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Adding Ammonium through Automated pH Control in Zero-discharge Liquid Hydroponics to Maintain Low, Steady-state Concentrations

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Abstract. **Low concentrations of ammonium in hydroponic solutions typically improve plant growth and better simulate field conditions, but it is challenging to achieve steady-state levels because ammonium uptake is several orders of magnitude faster than nitrate uptake. Millimolar additions of ammonium cause rapid pH decreases because ammonium uptake is coupled with proton release from roots. We used an automated pH control system to add micromolar concentrations of ammonium several times an hour in combination with nitric acid. This stabilized pH and allowed for the addition of 3% to 13% of the nitrogen as ammonium. The type of ammonium salt was important: ammonium sulfate led to sulfur accumulation in solution and ammonium dihydrogen phosphate led to phosphorus (P) accumulation. Both salts caused intermittent pH decreases from pH 6 to 4. When the pH control solution included ammonium nitrate in a 1:2-M ratio with nitric acid there was no anion accumulation and a stable root zone pH. The resulting micromolar equilibrium concentration of ammonium facilitated repeated cropping of lettuce in the same solution at an electrical conductivity (EC) of 0.4 mS/cm without a decrease in yield. This better simulates field environments where ammonium ions are present at a low, steady concentration in the root zone solution.**

Nitrogen (N) uptake dominates pH changes in hydroponic nutrient solutions.

Ammonium vs. nitrate. Ammonium uptake is coupled with proton release, which decreases root zone pH, and nitrate uptake is coupled with proton uptake, which increases root zone pH (Marschner and Marschner 2012); however, this ion exchange is not necessarily at a 1:1 M ratio. van Rooyen and Nicol (2022a) grew kale in liquid hydroponics and reported that ammonium and proton exchange occurred in a 1:1 ratio and nitrate and proton exchange occurred in a 1:0.5 ratio. This difference in exchange ratios leads to a decrease in pH if ammonium and nitrate are at equal concentrations in solution.

Nitric acid is preferred for pH control. Most nutrient solutions use mainly nitrate-N, so an acid must be frequently added to maintain pH. Sulfuric acid is commonly used, but sulfate can accumulate in zero-discharge systems. Phosphoric acid adds excess P, which can lead to accumulation, luxury uptake, and environmental pollution. Adding hydrochloric acid adds chlorine at macronutrient levels, which can lead to nutrient imbalances. Nitric acid is the acid of choice because it adds nitrate, which does not typically accumulate in solution (Lea-Cox et al. 1999).

Poor nutrient solution buffering in hydroponics. Hydroponic root zones are poorly buffered, so rapid pH changes are common. Phosphate species can add buffering capacity, but these ions are rapidly removed from solution via active uptake, which leads to hydroponic solutions having a buffering capacity approaching that of deionized water (van Rooyen and Nicol 2022b). Acidification from rapid ammonium uptake can lead to root membrane leakage, cellular ammonium buildup, and micronutrient toxicities (Britto and Kronzucker 2002).

Clark (1982) demonstrated pH changes in a nutrient solution without pH control as a function of nitrogen form. The nutrient solution pH increased from 5.5 to 7.0 after a week in treatments receiving only nitrate, decreased to 3.0 in treatments receiving only ammonium, and was stable between 5.0 and 6.0 when the nutrient solution contained 11% ammonium. This work shows the value of a combination of N forms for stabilizing pH, but implementation can be difficult because of rapid ammonium uptake. Bugbee (2004) mentioned using ammonium nitrate to stabilize pH by adding it to the pH control solution, but did not discuss optimization of the ammonium salt or the ammonium-to-nitrate ratio.

Ion antagonisms and the dangers of high ammonium. Elevated ammonium concentrations can inhibit the uptake of other cations, such as potassium and calcium (Marschner and Marschner 2012). Claassen and Wilcox (1974) saw reduced potassium and calcium content in corn grown in soil with 100% ammonium-N compared with 100% nitrate-N, but found little difference in yield. Weil et al. (2021) saw a significant decrease in potassium and calcium in lettuce leaf tissue when plants were grown with more than 25% ammonium-N. These inhibitions may induce nutrient deficiencies and stunt growth.

Ammonium and nitrate in the field. Ammonium-N binds tightly to negatively charged soil particles, and its availability in solution is often less than 50 μM. Most studies report its bulk concentration and rarely report its soil solution concentration. Kabala et al. (2017), for example, measured average ammonium-N concentrations of only 43 μM in soil solutions throughout the growing season when sorghum was fertilized with 180 $kg{\cdot}ha^{-1}$ of ammonium nitrate. There is no adsorption to a solid phase in liquid hydroponic solutions and all ammonium ions are bioavailable. Studies with equivalent rates of ammonium-N addition in liquid hydroponics, therefore, have higher ammonium availability than the field, and this complicates extrapolation to the field. Conversely, nitrate does not bind to soil particles and is completely bioavailable. In addition, nitrification is often significant in field studies. A method to provide low and steady-state ammonium-N concentrations would better replicate field conditions and reduce pH fluctuations.

Objective. Our objective was to achieve steady-state pH control across repeated plantings in zero-discharge liquid hydroponics by adding ammonium in small, frequent doses to the root zone. We hypothesized that these small amounts would be quickly taken up by plants, which would add small amounts of protons into solution, and reduce pH fluctuations over time from nitrate uptake. We also hypothesized that the ammonium salt used would affect ion concentrations in the nutrient solution. We predicted that sulfate and phosphate salts would lead to anion accumulation in the nutrient solution and a nitrate salt would avoid ion accumulation and improve pH control.

Methods

Hydroponic system. Lettuce (*Lactuca sativa* cv. Grand Rapids) was germinated on germination paper (blue blotter; Seedburo Equipment Company, Des Plaines, IL, USA) soaked in tap water and placed on a slant board for 7 d as described in Langenfeld and Bugbee (2022). After 7 d, seedlings with uniform root lengths were selected, placed into neoprene cloning collars, and transplanted

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into a deep-water culture hydroponic system described in Langenfeld and Bugbee (2024). The hydroponic system consisted of three gray polypropylene containers each filled with 50 L of a nutrient solution made with reverse osmosis water and containing 0.8 mM calcium nitrate tetrahydrate, 3.5 mM potassium nitrate, 0.4 mM monopotassium phosphate, 0.5 mM magnesium sulfate heptahydrate, 0.3 mM potassium silicate (AgSil16H), 1.0 mM nitric acid, 7 µM iron DTPA (diethylenetriaminepentaacetic acid, Sequestrene 330), 3 µM manganese EDTA (ethylenediaminetetraacetic acid) disodium hydrate, 3 µM zinc chloride, 16 µM boric acid, 2 µM copper EDTA disodium, 0.1 µM sodium molybdate dihydrate, and 0.1 µM nickel chloride hexahydrate. The initial pH was 5.80 and the initial EC was 0.95 mS per cm.

Eight seedlings in neoprene cloning collars were held in place in an extruded polystyrene cover above the nutrient solution in each container. The hydroponic system was located in a glass greenhouse at the Utah State University Research Greenhouses in Logan, UT, USA. The day/night temperature was controlled at 25/20 °C. Relative humidity was not controlled but averaged 50% ± 20%. The CO_2 concentration was ambient at 430 ppm (µmol·mol^{-1}). The daily light integral (DLI) was measured with an integrating quantum meter (model DLI-500; Apogee Instruments, Logan, UT, USA). Planting dates and DLI values are shown in Table 1.

pH control. The pH control system consisted of a pH electrode (single-junction, silver/silver chloride combination reference) submerged in the nutrient solution of each container, a pH controller (model 931700-0; Hanna Instruments, Woonsocket, RI, USA), a solenoid pinch valve (PG-PV solenoid pinch valve; PreciGenome, San Jose, CA, USA), and a control solution reservoir. The pH control system was set to maintain a pH of 5.80 with a 0.10 pH tolerance. When the pH as measured by the pH electrode reached 5.90, the controller opened the solenoid valve for 5 s via a time-delay relay (Droking, Guangzhou, China) to allow the control solution to enter the container. This released ≈12 mL of solution during each dose. The control solution consisted of 50 mM nitric acid and an ammonium salt described in the next section. The pH control volume (12 mL) was quickly diluted in the 50 L container. A 25-mM ammonium concentration in each pH injection resulted in a *6 µM ammonium concentration* in the nutrient solution following each injection. With 50 mM ammonium concentration in the pH control solution, this would dilute to 12 µM ammonium in the nutrient solution.

The pH control solution was directed at the pH electrode through a silicone tube to decrease the pH on contact and reset the controller for the next dose. The control cycle repeated automatically in each container as needed until the plants were harvested 28 d after transplanting (35 d after seeding). The pH control system is described in more depth in Langenfeld and Bugbee (2024).

Treatments. The pH control solution for each container was amended with an ammonium salt: 50 mM ammonium dihydrogen phosphate (ADP), 25 mM ammonium sulfate (AS), or 25 mM ammonium nitrate (AN). The salt concentration varied to maintain a 50 mM total N concentration in each treatment. There was one replicate of each treatment with four repeated plantings over time. After 28 d, mature plants were harvested, and 7-d-old seedlings were transplanted into the remaining nutrient solution. The nutrient solution was not modified or discarded between plantings but was refilled daily with fresh nutrient solution as needed to maintain 90% to 100% of the initial 50 L volume. Each container was refilled with the same nutrient solution.

Data collection

Water quality measurements. The EC was measured once a day before refilling (Supplemental Data 1) using an EC meter (model DiST 3; Hanna Instruments, Woonsocket, RI, USA).

The mV output from each pH controller was recorded by a separate differential channel on a datalogger (model CR1000; Campbell Scientific, Inc., Logan, UT, USA) every 10 s. A 5 min running average of the voltages was calculated and converted to pH using a multiplier of 0.0033 and an offset of −3.58. A 1 h running average was then calculated by averaging the 5-min average data (Supplemental Data 2).

After each harvest, a 50 mL sample of the remaining nutrient solution was taken from each container and the nutrient concentrations were analyzed using inductively coupled plasma optical emission spectroscopy (ICP-OES) at the Utah State University Analytical Laboratory in Logan, UT, USA. Nitrate-N in each nutrient solution was also measured by this laboratory using the cadmium reduction method for flow injection analysis [QuikChem Method 12-107-04-1-C, method W-1.80 in Gavlak et al. (2005)].

Plant tissue measurements. The shoot and root masses from the plants in each container were measured after each harvest. Tissues were then dried in an 80 °C oven for at least 2 d until a constant mass was obtained. The dry mass was recorded, and the young leaf tissue (most recently expanded upper leaves) was ground to a fine powder in a mortar and pestle. The tissue was then digested in 15.7 M nitric acid and 30% hydrogen peroxide as described in method B-4.25 from Gavlak et al. (2005) and subsequently analyzed for most essential elements using ICP-OES. Total N in the dry tissue was measured using an automated combustion method [method B-2.20 in Gavlak et al. (2005)].

Photon conversion efficacy. Photon conversion efficacy (PCE) was calculated for each container in each planting by dividing the total dry mass per container by the product of the container area (0.35 m^2) and the days to harvest (28 d). This value was then divided by the average DLI across the planting to derive PCE (Eq. [1]).

$$PCE = \frac{\left(\frac{g\ dry\ mass}{m^2 \times d}\right)}{\left(\frac{mol\ photons}{m^2 \times d}\right)} = \frac{\left(\frac{g\ dry\ mass}{0.35\ m^2 \times 28\ d}\right)}{DLI} \quad [1]$$

Statistical analysis. The PCE among plantings was compared using an analysis of variance in the "stats" package in R (version 4.0.5; Foundation for Statistical Computing, Vienna, Austria) with a Tukey's honestly significant difference post hoc test.

Results

Although there was little difference in plant growth among treatments, there were significant trends in the accumulation of ions in the nutrient solution.

EC. The EC decreased over time as nutrients were removed from the nutrient solution by the plant roots (Fig. 1). The EC trends among the treatments were similar, but the AN treatment maintained the highest EC and the ADP treatment maintained the lowest EC. The EC increased immediately after each harvest as each tank was topped off with fresh nutrient solution before the next planting.

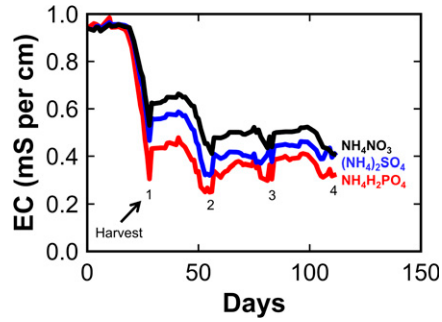

Fig. 1. The electrical conductivity (EC) of the nutrient solution with lettuce grown in zero-discharge liquid hydroponic containers receiving automated pH control with 50 mM nitric acid and 50 mM ammonium dihydrogen phosphate (red), 25 mM ammonium sulfate (blue), or 25 mM ammonium nitrate (black). There were four crop cycles in the same solution.

Table 1. The planting and harvest times in 2024 and average light intensities for lettuce grown in zero-discharge liquid hydroponic containers. The daily light integral was elevated by supplemental lighting.

Crop cycle	Transplant	Harvest	Avg daily light integral (mol·m^{-2}·d^{-1})
1	12 Apr	10 May	38.7
2	15 May	12 Jun	37.9
3	12 Jun	10 Jul	35.0
4	11 Jul	8 Aug	31.7

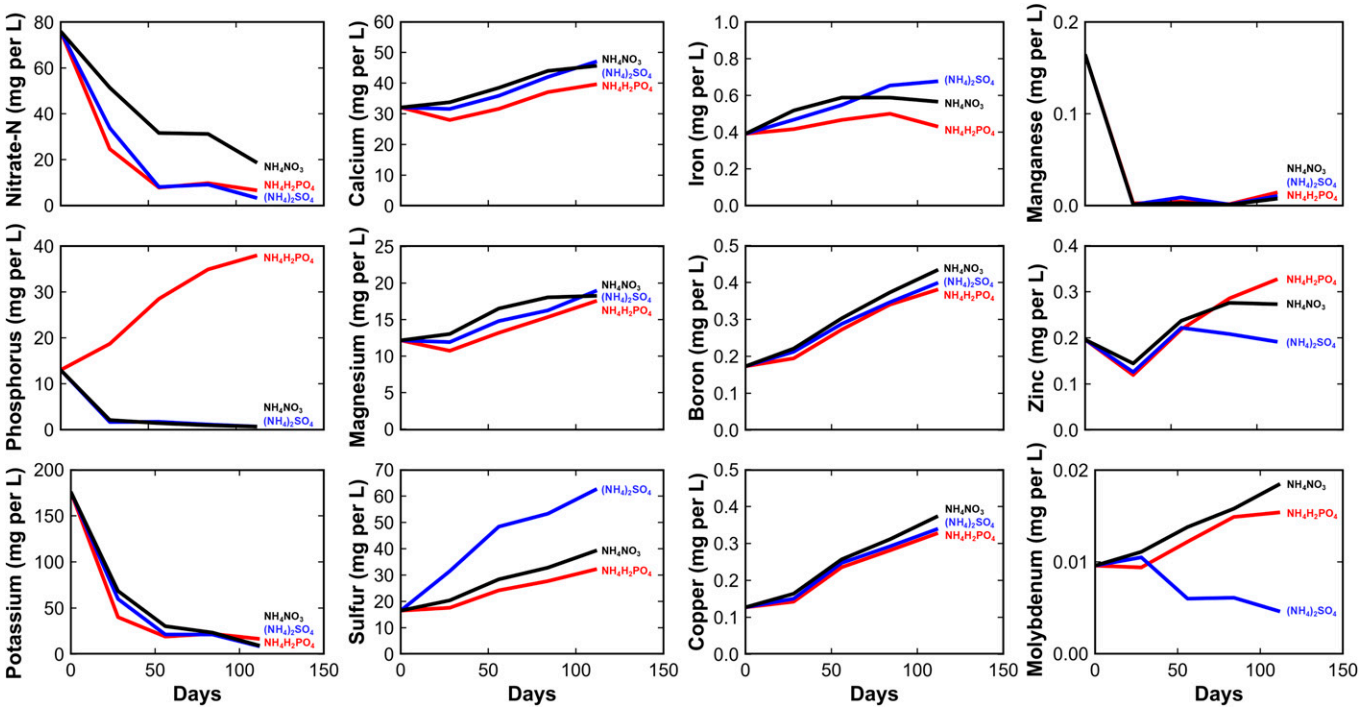

Fig. 2. The nutrient concentrations remaining in solution after the harvest of lettuce grown in zero-discharge liquid hydroponic containers receiving automated pH control with 50 mM nitric acid and 50 mM ammonium dihydrogen phosphate (red), 25 mM ammonium sulfate (blue), or 25 mM ammonium nitrate (black). There were four crop cycles in the same solution.

Nutrient concentrations in the nutrient solution. The nutrients remaining in the nutrient solution after each harvest were similar among treatments for most nutrients except nitrate, P, and sulfur (S). The nitrate concentration decreased at a slower rate in the AN treatment compared with the other treatments (Fig. 2). By the end of the fourth planting, the nitrate concentration was ≈20 mg·L^{-1} in the AN treatment and less than 10 mg·L^{-1} in the other treatments. The P concentration reached almost 40 mg·L^{-1} at the end of the fourth planting in the ADP treatment but was less than 1 mg·L^{-1} in the other treatments. The concentration of S in the AS treatment after the fourth planting was about double the concentration in the other treatments. There was an additional small separation of nutrient concentrations among treatments for iron, zinc, and molybdenum.

PCE. There was a small decrease in the PCE between the first and the second harvest, but no change among harvests two, three, or four (Fig. 3). Importantly, there was no significant difference in the PCE between planting one and planting four. The percent root mass (dry root mass divided by dry root and shoot mass) ranged from ≈10% to 15% for all treatments and plantings except the AS treatment during the third and fourth plantings.

Nutrient concentration in plant tissue. Plants receiving ADP had a higher P concentration and lower iron concentration in their young leaf tissue than plants receiving AS or AN (Fig. 4). N and boron were the most stable nutrients measured among plantings and varied less than 20% in all treatments. The S concentrations were the most stable nutrient measured among treatments, but the average concentration oscillated between 0.30% and 0.45% among plantings. The calcium and manganese concentrations were the most variable among plantings. Tissue concentrations were similar among treatments for most other elements but tended to vary among plantings.

Accuracy of pH control and contribution of ammonium. The automated pH control system maintained the nutrient solution pH below 5.9 during all four plantings for all treatments (Fig. 5). There were no differences in the pH over time during the first planting and each treatment received similar volumes of pH control solution (Table 2). Sharp transient pH decreases immediately after dosing represented localized nutrient solution pH at the electrode tip. The pH quickly recovered as the acid diluted into the bulk nutrient solution. The pH drifted down in the AS treatment in the second planting a couple of days before harvest. The broad troughs indicated that these pH decreases represented the bulk nutrient solution pH instead of the localized pH near the electrode tip. This treatment, and the ADP treatment, used less pH control solution than the AN treatment during the second planting. The magnitude of pH change increased during the third and fourth plantings in the AS treatment, and as a result the containers required less pH control solution than the other treatments. The pH of the ADP treatment never drifted below pH 5 in any of the four repeated plantings.

Discussion

The approach described here enabled the frequent addition of only 6 to 12 µM ammonium, which reduced pH fluctuations and resulted in a steady-state solution concentration of ammonium. This approach also facilitated the growth of multiple crops of lettuce without replacing the nutrient solution.

Automated control to stabilize pH. Our system is not the first to use ammonium salts to help control pH in recirculating hydroponics, but we are the first to show its long-term viability over repeated plantings in a zero-

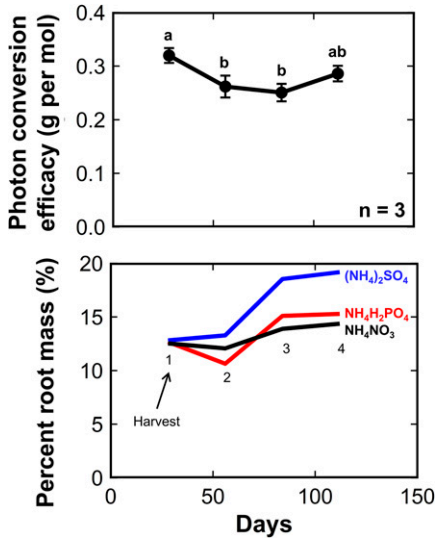

Fig. 3. The photon conversion efficacy (top) and percent root mass (bottom) of lettuce grown in zero-discharge liquid hydroponic containers receiving automated pH control with 50 mM nitric acid and 50 mM ammonium dihydrogen phosphate (red), 25 mM ammonium sulfate (blue), or 25 mM ammonium nitrate (black). There were four crop cycles in the same solution. Error bars represent the standard deviation of the ammonium treatments, n = 3.

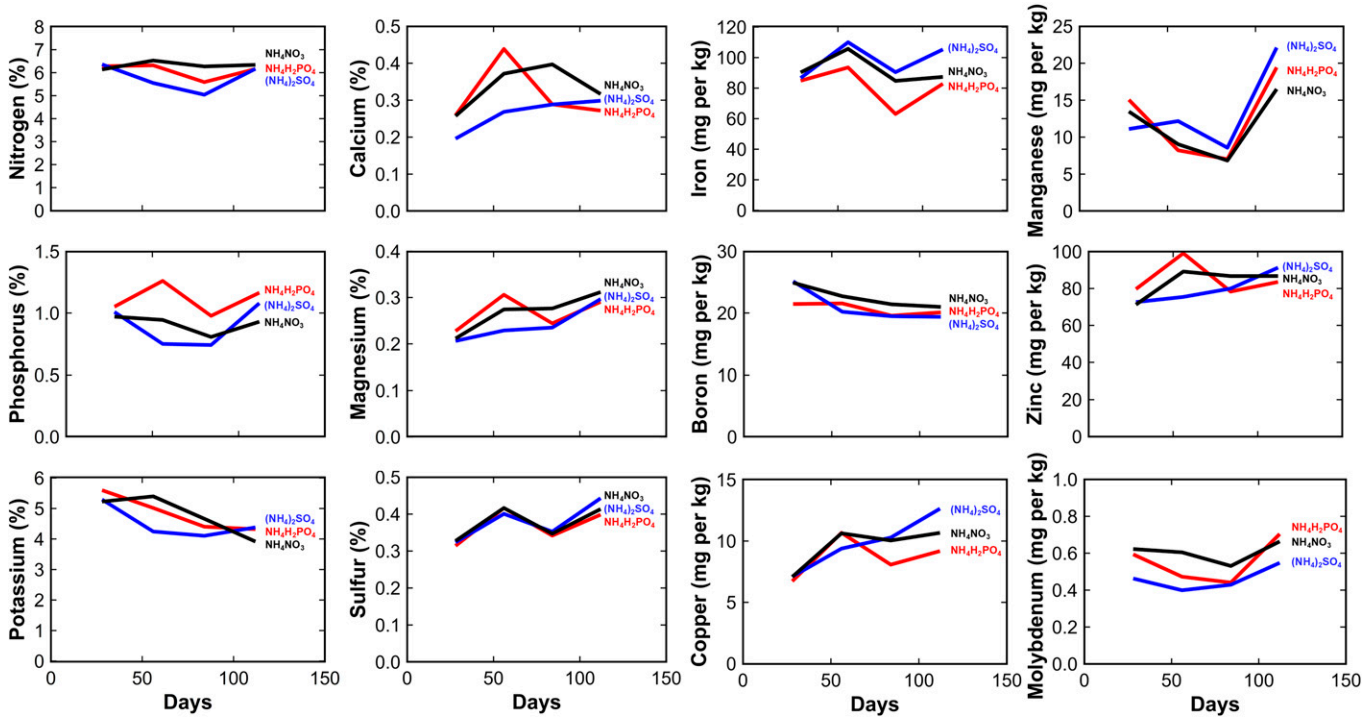

Fig. 4. The nutrient concentrations in the young leaf tissue of lettuce grown in zero-discharge liquid hydroponic containers receiving automated pH control with 50 mM nitric acid and 50 mM ammonium dihydrogen phosphate (red), 25 mM ammonium sulfate (blue), or 25 mM ammonium nitrate (black). There were four crop cycles in the same solution.

discharge nutrient solution. Bosman et al. (2024) recently maintained ammonium in a nutrient solution through automated control. They first calculated an ammonium-to-nitrate ratio to control pH. They then used an algorithm to determine the amount of N to add to the system to maintain EC and dosed proportions of the ammonium and nitrate salt solutions to maintain pH. The pH was controlled to within ± 0.5 pH units of their target (pH 6.1), but they did not use an acid or a base to avoid accumulating undesirable ions. Our approach does not require continuous EC monitoring or a control algorithm, avoids the accumulation of ions, and facilitates more stable pH control.

The trends we observed in the nutrient solution pH were largely as expected. We maintained the total N concentration instead of the ammonium-N concentration, which led to larger pH swings in the ADP and AS treatments that received more ammonium during each pH dose. Despite the AS treatment receiving the lowest amount of ammonium in trials three and four (Table 2), we observed the largest pH swings in this treatment. Although the ADP treatment received similar amounts of ammonium, the additional P provided may have helped buffer the rapid pH changes (van Rooyen and Nicol 2022b). Although the total ammonium received among treatments in plantings two through four was similar, the ammonium in the ADP and AS treatments was received less frequently and in larger doses than the AN treatment. This shows the value of a low, steady-state approach to ammonium management compared with larger, infrequent additions.

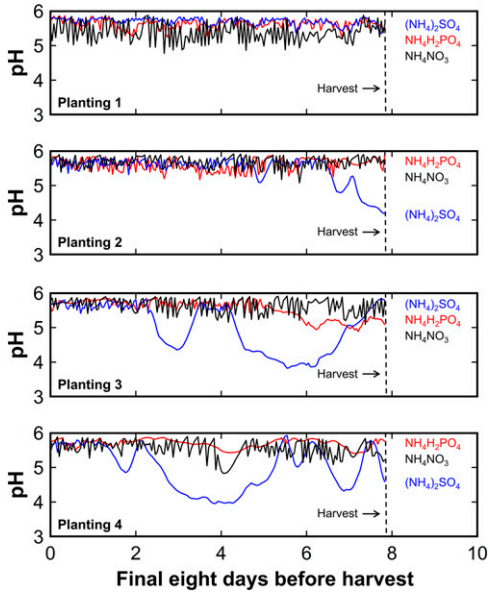

Fig. 5. The nutrient solution pH during the final 8 days of the 28-d crop cycles of lettuce grown in zero-discharge deep-water culture hydroponics with automated pH control. Because of exponential growth, most of the pH control solutions were used in the final 8 days. There were four replicate crop cycles in the same solution. The lines represent 1 h running average data plotted every hour. The treatments were as follows: 50 mM nitric acid and 50 mM ammonium dihydrogen phosphate (red line), 25 mM ammonium sulfate (blue line), or 25 mM ammonium nitrate (black line).

The ammonium-to-nitrate ratio. The literature is replete with discussions on optimal ammonium-to-nitrate ratios for plant growth. The optimum ratio varies among species but most studies indicate that some ammonium improves growth (Chen et al. 2024). We achieved up to 13% of the N delivered as ammonium (≈1:8 ratio) and saw no effect on yield compared with 4% ammonium. Our objective was not to optimize the ratio, but to stabilize pH, reduce ion accumulation, and better simulate field conditions.

Many hydroponic solutions, such as Hoagland's original solution number one (Hoagland and Arnon 1938), use only nitrate to simplify pH control. However, Hoagland realized the value of ammonium and, 12 years later, published Hoagland's solution number two with ≈7% ammonium-N (Hoagland and Arnon 1950).

Table 2. The ammonium received from the pH control solution during each crop cycle grown in zero-discharge liquid hydroponic containers receiving automated pH control with 50 mM nitric acid and 25 mM ammonium nitrate (AN), 50 mM ammonium dihydrogen phosphate (ADP), or 25 mM ammonium sulfate (AS). The portion of total nitrogen (N) received as ammonium was calculated by accounting for the N received from both the bulk nutrient solution and the pH control solution.

	pH control solution used (L)			Ammonium from pH control (mmol)			Portion of total N received as ammonium (%)		
Planting	AN	ADP	AS	AN	ADP	AS	AN	ADP	AS
1	1.36	1.60	1.36	34	80	68	5	13	11
2	1.19	0.74	0.82	30	37	41	5	6	7
3	0.84	0.50	0.34	21	25	17	4	5	3
4	0.95	0.48	0.38	24	24	19	4	5	4

Effect of solution EC on PCE. Managing nutrients by mass balance allows the elements with active uptake to be drawn down to low levels in the solution, which results in a low solution EC (Langenfeld et al. 2022). Solution EC is often maintained at a set point, but this often results in excessive concentrations of some nutrients in the recirculating solution.

The highest PCE occurred in the first planting in all treatments, decreased in the second planting, and increased again by the fourth planting. There was no trend in tissue nutrient concentrations over time, which indicates the PCE changes were not due to a nutritional stress. The EC was 0.4 $mS \cdot cm^{-1}$ at the beginning of planting four compared with 1 $mS \cdot cm^{-1}$ at the beginning of planting one, but because there was no significant difference between the PCE in planting one and four, the change in PCE cannot be linked to a decreasing EC over the course of the study. The second and third crop cycles had a lower PCE, but these crops were grown in the summer months in the greenhouse when higher air temperatures and a higher vapor pressure deficit may have contributed to the reduced PCE.

Relationship between ions in solution and EC. The nutrient solution EC is determined by the differential contribution of nutrient ions based largely on their concentration and square of their charge (Griffin and Jurinak 1973). The ADP treatment had the lowest concentration of calcium, magnesium, and S in solution among all treatments, which likely contributed to the lowest EC. Although the P concentration was the highest, dihydrogen phosphate is monovalent and was potentially overshadowed by the higher divalent ion concentrations. The AS treatment had the highest S concentration, but not the highest EC.

The higher concentration of nitrate maintained throughout the study in the AN treatment may have led to its slightly higher EC. Although a nitrate concentration of 20 $mg \cdot L^{-1}$ may seem low, this is more representative of field conditions and does not represent N stress. For example, van Rooyen and Nicol (2021) found no difference in the growth rate of hydroponic kale when the N concentration in the nutrient solution was maintained at 154 $mg \cdot L^{-1}$ compared with 1.4 $mg \cdot L^{-1}$, which is less than half the lowest concentration of nitrate-N measured in solution during any point in our study.

The initial EC was not maintained over time as plants were allowed to take up nutrients as needed. Maintaining EC often leads to ion accumulation over time, which we sought to avoid. The decreasing EC indicated that plants were healthy and had active nutrient uptake. This would have been difficult to observe if the EC was maintained. A lower EC is also more representative of field nutrient conditions.

The benefits of low ion concentration in solution. The EC was ≈0.4 $mS \cdot cm^{-1}$ in the later crop cycles, yet there were no significant decreases in nutrient concentration in leaf tissue. This shows the value of controlling nutrients by mass balance rather than by a setpoint EC. Nutrient accumulation in solution and luxury uptake have no effect on yield if adequate concentrations of nutrients are provided (Adler et al. 2000).

The ADP treatment resulted in higher P in solution and leaf tissue than the other treatments. The absence of a yield increase indicated that P was not limiting and did not benefit from luxury uptake. Penn et al. (2022) also found elevated P tissue concentrations in corn with increasing P concentrations but found no significant yield changes. Despite the elevated solution concentrations of S in the AS treatment, there was no difference in leaf tissue sulfur concentration. This indicates that lettuce does not take up S beyond that required for normal growth. At the high S concentrations measured in our study, the plants would have excluded S from uptake.

Because there was no difference in yield among treatments, excess nutrients were unnecessary and could lead to precipitation. The higher P concentration in the ADP treatment was correlated to a lower Fe concentration in both the nutrient solution and the young leaf tissue. This may be due to the precipitation of Fe as iron (III) phosphate. Amiri and Sattary (2004) studied nutrient solubility in solution culture and reported a 20% loss of Fe and a 15% loss of P from precipitation when their concentrations were doubled, which is similar to the decrease in Fe in solution that we observed in the final planting. It is thus beneficial to maintain low P concentrations to reduce Fe precipitation, which can lead to decreased bioavailability and iron chlorosis (Parry and Bugbee 2017).

Carbon partitioning to roots. A higher percent root mass is often indicative of a lower concentration of nutrients in solution where a plant partitions more energy toward root growth to maximize nutrient uptake (Thornley 1972). The percent root mass in the final two plantings was slightly higher than reported in the literature. Sakamoto and Suzuki (2015) measured a percent dry root mass ranging from 13% to 15% for hydroponic lettuce 'Red Wave' and Li et al. (2018) found a percent root mass of ≈10% in hydroponic lettuce 'Dasusheng' and 'Nenglv Naiyou'. In our study the first two plantings had a lower percent root mass. The higher nutrients in the first planting may have resulted in less energy partitioned to root growth, although the second crop cycle had a lower EC and a similar percent root mass. This indicates that changes in percent root mass may not be fully explained by concentrations in the nutrient solution.

Low pH is also a stress. The higher percent root mass in the last two crop cycles may have been caused by decreased pH. The replicates with the largest pH decreases were associated with the highest percent root masses.

Nitrification potential. Nitrification is common in the field but is minimal in liquid hydroponics. Most nitrifying organisms need a solid substrate to grow, which is absent in liquid hydroponics. Padgett and Leonard (1993) measured a nitrate accumulation of 0.35 mM nitrate in sand culture with 2 mM ammonium, but nitrate accumulation was less than 1 μM (0.001 mM) in liquid culture. Muhlestein (2001) reported a nitrification rate of ≈250 $\mu M \cdot d^{-1}$ in a nutrient solution containing isolite, but when plants were added, they likely competed with the bacteria for ammonium uptake and nitrification was not detectable. Collectively these studies indicate that nitrification is minimal in liquid hydroponics without a substrate.

Conclusions

Small additions of AN delivered with an automated pH control solution of nitric acid can maintain low, steady-state ammonium concentrations in hydroponic nutrient solutions and facilitate repeated crop cycles in the same solution. ADP led to an accumulation of P and AS led to an accumulation of sulfate. Both salts also led to large pH swings in several plantings. The addition of 25 mM AN in a 1:2 ratio with nitric acid supplements all-nitrate solutions with ammonium while minimizing pH changes and reducing anion accumulation. This low, steady-state approach leads to a stable rhizosphere that better simulates field soils.

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