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Optimizing Nutrient Compensation Intervals Based on Ionic Monitoring in Drainage Water from Open and Closed Tomato Hydroponics

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Abstract

Closed hydroponics (recirculating) is increasingly recognized as a sustainable approach for conserving water and fertilizer resources. However, concerns remain among growers regarding ionic imbalances and yield instability during nutrient–solution recirculation. This study aimed to clarify these issues through continuous ionic monitoring of drainage water and optimization of nutrient compensation intervals in commercial tomato (*Solanum lycopersicum* L.) cultivation. Two greenhouse systems, an open (non-recirculating) and a closed (recirculating) system, were compared. Electrical conductivity (EC), pH, and major ions (NO_3^-, K^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, PO_4^{3-}, and Na^+) were analyzed using ion chromatography. Based on ionic fluctuation trends, compensation intervals of 0, 2, and 4 weeks were evaluated in the closed system. Contrary to expectations of growers, open hydroponics exhibited greater ionic imbalance due to uncontrolled leaching. Periodic compensation (every 4 weeks) stabilized ionic ratios, reduced fertilizer input by 67–69%, and decreased water use by 33–36% compared with the open system. These findings demonstrate that drainage-based ionic monitoring and interval-based compensation can improve the environmental and economic performance of closed hydroponics.

Keywords: chromatography; ionic imbalances; recirculating; saving; sustainable

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1. Introduction

The decline in the farming population, aging of farmers, and reduced agricultural productivity have resulted in a serious shortage of agricultural labor and decreased production efficiency [1–3]. This decline in farmland and productivity poses a significant threat to the stability of the food supply. Research and development efforts in agricultural technology have been continuously pursued to improve both productivity and sustainability [4]. Among these technologies, hydroponics in protected horticulture is recognized for achieving high yields and productivity while requiring less land than open-field cultivation [4,5].

Hydroponic cultivation has become a cornerstone of modern protected horticulture because it enables precise nutrient and water management, stable crop production, and minimal environmental impact compared with soil-based cultivation [6,7]. In particular, the transition from open to closed hydroponic systems is regarded as a key strategy to reduce water use, fertilizer losses, and nutrient-rich effluent discharge that threaten

groundwater quality and aquatic ecosystems [8]. Closed systems recirculate drainage water after disinfection and chemical adjustment, thereby improving the efficiency of water and fertilizer use by up to 60% compared with open systems [9,10]. However, despite their environmental advantages, the adoption of closed hydroponic systems remains limited among commercial growers due to operational complexity, initial installation costs, and concerns about ionic imbalance during solution reuse [8,11,12].

Ionic imbalance in recirculating hydroponic systems results from differential nutrient uptake by roots, evaporation-driven concentration changes, and ionic adsorption–desorption dynamics in the substrate [13]. Over time, these processes alter the nutrient composition of the circulating solution, leading to suboptimal plant nutrition and physiological stress if not properly managed [14,15]. Sodium and chloride, in particular, tend to accumulate because they are poorly absorbed by most horticultural crops, whereas nitrate and potassium are rapidly depleted during periods of active growth [16]. Thus, maintaining ionic balance in the recycled solution is critical to ensure stable crop performance and long-term sustainability of closed systems.

Recent advances in sensing technologies have made real-time monitoring of nutrient solutions feasible through ion-selective electrodes (ISEs), electrical conductivity (EC) sensors, and integrated Internet-of-Things (IoT) platforms. IoT-interfaced solid-contact ISEs have been developed to monitor key ions such as K^+, NO_3^-, and NH_4^+ with high accuracy and wireless telemetry [17]. In parallel, smart IoT-based hydroponic systems now allow automated control of pH, EC, and nutrient dosing in real time [18]. Potentiometric ISE methods remain central to these advances because they convert ion-activity differences into voltage signals through selective membranes [19]. Complementary automated dosing frameworks using EC and pH feedback have also been reported, demonstrating increasing technical maturity and scalability [20]. Although the present study did not employ real-time ion-sensing technologies, the growing availability of such systems highlights the need for empirical benchmarks that can guide their practical application. The results of this study, based on periodic chemical analysis of drainage water, can provide fundamental reference data for calibrating and validating these emerging sensor-based irrigation control systems. Sensor-enabled irrigation systems have already been implemented in horticultural crops, reducing fertilizer inputs without compromising yield or quality [21]. Nevertheless, their adoption in large-scale tomato greenhouses remains limited because environmental variability, particularly in radiation, temperature, and drainage, complicates calibration and real-time feedback control [18]. Moreover, although these technologies can detect ionic fluctuations, there is still little empirical evidence regarding how frequently nutrient solutions should be adjusted or compensated to maintain ionic equilibrium in practical commercial production systems.

Previous studies have mainly focused on the formulation of nutrient solutions and the design of recirculating systems [22–24]. More recent research has addressed nutrient optimization models and system automation for closed hydroponics [25,26]. However, there remains a lack of systematic investigation into the temporal dimension of nutrient management, specifically, how frequently nutrient solutions should be compensated or renewed to correct ionic drift during long-term recirculation.

In commercial practice, growers often rely on empirical judgment or visual crop responses rather than quantitative criteria to determine when to adjust or replace nutrient solutions [27,28]. This unsystematic approach results in variable fertilizer efficiency and inconsistent crop performance, reducing the sustainability advantages of closed hydroponics. Few studies have combined continuous ionic monitoring with economic and environmental assessments at the farm scale [17,19]. Addressing this gap is essential to develop

data-driven strategies for nutrient compensation that ensure both resource efficiency and stable crop productivity.

Considering these challenges, this study aimed to optimize nutrient compensation intervals in closed tomato hydroponic systems based on ionic monitoring of drainage water. We hypothesized that periodic ionic compensation, guided by drainage-based ion analysis, would mitigate nutrient imbalance, reduce water and fertilizer consumption, and enhance the overall sustainability of closed hydroponic systems. To verify this hypothesis, two commercial-scale experiments were conducted: (1) continuous monitoring of ionic dynamics in open and closed tomato farms, and (2) evaluation of different nutrient compensation intervals (0, 2, and 4 weeks) on ionic balance, water use, and fertilizer efficiency. By linking on-farm monitoring data with economic assessment, this study provides practical strategies and baseline data to promote the wider adoption of closed hydroponic systems in sustainable horticultural production.

2. Materials and Methods

2.1. Ionic Monitoring in Commercial Tomato Farm (Exp. 1)

Two tomato (*Solanum lycopersicum* L.) farms had Venlo-type greenhouses, one with an open hydroponic system located in Haman, and another with a closed hydroponic system located in Gimje (Table 1 and Figure 1).

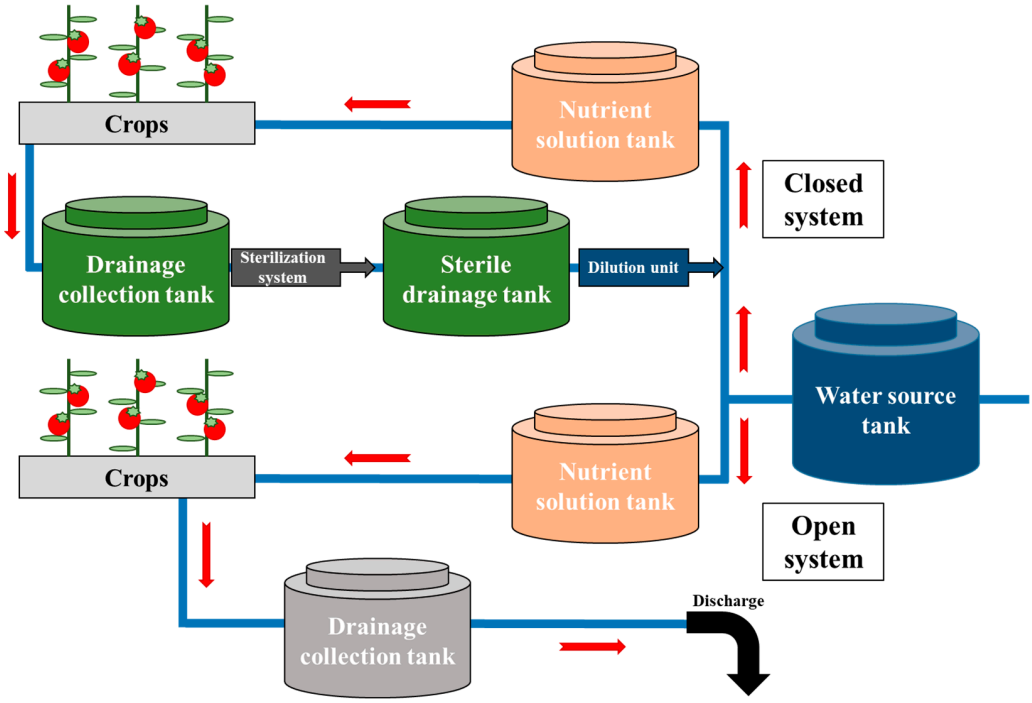


Figure 1. Schematic illustrating of open and closed hydroponic systems used for tomato cultivation.

The farm in Haman had a cultivation area of 6611 m^2 and grew the 'Dafnis' cultivar on rockwool substrate, using chemical sterilization on the supplied nutrient solution. The farm in Gimje had a cultivation area of 10,909 m^2 and cultivated the 'Dokia' cultivar on coir substrate, utilizing UV sterilization on the drainage water. These farms used nutrient solutions prepared according to the Netherlands PBG tomato hydroponic formulation (16.0 me·L^{-1} NO_3-N, 1.2 me·L^{-1} NH_4-N, 4.5 me·L^{-1} P, 9.5 me·L^{-1} K, 10.8 me·L^{-1} Ca, 4.8 me·L^{-1} Mg, and 8.8 me·L^{-1} S), and irrigation was performed based on solar radiation control. The EC, pH, and the concentration of each ion in the drainage water (K, Na, Ca, Mg, NO_3-N, Cl, SO_4, and PO_4) were analyzed from December 2021 to June 2022 to ensure that

they remained within the recommended range [29] for tomato cultivation recommended by the Netherlands PBG (Tables 2 and 3).

Table 1. Regional characteristics and cultivation conditions of two commercial tomato farms monitored under open and closed hydroponic systems, including substrate type, cultivar, greenhouse area, and water sterilization method.

Hydroponic Systems	Region	Area (m^2)	Cultivar	Substrate	Water Sterilization Method
Open hydroponic systems	Haman	6611	Dafnis	Rockwool	H_2O_2
Closed hydroponic systems	Gimje	10,909	Dokia	Coir	UV

Table 2. Recommended ranges of electrical conductivity (EC) and pH for the rhizosphere in tomato cultivation in both open and closed hydroponic systems.

Value	EC		pH	
	Open Hydroponics	Closed Hydroponics	Open Hydroponics	Closed Hydroponics
Minimum	2.5	2.5	5.0	5.0
Maximum	5.0	5.0	6.5	7.0

Table 3. Recommended concentration ranges of essential macro- and micro-elements for the rhizosphere in tomato growth in hydroponic systems.

Concentration	NO_3-N ($mg \cdot L^{-1}$)	SO_4 ($mg \cdot L^{-1}$)	Cl ($mg \cdot L^{-1}$)	PO_4 ($mg \cdot L^{-1}$)	K ($mg \cdot L^{-1}$)	Ca ($mg \cdot L^{-1}$)	Na ($mg \cdot L^{-1}$)	Mg ($mg \cdot L^{-1}$)
Minimum.	238.2	384.2	88.6	66.5	254.2	320.6	0.0	65.6
Maximum	392.3	864.5	425.4	189.9	391.0	481.0	183.9	158.0

Anions (NO_3^-, SO_4^{2-}, PO_4^{3-}, and Cl^-) were analyzed using ion chromatography (IC; ICS-5000, Dionex, Sunnyvale, CA, USA) operated at a flow rate of 0.7 $mL \cdot min^{-1}$. After baseline stabilization with eluent and regenerant flows, calibration curves were prepared using mixed standard solutions: 0, 5, 10, and 20 $mg \cdot L^{-1}$ for NO_3^- and SO_4^{2-}; 10, 20, and 40 $mg \cdot L^{-1}$ for PO_4^{3-} and Cl^-. Cations (K^+, Ca^{2+}, Mg^{2+}, Na^+, and NH_4^+) were determined using inductively coupled plasma optical emission spectrometry (ICP–OES; ICAP 7400, Thermo Scientific, Waltham, MA, USA). Calibration standards were prepared at 0, 25, 50, and 100 $mg \cdot L^{-1}$ for K and Ca, and 0, 12.5, 25, and 50 $mg \cdot L^{-1}$ for NH_4-N, Mg, and Na. The measured concentrations were multiplied by the corresponding dilution factors to obtain final ionic concentrations.

2.2. Effects of Nutrient Compensation Intervals in Closed Hydroponic Systems (Exp. 2)

Based on the results of Exp. 1, an experiment was conducted to evaluate the effects of different nutrient solution compensation intervals on nutrient imbalance, as well as on water and nutrient use efficiency in a closed hydroponic system. The nutrient solutions were prepared according to the Netherlands PBG tomato hydroponic formulation (16.0 $me \cdot L^{-1}$ NO_3-N, 1.2 $me \cdot L^{-1}$ NH_4-N, 4.5 $me \cdot L^{-1}$ P, 9.5 $me \cdot L^{-1}$ K, 10.8 $me \cdot L^{-1}$ Ca, 4.8 $me \cdot L^{-1}$ Mg, and 8.8 $me \cdot L^{-1}$ S), and irrigation was managed according to solar radiation levels. The tomato seeds were sown on 14 September 2022, transplanted on 6 October 2022, and the experiment was conducted on 1 June 2023. Plants were cultivated in 100 × 15 × 10 cm coir slabs (60% chips, 40% dust). Four treatment groups were

established: open hydroponic systems (control), closed hydroponic systems with compensation intervals of every 2 weeks (1 week of standard solution + 1 week of compensated solution), 4 weeks (2 weeks of standard solution + 2 weeks of compensated solution), and closed hydroponic systems with no compensation (Figure 2). The treatment intervals were chosen to represent practical nutrient–solution management cycles commonly adopted by commercial growers. Nutrient solution was supplied to maintain a drainage rate of 30–40% and EC 1.8–2.2 dS·m^{-1}. Each plant was irrigated with 100 mL per event, which was triggered by cumulative solar radiation of 80–120 J. The compensated solution was supplied by modifying the nutrient prescription according to the nutrient correction calculation method for recirculating hydroponics [30]. Drainage water was collected three different tanks, and ionic composition was analyzed using the same methods as described for Exp. I.

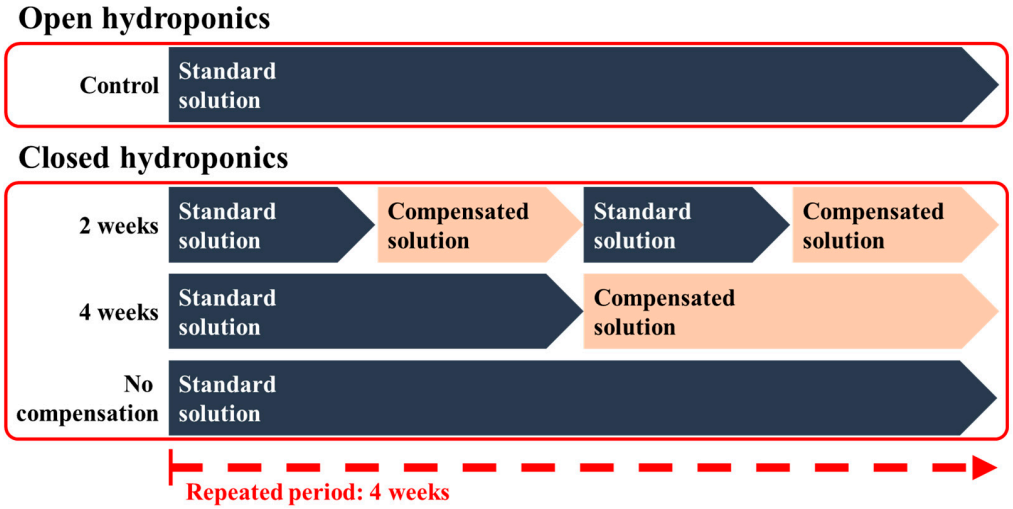


Figure 2. Experimental schematic illustrating the nutrient solution compensation intervals used in the closed hydroponic treatments (no compensation, every 2 weeks, every 4 weeks), with open hydroponic systems as the control.

2.3. Statistical Analysis

Exp. 1 was a monitoring study designed to track ionic changes in drainage water and was therefore analyzed descriptively without statistical testing. In Exp. 2, experimental treatments were conducted using a randomized complete block design with three replicates. All experiments were performed in triplicate. Data analysis was conducted using Statistical Analysis System (SAS 9.4; SAS Institute Inc., Cary, NC, USA). The results of the experiments were analyzed using analysis of variance (ANOVA) and Duncan's multiple range test. A significance level of $p \leq 0.05$ was used to determine differences. Graphs were plotted using the SigmaPlot software package (SigmaPlot 15.0; Systat Software Inc., San Jose, CA, USA). For economic evaluation, fertilizer and water use were quantified for each treatment and converted to a per-hectare basis. Fertilizer prices were obtained from the 2023 Rural Development Administration (RDA) database. Refer to past research [31], the total input cost reduction (fertilizer and water) was compared with operational expenses (UV sterilization, drainage analysis) to estimate the net annual cost savings of closed hydroponic systems.

3. Results and Discussion

3.1. Ionic Monitoring in Commercial Tomato Farm (Exp. 1)

The electrical conductivity (EC) and pH of the drainage solution in the closed hydroponic system were within the recommended ranges defined for tomato cultivation in Table 2 for most of the cropping period (Figure 3). A short deviation occurred from

March to April, when EC transiently exceeded the upper bound specified in Table 2. This excursion coincided with abnormally high solar radiation and a temporary malfunction of the automatic irrigation controller, which reduced irrigation frequency. After the controller was recalibrated, EC returned to the recommended range, and pH remained within the Table 2 range throughout. Overall, apart from this brief malfunction episode, the closed system maintained drainage EC and pH within agronomic thresholds.

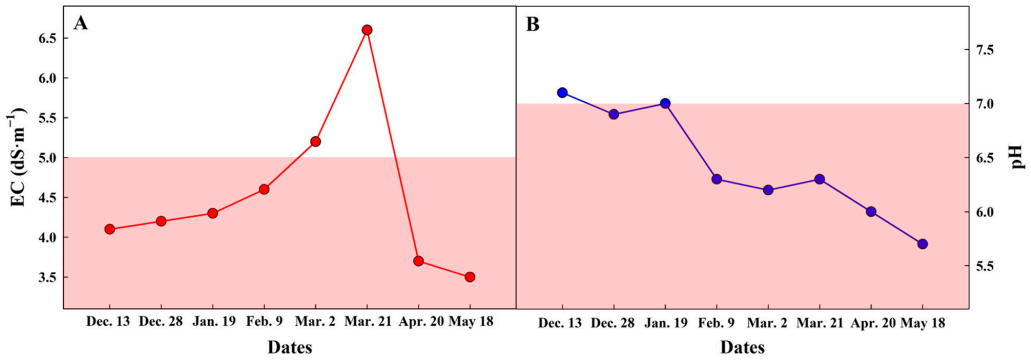


Figure 3. Changes in EC (**A**) and pH (**B**) in drainage water collected from commercial tomato farms monitored under closed hydroponic systems. The colored area indicates the recommended range of EC and pH, as shown in Table 2.

The change patterns of most cations and anions in the drainage water were similar to the change patterns of the EC levels in the supplied nutrient solutions (Figure 4). The concentrations of most elements were close to the recommended ranges. Nitrate (NO_3^-) concentrations exceeded the recommended range for most of the cultivation period, except in April and May, when reduced EC levels. Potassium (K^+) was oversupplied in December and March, coinciding with early and mid-fruiting stages when irrigation demand lagged behind plant uptake [13,25,32,33]. SO_4 is one of the elements that can accumulate in the nutrient solution during closed hydroponic systems [22]. It is sometimes managed at concentrations lower than the recommended level in PBG nutrient solution formulations to mitigate this [22]. The persistently low SO_4^{2-} levels likely reflect deliberate formulation practices to prevent sulfate accumulation in closed hydroponic systems, a measure aligned with contemporary nutrient-management frameworks that aim to suppress accumulation of underutilized ions and reduce salt stress [34].

The electrical conductivity (EC) of the drainage water in the open hydroponic system remained above the recommended range for tomato cultivation, except during April and May, when a sharp decline was observed (Figure 5). EC gradually decreased from January to February, increased again through March, and then dropped rapidly toward May.

The concentrations of most ions exhibited patterns similar to EC fluctuations: they decreased as EC declined (Figure 6). Sodium (Na^+) concentrations consistently stayed within the recommended range, whereas nitrate (NO_3^-), phosphate (PO_4^{3-}), and potassium (K^+) declined steadily and reached recommended levels only in April. In contrast to closed hydroponic systems, which typically perform drainage and supply solution analyses at 1–2-week intervals to maintain ionic balance, open hydroponic systems discharge drainage water immediately after use without feedback correction [25]. This operational characteristic, coupled with limited familiarity among growers with drainage-solution monitoring and the perception that nutrients are lost during irrigation, often leads to fertilizer applications exceeding the recommended levels [35]. Similar tendencies toward nutrient oversupply and high EC have been reported in commercial tomato greenhouses, emphasizing that over-fertilization is frequently used as a safety margin to prevent deficiencies [13,25,32]. Collectively, these findings highlight the structural inefficiency of open systems and un-

derscore the necessity of integrating drainage-based monitoring and nutrient recycling strategies to enhance sustainability in commercial hydroponics.

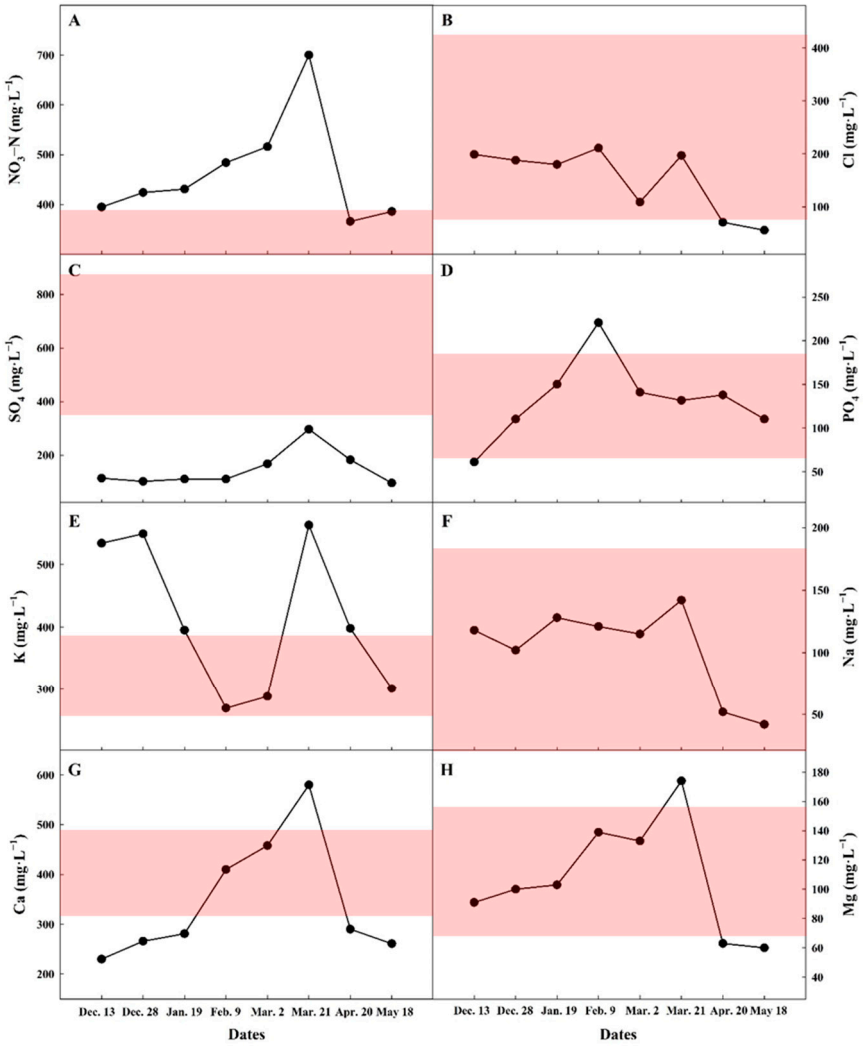


Figure 4. Changes in ion concentration of NO_3-N (**A**), Cl (**B**), SO_4 (**C**), PO_4 (**D**), K (**E**), Na (**F**), Ca (**G**), and Mg (**H**) in drainage water collected from commercial tomato farms monitored under closed hydroponic systems. The colored area indicates the recommended concentration range of elements, as shown in Table 3.

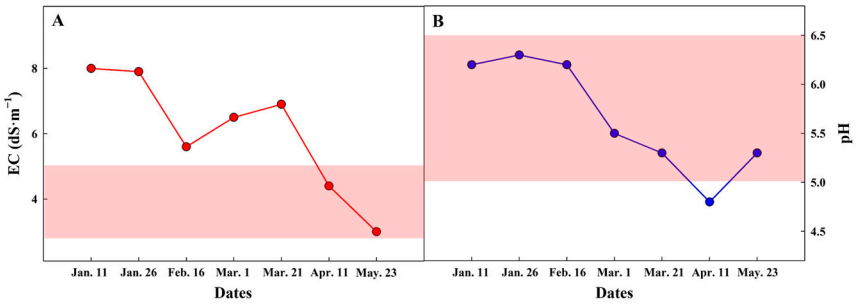


Figure 5. Changes in EC (**A**) and pH (**B**) in drainage water collected from commercial tomato farms monitored under open hydroponic systems. The colored area indicates the recommended range of EC and pH, as shown in Table 2.

The results of this experiment revealed that, contrary to the concerns of farmers, ion imbalance was more pronounced in closed hydroponic systems than in open hydroponic systems. This suggested that periodic management and compensation of the nutrient

solution based on drainage water monitoring results, rather than the hydroponic system itself, are crucial for resolving the issue of ion imbalance during tomato cultivation.

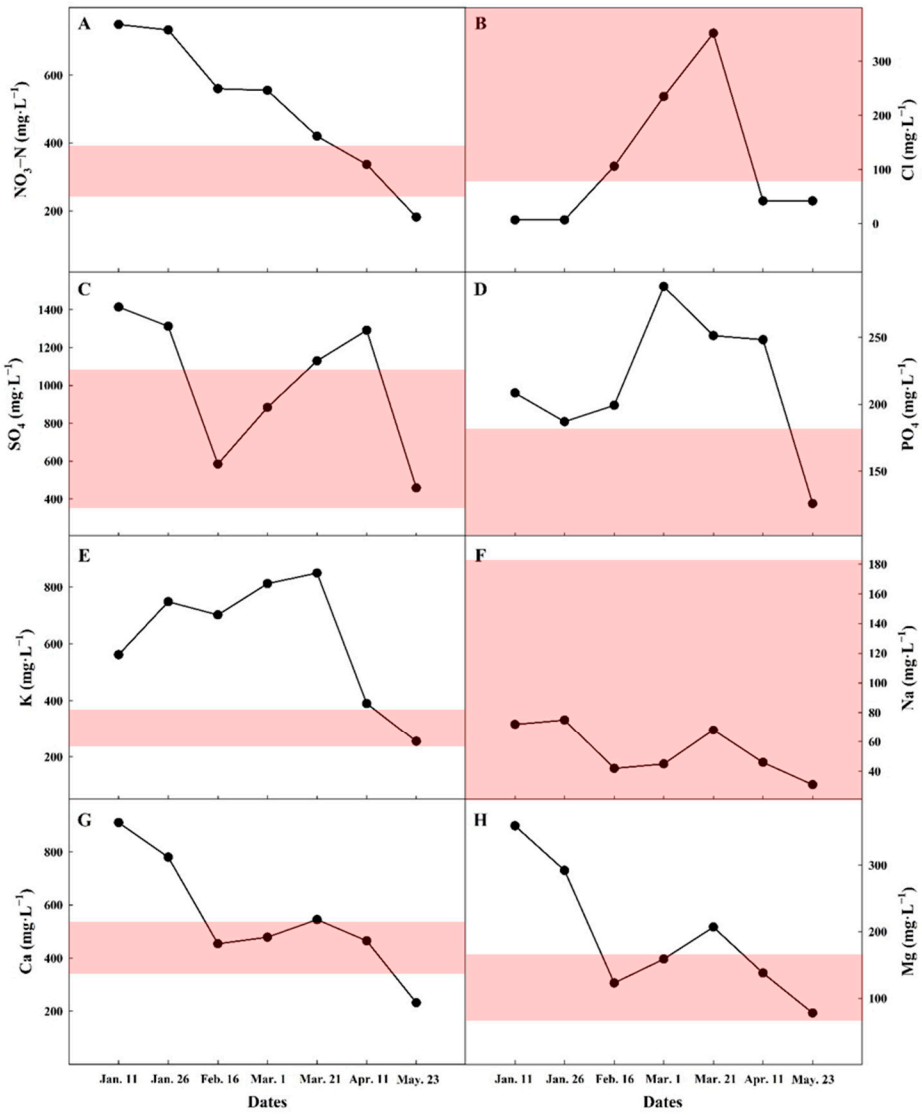


Figure 6. Changes in ion concentration of NO_3-N (**A**), Cl (**B**), SO_4 (**C**), PO_4 (**D**), K (**E**), Na (**F**), Ca (**G**), and Mg (**H**) in drainage water collected from commercial tomato farms monitored under open hydroponic systems. The colored area indicates the recommended concentration range of elements, as shown in Table 3.

3.2. Effects of Nutrient Compensation Intervals in Closed Hydroponic Systems (Exp. 2)

Building upon the insights gained from field monitoring in Exp. 1, Exp. 2 was conducted to evaluate the effects of different nutrient solution compensation intervals on minimizing nutrient imbalance and enhancing water and fertilizer use efficiencies in a closed hydroponic system. The Na^+ concentration was higher in the closed hydroponic treatments than in the control (Figure 7). In the absence of compensation, significant deviations were observed for NO_3-N, P, and S. Most elements in the nutrient solutions used in closed hydroponic systems were adjusted by replenishing the amount absorbed by the plants [36]. However, Na is not efficiently absorbed by crops, and its accumulation in closed hydroponic systems during cultivation has been reported [16,21]. The drainage water was immediately discharged in the control; however, the closed hydroponic groups did not discharge their drainage water. Specifically, unlike treatments in which deficient or excessive elements were compensated, the no-compensation treatment was managed by

continuously supplying the standard nutrient solution. In closed hydroponic systems, some elements in the root zone are rapidly consumed, while others accumulate in the substrate depending on the plant growth stage, leading to imbalances in the circulating nutrient solution due to the increase or decrease of elements if no compensation is performed [37]. Gradual increases or decreases in elements can occur in nutrient solutions, substrates, and crops in the long-term closed hydroponic cultivation of fruits and vegetables [22,38]. When the same nutrient solution is reused without correction, imbalances between highly absorbed ions such as NO_3^- and less absorbed ions such as Na^+ or SO_4^{2-} can intensify over time, leading to osmotic stress and reduced nutrient uptake efficiency [16,39,40]. Similar findings have been reported in hydroponic tomato production, where longer compensation intervals accelerated ionic drift and EC fluctuations [10,41]. As the reasons for the increase or decrease in specific elements vary depending on the plant growth stage, degree of element absorption, environmental factors, and other factors [22], providing a specific explanation is challenging. However, the nutrient imbalance was observed only in the no-compensation treatment, suggesting that periodic compensation is absolutely necessary in closed hydroponic systems.

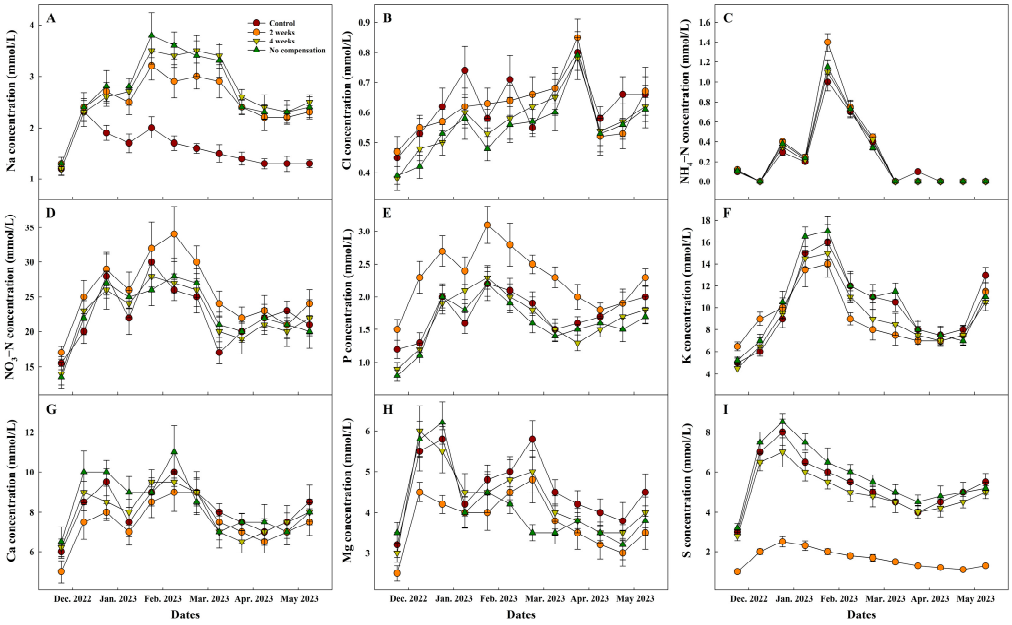


Figure 7. Changes in ion concentration of Na (**A**), Cl (**B**), NH_4-N (**C**), NO_3-N (**D**), P (**E**), K (**F**), Ca (**G**), Mg (**H**), and S (**I**) in drainage water affected by different compensation intervals (no compensation, 2 weeks, and 4 weeks) during tomato cultivation. Control refers to open hydroponic systems. Vertical bars indicate standard errors of the mean values (n = 3).

All closed hydroponic treatments reduced water use by 33–36% compared to the control (Figure 8). When comparing the amount of elements supplied per treatment, calculated based on fertilizer input, the control utilized the largest amount of elements, followed by the no-compensation, 4 weeks, and 2 weeks treatments (Figure 9). The sum of macro elements for each treatment was calculated as 893.88, 479.70, 248.81, and 244.49 mmol/plant for the control, no compensation, 4 weeks, and 2 weeks treatments, respectively. These values demonstrated potential nutrient savings of approximately 46% in the no-compensation treatment and 72–73% at 2 and 4 weeks compared to the control. In open hydroponic systems, the nutrient solution is not reused but discarded [25,42]. This practice leads to continuous nutrient losses, increased fertilizer demand, and environmental concerns due to nutrient-rich effluent discharge into surrounding ecosystems. However, nutrient solutions are recycled in closed hydroponic systems [43], where the drainage water is collected,

disinfected, and adjusted for nutrient concentration before being reused. This process substantially improves water and nutrient-use efficiency by reducing leaching losses and maintaining more stable ionic compositions in the root zone. Therefore, closed hydroponic systems are a more economical and sustainable approach to conserving water and nutrients [44,45]. In a broader review across multiple crops and hydroponic and aeroponic systems, reductions in fertilizer use of up to 60% have been reported depending on the system and crop [8,45]. In this experiment, although there was no significant difference between 2 weeks and 4 weeks, no compensation showed significant deviations in the ion balance, water use, and fertilizer input. Therefore, considering the periodic costs associated with drainage solution analysis, it can be concluded that even a 4-week compensation interval is necessary in closed hydroponic systems to prevent nutrient imbalance, improve economic efficiency, and conserve water resources.

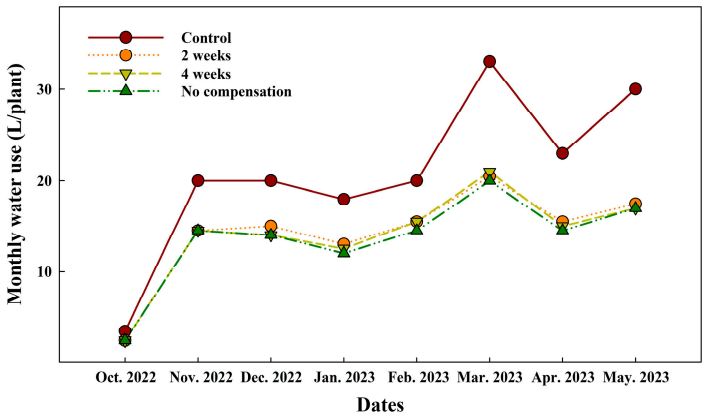


Figure 8. Changes in monthly water use affected by different compensation intervals (no compensation, 2 weeks, and 4 weeks) during tomato cultivation. Control refers to open hydroponic systems.

3.3. Economic Comparison of Closed and Open Hydroponic Systems Based on Fertilizer Input (Exp. 2)

A comparative evaluation was performed to quantify the fertilizer input requirements and cost-effectiveness of the control and closed hydroponic systems for tomato (*Solanum lycopersicum* L.) cultivation under greenhouse conditions. All values were normalized to a 1 ha cultivation area, with monetary values converted to 2023 USD. As summarized in Table 4, total chemical fertilizer consumption in the control group was considerably higher than that in the closed hydroponic groups. For example, Ca $(NO_3)_2 \cdot 10H_2O$ usage reached 30.3 T/ha/year in the control, while the 2 and 4 week treatments required only 7.17 and 6.91 T, respectively. Similar trends were observed for KH_2PO_4, KNO_3, K_2SO_4, and $MgSO_4 \cdot 7H_2O$, which exhibited reductions of over 60% when recirculation was implemented. The annual fertilizer cost in the control was estimated at USD 59,985. In contrast, this was reduced to USD 19,585 (2 weeks) and USD 18,392 (4 weeks) un the closed hydroponic systems, representing cost savings of approximately 67–69%. These savings may be attributed to the recapture of nutrients in the drainage water and the reduced frequency of full-solution replacement.

Additionally, a total of 4030 T/ha/year of irrigation water was conserved, equivalent to financial savings of USD 2216.5, based on a national average water price of USD 0.55/m^3 (Table 5). Operational expenditures for closed hydroponic systems, comprising equipment depreciation (USD 5769.2/year), drainage water analysis (USD 1845.6/year), and UV sterilization (USD 99.0/year), amounted to USD 7713.8/year. The resulting net economic benefit of USD 34,902.7 per ha per year indicates a favorable return on investment for adopting closed hydroponic systems. The marked reduction in both fertilizer and water input implies that closed hydroponic systems can make a meaningful contribution to

sustainable horticultural practices. Beyond economic incentives, closed hydroponic systems also mitigate nutrient discarding and reduce the external environmental effects associated with excess chemical input.

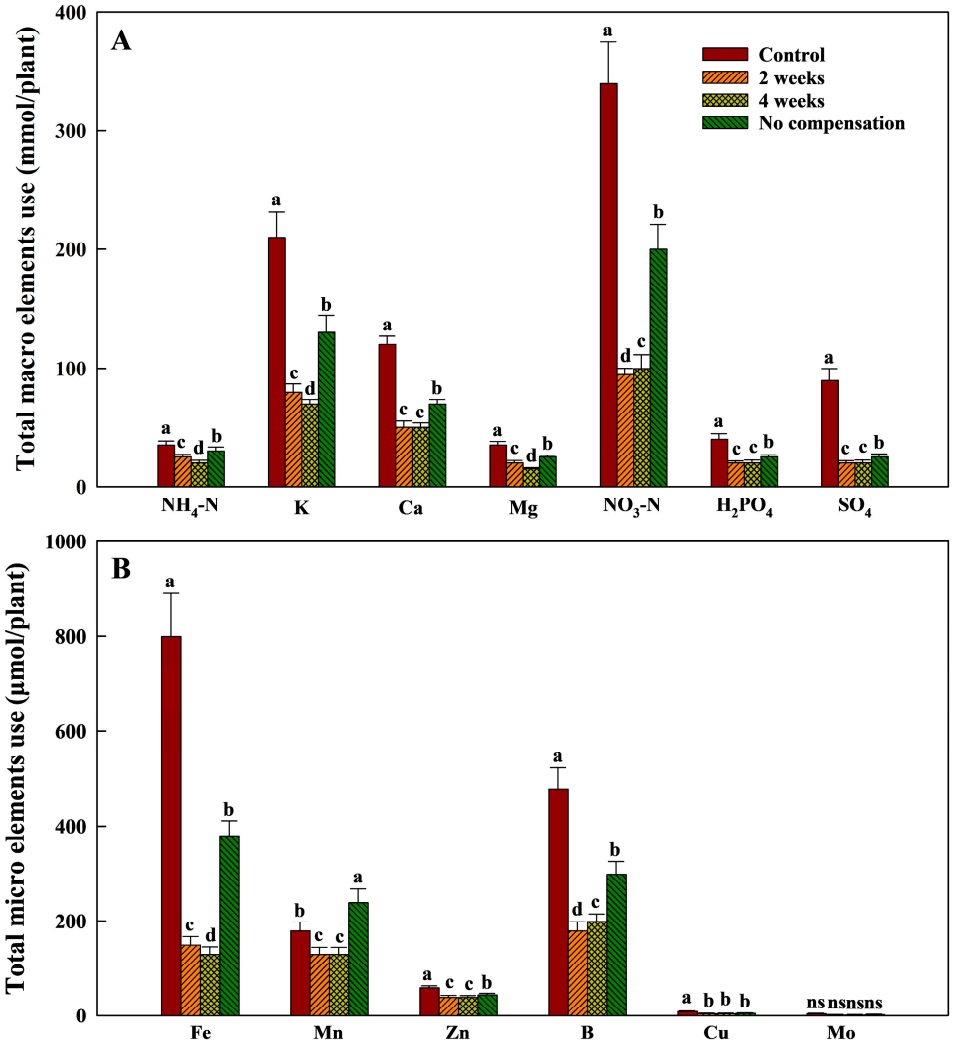


Figure 9. Total macro elements use (**A**) and total micro elements use (**B**) affected by different compensation intervals (no compensation, 2 weeks, and 4 weeks) during tomato cultivation. Control refers to open hydroponic systems. Vertical bars indicate standard errors of the mean values (n = 3). Lowercase letters indicate significant differences at $p \leq 0.05$, as determined by Duncan's multiple range test.

Table 4. Comparison of annual fertilizer consumption between open and closed hydroponic systems.

Fertilizer Type	Unit Price (USD/25 kg)	Control (T/ha)	2 Weeks (T/ha)	4 Weeks (T/ha)
KH_2PO_4	43.08	5.69	1.97	1.88
KNO_3	41.92	13.90	4.71	4.32
K_2SO_4	20.38	7.69	3.10	2.88
$Ca(NO_3)_2 \cdot 10H_2O$	12.69	30.30	7.17	6.91
$MgSO_4 \cdot 7H_2O$	7.23	15.60	2.72	2.69
NH_4NO_3	29.23	0.66	1.15	1.08
Summary of price (USD)	-	59,985	19,585	18,392

Table 5. The analysis of estimated annual savings in fertilizer and water use under closed hydroponic systems.

Benefit Factor (A)	**Loss Factor (B)**
(1) Fertilizer costs: USD 59,985/ha/year − USD 19,585/ha/year = USD 40,400/ha/year	(1) Closed hydroponic system installation cost and depreciation: USD 57,692/10 years = USD 5769.2/year
(2) Agricultural water (tap water) use costs: 4030 T/ha/year × USD 0.55/T = USD 2216.5/ha/year	(2) Closed hydroponic system management costs: (2–1) Analysis costs USD 76.9 × 2/month × 12 months = USD 1845.6/year (2–2) UV sterilization operating costs: EUR 0.09/m^3/10 years × USD 1.1/EUR × 10,000 m^2 = USD 990/10 years = USD 99.0/year
Total (A): USD 42,616.5 (Calculated as USD 40,400 + USD 2216.5)	Total (B): USD 7713.8 (Calculated as USD 5769.2 + USD 1845.6 + USD 99.0)
Estimated annual cost saving profit (A − B): 42,616.5 − 7713.8 = **USD 34,902.7**	

4. Conclusions

The results of this study, combined with the field monitoring from Exp. 1 and periodic compensation (4 weeks) of the nutrient solution from Exp. 2, revealed that, contrary to the concerns of farmers, ion imbalance was more pronounced in open than in closed hydroponic systems. This counterintuitive finding suggested that, rather than the hydroponic system type itself, periodic management and compensation of the nutrient solution based on drainage water monitoring results are crucial for resolving the issue of ion imbalance during tomato cultivation. These findings highlight the critical importance of grower education and the availability of user-friendly monitoring tools for the successful adoption of closed hydroponic systems. Furthermore, the principles demonstrated in this study, periodic nutrient compensation and drainage-based monitoring, may be applicable to other hydroponically grown crops such as cucumber, pepper, or potato. Future research should verify these relationships across different species and environmental conditions to establish crop-specific nutrient-management protocols for closed hydroponic systems.

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