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Impact of Essential Nutrient Deficiency on the Growth and Yield of Four Hydroponic Vegetable Crops Using a Split-Plot Design in Hydroponic Systems (Applied Plant Physiology Study)

Abd. Hadid[1*], Rois[1], Abdul Rahman[1], Chitra Angriani Salingkat[1], Jusriadi[1], Mustakim[2], Mustamin[2], Made Aditiya Dharma[3], Ni Ketut Dewi Kusuma Arsani[1]

[1] Agrotechnology Study Program, Faculty of Agriculture, Tadulako University, Palu, Indonesia
[2] Agrotechnology Study Program, Faculty of Agriculture and Animal Husbandry, Abdul Azis Lamadjido University, Palu, Indonesia

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Corresponding Author:
Abd. Hadid
hadidabd64@gmail.com

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Abstract: Essential nutrients play critical roles in plant physiology; therefore, nutrient imbalance in hydroponics can rapidly reduce growth and yield. This study evaluated the effects of N, P, and K deficiencies on four hydroponic vegetable crops using a split-plot design to support nutrient-deficiency diagnosis and practical nutrient management. This study used a split-plot design, with four nutrient types as main plots: N0 (balanced N, P, K), N1 (nitrogen deficiency), N2 (phosphorus deficiency), and N3 (potassium deficiency). The second factor consisted of four types of vegetable crops as subplots: S1 (Pakcoy), S2 (Caisim mustard), S3 (Green Romaine), and S4 (Kangkung), resulting in 16 treatment combinations, each repeated four times, for a total of 64 experimental units. The results indicate that deficiencies in nitrogen (N), phosphorus (P), and potassium (K) significantly affect growth and yield in hydroponic systems. Across crops, N deficiency most consistently reduced vegetative growth and fresh weight, P deficiency primarily constrained root-related traits and leaf expansion, and K deficiency affected yield-related performance and quality attributes.

Keywords: Hydroponics; Nutrient deficiency; Vegetable crops.

Introduction

The process of changing the agricultural sector for the better is known as agricultural development (Soekartawi, 2005; Mukhlis et al., 2019). Sustainable agriculture is a major challenge and necessity amid global population growth, climate change, and limited productive land (Khan et al., 2018). Within this context, hydroponics provides a controlled cultivation system that is also suitable as an experimental platform for applied plant physiology, including nutrient-deficiency diagnosis and data-driven evaluation of plant responses. Sustainable farming sytems were agricultural practices that do not harm, create a balance, and work in harmony with nature, which can be realized through four different systems (Salikin, 2011; Rasyid et al., 2024; Asgaf et al., 2025). One of the models that can be used in the implementation of sustainable agriculture is the integrated farming system (Mukhlis et al., 2023).

One innovative approach to addressing this challenge is hydroponics, a method of growing plants without soil by using nutrient solutions. Hydroponics is known for its efficiency in water and land use and can be applied in various environments, including urban areas with limited green space (Aini and Azizah 2018; Aksa, et al. 2016). However, one of the main challenges in hydroponics is nutrient management (Sutopo et al., 2025). **S**ystematic evaluation of nutrient-deficiency effects across crop species is therefore essential to establish practical diagnostic indicators and optimize nutrient formulation.

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Hydroponic plants are highly dependent on the balance and availability of essential nutrients, such as nitrogen, phosphorus, potassium, magnesium, and other microelements (Nurdin, 2017). A deficiency in any of these elements can cause growth disorders, reduced yields, and even plant death. Nutrient deficiencies can also be identified from various specific symptoms or characteristics in plants, which are often important indicators in diagnosing plant conditions. For example, nitrogen deficiency typically causes leaves to turn pale green or yellow (Hafizah, et al. 2019). Phosphorus deficiency can inhibit root growth and cause leaves to turn purple (Nuryani, et al. 2019). Potassium deficiency is often characterized by the appearance of necrotic spots on leaves and weakening of stems (Prakoso, et al. 2022). Nevertheless, symptom expression and growth reduction can differ among crop species, so comparative testing under the same hydroponic conditions is needed to strengthen diagnosis and management recommendations.

Research on the characteristics of plants lacking nutrients is important in understanding how nutrient deficiencies affect plants and how these symptoms can be used for early diagnosis of nutrient deficiency problems. With this understanding, nutrient management can be improved through more targeted strategies, such as more efficient and timely fertilization, which will ultimately increase agricultural productivity and quality. Despite many studies describing nutrient-deficiency symptoms, comparative evidence across multiple vegetable crops within one hydroponic experiment remains limited, particularly using a split-plot approach that explicitly tests crop × deficiency responses. This study addresses that gap by evaluating four vegetable crops under N, P, and K deficiency treatments in a single controlled hydroponic setting, thereby providing practical indicators for early diagnosis and nutrient-management strategies.

This study aims to analyze the impact of deficiencies in essential nutrients on the growth and yield of hydroponic vegetable crops and to identify crop-specific response patterns that can support early nutrient-deficiency diagnosis and practical hydroponic nutrient management.

Method

This study used hydroponic technology with self-formulated Ab Mix nutrients to observe plant responses to nutrient deficiencies. This research was conducted at PT. Nina Agro Jaya, Pombewe Village, Sigi Regency, Central Sulawesi Province (April–August 2025). A split-plot design was used, with four nutrient types as main plots: N0 (balanced N, P, K), N1 (nitrogen deficiency), N2 (phosphorus deficiency), and N3 (potassium deficiency). The second factor consisted of four vegetable crops as subplots: S1 (Pakcoy), S2 (Caisim Mustard), S3 (Green Romaine), and S4 (Kangkung), resulting in 16 treatment combinations repeated four times (64 experimental units). To improve replicability, the Ab Mix formulation (initial N–P–K concentration) and the reduction level for each deficiency treatment, as well as hydroponic solution pH and EC monitoring procedures, should be specified in this section.

The observed variables were: plant height, number of leaves (sheets), leaf area, root length (cm), wet plant weight (g), and root volume (ml). The data obtained were analyzed using analysis of variance (ANOVA) to determine the effect of the treatment, followed by a 5% level Honest Significant Difference (HSD) test. Prior to ANOVA, normality and homogeneity of variance should be evaluated (e.g., Shapiro–Wilk and Levene tests), and data transformation should be applied when assumptions are not met, to ensure statistical validity under a split-plot model.

Result and Discussion

This section first summarizes the visible morphological responses of each crop to N, P, and K deficiency, followed by quantitative comparisons of growth and yield parameters. Figures are presented as visual references of deficiency symptoms, whereas Tables provide statistical evidence (ANOVA and HSD 5%) for treatment differences across crops as shown in Figures 1 -

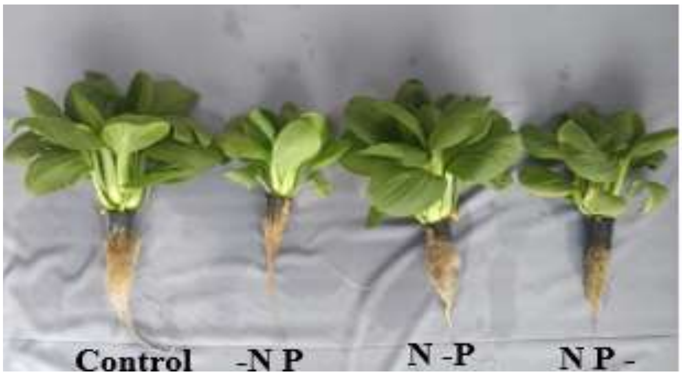

Figure 1. Pakcoy plants under treatment, deficient in essential nutrients

Figure 2. Mustard plants under essential nutrient deficiency treatment

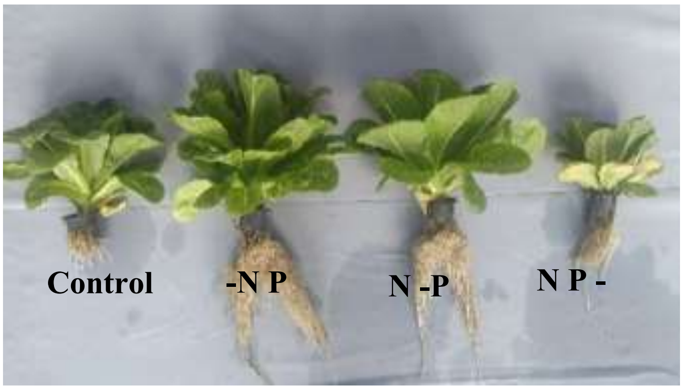

Figure 3. Pakcoy plants under essential nutrient deficiency treatment

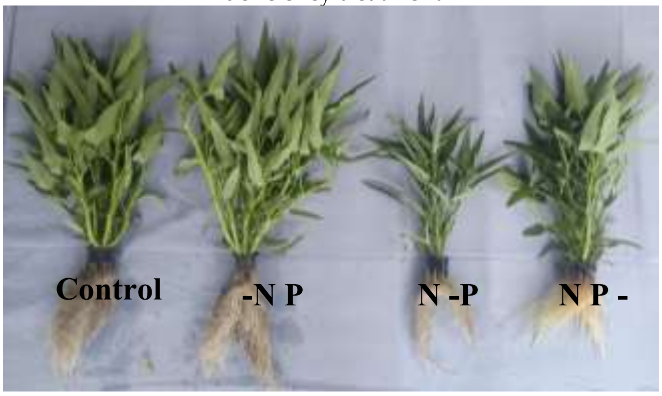

Figure 4. Water spinach plants under essential nutrient deficiency treatment

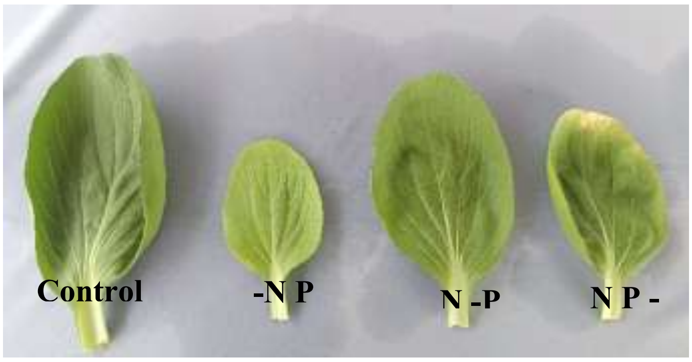

Figure 5. Pakcoy shoots under essential nutrient deficiency treatment

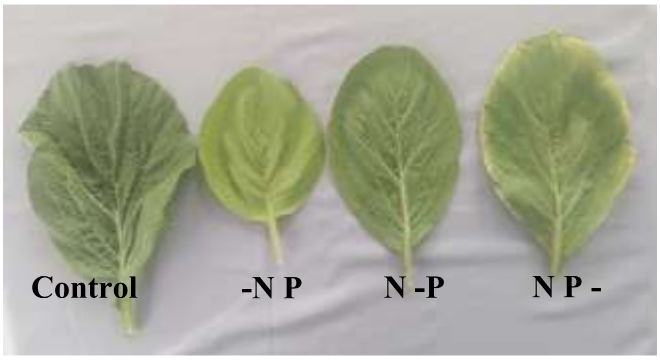

Figure 6. Leaf mustard in the treatment of essential nutrient deficiency

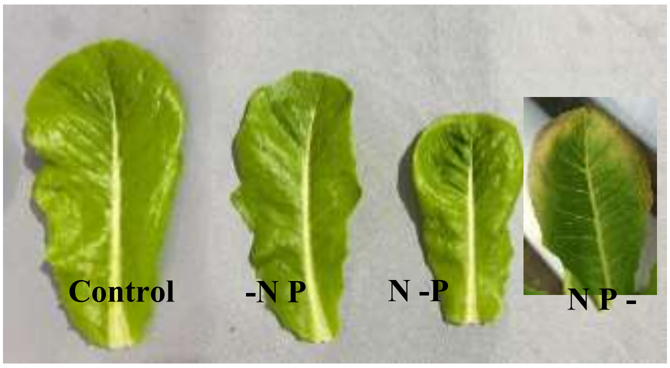

Figure 7. Romaine stems under essential nutrient deficiency treatment

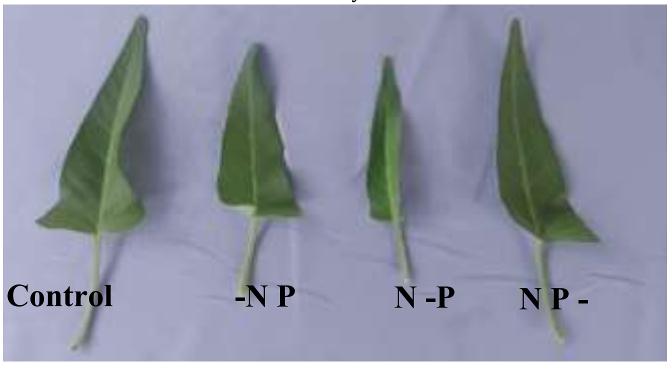

Figure 8. Water spinach stems under essential nutrient deficiency treatment

Plant Height

Plant height was evaluated weekly (1–4 WAP) to capture the initial and cumulative growth responses under nutrient deficiency treatments. The following table reports the average plant height for each plant across nutrient treatments, with different letters indicating significant differences at 5% HSD as shown in Table 1.

Tabel 1. Average plant height 1 MST (cm)

Nutrient Type	Plant Type				BNJ 5%
	Pakcoy	Sawi	Romaine	Kangkung	
NPK	${}_{q}8.65^{b}$	${}_{q}7.89^{b}$	${}_{p}5.01^{a}$	${}_{r}14.20^{b}$	1.21
N deficiency	${}_{q}6.62^{a}$	${}_{q}6.56^{a}$	${}_{p}5.13^{a}$	${}_{r}15.97^{c}$	1.21
P deficiency	${}_{q}7.32^{ab}$	${}_{q}7.14^{ab}$	${}_{p}4.33^{a}$	${}_{r}11.29^{a}$	1.21
K deficiency	${}_{q}8.03^{b}$	${}_{q}7.31^{ab}$	${}_{p}4.84^{a}$	${}_{r}13.80^{b}$	1.21
BNJ 5%	1.21	1.21	1.21	1.21	

Pakcoy and mustard greens treated with balanced N, P, K nutrients in the ab mix produced the highest plant height at 1 MSTs (8.65 cm and 7.89 cm) but did not differ from the ab mix lacking nutrients s of P (7.32 cm and 7.14 cm) and K (8.03 cm and 7.31 cm). Romaine plants in the ab mix treatment deficient in N produced the highest plant height at 1 MST (5.13 cm) but were not significantly different from the other treatments. Water spinach plants in the ab mix treatment deficient in N produced the highest plant height at 1 MST (15.97 cm) and were significantly taller than those in the other treatments.

Table 2. Average plant height at 2 MST (cm)

Nutrient Type	Plant Type				BNJ 5%
	Pakcoy	Mustard	Romaine	Water spinach	
NPK	q 15.01c	q 15.27b	p 8.26ab	r 26.34c	1.55
N deficiency	p 11.40a	p 11.80a	p 11.01c	q 32.32d	1.55
P deficiency	q 14.34bc	q 14.28b	p 8.82b	r 22.31a	1.55
K deficiency	q 13.32b	q 13.78b	p 6.86a	r 23.98b	1.55
BNJ 5%	1.55	1.55	1.55	1.55	

Pakcoy plants treated with ab mix nutrients with balanced N, P, and K nutrients produced the highest plant height at 2 MST (15.01 cm), but this was not different from ab mix nutrients deficient in P (14.34 cm). Mustard plants treated with an ab mix with balanced N, P, and K nutrients produced the highest plant height (15.27 cm), but this was not different from ab mix nutrients lacking P and K nutrients (14.28 cm and 13.78 cm). Romaine lettuce plants in the ab mix treatment lacking N nutrients produced the highest plant height (11.01 cm) and differed from other ab mix nutrients. Water spinach plants in the ab mix treatment lacking N nutrients produced the highest plant height (32.32 cm) and differed from other nutrients.

Table 3. Average plant height 3 MST (cm)

Nutrient Type	Plant Type				BNJ 5%
	Pakcoy	Mustard	Romaine	Water spinach	
NPK	q 21.88c	r 25.56c	p 11.88b	s 43.44c	2.26
N deficiency	pq 15.98a	q 17.63a	p 14.40c	r 44.32c	2.26
P deficiency	q 20.41bc	q 22.64b	p 12.68bc	r 28.78a	2.26
K deficiency	q 18.79b	r 22.16b	p 9.48a	s 39.21b	2.26
BNJ 5%	2.26	2.26	2.26	2.26	

Pakcoy plants treated with an ab mix containing balanced N, P, and K had the highest plant height at 3 MST (21.88 cm), but this was not different from plants treated with an ab mix lacking P (20.41 cm). Mustard plants in the ab mix treatment with balanced N, P, and K nutrients produced the highest plant height (25.56 cm) and differed from other ab mix nutrients. Romaine plants in the ab mix treatment lacking N nutrients produced the highest plant height at MST (14.40 cm) but did not differ from the ab mix lacking P nutrients (12.68 cm). Water spinach plants in the ab mix treatment lacking N nutrients produced the highest plant height (44.32 cm), but did not differ from those in the ab mix treatment with balanced N, P, and K nutrients (43.44 cm).

Table 4. Average plant height 4 MST (cm)

Nutrient Type	Plant Type				BNJ 5%
	Pakcoy	Mustard	Romaine	Water spinach	
NPK	q 26.36c	r 36.94d	p 17.16b	s 51.99c	2.73
N deficiency	p 18.07a	q 21.97a	p 18.26b	r 50.31c	2.73
P deficiency	q 26.59c	r 33.97c	p 17.40b	r 32.01a	2.73
K deficiency	q 22.64b	r 30.63b	p 12.31a	s 46.83b	2.73
BNJ 5%	2.73	2.73	2.73	2.73	

Pakcoy plants treated with an ab mix lacking P nutrients produced the highest plant height at 4 weeks after planting (26.59 cm), but this was not significantly different from an ab mix with balanced N, P, and K nutrients (26.36 cm). Mustard plants in the ab mix treatment with balanced N, P, and K nutrients produced the highest plant height (36.94 cm) and differed from other ab mix nutrients. Romaine lettuce plants in the ab mix treatment lacking N nutrients produced the highest plant height (18.26 cm) but did not differ from the ab mix with balanced N, P, and K nutrients (17.16 cm) and the ab mix lacking P nutrients (17.40 cm). Water spinach plants in the balanced N, P, K ab mix treatment produced the highest plant height (51.99 cm), but did not differ from those in the N-deficient ab mix (50.31 cm).

Number of Leaves

Pakcoy, mustard greens, and romaine lettuce plants in the ab mix treatment lacking P nutrients produced the highest number of leaves at 1 MST (5.89, 5.13, and 5.89 leaves), and differed from other ab mixes. Kangkung plants in the ab mix treatment deficient in N produced the highest number of leaves (6.39 leaves), but did not differ from the ab mix with balanced N, P, and K content (6.11 leaves) or the ab mix treatment deficient in P (5.78 leaves)

Table 5. Average number of leaves 1 MST (pieces)

Nutrient Type				Plant Type	BNJ 5%
	Pakcoy	Mustard	Romaine	Water spinach	
NPK	q 4.11a	p 3.00a	q 3.78a	r 6.11b	0.34
N deficiency	q 5.17b	p 4.72b	q 5.33b	r 6.39b	0.34
P deficiency	q 5.89c	p 5.13c	q 5.89c	q 5.78ab	0.34
K deficiency	q 3.94a	p 3.00a	q 3.72a	r 5.61a	0.34
BNJ 5%	0.34	0.34	0.34	0.34	

Pakcoy, mustard greens, and romaine lettuce plants in the ab mix treatment lacking P nutrients produced the highest number of leaves at 2 MST (9.11, 7.50, and 8.28 leaves), and differed from other ab mix treatments. Kangkung plants in the ab mix treatment with balanced N, P, and K nutrients produced the highest number of leaves (14.56 leaves) but did not differ from the ab mix lacking N nutrients (13.61 leaves).

Table 6. Average number of leaves at 2 MST (leaves).

Nutrient Type				Plant Type	BNJ 5%
	Pakcoy	Mustard	Romaine	Water spinach	
NPK	q 7.44a	p 5.11a	q 6.44a	r 14.56c	1.04
N deficiency	q 7.67a	p 5.94a	pq 6.94a	r 13.61c	1.04
P deficiency	q 9.11b	p 7.50b	pq 8.28b	q 9.72a	1.04
K deficiency	q 7.78a	p 5.72a	p 6.67a	r 11.28b	1.04
BNJ 5%	1.04	1.04	1.04	1.04	

Pakcoy, mustard greens, and romaine lettuce plants treated with ab mix nutrients deficient in P produced the highest number of leaves at 3 weeks after planting (14.00, 9.78, and 11.61 leaves), but were not different from those in the ab mix treatment with balanced N, P, and K nutrient content (12.00, 7.00, and 10.44 leaves) and the ab mix treatment deficient in K (12.17, 8.06, and 9.89 leaves). Water spinach plants treated with an ab mix with balanced N, P, and K nutrients produced the highest number of leaves (38.39 leaves) but did not differ from ab mix deficient in K nutrients (37.44 leaves).

Table 7. Average number of leaves at 3 MST (leaves)

Nutrient Type				Plant Type	BNJ 5%
	Pakcoy	Mustard	Romaine	Water spinach	
NPK	q 12.00ab	p 7.00ab	q 10.44ab	r 38.39c	2.94
N deficiency	q 9.22a	p 5.94a	pq 8.56a	r 20.83b	2.94
P deficiency	q 14.00b	p 9.78b	pq 11.61b	q 14.61a	2.94
K deficiency	q 12.17b	p 8.06ab	pq 9.89ab	r 37.44c	2.94
BNJ 5%	2.94	2.94	2.94	2.94	

Pakcoy plants treated with an ab mix containing balanced N, P, and K nutrients produced the highest number of leaves at 4 weeks after planting (18.39 leaves), but this was not different from other ab mix treatments. Mustard plants in the ab mix treatment lacking P produced the highest number of leaves (11.33 leaves), but this was not different from other ab mix treatments. Romaine lettuce plants in the ab mix treatment with balanced N, P, K nutrient content produced the highest number of leaves (18.72 leaves) but did not differ from the ab mix lacking P nutrients (13.44 leaves). Water spinach plants in the ab mix treatment lacking K produced the highest number of leaves (63.61) but did not differ from those in the ab mix treatment with balanced N, P, and K (62.22).

Table 8. Average number of leaves at 4 MST (leaves)

Nutrient Type				Plant Type	BNJ 5%
	Pakcoy	Mustard	Romaine	Water spinach	
NPK	q 18.39a	p 11.00a	q 18.72b	r 62.22c	5.45
N deficiency	q 13.89a	p 7.14a	q 12.78a	r 28.06b	5.45
P deficiency	q 18.11a	p 11.33a	pq 13.44ab	q 19.50a	5.45
K deficiency	q 17.83a	p 10.06a	pq 12.72a	r 63.61c	5.45
BNJ 5%	5.45	5.45	5.45	5.45	

Leaf Area

Pakcoy plants treated with an ab mix nutrient treatment containing balanced levels of N, P, and K produced the widest leaf area (83.50 c**m²**), but this was not different from the ab mix nutrient treatment lacking P and K (75.39 and 74.44 c**m²**). Mustard plants in the ab mix nutrient treatment with balanced N, P, and K nutrient content produced the widest leaf area (187.27 c**m²**) but did not differ from the ab mix lacking P (174.88 c**m²**). Romaine lettuce plants in the ab mix nutrient treatment lacking N produced the widest leaf area (64.37 c**m²**) and differed from the other ab mix treatments.

Table 9. Average leaf area (cm^2)

Nutrient Type				Plant Type	BNJ 5%
	Pakcoy	Mustard	Romaine	Water spinach	
NPK	q 83.50b	r 187.27c	p 44.04b	p 45.52b	13.98
N deficiency	pq 39.64a	q 50.14a	r 64.37c	p 33.59ab	13.98
P deficiency	r 75.39b	s 174.88c	q 47.36b	p 21.02a	13.98
K deficiency	r 74.44b	s 122.99b	p 16.80a	q 41.67b	13.98
BNJ 5%	13.98	13.98	13.98	13.98	

Pakcoy plants treated with an ab mix nutrient treatment containing balanced levels of N, P, and K produced the widest leaf area (83.50 cm^2), but this was not different from the ab mix nutrient treatment lacking P and K (75.39 and 74.44 cm^2). Mustard plants in the ab mix nutrient treatment with balanced N, P, and K nutrient content produced the widest leaf area (187.27 cm^2) but did not differ from the ab mix lacking P (174.88 cm^2). Romaine lettuce plants in the ab mix nutrient treatment lacking N produced the widest leaf area (64.37 cm^2) and differed from the other ab mix treatments. Water spinach plants in the ab mix nutrient treatment with balanced N, P, and K nutrient content produced the widest leaf area (45.52 cm^2) but did not differ from the ab mix treatments deficient in N and K nutrients (33.59 and 41.67 cm^2).

Root Length

Pakcoy plants treated with an ab mix nutrient containing balanced levels of N, P, and K produced the longest roots (31.20 cm), but were not significantly different from plants treated with other ab mix nutrients. Chinese cabbage plants in the ab mix nutrient treatment with balanced N, P, and K nutrient content produced the longest root length (33.46 cm) and differed from other ab mix treatments. Romaine lettuce plants in the ab mix nutrient treatment lacking N produced the longest root length (30.88 cm)but did not differ from the ab mix nutrient treatment lacking P (28.30 cm). Kangkung plants in the ab mix nutrient treatment lacking N produced the longest root length (48.92 cm) and differed from other ab mix nutrient treatments.

Table 10. Average root length (cm)

Nutrient Type				Plant Type	BNJ 5%
	Pakcoy	Mustard	Romaine	Water spinach	
NPK	qr31.20a	q 33.46c	p 5.65a	q 29.81a	4.63
N deficiency	pq 27.73a	p 25.85ab	q 30.88c	r 48.92b	4.63
P deficiency	qr 29.22a	p 21.44a	q 28.30c	r 33.65a	4.63
K deficiency	q 28.79a	q 28.61b	p 17.30b	q 33.03a	4.63
BNJ 5%	4.63	4.63	4.63	4.63	

Root Volume

Pakcoy and mustard plants treated with an ab mix nutrient deficient in P produced the highest root volume (31.89 cm^3 and 40.61 cm^3) and differed from other ab mix nutrient treatments. Romaine lettuce plants in the ab mix nutrient treatment lacking P produced the highest root volume (61.11 cm^3) but did not differ from the ab mix nutrient treatment lacking N (59.22 cm^3). Water spinach plants in the ab mix nutrient treatment lacking N produced the highest root volume (65.72 cm^3) and differed from other ab mix nutrient treatments.

Table 11. Average root volume (cm^3)

Nutrient Type				Plant Type	BNJ 5%
	Pakcoy	Mustard	Romaine	Water spinach	
NPK	pq 23.03b	q 27.50c	p 20.33b	r 35.17b	5.86
N deficiency	p 12.56a	p 10.81a	q 59.22c	r 65.72c	5.86
P deficiency	q 31.89c	r 40.61d	s 61.11c	p 23.61a	5.86
K deficiency	q 19.78b	q 19.56b	p 8.56a	r 32.78b	5.86
BNJ 5%	5.86	5.86	5.86	5.86	

Fresh Weight of Plants

Pakcoy plants treated with ab mix nutrients deficient in P produced the heaviest fresh weight (297.98 g), but this was not different from plants treated with ab mix nutrients containing balanced N, P, and K (275.11 g). Mustard plants in the ab mix nutrient treatment with balanced N, P, and K nutrient content produced the heaviest fresh weight (229.56 g) but did not differ from the ab mix nutrient treatment deficient in P (216.19 g).

Table 12. Average fresh weight (g)

Nutrient Type				Plant Type	BNJ 5%
	Pakcoy	Mustard	Romaine	Water spinach	
NPK	s 275.11c	r 229.56c	p 121.14a	q 182.69b	44.05
N deficiency	p 87.26a	p 57.44a	q 194.99b	q 181.17b	44.05
P deficiency	r 297.98c	q 216.19c	q 188.07b	p 69.69a	44.05
K deficiency	q 166.12b	pq 131.25b	p 105.19a	q 167.17b	44.05
BNJ 5%	44.05	44.05	44.05	44.05	

Romaine lettuce plants in the ab mix nutrient treatment lacking N produced the heaviest fresh weight (194.99 g) but did not differ from the ab mix nutrient treatment lacking P (188.07 g). Water spinach plants in the ab mix nutrient treatment with balanced N, P, and K nutrient content produced the heaviest fresh plant weight (182.69 g) but did not differ from the ab mix nutrient treatment deficient in N (181.17 g) and K (167.17 g).

Discussion

Each plant shows a different response to the availability of nitrogen (N), phosphorus (P), and potassium (K) nutrients. These differences are influenced by each plant's physiological needs and the specific role of each nutrient in the growth process. Importantly, the split-plot design enables evaluation of whether nutrient-deficiency effects depend on crop species (crop × deficiency interaction), which is essential for identifying crop-specific sensitivity patterns and diagnostic indicators.

In several parameters, deficiency treatments produced values comparable to or higher than the control. This pattern can reflect short-term compensatory responses (e.g., altered biomass allocation or root exploration under limited nutrients), differences in species-specific nutrient demand, or non-linear responses when the control concentration is not the physiological optimum for a given crop. Therefore, interpretation should emphasize statistically significant differences (HSD 5%) and relate unexpected increases to plausible adaptive mechanisms rather than assuming deficiency always reduces all traits.

The results of the study show that Pakcoy plants produce the best results with a balanced N, P, and K nutrient supply and an ab mix nutrition deficient in P, as indicated by plant height, number of leaves, leaf area, root length, and plant fresh weight. The best root volume was obtained with an ab mix treatment deficient in P. Mustard plants produce the best results when treated with a nutrient mix containing balanced levels of N, P, and K. This is evident in plant height, number of leaves, leaf area, root length, and plant fresh weight. The best root volume is produced when treated with an ab mix that is deficient in P.

Romaine lettuce plants produced the best results with the ab mix nutrient treatment deficient in N and P, as indicated in plant height, root length, root volume, and fresh plant weight. The best leaf area was observed in the ab mix nutrient treatment deficient in N nutrients, and the best number of leaves was observed in the ab mix nutrient treatment with balanced N, P, and K nutrient content.

Water spinach plants produce the best results when treated with a balanced nutrient mix containing N, P, and K at equal levels. This is evident in plant height, number of leaves, leaf area, and fresh weight. The best root length and volume are produced when treated with a nutrient-deficient in. The balanced N, P, K ab mix nutrient treatment had a negative impact on the root length of romaine and water spinach plants, as well as the fresh weight of romaine plants.

Nitrogen (N) deficiency has a detrimental effect on the growth and yield of all types of vegetable crops (Fan et al., 2021; Wang et al., 2019). Pakcoy plants deficient in N exhibit low plant height, fewer leaves, smaller leaf area, shorter roots, lower root volume, and lower fresh weight. Mustard plants exhibit reduced plant height, fewer leaves, smaller leaf area, reduced root volume, and lower fresh plant weight. Romaine plants only exhibit fewer leaves. Meanwhile, nitrogen deficiency in water spinach plants does not adversely affect plant growth and yield.

Phosphorus (P) deficiency negatively impacts water spinach plants, resulting in shorter plants, fewer leaves, smaller leaves, reduced root volume, and lower fresh weight. Meanwhile, in pak choi and mustard greens, it only causes shorter roots. However, P deficiency does not affect romaine lettuce. Potassium (K) deficiency negatively impacts romaine lettuce, resulting in shorter plants, fewer leaves, smaller leaf area, reduced root volume, and lower fresh weight. Mustard greens produce fewer leaves, while pak choi produces shorter roots.

Nitrogen is the most essential macronutrient for plant growth because it plays a role in the formation of amino acids, proteins, and chlorophyll (Braos et al., 2022; Tei et al., 2020; Valenzuela, 2023). Based on the research results, nitrogen-deficiency treatment resulted in a significant decrease in all growth parameters, including plant height, leaf number, leaf area, and fresh plant weight. This decline is directly related to reduced chlorophyll synthesis and photosynthesis rates (Martínez-Dalmau, et al. 2021; Zhou et al. 2023). Plants deficient in N exhibit paler leaf color, slower growth, and longer roots as a compensatory response to nutrient limitations (Gao et al., 2022; Chen et al. 2020).

Phosphorus plays a crucial role in energy metabolism, ATP formation, and root development (Meng et al., 2021). Research results indicate that phosphorus deficiency causes a significant reduction in plant height, leaf area, and root volume.

Phosphorus affects lateral root development and water absorption, so its deficiency reduces nutrient exploration efficiency (Xue et al., 2022). In this study, romaine lettuce and water spinach were most sensitive to P deficiency, with significant reductions in leaf area and fresh weight (Sun et al., 2024). Interestingly, some plants, such as pakcoy, still show relatively stable growth responses to P deficiency. This indicates physiological efficiency or rhizosphere microbial symbiosis that supports the absorption of residual P nutrients. This mechanism can increase the total nutrient efficiency of the land because the roots of various plants utilize different soil layers (Mishra et al., 2024; M. Zhou et al., 2022).

Potassium plays a role in osmotic regulation, enzyme activation, and the transport of photosynthetic products (Cui et al., 2024; Torabian et al., 2021). Based on research data, potassium deficiency causes a decrease in leaf area in romaine lettuce and rust on leaf edges, especially in pak choi, mustard greens, and romaine lettuce. This indicates that potassium is highly mobile and rapidly affects plant physiology (Sardans &

Penuelas, 2021). Potassium deficiency causes disruption in stomatal opening and the distribution of photosynthetic products, so that although leaves appear normal at the beginning of growth, biomass accumulation decreases over time (Kusaka et al., 2021; Liu et al., 2021).

Conclusion

Based on the study's results, it can be concluded that deficiencies in nitrogen (N), phosphorus (P), and potassium (K) significantly affect the growth and yield of hydroponic vegetable crops. However, the magnitude and direction of responses vary by crop and parameter, indicating crop-specific sensitivity patterns that should guide nutrient management and diagnosis in hydroponic production. Nitrogen deficiency causes a significant decrease in plant height, leaf number, and fresh weight. Phosphorus deficiency inhibits root development and leaf area, while potassium deficiency affects yield and plant quality. Practically, these results support prioritizing stable N availability to maintain vegetative growth, monitoring P status to prevent root and leaf-expansion constraints, and ensuring adequate K to protect yield performance and quality. Study limitations include the focus on three macronutrients (N, P, K) and the need for clearer reporting of hydroponic environmental parameters (e.g., pH and EC), which should be addressed in future work by testing graded deficiency levels and incorporating additional nutrients and environmental monitoring.

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The authors declare no conflict of interest.

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