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Closed Loop Phosphorus Recovery and Recycling for Sustainable Hydroponic Farming

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ABSTRACT

This study explores the viability of in-situ recycling of hydroponic waste nutrient solutions using alkali treatment to produce micro-calcium phosphate. The recovered precipitate was converted into a usable liquid form (called Part C) and assessed for its effectiveness as a source of phosphorus, replacing 40% of the commercial Part B fertiliser in a hydroponic nutrient solution. The pilot study was conducted in a controlled greenhouse equipped with an automated fertigation system to ensure precise nutrient delivery and environmental control. Snow peas (*Pisum sativum L.*) were grown for 21 days using this nutrient solution, and its performance was compared with a control system employing commercial fertilisers. Results demonstrated that the test system, incorporating Part C, required 33% less commercial fertiliser while maintaining comparable plant growth, yield, and nutrient uptake. Except for a slightly lower chlorophyll content, plants in the test system exhibited no nutrient deficiencies; exhibited stable phosphorus, and enhanced calcium and magnesium uptake. Moreover, Part C contributed to improved pH and EC stability, reducing the need for frequent nutrient adjustments compared to the control. The economic analysis indicated a significant cost reduction without compromising plant health or productivity, highlighting the potential for broader application in sustainable hydroponic farming.

1 | Introduction

Phosphorus (P) is a critical nutrient for global food production, primarily sourced from finite rock phosphate reserves. The mining and processing of phosphate rock involve mechanical beneficiation and acidulation, producing phosphoric acid for fertiliser production. However, this process generates significant environmental waste and remains highly dependent on geopolitically sensitive supply chains (Bastida et al. 2023; Wellmer and Scholz 2017). Global disruptions, such as the Russia-Ukraine war and export restrictions from key suppliers like China, have intensified price volatility and threatened agricultural sustainability (Lamghari et al. 2024; Mew et al. 2023; Shahini et al. 2022).

The extraction of rock phosphate involves mechanical methods such as crushing, grinding, and screening. In the pre-enrichment phase, techniques like attrition, scrubbing, washing, and de-sliming are employed to remove clays and fine silicates. Common beneficiation methods for phosphate ore include flotation, calcination, electromagnetic separation, leaching, gravity separation, and magnetic separation (Amar et al. 2022; Lawver et al. 1982; Taha et al. 2021). The principal component, calcium phosphate, insoluble in water at neutral pH, undergoes an acidulation process to extract phosphoric acid (H_3PO_4) from the rock, leaving calcium sulphate (gypsum) as a byproduct (Charleston et al. 1988; Davies 1984; Hammond et al. 1980; Zhao et al. 2024). The simplified chemical reaction is given in Equation 1 (US-EPA 1993).

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$$Ca_3\left(PO_4\right)_2 \ + \ 3H_2SO_4 + 6H_2O \rightarrow 2H_3 PO_4 + 3\left[CaSO_4 \ \ 2H_2O\right]\downarrow \quad (1)$$

Despite the variable grades of rock phosphate, which range from 12% to 35% calcium phosphate, its price depends on the Bone Phosphate of Lime (BPL) content, with the World Bank pricing it based on a 70% BPL grade (Amar et al. 2022; Geissler et al. 2023). The efficiency of rock phosphate processing can impact recovery rates, potentially reducing extractable phosphate by up to 25% (Koppelaar and Weikard 2013). A finer particle size of calcium phosphate leads to more efficient acidulation and higher phosphate extraction ratios (Amar et al. 2022).

Significant research has focused on optimising the use of existing phosphate resources to reduce dependency on mining. This includes improving mining efficiencies and exploring phosphate recovery from wastewater (including agricultural runoff) through processes such as chemical precipitation, biological treatment, constructed wetalnds and microalgae (Abbassi et al. 2011; Arun et al. 2020; Cowan et al. 2022; Du et al. 2023; Lamghari et al. 2024; Masindi and Foteinis 2021; Occhipinti et al. 2024; Oumabady et al. 2023; Tang et al. 2025). In the author's previous work, Malkawi et al. (2024a) and Malkawi et al. (2024c) explored the recovery of micro-calcium phosphate from hydroponics waste nutrient solutions (HWNS) and examined its economic viability. Building on these principles, this study investigates an in-situ approach for recovering calcium phosphate from HWNS, converting it into a liquid phosphorus source (Part C) for reuse in hydroponic systems. Using alkali precipitation followed by acidulation, this study assessed Part C's effectiveness in substituting 40% of the phosphorus supplied by conventional commercial phosphorus fertiliser (Part B) with a recovered fertiliser solution (Part C). The proposed nutrient-recycling approach offers a practical and scalable solution that reduces demand for newly manufactured fertilisers while maintaining optimal plant growth.

2 | Materials and Methods

This study involved collecting HWNS samples from a local tomato farm in NSW, applying alkali treatment to recover calcium phosphate, and processing it via acidulation into a phosphate-based fertiliser. The fertiliser was integrated into a balanced nutrient solution and tested in a pilot hydroponic system for snow pea cultivation. Plant growth, nutrient solution stability, and economic feasibility were evaluated to assess its potential for sustainable agriculture.

2.1 | Sample Collection and Alkali Treatment

A 1000 L of HWNS was collected from a hydroponic farm located in Wallacia, NSW, Australia. This farm specialises in growing heirloom tomatoes using drip irrigation technology across four greenhouses, totalling an area of approximately 9000 m^2. The tomatoes are cultivated in a soil planting mix, with plants spaced 1 m apart in the rows and with a spacing of 0.8 to 1.2 m between the rows. Irrigation is applied 5 to 7 times daily, adjusted based on solar energy received, and monitored through energy sensors. The solution volume was maintained at a fixed operating level by a mechanical float valve connected to the mains supply. When the level dropped due to uptake or evaporation, the valve was opened to allow makeup water, and an in-line dosing controller adjusted nutrient concentrates and acid/base was added to maintain target electrical conductivity (EC) and pH setpoints. The collected HWNS was transported to a greenhouse facility in Western Sydney University-Kingswood for processing and phosphorus recovery through alkali treatment.

For the alkali treatment at a pH of 9.5, adhering to the author's previous work Malkawi et al. (2024a), calcium hydroxide ($Ca(OH)_2$), commonly known as lime, was utilised. Unlike the authors' previous work, lime was employed instead of sodium hydroxide to prevent sodium accumulation in the nutrient solution. Three separate 1 L samples of HWNS were treated with lime to precisely determine the amount required to achieve a pH of 9.5. The average quantity of lime needed was established at 1.1 ± 0.015 g/L. The initial pH of the HWNS was measured at 6.72, and the EC was recorded at 2.47 mS/cm.

Using this lime-to-volume ratio, the calculated mass of lime was applied to a 240 L subsample of the HWNS, requiring 26.4 g of 98% reagent-grade lime. The solution was mixed vigorously with a steel rod and allowed to settle for 2 h to ensure complete sedimentation. The supernatant was decanted, yielding an 18.5 L solution containing the precipitates.

The phosphorus concentration in the initial HWNS was 20.8 ± 1.6 mg/L, which was reduced to 1.17 ± 0.06 mg/L in the supernatant after alkali treatment at pH 9.5, achieving a removal efficiency of 94%. This was calculated following the methodology adopted by Malkawi et al. (2024a).

2.2 | Preparation of Part C and Nutrient Solution Mix Design

The 18.5 L sample containing precipitates, as detailed in the preceding section, was transferred to the laboratory for acidulation. This process aimed to release phosphate ions from the precipitated calcium phosphate, creating what is referred to as Part C solution. Sulphuric acid, commonly used in acidulating rock phosphate, was employed to dissolve the precipitates (Al-Fariss et al. 1993; Becker 1989). Nitric acid was also used to provide nitrogen to Part C, thereby simulating the major nitrogenous components of commercial fertilisers in Part B. Supplementary Table S1 presents the chemical analysis of the main compositions of commercial fertilisers—Part A and Part B (Optimum Grow twin pack hydroponic nutrient obtained from Fernland (2024)) —and the prepared Part C solutions. Also, the table shows concentrations of key nutrients such as phosphorus, nitrogen, potassium, magnesium, and calcium, along with the EC and pH values. To ensure the final Part C solution integrated seamlessly with commercial fertilisers (Parts A and B), its pH was adjusted to a defined setpoint of 3.2 ± 0.25, adhering to established acidulation conditions for dissolving calcium phosphate and releasing phosphate ions (da Silva

Cerozi 2016; Labgairi et al. 2020; Raviv et al. 2019). This set-point lies between the supplier pH specifications for Part A (pH ≈ 2.2) and Part B (pH ≈ 3.8), ensuring compatibility during blending (see Supplementary Table S1).

The acidulation process involved adding 10 mL of 98% sulphuric acid and 10 mL of 70% nitric acid to 18.5 L of precipitate solution recovered from 240 L of HWNS. This adjustment resulted in a final pH of 3.19 and an EC of 6.15 mS/cm.

2.2.1 | Details of the Nutrient Solution Mix

Control and Test Feed Tanks: Both tanks contained approximately the same initial phosphorus mass to ensure comparability.

- **Phosphorus Sources:** In the test experiment's feed tank, phosphorus will be sourced from both Part B (60%) and the recovered precipitates Part C (40%). Part B will be the sole source of phosphorus in the control tank.
- **Tank Volume:** Both test and control tanks will hold 200 L of nutrient solution, consistent with the capacity of the fertigation units.
- **Electrical Conductivity:** EC will be maintained using Part A and Part B for both the control and test systems, serving as the standard measure for fertiliser dosing to assess the solution's strength, in line with standard commercial hydroponics practices and the fertigation system used (INTA).
- **Fertiliser Ratio:** The liquid fertilisers Part A, B and C are added into the control and test tanks as explained in Table 2.
- **Target pH Level:** Part C, with a pH of 3.2, will aid in achieving the desired target pH level of 6.5 in the test tank when diluted with tap water and mixed with Parts A and B.

2.2.2 | Preparation of Control Nutrient Solution

A control nutrient solution was manually prepared in a 200 L feed tank by mixing Part A, Part B, and tap water. The solution was adjusted to achieve an EC of 2.3 mS/cm and a pH of 6.5, aligning with the optimal levels for growing snow peas in a hydroponic setup, as recommended by the literature. The EC range recommended is 1.5–3.5 mS/cm (Swain et al. 2021), and the pH range is 5.5–6.5 (Ciuta et al. 2020; Demir et al. 2023; Moraru et al. 2022; Thuong and Minh 2020). A dummy control solution was previously prepared by mixing 760 mL of Part A and 760 mL of Part B with 150 mL of 3% sulphuric acid to reach the desired pH level. Part A to Part B ratios were adopted from the manufacturer's data sheet (Fernland 2024). This dummy solution was prepared to estimate the final phosphorus concentration under the desired EC, measured at 35.1 ± 0.4 mg/L, serving as the baseline for the optimal P content required.

2.2.3 | Nutrient Solution Mix for the Pilot Study

As per the assumptions detailed in Section 2.2.1, only a portion of the prepared Part C solution was used in the pilot study, contributing 40% of the phosphorus mass in the nutrient solution. The remaining 60% was sourced from Part B, which was utilised not only to supply phosphorus but also to maintain the other essential nutrients included in Part B, such as nitrogen and potassium. The nutrient composition of Parts A and B are presented in (Malkawi et al. 2024b).

The determined concentrations, along with the measured phosphorus concentrations in Part B and Part C nutrient solutions, informed the design mixes of the final nutrient solutions for the test tank. These are summarised in Table 1.

2.3 | Fertigation System Operations, Conditions and Control

The nutrient solution was manually mixed in the feed nutrient solution tanks of the fertigation units according to the design specifications (Table 1). The tanks were filled halfway with tap water before adding the fertiliser components. Once the fertigation system was activated, it automatically filled the tanks and mixed the nutrients. Upon reaching the desired volume, a float valve regulated the system to stop tap water flow automatically. After preparing the nutrient solutions, the operating conditions of both the test and control fertigation units were entered into the INTA platform according to the target values.

The volume of nutrient solution was maintained constant in the feed tanks at full capacity (200 L) through the floating valve, and tap water was continuously supplied to compensate for evaporation losses. Water flow remained the same for both runs as the feed pump supplied 215 ± 4.3 L/h to the system, distributing ~ 53.75 L/h per channel across both runs. Parts A and B were set to be pumped into the tanks throughout the run using dosing pumps to adjust the EC to the desired level in the recommended proportion of 1:1 (Part A to Part B) as specified by the manufacturer (Fernland 2024; Growth Technology 2024). The target values for EC and pH in both the control and test nutrient solutions were set to 2.5 mS/cm and pH 6, respectively, within the fertigation system platform. These values fall within the typical ranges reported in the literature, which suggest an EC of 1.5–3.5 mS/cm (Swain et al. 2021) and a pH of 5.5–6.5 (Ciuta et al. 2020; Demir et al. 2023; Moraru et al. 2022; Thuong and Minh 2020). The greenhouse conditions were also maintained consistently across both systems, with temperature ranging from 7°C to 25°C and relative humidity (RH) between 40% and 70%, aligning closely with established standards of 7°C–27°C and 40–90% (Nonnecke et al. 1971; Rasiukevičiūtė et al. 2011). It is important to note that the EC and pH values were deliberately set slightly above the design criteria outlined in Table 1 to compensate for calibration errors identified in the sensors. Detailed calibration curves are provided in the Supporting Material (Figures S6–S9).

2.4 | Snow Peas Microgreens Germination, Seedling and Harvesting

Microgreens are young, nutrient-rich plants harvested shortly after the cotyledons have developed, typically between 7 and

TABLE 1 | Nutrient solution mix for control and test tanks of the pilot study. Both tanks were prepared with identical volumes and near-identical pH and EC levels. In the test tank, 40% of the phosphorus was substituted with Part C, derived from HWNS. Volumes of each component were calculated based on target phosphorus contribution.

Specification	Control tank	Test tank	Comments
Tank volume (L)	200	200	The feed tank is identical in both setups
P concentration in Part B (mg/L)	10610 ± 202	10610 ± 202	Analysed value (ICP-OES as described in Section 2.5, Analytical Method)
P concentration in Part C (mg/L)	N/A	289 ± 9	As above
P mass estimate in the tank (mg)	8032	8032	Calculated by multiplying the analysed P concentration in the tank by its volume.
P mass contribution from Part B (mg)	8032	4819	P mass contributed by Part B fertiliser in the test tank was assumed to account for 60% of the total intended phosphorus concentration for the tank.
P mass contribution from Part C (mg)	0	3213	P mass contributed by Part C fertiliser in the test tank was assumed to make up the remaining 40% of the total intended phosphorus concentration for the tank.
Volume of Part A required (mL)	760	760	Was set to contribute 50% of the total EC of both solutions, as determined during the preparation of the dummy solution and outlined in the assumptions (Section 2.2.1)
Volume of Part B required (mL)	760	450	The volume of Part B for the control solution was determined using the same approach. However, the required volume for the test tank is calculated by dividing its mass contribution (60% of the phosphorus mass) by the phosphorus concentration in Part B.
Volume of Part C required (L)	0	11.1	The required volume of Part C for the test tank is determined by dividing the phosphorus mass contribution from Part C by the phosphorus concentration in Part C.
Volume of 3% sulphuric acid (mL)	150	0	No additional acid was required for the test tank to achieve the desired pH, likely because the acid added during the preparation of Part C was sufficient to buffer the final solution to an adequate pH level.
Solution EC (mS/cm)	2.33	2.35	
Solution pH	5.72	5.74	

21 days post-germination. These greens, including varieties like snow peas, are known for their vibrant colours, intense flavours, and high nutrient content, making them a popular choice for culinary uses and home gardening (Verlinden 2020).

Using snow peas (*Pisum sativum. L*) as microgreens provides several research advantages due to their rapid growth cycle, allowing for multiple experiments in quick succession. They are space-efficient and thrive in controlled environments, making them ideal for urban agriculture research. Snow pea microgreens are also nutrient-dense, offering valuable data on nutritional content relevant to health and diet studies (Di Gioia et al. 2017; Ferguson and Paull 2019; Verlinden 2020). Seeds were sourced from a local store and branded as *Mr Fothergill's Mammoth Climbing Snow Pea Vegetable*.

To prepare the seeds for germination, they were washed with Milli-Q water and placed on a seedling tray ($35\,cm \times 25\,cm$) covered with a moist, disinfected cloth treated with 3 mM hydrogen peroxide to maintain humidity and reduce contamination, enhancing germinability, adhering to the procedure outlined by Barba-Espin et al. (2010). The seeds were incubated in the dark at 25°C for 72 h (Senevirathne et al. 2019). Immediately afterwards, the fertigation system (INTA) was set into operation, with nutrients circulating through the system (per the target values outlined in Table 1).

After germination, 64 seedlings with successfully developed radicles were selected for use in both control and test systems. For seedling preparation, rock wool was moistened with tap water, and one block ($2\,cm \times 2\,cm$) was placed in each of 32 seedling cells (2.5 cm in diameter) arranged in NFT channels. One seed was then placed on each rock wool block. To ensure the seeds remained in darkness and retained sufficient moisture, another layer of rock wool was used to cover them.

When determining the appropriate harvest time for microgreen peas, 7 to 21 days was found suitable to ensure the second genuine leaf is developed, based on studies by Di Gioia et al. (2017) and Eissa et al. (2018). For this study, the harvest

occurred after 21 days by cutting the stems just below the hypocotyl and above the rock wool, as supported by Graham et al. (2019).

2.5 | Analytical Method

Non-destructive tests were conducted on the plants just before harvest, including measuring the height of the hypocotyl, polyembryony, and relative chlorophyll content (SPAD) as described in Al-Majdi et al. (2020) and Mehrabi and Sepaskhah (2022).

The SPAD-502Plus Chlorophyll Meter was acquired from Konica Minolta. Each of the 32 plants was harvested separately, weighed for fresh mass, and then oven-dried at 70°C for 4 days until a constant mass was reached, following Moraru et al. (2022). The samples were not washed to preserve the integrity of the delicate microgreens, which were grown indoors under controlled conditions, as supported by Moraru et al. (2022) and Galieni et al. (2020).

After determining the dry mass for each plant separately, all control samples were combined, and all test samples were combined for digestion and macronutrient analysis. Leaves were manually separated from the stems of the dried samples, crushed into a fine powder using a mortar and pestle, passed through a 0.05 mm sieve, and thoroughly mixed. A 0.1 g sample was then taken for digestion, according to Rayment and Lyons (2011).

The analysis of macro and micronutrients in the digested shoot samples and nutrient solutions was conducted according to standard methods (APHA-AWWA-WEF 2012). The instrumentation included the Hach HQ40d for pH and EC measurements, a Gallery Thermo-Scientific analyser for nitrogen species, and ICP-OES (Agilent Technology 700 series) for cations, including phosphorus, calcium, potassium, magnesium, sodium, sulphur, copper, and iron. Dissolved organic carbon (DOC) was determined using a TOC-L Shimadzu Total Organic Carbon Analyser. ICP-OES standards were sourced from Choice Analytical Pty Ltd, specifically the 68 Element Std Solution A @100ppm 100 mL and Sulphur 10,000 ppm in H2O 100 mL. Nitric acid, sulphuric acid, and other reagent-grade chemicals were obtained from Sigma Aldrich. Thermo-Scientific™ Gallery™ supplied reagents and disposables for the Gallery. All samples underwent triplicate analysis to ensure reliability and accuracy, allowing for calculating mean values and standard deviations.

2.6 | Economic Analysis – Pilot

To evaluate the viability of recycling calcium phosphate-based precipitates and employing them within the pilot setup, the following assumptions and considerations were made:

- Capital Costs: No capital cost (CapEx) was considered in this evaluation, as the chemical precipitation process and the acidulation of these precipitates employed locally available assets commonly found in all hydroponic farms. These assets include a 1000 L water tank (acting as a reactor), a steel rod or stick as a mixer, a water hose (used for decanting the supernatant via syphon/gravity), an acid handling kit and procedure (for acidulating the precipitates) already used by growers to control the pH of the nutrient solution, and a pH & EC measurement multimeter and kit used by growers for preparing their Part A and Part B fertilisers from fertiliser salts.
- Operational Costs: The costs of the recycling process were assumed to be directly related to the alkali and acid costs used in the process. The cost of lime used for the chemical precipitation process was determined using the previously established lime to HWNS ratio (i.e., 0.11 g Lime/L of HWNS). The cost of lime per tonne was adopted from (Tom Grady Rural Merchandise 2024), set at $1,325/tonne. The costs of sulphuric and nitric acids were adopted from (Paramount Chemicals 2024b), standing at $60/5 L for 99% sulphuric acid and $155/20 L for 68% nitric acid. Costs of Part A and Part B fertilisers were considered based on the supplier's price (Fernland 2024). The price was $267/40 L (excluding GST). Both parts (A&B) were assumed to have equal prices for ease of calculations. For farm-scale deployment, it is worth noting that site-specific costs (such as power, labour, chemicals and waste handling, and compliance) may vary and should be confirmed during detailed design.
- **Acid Requirements:** For economic analysis, acid volumes required to acidulate 1 L of settled precipitates were calculated based on treating the entire HWNS sample (240 L), which produced 18.5 L of precipitates (Part C) and consumed 10 mL of each acid (68% nitric acid and 99% sulphuric acid). Since only 11.1 L of the Part C sample was used in the pilot study, a correction factor was applied to estimate the acid volumes for this portion based on the proportionality between the sample and acid volumes.
- **Fertiliser Dosing Consumption:** Part A and B were dosed in the test and control experiments to maintain the EC at the desired level throughout the run, which were measured continuously.

3 | Results and Discussions

Climate data for the greenhouse was acquired from the fertigation system platform (INTA) and is presented in Supplementary Figure S1. The temperature of the greenhouse, which was initially set not to exceed 25°C, averaged 14 ± 3.84°C throughout the experiment, with a maximum of 25.55°C and a minimum of 5.8°C. Understanding the climatic control mechanism in the greenhouse is crucial to interpreting these lower temperatures rather than higher ones.

The greenhouse has a set of fans and a wet wall, which work simultaneously to control temperature and humidity. When the temperature rises, the fans activate, and the wet walls receive water from the pump to cool the greenhouse. However, both systems shut off at low temperatures, leaving the greenhouse at its current temperature.

Relative humidity (RH%) in the greenhouse averaged 56.6 ± 10%, with a minimum value of 27% and a maximum of 75%. These conditions align with the operational parameters outlined in Section 2.3, where the greenhouse temperature was maintained between 7 and 25°C, and the relative humidity ranged from 40% to 70%, ensuring an optimal environment for the growth of snow pea microgreens (Rasiukevičiūtė et al. 2011).

3.1 | Nutrient Solution Performance and Experimental Observations

The nutrient solution temperatures in the control and test systems averaged at 22.9 ± 2°C (18.5°C to 29.9°C) and 24.9 ± 2.5°C (18.4°C to 30.37°C), respectively (Supplementary Figures S2 and S3). Notably, the INTA fertigation system lacks a water temperature controller, which could have influenced these temperature ranges.

The EC and pH readings for both systems, shown in Supplementary Figures S4 and S5, were measured using a calibrated Hach Multimeter with appropriate probes. Calibration curves (Supplementary Figures S6 and S7) confirmed the accuracy of sensor readings for both test and control solutions. The paired t-test analysis indicated no statistically significant differences in EC ($p = 0.123$) and pH ($p = 0.531$) between the test and control experiments. However, the test system exhibited visibly lower short-term variability, with fewer fertiliser additions (Table 2, Supplementary Figures S4 and S5) and partial buffering/gradual release of Ca–P phases present in Part C (LIU et al. 2006; Xie et al. 2020).

Despite maintaining similar EC and pH stability, the test system required considerably less fertiliser dosing throughout the experiment (Table 2). The control system consumed significantly higher volume of Part A (1125 mL vs. 910 mL) and Part B (1075 mL vs. 605 mL) compared to the test system. On the other hand, the test system required more volume of 3% sulphuric acid (657 mL vs. 575 mL), as larger pH fluctuations triggered more frequent dosing events to maintain pH at 6.

The macronutrient analysis (Figure 1) revealed significant differences between the two systems. T-test analysis showed statistically significant differences in phosphorus, potassium, calcium, and magnesium levels ($p < 0.05$), with total nitrogen (TN) as the only parameter not showing a significant difference ($p = 0.577$). These findings underscore the influence of nutrient solution composition and dosing strategies on nutrient stability and availability.

Initial nutrient concentrations (Figure 1) were similar between systems, with phosphorus at ~26 mg/L in the control and ~29 mg/L in the test system—an acceptable difference for experimental comparability. Potassium levels were also close, but TN in the test system (~295 mg/L) was notably higher than in the control (~190 mg/L), likely due to the use of nitric acid in preparing Part C.

Higher calcium levels in the test system (Figure 1) stemmed from using calcium phosphate as a phosphate source. Both systems initially showed a decline in nutrient concentrations in the first 4 days after germination due to dilution. The control system's nutrients decreased despite higher dosing (Table 2). In contrast, the test system incorporated the recovered nutrients from the nutrient recovery phase, suggesting a buffering effect from Part C.

An anomaly in the test system showed a sharp nutrient increase post-5 days of germination without significant dosing. This may indicate gradual nutrient release from Part C, supporting prolonged nutrient availability. In contrast, the control system's frequent dosing did not prevent persistent nutrient declines, possibly due to higher solubility, plant uptake, or unaccounted losses.

The test system demonstrated superior stability with reduced dosing needs, suggesting potential for lower fertiliser use and increased efficiency. Further research is needed to understand whether the partially soluble Part C (ie., gradual phosphorus buffering from sparingly soluble Ca–P phases in Part C) offers slow-release characteristics that contribute to this stability as observed by Xie et al. (2020) and LIU et al. (2006).

3.2 | Yield Analysis - Fresh & Dry Masses, Hypocotyl Height, Relative Chlorophyll Content (SPAD) and Nutrients Content in Leaves, Roots and Stems

Plants in both systems did not show any signs of nutrient deficiency, and the nutrient solutions effectively supported the

TABLE 2 | Comparison of fertiliser component consumption in control and test systems. Values reflect the initial volume added (from Table 1) and additional dosing during the crop growth period.

Component	Control System			Test System		
	Initial volume added	Volume dosed during growth	Total	Initial volume added	Volume dosed during growth	Total
Part A (mL)	760	365	1125	760	150	910
Part B (mL)	760	315	1075	450	155	605
Part C (mL)	0	0	0	11.1	0	11.1
3% Sulphuric Acid (mL)	150	425	575	327	330	657
68% Nitric Acid (mL)	0	0	0	10	0	10
Calcium hydroxide - Lime (g)	0	0	0	15.8	0	15.8

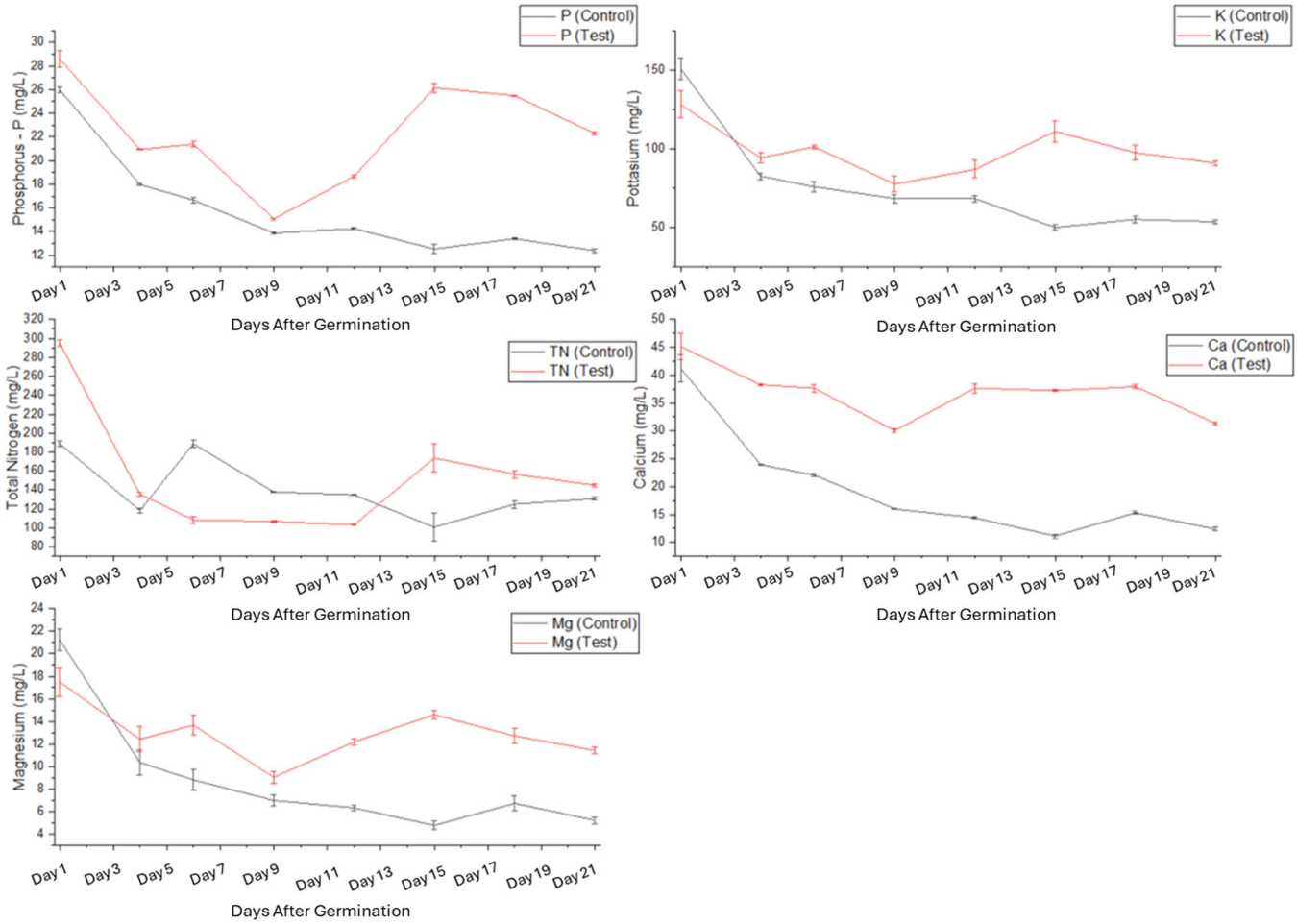


FIGURE 1 | Analysis of the macronutrients (phosphorus, total nitrogen, magnesium, potassium and calcium) in the nutrient solutions of both the control and test system, with nutrient solution samples collected every 2 days throughout the 21-day growth period.

growth of snow peas. However, not all seeds transplanted to the NFT channels sprouted successfully despite germinating successfully (Supplementary Figure S10). The specific cause of these isolated failures was not determined; in the absence of damping-off or other disease symptoms, isolated pre-/peri-transplant factors (e.g., low seed vigour, handling damage, transient plug desiccation, or plug-level microbial load) are more plausible than a system-wide issue, as the remaining plants established successfully (Bai et al. 2022; Lamichhane et al. 2017; Marcos Filho 2015; Thomas 2008).

Early germination and establishment are sensitive to oxidative and hormonal status, which can yield variable emergence even under uniform conditions (Barba-Espin et al. 2010). In this experimental setup, three seeds did not succeed in the test system (Plant IDs 16, 17, and 18) and one in the control system (Plant ID 15).

The growth parameters of plants in both the control and test systems showed no significant differences based on the t-test results (Table 3). These findings are further illustrated in Figure 2.

Hypocotyl height, polyembryony, fresh mass, and dry mass were statistically similar, indicating that the test conditions did not notably impact these growth aspects compared to the control (Figure 2). The relative chlorophyll content (SPAD) was the only parameter with a significant difference ($p = 2.70\text{E-}02$), showing a slightly higher content in the control plants (median = 29.8 SPAD) compared to the test plants (median = 29.0 SPAD).

The digestion analysis of leaves, stems, and roots showed generally similar nutrient contents in leaves and roots between test and control systems (Figure 3). However, significant differences were observed in stems, with higher phosphorus ($p = 1.40 \times 10^{-2}$), calcium ($p = 1.18 \times 10^{-5}$), potassium (21.7 mg/L vs. 11.7 mg/L, $p = 6.64 \times 10^{-4}$), and magnesium (1.05 mg/L vs. 0.32 mg/L, $p = 1.32 \times 10^{-5}$) for the plants in the test system.

While the leaves showed slightly higher phosphorus ($p = 9.07 \times 10^{-3}$) and calcium ($p = 1.93 \times 10^{-2}$) in the test samples, the total nitrogen (TN) content did not differ significantly ($p = 1.47 \times 10^{-1}$). In the roots, the test system exhibited significantly higher phosphorus ($p = 1.13 \times 10^{-5}$), calcium ($p = 2.66 \times 10^{-2}$), and total nitrogen ($p = 1.82 \times 10^{-4}$), while potassium (26.52 mg/L vs. 29.10 mg/L, $p = 1.07 \times 10^{-4}$) and magnesium (2.39 mg/L vs. 3.19 mg/L, $p = 4.67 \times 10^{-4}$) were also notably different.

Overall, both test and control systems demonstrated comparable behaviour regarding nutrient profile, particularly in leaves and roots, with minor differences in some of the nutrient contents of the stems, where the test system slightly outperformed

TABLE 3 | Summary of yield parameters for test and control systems, including mean, standard deviation, and median for hypocotyl height, polyembryony rate, relative chlorophyll content, fresh mass, and dry mass. Statistical comparison was conducted using a two-tailed t-test. Total fresh and dry yield calculations are based on 31 control plants and 29 test plants. One control plant and three test plants were excluded due to unsuccessful germination.

	Control Plants			Test Plants			Statistical analysis (T – Test)
Parameter	**Mean**	**St. Dev.**	**Median**	**Mean**	**St. Dev.**	**Median**	***p*-value**
Hypocotyl Height (cm)	16.1	4.5	17.5	16.3	5.9	18	$0.874 \geq 0.05$
Polyembryony (No.)	2.8	1.3	3.0	3.4	1.7	4.0	$0.102 \geq 0.05$
Relative Chlorophyll Content (SPAD)	30.4	2.3	29.8	26.6	8.9	29.0	$0.027 < 0.05$
Fresh Mass per Plant (g)	7.0	4.2	8.1	7.7	5.2	9.1	$0.540 \geq 0.05$
Dry Massper plant (g)	0.8	0.5	1	0.9	0.6	1.0	$0.485 \geq 0.05$
Total Fresh Mass (Fresh Yield) (g)	217.25 (31 plants)			247.7 (29 plants)			
Total Dry Mass (Dry Yield) (g)	25.6 (31 plants)			26.8 (29 plants)			

the control. Both systems also performed similarly in yield, hypocotyl height, and polyembryony, with a small difference in SPAD values showing slightly higher chlorophyll content in the control system.

3.3 | Economic Analysis Findings

Table 4 presents the detailed analysis of costs and consumption for both the test and control systems. It is apparent that the test system, which incorporated recycled calcium phosphate precipitates, demonstrated significant economic and operational efficiencies.

The total chemical cost for the test system, including the recovery process and fertilisers, was $10.37, compared to $14.89 for the control system, equating to a 33% cost reduction when adjusted for yield.

The cost analysis outlines the complete process from the initial recovery of calcium phosphate from HWNS to the final application as Part C in the nutrient solution. The process involved recycling 240 L of HWNS, consuming 26.4 g of lime and minimal amounts of sulphuric and nitric acids, resulting in a total recovery process cost of only $0.23 per 240 L. The actual cost of Part C for the experimental feed tank was $0.14, contributing to the substantial overall savings.

Regarding operational efficiency, the test system required significantly less dosing of commercial fertilisers. Specifically, Parts A and B consumption in the test system was reduced to 0.91 L and 0.605 L, respectively, compared to 1.125 L and 1.075 L in the control system. Additionally, acid dosing in the test system was reduced by over 40%, highlighting the potential buffering effect of the recycled nutrients.

The cost per gram of dry mass yield was $0.39 for the test system, compared to $0.58 for the control. These figures reflect only the chemical costs of producing the specific yield in this study. In practical hydroponic operations, the same nutrient solution can be reused for extended periods, significantly lowering the actual cost per gram of yield. This study did not exhaust the nutrient solution's viability, suggesting further potential for cost reduction in long-term use.

These findings reinforce the feasibility of integrating recycled calcium phosphate into hydroponic systems as a sustainable and economically beneficial practice, offering a clear pathway toward reducing operational costs and enhancing environmental sustainability.

While the results demonstrate economic benefits at a pilot scale, scaling up this approach for large-scale commercial hydroponic farms presents several key challenges. The feasibility of on-site HWNS recovery will depend on factors such as:

i. Infrastructure Requirements – Larger systems may need automated pH adjustment and precipitation tanks to recover calcium phosphate.
ii. Process Optimisation – The acidulation step must be optimised to handle varying HWNS volumes while maintaining consistent nutrient availability.
iii. Economic Viability at Scale – While Part C reduces fertiliser costs, long-term studies are needed to confirm its effectiveness across multiple crop cycles.

Future research should focus on validating these factors in commercial hydroponic setups, ensuring that this recovery method remains scalable, cost-effective, and operationally viable for high-yield crop production.

4 | Conclusions

This study addressed the critical issue of phosphorus scarcity and rising fertiliser costs by exploring an innovative method for in-situ recovery and reuse of calcium phosphate from hydroponic waste nutrient solution (HWNS). Phosphorus, a finite and geopolitically sensitive resource, is essential for global food

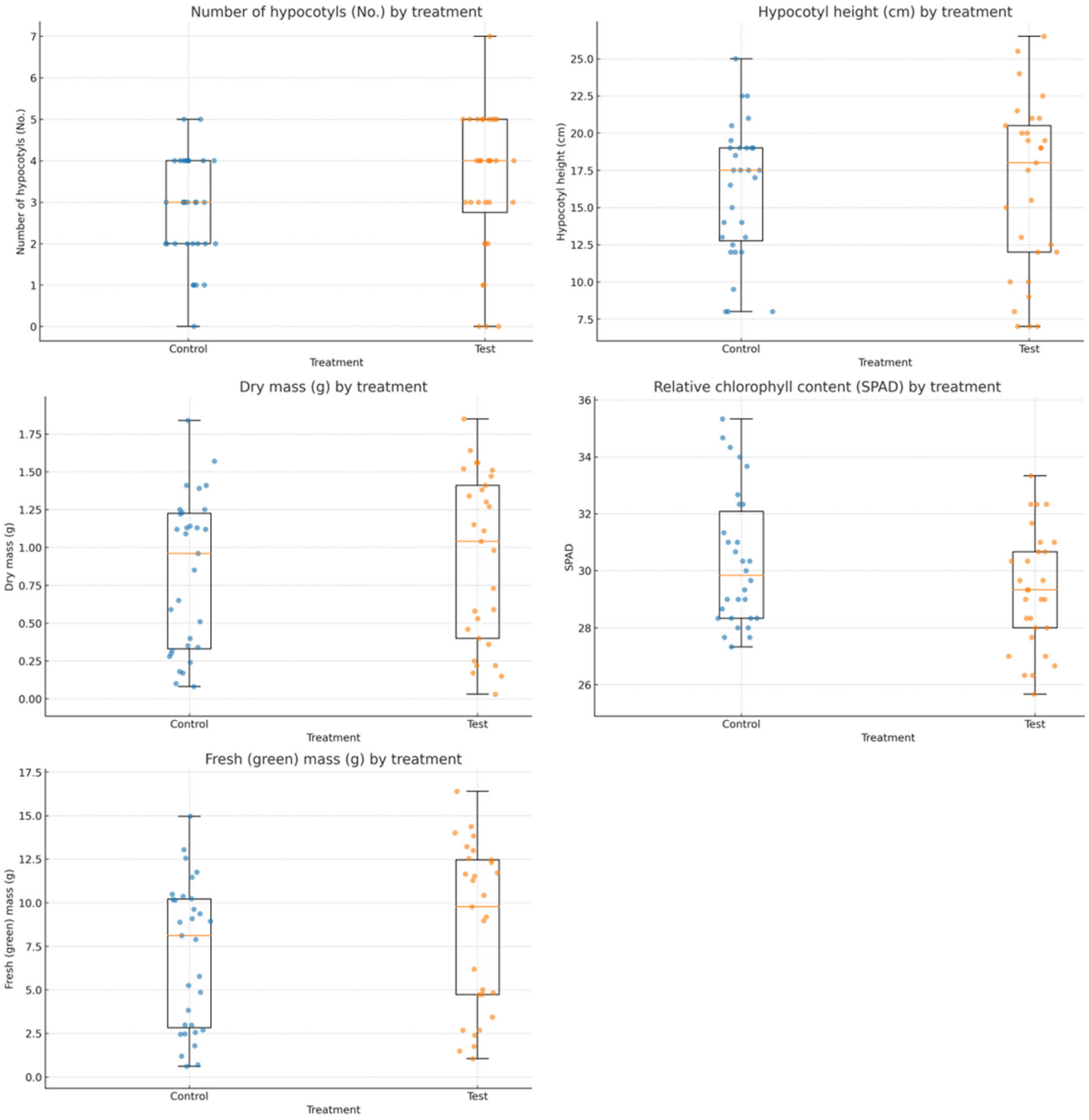


FIGURE 2 | Distributions of plant-level metrics (Control vs Test) shown as side-by-side boxplots with overlaid points: Hypocotyl height, SPAD, fresh mass, dry mass, and number of hypocotyls. Boxes = Interquartile Range (IQR – 25th percentile -75th percentile), line = median; whiskers = Tukey (1.5 × IQR).

production. The current agricultural practices remain heavily dependent on mined rock phosphate.

The research investigated whether an alkali treatment could effectively recover micro-calcium phosphate from HWNS collected from a local tomato hydroponic farm. The approach aimed to utilise existing assets without the need for new investments, converting the recovered phosphate into a liquid fertiliser (Part C) compatible with current agricultural practices and fertigation systems in the Australian market.

The methodology involved alkali precipitation using lime and acidulation to produce a liquid nutrient solution suitable for commercial hydroponic systems. The pilot study was conducted in a controlled greenhouse environment, where snow peas (*Pisum sativum L.*) were grown in nutrient film technique (NFT) channels using a nutrient solution incorporating 40% of the phosphorus from Part C. The test system's performance was compared with a control system using only commercial fertilisers, focusing on plant growth metrics, nutrient consumption, and economic viability.

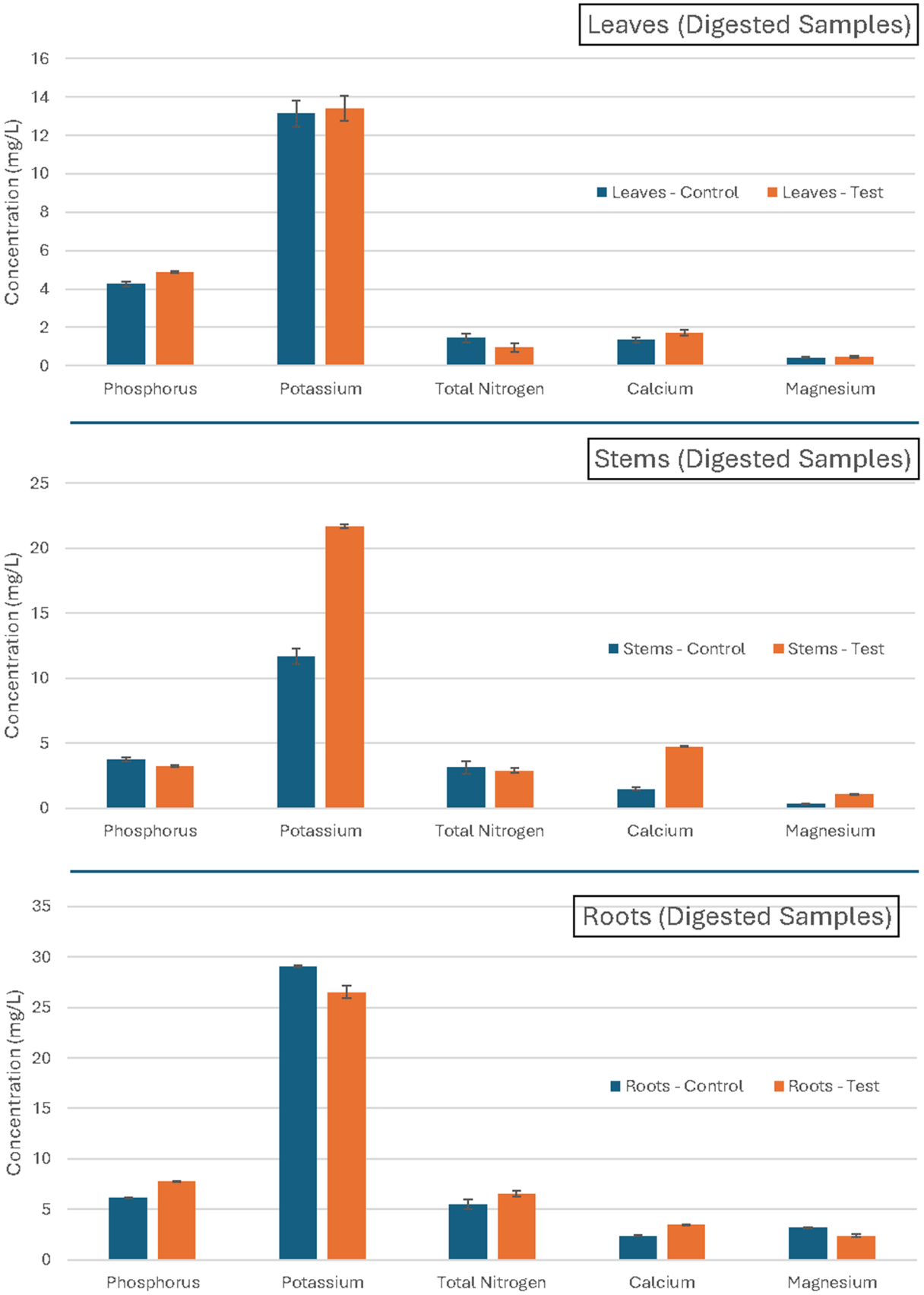


FIGURE 3 | Nutrient content of digested leaves, stems, and roots of pea plants grown in the control and test systems. Digestion was performed on 0.1 g dry mass with a final volume of 250 mL after digestion. Error bars represent the standard deviation of triplicate samples.

TABLE 4 | Detailed cost analysis and chemical consumption for the test and control systems throughout the experiment. All costs are in Australian dollars. Lime was priced at A$27 per 20 kg (Blacktown Building Supplies 2024). Sulphuric acid (98%) was priced at A$60 per 5 L, and nitric acid (68%) at A $155 per 20 L ((Paramount chemicals 2024c) (Paramount chemicals 2024a). Optimum Grow Part A and Part B fertilisers were priced at A$267 per 40 L (Fernland 2024). Cost savings reflect the reduction in total chemical input cost per gram of dry yield in the test system compared to the control.

Parameter	Test	Control	Unit
Volume of HWNS recycled	240	—	L
Mass of lime consumed	26.4	—	g/240L-HWNS
Cost of lime consumed	$0.03	—	A$/240L-HWNS
Sulphuric acid consumed	10	—	mL/240L-HWNS
Nitric acid consumed	10	—	mL/240L-HWNS
Sulphuric acid cost	$0.12	—	A$/240L-HWNS
Nitric acid cost	$0.08	—	A$/240 L
Cost of Part C recovered	$0.23	—	A$/240 L
Volume of Part C produced by 240 L HWNS	18.5	—	L
Volume of Part C needed for the experiment	11.1	—	L
Specific volume ratio HWNS required for replacing 40% of Part B in the test tank (200 L)	0.6	—	L/L
Actual Part C cost for the feed tank (200 L) (Cost of Part C Precipitation for utilised precipitates)	$0.14	—	A$
Part A Price	$6.68	$6.68	A$/L
Part B Price	$6.68	$6.68	A$/L
Part A consumption (initial mix)	0.76	0.76	L
Part B consumption (initial mix)	0.45	0.76	L
Volume of Part A dosed during the experiment	0.15	0.365	L
Volume of Part B dosed during the experiment	0.155	0.315	L
Volume of sulphuric acid dosed (Equivalent to 98%SA)	10	17.4	L
Volume Part A consumed - Total	0.91	1.125	L
Volume Part B consumed - Total	0.605	1.075	L
Cost of Part A - Total	$6.07	$7.51	A$
Cost of Part B - Total	$4.04	$7.18	A$
Cost of Part C - Total	$0.14	$-	A$
Cost of 98%SA dosed	$0.12	$0.21	A$
Total fertiliser and other chemicals used	**$10.37**	**$14.89**	**A$**
Yield (Dry mass)	26.8	25.6	g
Cost of chemicals per yield produced	**0.39**	**0.58**	**($/g – dry mass)**
Cost savings	**33%**		

The results demonstrated that the test system maintained stable electrical conductivity and pH levels while reducing fertiliser consumption and enhancing nutrient stability. Key findings included significantly lower nutrient dosing requirements, improved nutrient retention within the solution, and comparable plant growth outcomes, including fresh and dry mass yield, hypocotyl height, polyembryony rate, and relative chlorophyll content (SPAD). An economic analysis revealed a 33% reduction in fertiliser costs, highlighting tangible financial benefits alongside sustainability gains.

This study provides plausible evidence that integrating recycled calcium phosphate into hydroponic systems can reduce agricultural dependence on mined phosphorus, lower operational costs, and support a circular economy model in nutrient management. Future research could expand on these findings by testing a broader range of crops and hydroponic conditions, examining the long-term behaviour of the nutrient solution, and assessing the wider environmental impacts of this approach.

Given its low capital requirements and compatibility with existing fertigation systems, this approach can seamlessly integrate into commercial hydroponic operations with minimal disruption. The ability to recover phosphorus on-site reduces dependency on external fertilisers while maintaining nutrient

solution stability and crop performance, making it a viable solution for achieving sustainable agriculture.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

While preparing this study, the authors used the OpenAI - ChatGPT Tool to improve the manuscript's readability and language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

Author Contributions

Conceptualisation, S.M. and D.H.; Methodology, S.M., D.H. and B.M.; Investigation, S.M.; Formal analysis, S.M.; Data curation, S.M., D.H. and B.M.; Writing – original draft, S.M.; Writing – review and editing, D.H. and B.M.; Visualisation, S.M. and D.H.; Validation, S.M. and D.H.; Supervision, D.H.; Project administration, D.H.

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Conflict of Interests

The authors declare no conflict of interests.

Data Availability Statement

A supporting data file has been prepared and is included as part of this paper. Raw data can be obtained by contacting the corresponding author.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.
Supporting Data Closing the Nutrient Loop V6 Clean.