destructive harvest data were analysed using unpaired *t*-tests, as treatments represented independent groups and only Treatment 1 and Treatment 2 produced plant samples (there being no biological component in the Control group). Assumptions of normal distribution and equality of variance within and between groups were tested. In the two instances where these assumptions were not met, the Mann–Whitney *U* test was applied to compare medians (Birlanga et al. 2021; Eriksen et al. 2016; Toro-Herrera and Raudales 2025).

In addition, exploratory regression analyses were conducted in R (v4.3.2) to evaluate whether EC values could serve as a proxy for individual nutrient concentrations. For each Treatment × Nutrient combination, ordinary least squares regression was first fitted, with model assumptions assessed using the Shapiro–Wilk, Breusch–Pagan, and Ramsey RESET tests (Bu et al. 2022). Where assumptions were violated, or sample sizes were insufficient, Spearman's rank correlation was applied as a non-parametric alternative. Outputs included model coefficients, test statistics, and annotated scatterplots.

All visualisation of data in figures was undertaken in R (v4.3.2) using the ggplot2, tidyverse, and scales packages within RStudio. Standard deviations were added around means, and vertical reference lines were included to denote distinct DAS intervals.

3 | Results

3.1 | Control

Within the Control nutrient solution, nutrient concentrations showed only minimal decreases, with the exception of magnesium which remained stable throughout (Figure 2). The largest overall decline was observed in phosphate, which fell by just 1.8% between 14 and 40 DAS. In contrast, EC declined steadily from 1.2 mS cm^{-1} at 14 DAS to 1.1 mS cm^{-1} by 35 DAS, remaining at this level until harvest. While EC showed a significant decline ($p < 0.05$), none of the nutrient concentrations changed significantly, indicating stable nutrient levels.

3.2 | Treatment 1

In Treatment 1, where 70 L of the circulating nutrient solution was replaced weekly, macronutrient and micronutrient concentrations generally declined over time, although the magnitude of change varied by nutrient (Figure 3). Normalised data illustrate a broad downward trend, with the steepest declines typically observed in the final interval prior to harvest (35–40 DAS). Repeated-measures analysis confirmed significant differences in percentage change between intervals for several nutrients, with phosphate showing the most consistent stability relative to other macronutrients. EC remained within the target range of 1.0–1.2 mS cm^{-1} throughout the cycle (Hosseini et al. 2021; Touliatos et al. 2016) and did not differ significantly between intervals. The total nutrient decline observed between successive solution replacements closely matched the nutrient concentration of the fresh solution applied, indicating that weekly top-ups effectively replenished system inputs. Full nutrient and EC measurements

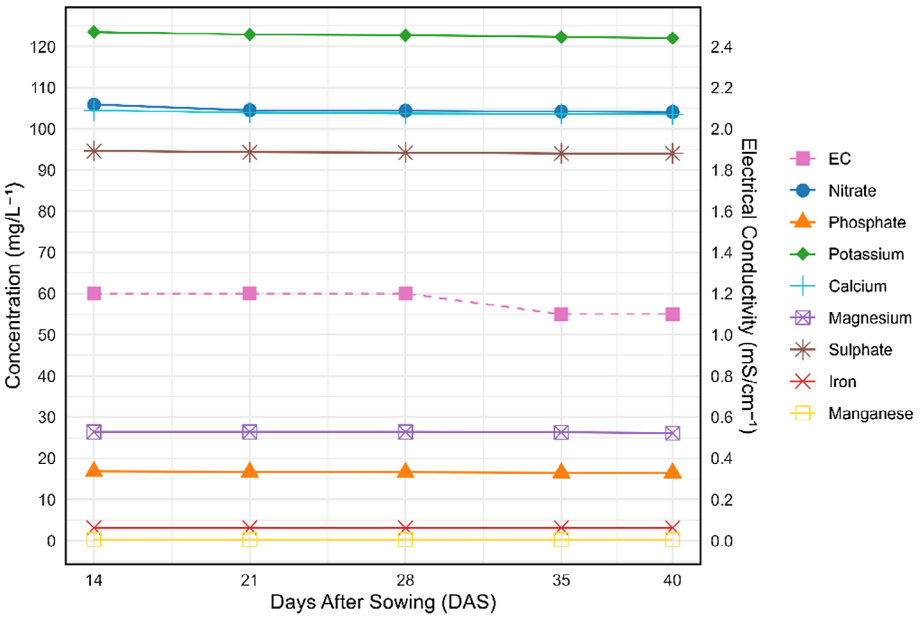

FIGURE 2 | Control fertigation macronutrient and micronutrient concentrations and EC, recorded in the absence of plant samples alongside Treatment 1 from 14 to 40 DAS.

across the grow cycle are provided in Table S2 (Treatment 1) and Table S3 (Treatment 2) in Supporting Information.

Between-treatment differences were limited early in the cycle and became more frequent toward harvest (Figure 3). Across all intervals there were 10 significant Control–Treatment 1 contrasts in percentage change ($p < 0.05$): 1 at 14–20 DAS, 2 at 21–27 DAS, 2 at 28–34 DAS, and 5 at 35–40 DAS. By nutrient, nitrate differed in three intervals (14–20, 21–27, 28–34 DAS); potassium in two (28–34, 35–40 DAS); and calcium, magnesium, iron, and sulphate each at 35–40 DAS. Phosphate differed at 21–27 DAS. Manganese and EC showed no significant Control–Treatment 1 differences in any interval.

Repeated-measures tests indicated an effect of interval for several nutrients in Treatment 1 ($p < 0.05$ for EC, magnesium, nitrate, potassium, and sulphate). After B-H adjustment, significant pairwise differences were confined to magnesium and sulphate, each showing steeper declines in the final interval: 35–40 DAS differed from 14 to 20, 21 to 27, and 28 to 34 DAS (three contrasts per nutrient; $p.\text{adj} < 0.05$). No adjusted pairwise differences were detected for nitrate, phosphate, calcium, potassium, iron, or manganese. In total, six significant interval contrasts were observed, all involving 35–40 DAS, indicating that within Treatment 1 the most pronounced changes were concentrated in the late pre-harvest period, while earlier intervals were comparatively stable. EC remained within the target range (1.0–1.2 mS cm^{-1}) and, despite an overall effect, did not exhibit significant adjusted pairwise differences between specific intervals.

3.3 | Treatment 2

In Treatment 2, where volume was maintained by top-ups without replacement, nutrient concentrations declined over time, with the steepest changes emerging mid- to late-cycle (Figure 4). Repeated-measures tests identified significant effects of interval for magnesium, manganese, nitrate, potassium, and sulphate ($p < 0.05$) and a weaker overall effect for calcium. After B-H adjustment, post hoc differences were extensive: sulphate differed across all six interval pairs; nitrate and potassium each in five of six; manganese in four; and magnesium in two (both involving 28–34 DAS vs. earlier intervals). The earliest detectable shift occurred for sulphate (14–20 vs. 21–27 DAS, $p.\text{adj} < 0.05$). Aggregated across nutrients, significant contrasts most often involved 28–34 DAS ($n = 13$) and 35–40 DAS ($n = 12$), compared with 14–20 ($n = 10$) and 21–27 DAS ($n = 9$), indicating that dynamics intensified from mid-cycle onward. By contrast, phosphate, iron, and EC showed no significant pairwise differences between intervals (EC also non-significant overall), underscoring that bulk conductivity did not capture nutrient-specific changes under top-ups.

The largest number of between-treatment differences occurred between the Control and Treatment 2 ($n = 21$, B-H-adjusted $p < 0.05$), concentrated at 21–27 DAS and 35–40 DAS (7 contrasts each), followed by 28–34 DAS (5) and 14–20 DAS (2). By nutrient, calcium differed significantly in all four intervals; phosphate, potassium, and sulphate each in three; magnesium, iron, and nitrate in two; and manganese and EC in one interval each. Differences at 28–34 DAS were particularly marked for nitrate, potassium, and sulphate.

Across all treatments, significant between-treatment differences in mean daily percentage change were detected for every analyte at one or more intervals. By nutrient, calcium differed in all four intervals; nitrate, phosphate, potassium, sulphate, and iron each in three; magnesium in two; EC in two (early 14–20 DAS and late 35–40 DAS); and manganese in one (late). The number of nutrients showing a treatment effect increased over time: 4 at 14–20 DAS, 7 at 21–27 DAS, 5 at 28–34 DAS, and 8 at 35–40 DAS, indicating growing divergence among treatments as the cycle progressed. Most significant pairwise contrasts were between the Control and Treatment

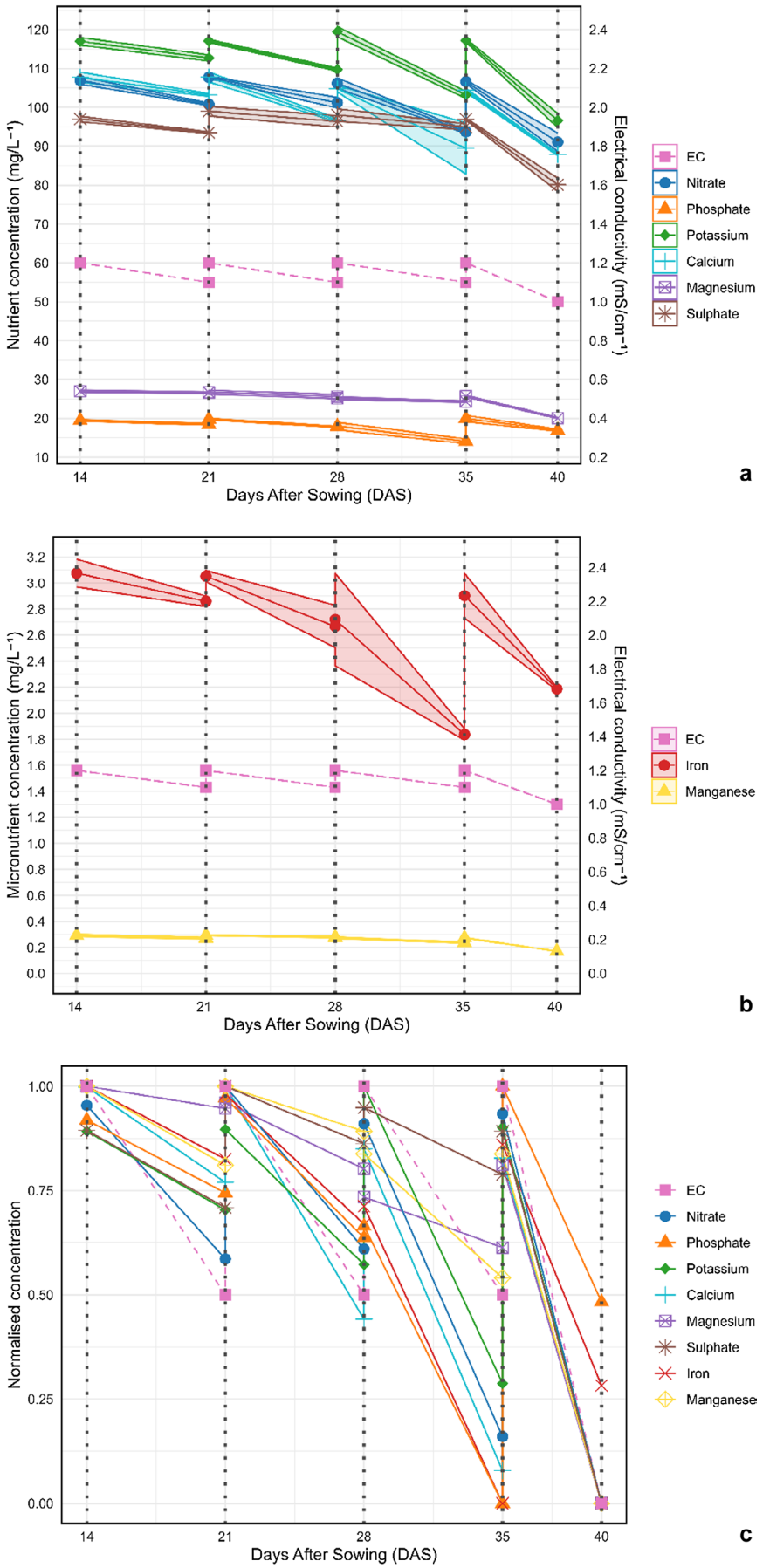

FIGURE 3 | Legend on next page.

FIGURE 3 | Treatment 1 fertigation macronutrient (a) and micronutrient (b) concentrations and EC throughout grow cycle from transplant to harvest. Each datapoint represents the mean of the triplicate systems, with the envelope showing the standard deviation across these. Each of the three replicates received a total of 280 L half strength Hoagland's solution, with 70 L being replaced on a weekly basis. Duplicate datapoints on the same day represent the before and after dosing. Min-max normalised fertigation (mean), scaling values between 0 and 1 for macronutrient and micronutrient concentrations and EC throughout grow cycle from transplant to harvest (c).

2 ($n = 21$), followed by Control and Treatment 1 ($n = 10$) and between Treatments 1 and 2 ($n = 7$). Figure 5 illustrates this pattern, with the densest clusters from mid- to late-cycle in most nutrients.

3.4 | Total Nutrient Loss

As would be expected, the decrease of all macronutrients and micronutrients was significantly ($p < 0.05$) higher in both treatments compared with the Control (Figure 6). In all cases, total macronutrient loss was significantly ($p < 0.05$) greater in Treatment 2 than Treatment 1. Sulphate had the greatest total loss compared with Treatment 1, at 29.07 mg/L^{-1} (111.8% greater), followed by magnesium at 7.13 mg/L^{-1} (90.3% greater) and nitrate at 19.50 mg/L^{-1} (47.9% greater). Across all treatments, no more than 30% of the total supply of macronutrients was exhausted from the half strength Hoagland's solution.

The greatest percentage loss of micronutrients in the Control treatment was in iron, which declined by 0.02 mg/L^{-1} (0.6%). Contrasting the macronutrient data, there was no significant difference ($p > 0.05$) in the total micronutrient decline between Treatment 1 and Treatment 2.

When expressed as a percentage of input, the total decline of each micronutrient was significantly greater ($p < 0.05$) in Treatment 2. In Treatment 1, the highest percentage decline was in iron, by approximately 21% of the total that was input. In Treatment 2, the majority of nutrients declined by over 20% of the total input, the highest percentage also being in iron, at approximately 35%.

3.5 | Regression and Correlation Analysis of EC–Nutrient Relationships

Across all treatment–nutrient combinations, a total of 17 statistically significant relationships with EC were identified. The majority occurred under Treatment 1 ($n = 8$) and Treatment 2 ($n = 7$), with comparatively few in the Control ($n = 2$). Nutrients most frequently associated with EC included manganese and phosphate (3 instances each), followed by calcium, magnesium, nitrate, potassium, and sulphate (2 instances each), and iron (1 instance). All significant associations were positive, with no significant negative relationships detected.

Alongside these associations, the underlying time-series exhibited intervals of non-concordance between EC and individual nutrient trajectories. In Treatment 2, EC increased by 22.2% during the first 2 weeks while all measured nutrients declined. In Treatment 1, EC declined by 8.3% whereas iron and manganese decreased more steeply (−19.2% and −30.5%, respectively); later in Treatment 2, EC fell by 33.3% while iron declined by 68.2%. In the Control, EC decreased by 8.3% despite minimal change in most nutrients. These observations indicate that statistically significant EC–nutrient associations co-occurred with temporal mismatches and disproportionate magnitudes of change in several phases of the grow cycle.

3.6 | Destructive Harvest

On every morphological parameter, samples from Treatment 1 were significantly ($p < 0.05$) greater than samples from Treatment 2 (Table 1). The greatest difference between treatments was observed in leaf number, which was 24% higher in Treatment 1 samples. Treatment 1 samples were also 23% greater in yield component fresh weight and 19% greater in dry weight (Figure 7).

3.7 | Economic Analysis of Solution Use

Half strength Hoagland's solution cost £0.12 per litre to prepare. With frequent replacement, Treatment 1 consumed more nutrients, requiring 280 L per grow system compared with 140 L per system in Treatment 2. This equated to a cost of £33.60 per system in Treatment 1, and £16.80 per system in Treatment 2. In terms of biomass production, this was an average cost across the three replicates of £0.08 per gram of fresh weight and £1.54 per gram of dry weight in Treatment 1. For Treatment 2, this was £0.05 per gram of fresh weight and £0.96 per gram of dry weight, which was significantly ($p < 0.001$) less than in Treatment 1 in both instances. This is a 62.6% and 66.0% greater cost per gram of fresh and dry weight respectively in Treatment 1 compared with Treatment 2.

4 | Discussion

4.1 | Influence of Crop Developmental Stage on Nutrient Concentration and Ratios

Across the growth cycle, developmental stage exerted a clear influence on nutrient dynamics, with interval-wise differences concentrated from mid- to late-cycle (Figures 3–4). In Treatment 1, significant adjusted pairwise differences were restricted to magnesium and sulphate, each exhibiting steeper declines in the final interval (35–40 DAS vs. earlier intervals), consistent with the late-cycle decline shown in Figure 3. In Treatment 2, interval effects were broader, matching the intensified mid- to late-cycle declines visible in Figure 4. Sulphate differed across all six interval pairs, nitrate and potassium in five of six, manganese in four, and magnesium in two (both involving 28–34 DAS vs. earlier). The earliest detectable change occurred for sulphate (14–20 vs. 21–27 DAS). By contrast, phosphate, iron, and EC showed

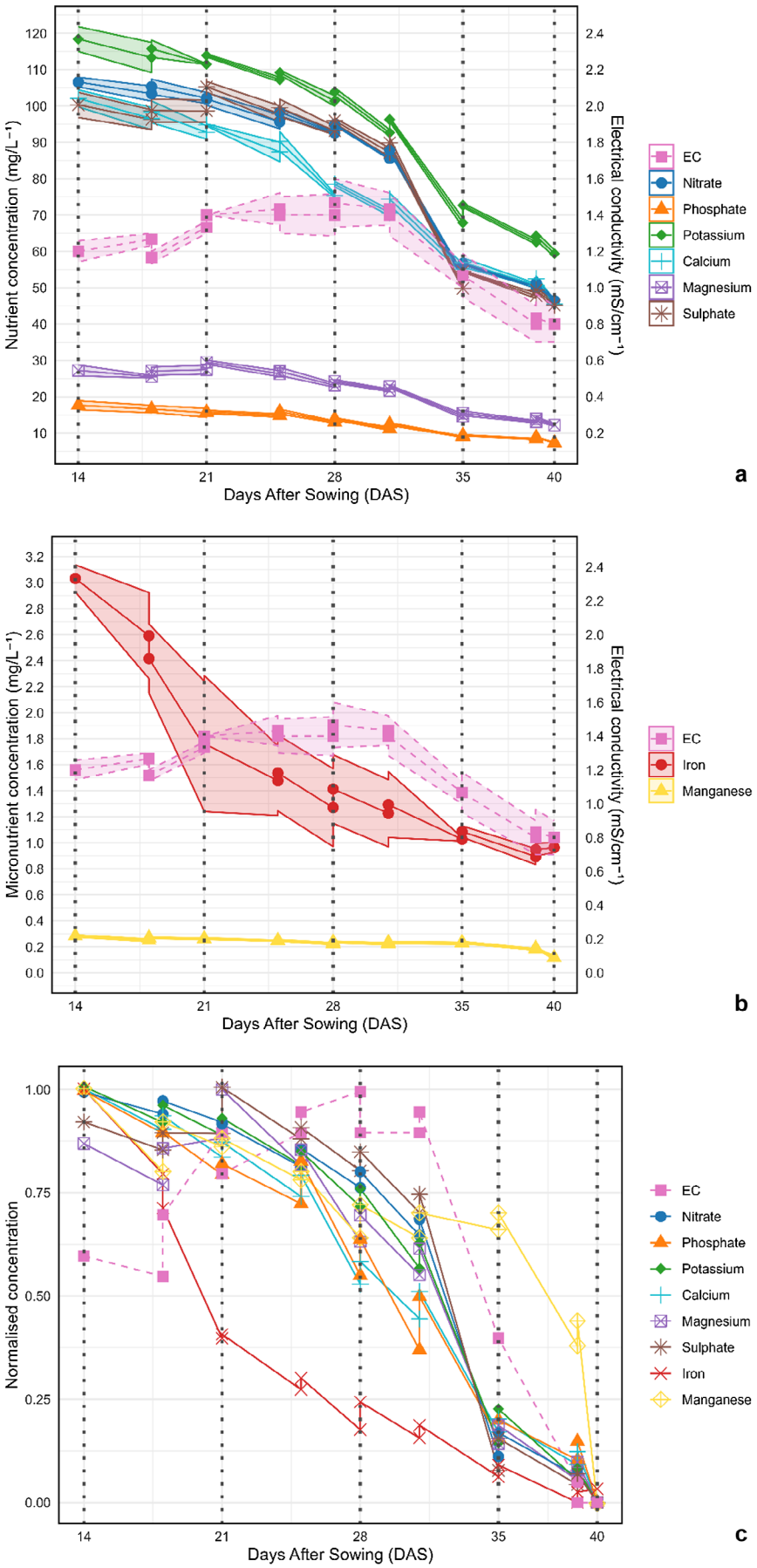

FIGURE 4 | Legend on next page.

FIGURE 4 | Treatment 2 fertigation macronutrient (a) and micronutrient (b) concentrations and EC throughout the grow cycle from transplant to harvest. All three replicates received a total of 140 L half strength Hoagland's solution which was added as required to a predetermined sump tank level. Min-max normalised fertigation (mean), scaling values between 0 and 1 for macronutrient and micronutrient concentrations and EC throughout the grow cycle from transplant to harvest (c).

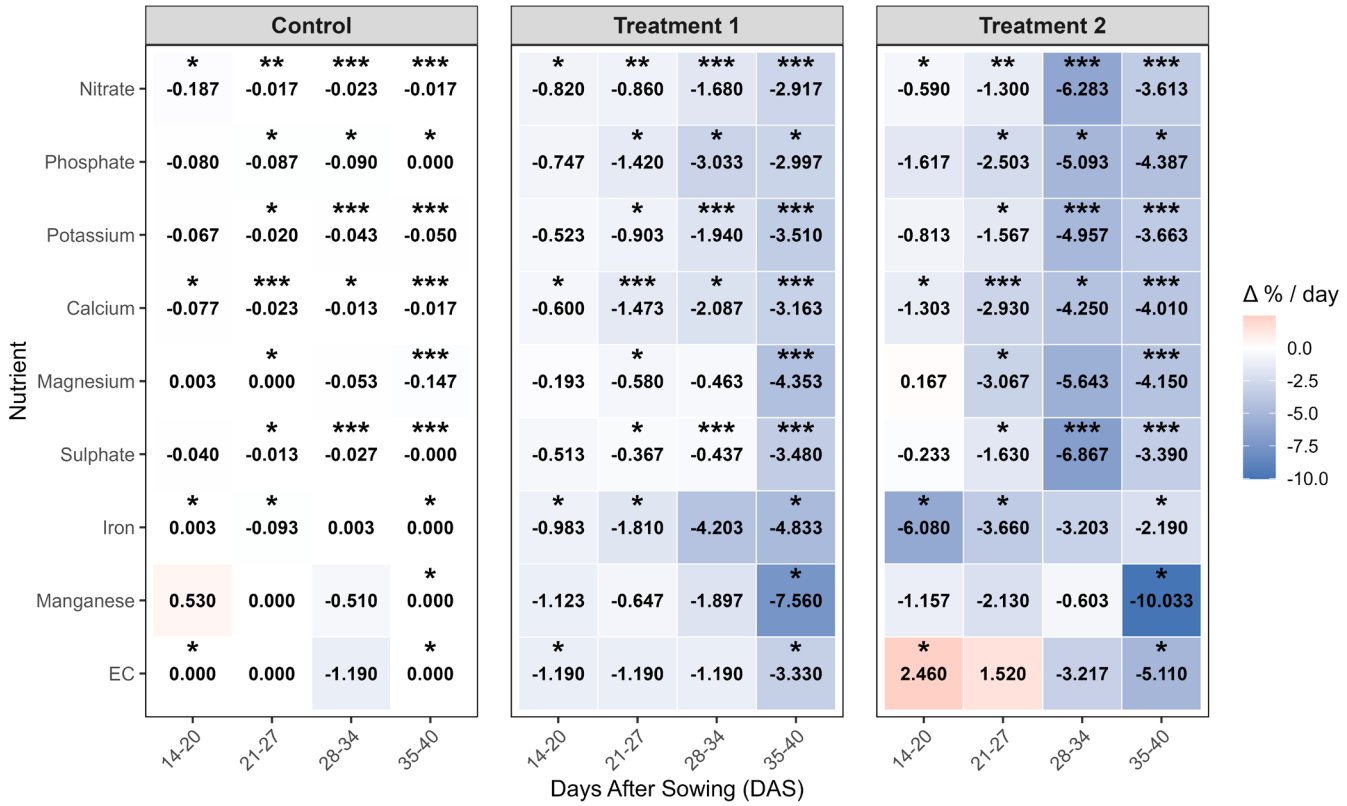

FIGURE 5 | Mean daily percentage change in nutrient concentrations between Control, Treatment 1, and Treatment 2 solutions across DAS intervals. Asterisks indicate statistically significant differences between treatments for a given nutrient × DAS combination (*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$), determined using a one-way ANOVA when test assumptions were met, or a Kruskal–Wallis test when these assumptions were violated.

no significant pairwise differences between intervals under Treatment 2. Taken together, these results support Hypothesis 1: that fluctuations in nutrient concentrations (and thus ratios) are significantly influenced by growth stage, with the strongest deviations emerging from 28 to 34 DAS onwards.

Under Treatment 2, significant declines in nitrate, potassium, and sulphate suggest intensified assimilation and possible non-uptake related losses, as solution composition drifted, shifting nutrient ratios even when EC remained comparatively stable. Such timing aligns with acclimation to emerging nutrient limitation (Kerbiriou et al. 2016). Physiologically, this pattern is consistent with increased metabolic demand and sink strength as lettuce approaches maturity, amplifying uptake of key macronutrients (Djidonou and Leskovar 2019; Zhang et al. 2024). Nitrate demand rises with photosynthetic capacity and rapid biomass accumulation (Alvarado-Camarillo et al. 2019; Mahlangu et al. 2016; Wenceslau et al. 2021), while potassium demand typically escalates at later vegetative stages to sustain stomatal regulation and turgor-driven leaf expansion and to support phloem loading and long-distance transport of assimilates (Ragel et al. 2019; Sardans and Peñuelas 2021; Xu et al. 2022; Zhang et al. 2017). In parallel, late-stage rises in sulphate uptake reflect higher requirements for S-amino acids and glutathione, alongside anion–cation balancing during intensified nitrate and potassium uptake (Jobe et al. 2019; Coleto et al. 2017; Kong et al. 2024).

Between treatments (within each interval), divergence increased with time: the number of nutrients showing a treatment effect rose from 4 at 14–20 DAS to 8 at 35–40 DAS. Most pairwise differences were between Control and Treatment 2 ($n = 21$ across analytes/intervals), with fewer for Control vs. Treatment 1 ($n = 10$) and Treatment 1 vs. Treatment 2 ($n = 7$). By nutrient, nitrate and calcium differed in all four intervals across one treatment comparison; phosphate, potassium, sulphate and iron each differed in three; magnesium in two; EC in two; and manganese in one. Notably, the densest clusters of significance occurred at 28–34 DAS, particularly for nitrate, potassium, and sulphate, consistent with the within-treatment findings for Treatment 2.

Finally, the limited and inconsistent significance for EC (two between-treatment intervals overall, and no adjusted pairwise differences between intervals within Treatment 2) underscores that bulk conductivity does not reliably track nutrient-specific changes. As nutrient-specific declines diverged (especially

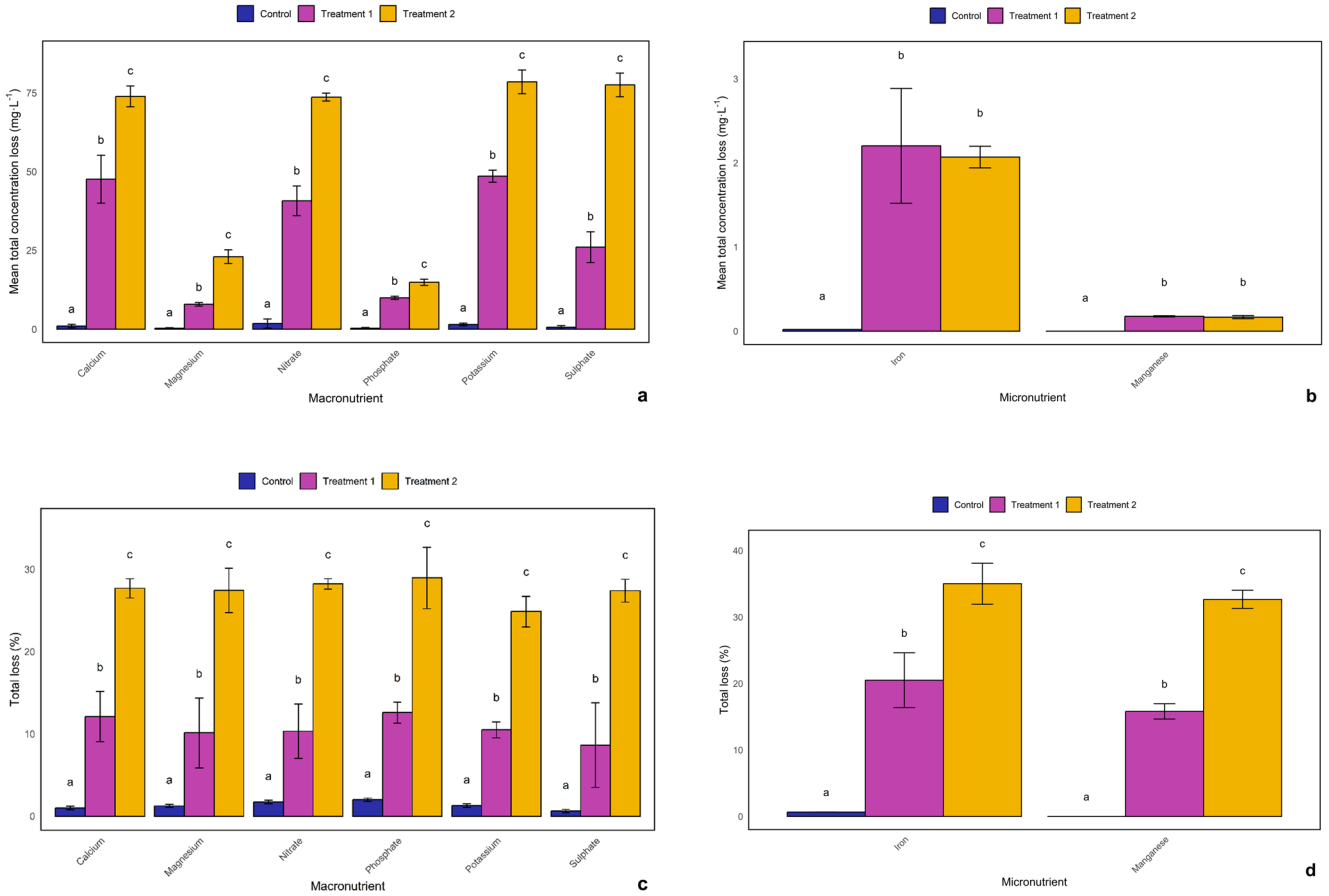

FIGURE 6 | Mean total macronutrient (a) and micronutrient (b) cumulative loss (mg L^{-1}) from solution and mean total cumulative loss as a percentage of the total macronutrient input (c and d) in each treatment during the 26 days from transplant to harvest. Macronutrients were supplied by 70 L of half strength Hoagland's solution in the Control, 280 L in Treatment 1 and 140 L in Treatment 2. Letters denote ANOVA results, there being a significant difference between treatments with different letters for each macronutrient.

mid- to late-cycle), ratios among ions shifted in ways not captured by EC alone, and this was clearly reflected in Figures 3–4.

4.2 | Impacts of Periodic Nutrient Solution Replacement

4.2.1 | Nutrient Availability

Treatment 2 showed significantly ($p < 0.05$) higher percentage declines in nitrate, magnesium, and sulphate (47.9%, 90.3%, and 111.8% higher than Treatment 1, respectively), visible in Figure 6a. This likely reflects nutrient stress-induced adaptations, such as increased root proliferation and transporter upregulation (Kumar et al. 2022; Guo et al. 2016). Similar responses have been observed in lettuce under nitrogen or sulphur limitation, where root exudation and increased surface area support continued uptake despite scarcity (Kerbiriou et al. 2013; Sardans et al. 2023).

In contrast, nutrient decline in Treatment 1 followed a trajectory aligned with plant development, macronutrient uptake accelerating toward the end of the trial, likely due to increased metabolic demand, protein synthesis, and photosynthetic activity (Djidonou and Leskovar 2019; Pinto et al. 2014). These findings support Hypothesis 1 and are consistent with literature reporting increased nutrient assimilation after 14 days post-transplant (Carvalho et al. 2018; Stefanelli et al. 2012).

Phosphate and iron uptake deviated from this pattern in Treatment 2. Phosphate showed no significant increase over time, despite its importance in growth processes. Phosphate uptake efficiency under scarcity has been reported to improve without yield penalty, possibly explaining this observation (Malhotra et al. 2018; Neocleous and Savvas 2019). Iron uptake remained comparatively high and stable across both treatments, likely due to its immobility within leaves and relatively low demand (Msilini et al. 2013; Yoneyama 2021). The absence of chlorosis (visible in Figure 7) further suggests adequate iron availability, consistent with lettuce's known tolerance to a wide range of iron levels (Khan et al. 2023; Xu et al. 2022).

However, declines in phosphate and iron concentrations from the nutrient solution may not solely reflect plant uptake. In hydroponic systems, phosphate can precipitate with calcium or magnesium under elevated pH, forming insoluble complexes (Sambo et al. 2019). Iron, often stabilised using chelates like EDTA or DTPA, can precipitate as hydroxides or phosphates if chelates degrade under UV or oxidative conditions (López-Vinent et al. 2022; Lucena 2006). Although UV sterilisation was

TABLE 1 | Yield component morphology for Treatment 1 and Treatment 2 (mean ± SD), with statistical comparisons between treatments.

	Treatment 1 mean	Treatment 2 mean	Test	Difference	*p*	% Change
Length of longest leaf (mm)	168 ± 22	150 ± 10	Unpaired *t* test	18 ± 3	$p < 0.0001$	11.8 ± 1.3
Width of widest leaf (mm)	131 ± 18	118 ± 8	Unpaired *t* test	13.5 ± 2.4	$p < 0.0001$	11 ± 3
Leaf area (mm^2)	1340 ± 80	1160 ± 130	Unpaired *t* test	180 ± 50	$p < 0.01$	13 ± 13
Yield component fresh weight (g)	60 ± 60	47 ± 7	Unpaired *t* test	10.7 ± 1.6	$p < 0.0001$	22.8 ± 1.4
Yield component dry weight (g)	2.9 ± 0.5	2.4 ± 0.3	Unpaired *t* test	0.51 ± 0.08	$p < 0.0001$	19.3 ± 2.3
Rosette width at widest point (mm)	312 ± 3	286 ± 18	Mann Whitney test	26 ± 4	$p < 0.0001$	8.9 ± 1.4
Leaf number	22.8 ± 2.3	18.4 ± 1.3	Mann Whitney test	4.5 ± 0.7	$p < 0.0001$	24 ± 3

not used in this study, Treatment 2's extended recirculation may have allowed for pH drift and ion accumulation, increasing the likelihood of these losses.

These chemical processes may have been enhanced in systems with live samples compared with the Control. Organic compounds such as root exudates and microbial byproducts can alter pH and redox potential, destabilising chelates and promoting precipitation (Dakora and Phillips 2002). Conversely, some root exudates (particularly organic acids and siderophores) may solubilise otherwise unavailable phosphates and iron, depending on concentration and context (Yang et al. 2024). Such dynamics may explain differences observed between treatments.

At harvest, all macro- and micronutrient concentrations were higher in Treatment 1 systems, confirming that periodic solution replacement improves nutrient availability, and therefore Hypothesis 2.1 can be accepted. In Treatment 2, discrepancies between nutrient inputs, measured declines, and final concentrations suggest losses beyond plant uptake, an observable trend when comparing Figure 6a,b with Figure 6c,d. These are likely due to dilution effects from topping up a continuously weakening solution (Sambo et al. 2019), stoichiometric imbalances limiting ion detectability or uptake (Jeong and Lee 2008; Kudirka et al. 2023), or precipitation and volatilisation, despite pH adjustments.

Root exudates and allelochemicals may also have played a role. Prolonged exposure and increasing stress from 21 DAS in Treatment 2 likely elevated exudation, which can alter ionic availability both directly and indirectly (Ma et al. 2016; Hosseinzadeh et al. 2017). Allelochemicals associated with autotoxicity may also have contributed to the reduced yield observed in this treatment (Cai et al. 2024).

Nutrient dropout was less pronounced in Treatment 1, where measured nutrient declines aligned closely with expected uptake based on inputs and harvest data. This suggests that periodic nutrient solution replacement helped maintain more stable nutrient levels, potentially limiting dilution effects and the accumulation of root exudates or other interfering compounds seen in Treatment 2. However, both treatments exhibited nutrient fluctuations influenced by plant growth stages and metabolic demands.

4.2.2 | Crop Yield and Economic Efficiency

Treatment 1 consistently outperformed Treatment 2 across all measured morphological parameters ($p < 0.05$), as summarised in Table 1, Figure 7 (as well as in Figures S2 and S3 in Supporting Information). Improvements included leaf dimensions and area, leaf number, fresh and dry weight, with leaf number showing the greatest increase at 24%. This was followed by fresh weight, dry weight, leaf area, length of the longest leaf, rosette width, and width of the widest leaf. These results support Hypothesis 2.2, that periodic nutrient replacement can improve yield. Macronutrient concentrations in Treatment 1 deviated by no more than 25% from optimal levels, and micronutrients by no more than 40%, throughout the growth cycle. In contrast, Treatment 2 experienced a macronutrient deviation from optimal exceeding 55% and a micronutrient deviation of up to 68% in the final week. Correspondingly, EC remained above 1 mS/cm in Treatment 1, within healthy growth ranges (Huett 1994), but dropped to 0.8 mS/cm in Treatment 2, corroborating established links between EC and crop yield (Gent 2017; Samarakoon et al. 2020; Sublett et al. 2018).

Despite these differences, there was no significant difference ($p > 0.05$) in the fresh-to-dry weight ratio between treatments, with approximately 20 g of fresh weight per gram of dry weight, indicating comparable water accumulation relative to biomass. This suggests that although Treatment 2 plants faced potential nutrient deficiencies, they maintained adequate water status and nutrient uptake (Vitalis et al. 2023; Wang et al. 2022).

Notably, Treatment 2 showed significantly greater variability in leaf length, rosette width, and leaf number ($p < 0.05$), likely caused by nutrient deficiency-induced intraspecific competition (Corrado et al. 2021; Wang et al. 2015). Additionally, the continuous recirculation and topping up of the nutrient solution in Treatment 2 may have promoted accumulation of

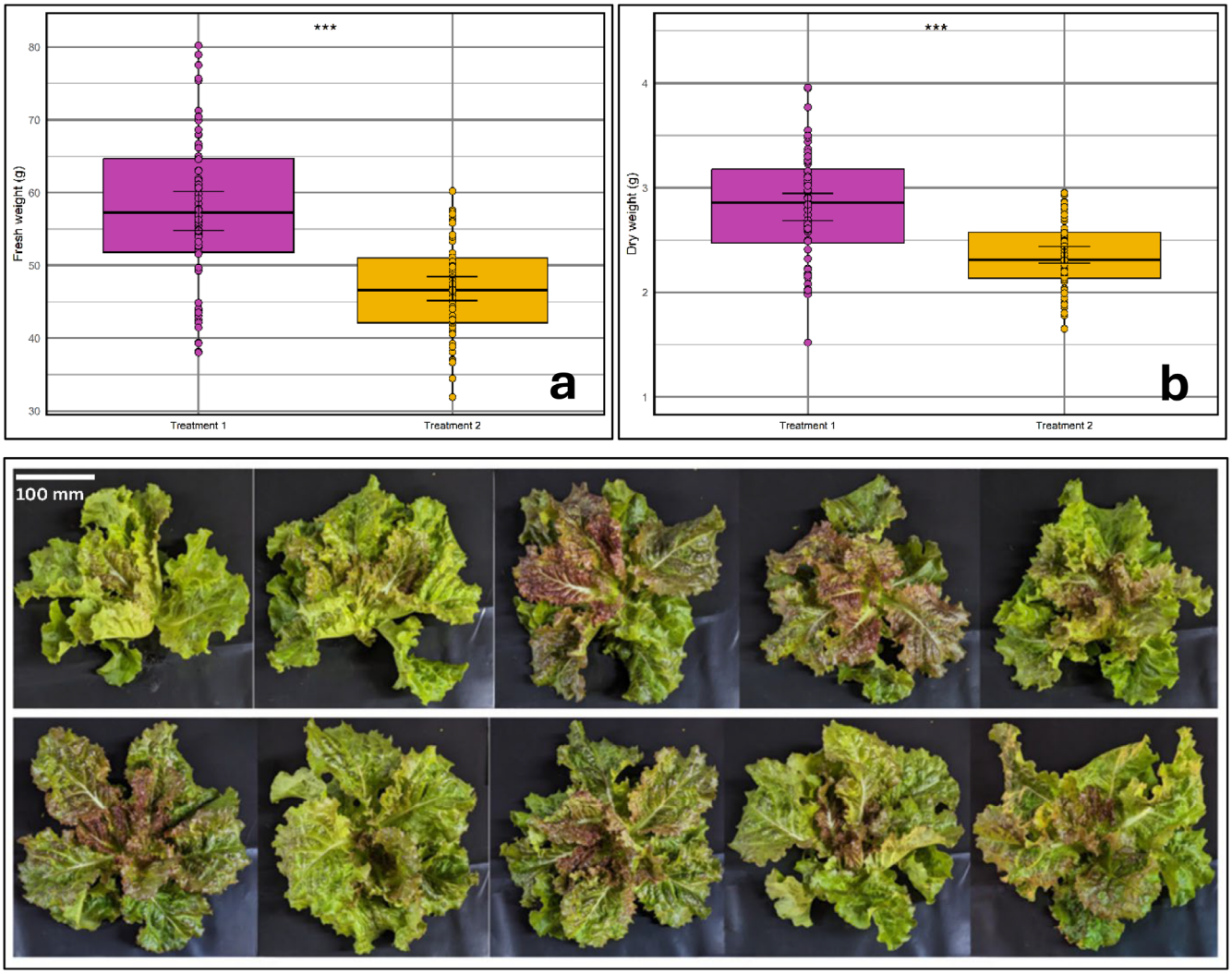

FIGURE 7 | (a) Fresh and (b) Dry weight data for Treatment 1 and Treatment 2 samples. Standard deviation bars and significance levels derived from independent *t*-tests were generated using the ggplot function in R to visualise destructive harvest data. (c) Images of samples taken from Treatment 1 (top row) and samples from Treatment 2 (bottom row) with the camera at a height of 30 cm.

allelochemicals, which can negatively affect growth and yield through various mechanisms (Kaur et al. 2024; Talukder et al. 2020).

In line with previous research, the stability of nutrient availability in Treatment 1 likely supported enhanced leaf expansion, photosynthesis, and yield (Gent 2017; Samarakoon et al. 2020). However, despite smaller plants and reduced biomass, Treatment 2 was 62.6% more cost-efficient per gram of biomass, requiring no fresh nutrient input. This increased cost efficiency, however, must be balanced against the greater morphological variability observed, which may reduce commercial grading quality and consumer acceptance, particularly under EU regulations (Porter et al. 2018).

While Treatment 1 delivered premium uniformity and higher yields, it generated substantial nutrient waste. Approximately 280 L of nutrient solution was used and disposed of to produce around 3.69 kg of produce per grow system, compared to 2.98 kg for Treatment 2. This disposal poses environmental cost due to potential impacts on local ecosystems and human health (Kumar and Cho 2014; Richa et al. 2020), as well as increased labour costs.

Economically, although Treatment 2 reduced input costs significantly, Hypothesis 2.3, that periodic replacement improves economic efficiency per gram of saleable biomass, cannot be accepted. Yield quality, encompassing mineral content, secondary metabolites, vitamins, and plant health, also plays a critical role in crop value (Managa et al. 2018). No spoilage or chlorosis was observed in Treatment 2 plants (Figure 7; Sapkota et al. 2019), but higher variability could negatively impact marketability under EU standards (Mampholo et al. 2015; Porter et al. 2018).

From an industry perspective, the hydroponics sector faces challenges including low profit margins, high capital costs, and knowledge gaps, contributing to a high failure rate among startups (den Besten 2019; Gerrewey et al. 2022; de Oliveira et al. 2022). Strategies that maintain the yield and uniformity seen in Treatment 1 while reducing nutrient inputs could improve economic viability and sustainability. For example, achieving Treatment 1 yields with Treatment 2's input level

would lower costs per gram of biomass by approximately 19%. Reduced nutrient use would also decrease associated costs such as transport, storage, labour, protective equipment, and disposal (Benke and Tomkins 2017).

4.3 | EC as a Proxy Measure for Nutrient Concentrations

While EC is widely used in hydroponics to infer nutrient concentration, findings from this study reiterate its limitations as a reliable proxy for nutrient monitoring, particularly for micronutrients (Lim et al. 2024). Regression and correlation analyses indicated that, in the majority of cases, nutrient concentrations were positively and significantly associated with EC, especially under active dosing regimes (Treatments 1 and 2). This outcome reflects the broad proportionality between EC and total ion content. However, a closer examination of the temporal data revealed that these statistical associations did not consistently translate into proportional nutrient–EC correspondence.

In Treatment 2, for example, EC increased by 22.2% during the first 2 weeks despite a consistent decline in all measured nutrients. This divergence is likely attributable to the accumulation of root exudates, able to alter solution charge but not reflective of nutritional status (Hinsinger et al. 2003; Custos et al. 2020). Exudate composition is known to vary with environmental factors including temperature, nutrient stress, and CO_2 concentration, each of which can modulate EC independently of nutrient flux (Huang et al. 2015; Steinauer et al. 2016). The subsequent sharp decline in EC between 28 and 40 DAS in Treatment 2 coincided with steep reductions in nitrate, potassium, sulphate, and manganese ($p < 0.05$), illustrating that correspondence may emerge intermittently but not uniformly.

In Treatment 1, EC exhibited a closer alignment with nutrient depletion but still revealed disproportionate declines. For instance, EC decreased by 8.3% while iron and manganese concentrations fell by 19.2% and 30.5%, respectively. Similarly, in later phases of Treatment 2, EC fell by 33.3% while iron declined by 68.2%, highlighting EC's insensitivity to micronutrient depletion. Most strikingly, in the Control, EC decreased by 8.3% despite relative stability in nutrient concentrations. These patterns emphasise that although EC often correlates positively with nutrient concentrations at a single time point, it does not reliably capture the magnitude or nutrient-specific direction of change.

These findings are consistent with previous studies cautioning against reliance on EC alone for nutrient management (Ahn et al. 2021; Kim et al. 2013; Rouphael et al. 2016). In commercial practice, many hydroponic growers maintain fixed EC levels across developmental stages, often due to logistical constraints such as shared reservoirs (Fathidarehnijeh et al. 2024; Son et al. 2020). While convenient, this approach risks undetected deficiencies, particularly in micronutrients, with consequent impacts on yield quality and economic return (Msilini et al. 2012). Emerging ion-specific monitoring technologies, such as ion-selective electrodes, show promise for providing more accurate, responsive, and sustainable nutrient management strategies (Jung et al. 2015; Cho et al. 2018; Lim et al. 2024), although technical barriers remain to their full integration into closed-loop systems (Son et al. 2020).

While EC demonstrated statistically significant positive associations with nutrient concentrations in many cases, it did not reliably reflect the specific concentrations of key nutrients, especially micronutrients, due to disproportionate responses and potential confounding factors such as root exudates and ion accumulation. Therefore, EC alone is insufficient as a proxy for nutrient status in hydroponic systems, leading to the rejection of Hypothesis 3.

5 | Conclusion

This study presents a systems-level comparison of two nutrient dosing strategies in closed-loop hydroponic production, highlighting important trade-offs between yield, input efficiency, and environmental sustainability. Periodic nutrient replacement supported more stable nutrient availability and higher, more uniform yields. However, it also increased labour and energy demands, generated greater nutrient waste with related environmental costs, and led to higher cost per gram of biomass, raising concerns around economic and environmental sustainability.

Nutrient fluctuations occurred in both treatments and were closely linked to plant developmental stages, emphasising the need for dynamic nutrient management even when solutions are periodically refreshed. Across both treatments, iron, manganese, nitrate, and phosphate declined most rapidly, likely due to a combination of high plant uptake, chelate instability, and root-nutrient interactions.

EC, while commonly used, failed to accurately represent ion-specific fluctuations, particularly for micronutrients. The influence of root exudates and passive ion accumulation likely further compromised its reliability as a sole proxy for nutrient status. These findings reinforce earlier research cautioning against exclusive reliance on EC and highlight the need for more adaptive, ion-specific monitoring approaches in closed-loop systems.

Taken together, these results demonstrate the complexity of nutrient management in closed-loop hydroponics, where strategies that optimise one outcome often compromise another. Achieving sustainable production will therefore require approaches that integrate plant developmental dynamics with technologies capable of monitoring nutrient composition at higher resolution than EC alone. Such innovations could enable growers to balance yield, efficiency, and environmental impact more effectively, strengthening the long-term viability of controlled-environment agriculture.

Funding

This research was funded by the Natural Environment Research Council Cross-disciplinary research for Discovery Science NE/X018423/1 and partially funded by the Low Carbon Eco-Innovatory (Grant 22R16P00567).

Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data supporting the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.18804397.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Composition of the half-strength Hoagland nutrient solution used in this study, including final

concentrations, ion contributions, and reagent sources. **Table S2:** Treatment 1 macronutrients, micronutrients and EC (means ± standard error [SE]) with initial readings on day of transplanting (14 DAS), before and after every time solution was replaced, and on day of harvest (40 DAS). **Table S3:** Treatment 2 macronutrients, micronutrients, EC (means ± SE) and percentage change with initial readings on day of transplanting (14 DAS), every week thereafter, and on day of harvest (40 DAS). **Figure S1:** Macro and micronutrient data collected from the Control sump tank. Half strength Hoagland's solution was recirculated alongside Treatment 1 systems, in the absence of any biological component. No solution amendments were made throughout. **Figure S2:** Boxplots for destructive harvest data including Rosette width at widest points (mm) (a), Leaf area (mm^2) (b), Leaf number (c), Length of longest leaf (mm) (d) and Width of widest leaf (mm) (e). **Figure S3:** The cost of half strength Hoagland's solution per gram of Fresh weight (a) and Dry weight (b), when made for £ 0.12 per litre.