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Change in Substrate Macronutrients and Growth Traits as Affected by Companion Cropping Ratios of Perilla with Kidney Bean in Container Cultivation

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Abstract

This study investigated the effects of companion cropping on substrate macronutrient content and on plant growth when perilla (*Perilla frutescens* L.) was grown as the main crop and kidney bean (*Phaseolus vulgaris* L.) as the companion plant. Five treatments were established according to planting ratio: perilla monoculture (PC); perilla and kidney bean mixtures at 2:1 (P2K1), 1:1 (P1K1), and 1:2 (P1K2); and kidney bean monoculture (KC), all grown in containers under greenhouse conditions. Companion planting with kidney bean improved neither substrate macronutrient status nor the growth of perilla in containers. Substrate analysis showed that macronutrients (nitrogen, phosphorus, and potassium) declined significantly and rapidly in the mixed treatments relative to the perilla monoculture ($p < 0.05$). Compared with the monoculture, companion cropping with kidney bean significantly reduced the leaf length, leaf width, leaf number, chlorophyll content, chlorophyll fluorescence, stem diameter, and biomass of perilla ($p < 0.05$). The land equivalent ratio (LER) did not differ significantly among the P2K1, P1K1, and P1K2 treatments, although the relative yield (RY) and competitive ratio (CR) of kidney bean decreased with decreasing perilla cropping ratio, indicating that kidney bean was more competitive than perilla. Perilla monoculture is therefore more suitable than companion planting with kidney bean for short-duration container vegetable gardening.

Keywords: legume; leafy green vegetables; plant growth; *Perilla frutescens*; *Phaseolus vulgaris*; sustainable farming; urban agriculture

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1. Introduction

Containers are a common production system in urban farming. They can be constructed and adapted to fit the small and confined spaces found in urban areas [1], and they also reduce soil compaction in the growing area by preventing foot traffic, which allows water to move more freely [2,3]. Container-grown crops require optimal conditions for growth and development over a short period. The growing medium in particular should supply nutrients at an optimal concentration, ratio, and release rate, supporting both the aboveground parts of the plant and the root system below [4]. Synthetic water-soluble fertilizers can be highly effective for horticultural crop yields in this respect, but the quantity of fossil fuel used to produce them is very high, and because they are water-soluble, their

nutrients leach readily into runoff [5]. Such problems are often addressed through the use of specific production systems and practices.

Companion cropping, also referred to as intercropping, mixed cropping, or polyculture, is the agroecological practice of cultivating two or more crops simultaneously. Farmers have employed it for millennia, and it remains present in cropping systems around the world [6]. Its recent resurgence is most marked in cereal–legume intercropping systems and is attributed largely to the substantial benefits derived from spatiotemporal niche complementarity [7]. These features have the potential to improve the efficiency and sustainability of vegetable and flower production. Maize is a common component of intercropping systems, and abundant research has shown that maize intercropped with pea bean, broad bean, soybean, or peanut yields significantly more than maize in monoculture [8]. Wang et al. (2016), by contrast, found that maize/alfalfa intercropping reduced yield relative to monoculture while increasing economic returns [9]. Coll et al. (2012) reported that intercropping sunflower with maize produced a 20% lower grain yield than sole cropping [10]. Not all crop combinations in an intercropping system, then, deliver mutual benefits.

Companion cropping systems have been shown to reduce dependence on fertilizers and the risk of nitrate leaching relative to sole cropping. The practice is particularly suited to low-nitrogen systems, although a fuller mechanistic understanding is needed before generic crop management procedures can be proposed [11]. Used in combination with companion cropping, this approach can maximize food production in urban areas where space is limited [12]. Legumes as component crops play versatile roles, including biological nitrogen fixation and soil quality improvement, additional yield output such as protein, and the creation of functional diversity [13]. Growing two or more crops together nonetheless demands additional care and management if competition among species is to be minimized and natural resources used efficiently [14]. Previous studies have demonstrated the potential of legume nitrogen fixation to promote plant production and to alleviate abiotic and biotic stress in the field [15–18], but studies of its use in controlled environments such as containers and greenhouses remain limited.

Leafy green vegetables are considered desirable crops for companion cropping because they mature quickly. The category encompasses a wide variety of vegetables with edible leaves. Perilla (*Perilla frutescens* L.) is an annual plant belonging to the mint family, Lamiacea, and is primally cultivated in Asian countries. It is an edible vegetable used in salads, sushi and soups, as well as for pickles and garnishes [19]. In Korea, perilla is one of the most important leafy vegetables and is commonly used as a "wrap-up vegetable" together with leaf lettuce, kale, and pak-choi; it is widely grown in home gardens and on balconies for its flavor and health benefits [20]. Nutrient management may play a large role in potential yield and crop quality. A moderate increase in nutrient supply often raises yield, with diminishing returns at higher rates of application [21], and differences in nitrogen application and in nitrogen availability from different sources can also affect the yield of greens [22,23].

Kidney bean (*Phaseolus vulgaris*) has strong adaptability, grows in poor soil and is drought resistance [24]. Growing legumes, a major biological source of nitrogen, is also a powerful means of reducing the use of synthetic nitrogen fertilizers and the associated consumption of fossil energy [25]. The agronomic efficacy of legume-based companion planting is nevertheless governed strongly by subterranean volume constraints and by interspecific competition. Determining the optimal ratios of the component crops is therefore an essential next step in promoting companion cropping as a sustainable practice [6]. Therefore, the purpose of this study was to evaluate the effects of a legume companion crop on substrate macronutrients and on leafy vegetable growth in the absence of supplementary fertilization and to explore the possibility of integrating legumes into container-grown vegetable garden systems.

2. Materials and Methods

2.1. Experimental Design, Plant Materials, and Growth Conditions

The experiment was conducted in a greenhouse at the Department of Green Technology Convergence, Konkuk University Glocal Campus, Chungju-si, Chungcheongbuk-do (lat. 36°56′ N, long. 127°54′ E), from April to July 2022. The growth cycles of leafy vegetables and common bean typically span approximately 30 to 45 days after transplanting. Over the experimental period the cultivation environment recorded a mean photosynthetic photon flux density of 365.8 μmol·m^{-2}·s^{-1}, a mean temperature of 20.2 °C, and a mean relative humidity of 65.8%.

Thirty-day-old perilla and kidney bean seedlings were raised from seed in a cocopeat substrate to mean plant heights of 5 and 20 cm, respectively. Two plant species were transplanted together on 3 May 2022 into the same plastic containers measuring 60 cm × 20 cm × 15 cm (length × width × height). To determine the direct effects of companion cropping on substrate macronutrients and plant growth under container cultivation, both crops were planted at a high density with 10 cm × 10 cm spacing.

A non-woven fabric (CG-RPRS, CityGreen Co., Daegu, Republic of Korea) was laid in each container, followed by 2 cm of perlite (New-perlshine, GeenFireChmical Co., Hongseong, Republic of Korea) and 12 cm of horticultural substrate (Hanpanseung, SamhwaGreenTech Co., Anyang, Republic of Korea) consisting of 74.84% cocopeat, 15% vermiculite, 5% biotite, 5% perlite, 0.158% fertilizer, and 0.002% wetting agent.

The five treatments comprised the following companion cropping ratios of perilla and kidney bean: PC, 12 perilla + 0 kidney bean; P2K1, 8 perilla + 4 kidney bean; P1K1, 6 perilla + 6 kidney bean; P1K2, 4 perilla + 8 kidney bean; KC, 0 perilla + 12 kidney bean. Treatments were arranged in a completely randomized design with three replications, and the containers per treatment were placed on expanded concrete platforms raised 100 cm above the greenhouse floor. An equal volume of water (350 mL per container) was applied manually twice a week from transplanting until final harvest. No supplementary chemical fertilizer was applied, so that changes in the macronutrient status of the growing medium could be tracked under each cropping configuration.

2.2. Substrate Macronutrients and Growth Characteristics

Substrate and growth measurements were taken 7, 14, 21, 28, 35, and 42 days after transplanting (DAT) for both perilla and kidney bean. The macronutrients (nitrate, phosphorus, and potassium) contents of the substrate supporting each plant were determined with a portable soil multi-parameter analyzer (SOIL6CH, Testauction Co., Seoul, Republic of Korea). Measuring spikes were inserted vertically into the substrate at five points (four corners and the center) per container, each more than 5 cm from the container wall, and the mean of these readings was used for analysis.

All values were expressed in mg·kg^{-1}. The initial mean macronutrient contents of the substrate in the containers were 44.00 ± 14.05, 68.29 ± 20.19, and 139.43 ± 14.05 mg·kg^{-1} for nitrogen, phosphorus, and potassium, respectively.

Growth measurements began at 7 DAT, which served as the baseline for subsequent growth analysis. For each growth trait, three plants per container were randomly selected. Plant height was measured from the surface of the growing medium to the shoot tip; leaf length was measured parallel to the midrib from the lamina apex to the petiole base; leaf width was measured at the widest point perpendicular to the primary leaf axis; and leaves were counted manually. Relative chlorophyll content was measured on the third leaf counted from the top of each plant with a chlorophyll meter (SPAD-502, Konica Minolta Co., Ltd., Osaka, Japan); twelve readings were taken from different points on the leaf in each plant; and the mean of these readings was used.

2.3. Leaf Color, Photochemistry, and Biomass of Perilla Grown at Different Companion Planting Ratios with Kidney Bean

The visual quality and physiological responses of perilla leaves were recorded as yield parameters in July, when the plants had reached peak harvest. The color of the upper leaf surface was measured with a chroma meter (CR-400, Konica Minolta Co., Ltd., Osaka, Japan) on the third leaf from the top of each plant and recorded as lightness (L^*), red-green (a^*), and yellow-blue (b^*) values.

Chlorophyll fluorescence parameters were measured at room temperature with a pulse-modulated fluorometer (Junior-PAM, Walz, Effeltrich, Germany). Perilla leaves were excised, immediately placed in Petri dishes filled with distilled water, and transferred to a shaded growth chamber at ambient temperature; after 60 min of dark adaptation, chlorophyll fluorescence was measured on the adaxial leaf surface. Minimal fluorescence (Fo) was measured with a measuring light pulse (0.1 μmol·m^{-2}·s^{-1} PPFD), and maximal fluorescence (Fm) was determined after a 0.8 s saturating white light pulse (10,000 μmol·m^{-2}·s^{-1} PPFD). Fv/Fm, calculated as (Fm − Fo)/Fm, represents the maximum yield of photosystem II photochemistry in the dark-adapted state. The stem diameter of perilla was measured at the second node above the substrate. Nine plants from each treatment were washed free of substrate, and the fresh weights of shoots and roots were measured on a digital balance (IP65, A&D Co., Tokyo, Japan). Dry weight was determined after drying in a forced-air oven (C-DF, CHAGSHIN Sci Co., Seoul, Republic of Korea) at 80 °C, to constant weight.

2.4. Relative Yield (RY), Land Equivalent Ratio (LER), and Competitive Ratio (CR) of Perilla and Kidney Grown at Different Companion Planting Ratios in Containers

The relative yield (RY) and land equivalent ratio (LER) indices were used to evaluate the ability of perilla and kidney bean plants to utilize resources in companion-cropped containers. For the LER calculation, the total fresh biomass of each crop in monoculture and in companion-cropped containers was taken as the yield of each experimental unit. The competitiveness of perilla and kidney bean was also assessed using the competitive ratio (CR) index, which indicates the degree to which one crop is more competitive than the other. RY, LER, and CR were calculated using the equations proposed by Ribas et al. [18] and Marinez et al. [26].

2.5. Statistical Analysis

All statistical analyses were performed with SPSS v.30.0 (SPSS Inc., Chicago, IL, USA). Five treatments were evaluated in a completely randomized design with three replications. The effects of companion cropping ratio on the substrate and growth parameters of perilla and kidney bean were analyzed by one-way analysis of variance (ANOVA), and significant differences among treatment means were identified by Duncan's multiple range test ($p < 0.05$) at each DAT. Figures were prepared with SigmaPlot v.12.3 (Systat Software, Inc., Cary, NC, USA).

3. Results

3.1. Changes in Substrate Macronutrients as Affected by Companion Planting Ratio of Perilla and Kidney Bean in Container Cultivation

At the start of the experiment (7 DAT), nitrogen content ranged from 28.84 to 34.43 mg·kg^{-1} across all treatments. A sharp drawdown followed at 14 DAT: the perilla monoculture (PC) retained a comparatively high nitrogen content of about 35.86 mg·kg^{-1}, whereas the kidney bean monoculture (KC) and all three mixed configurations (P2K1, P1K1, and P1K2) fell to 15.71–22.14 mg·kg^{-1}. This downward trend continued after 21 DAT

and was most rapid in the kidney bean monoculture. By 28 DAT, nitrogen in all cropped containers had declined to about 3.71–10.00 mg·kg^{-1}. Values varied slightly at 35 DAT, but at the final measurement (42 DAT), no significant difference remained among treatments, all of which had fallen to 5.14–8.00 mg·kg^{-1} (Figure 1).

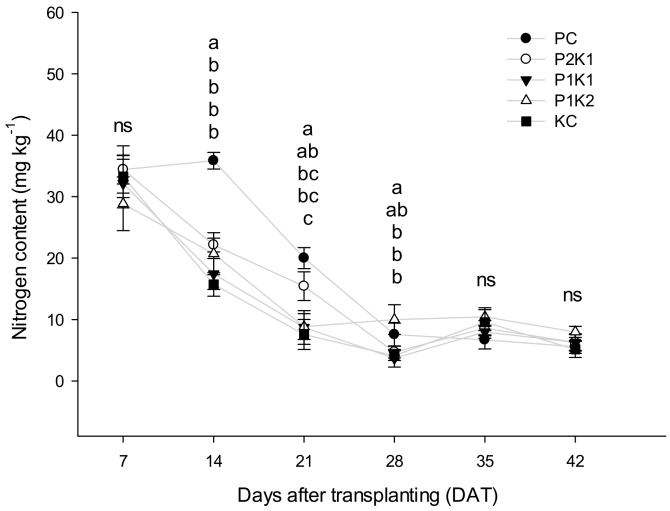


Figure 1. Changes in nitrogen content (mg·kg^{-1}) in substrate as affected by companion cropping ratios of perilla and kidney bean during 42 days after transplanting (DAT) in containers under greenhouse conditions. PC, 12 perilla seedlings; P2K1, 8 perilla seedlings + 4 kidney bean seedlings; P1K1, 6 perilla seedlings + 6 kidney bean seedlings; P1K2, 4 perilla seedlings + 8 kidney bean seedlings; KC, 12 kidney bean seedlings. Values are mean ± standard error (SE) based on three replicates ($n = 3$). Different lowercase letters at each DAT indicate significant differences among treatments according to Duncan's multiple range test ($p < 0.05$), while "ns" denotes no significant difference.

Changes in substrate phosphorus closely resembled the pattern observed for nitrogen. Initial phosphorus values at 7 DAT were approximately 42.29–54.00 mg·kg^{-1} in all containers, with no significant difference among treatments. Phosphorus content in the perilla monoculture (PC) was 53.00 mg·kg^{-1} at 14 DAT and 28.86 mg·kg^{-1} at 21 DAT. In the P2K1, P1K1, P1K2, and KC treatments, by contrast, it fell rapidly to 22.14–31.57 mg·kg^{-1} by 14 DAT and further to 13.00–17.84 mg·kg^{-1} by 21 DAT. From 28 DAT onward, phosphorus in all treatments was below 16.00 mg·kg^{-1}, and at 42 DAT it ranged from 7.43 to 11.43 mg·kg^{-1} with no significant differences among treatments (Figure 2).

Potassium was the most abundant of the three macronutrients, ranging from 85.57 to 113.57 mg·kg^{-1}, but its decline over time followed the same patterns as nitrogen and phosphorus. At 14 DAT, the PC treatment showed a gradual lag phase and maintained a higher potassium concentration (approximately 105 mg·kg^{-1}) than the other treatments, whereas potassium declined rapidly in the containers that included kidney bean. The KC treatment declined fastest between 14 and 21 DAT, falling to approximately 28 mg·kg^{-1}. At 28 DAT, the highest value was recorded in P1K2 (31.00 mg·kg^{-1}) and the lowest in KC (12.71 mg·kg^{-1}), but from 35 DAT onward, the treatments did not differ significantly (Figure 3).

3.2. Changes in Growth Characteristics as Affected by Companion Planting Ratio of Perilla and Kidney Bean in Container Cultivation

Both species followed a typical S-shaped growth curve over the cultivation period, but plant height was strongly influenced by companion cropping ratio within containers. Perilla height increased steadily from 7 to 42 DAT in all treatments. At 7 DAT, perilla height did not differ significantly between the monoculture (PC) and the mixed-cropped treatments;

the highest values were recorded in P1K1 from 14 to 28 DAT; and from 35 DAT onward, the treatments did not differ significantly (Figure 4a). Kidney bean height varied markedly among treatments. The kidney bean monoculture (KC) recorded the lowest height at every measurement, reaching only about 32 cm at 42 DAT. Where perilla was mixed in, by contrast, vertical growth of kidney bean was promoted, an effect particularly pronounced in P2K1, the configuration with the highest proportion of perilla, which peaked at about 38 cm at 28 DAT before declining slightly (Figure 4b).

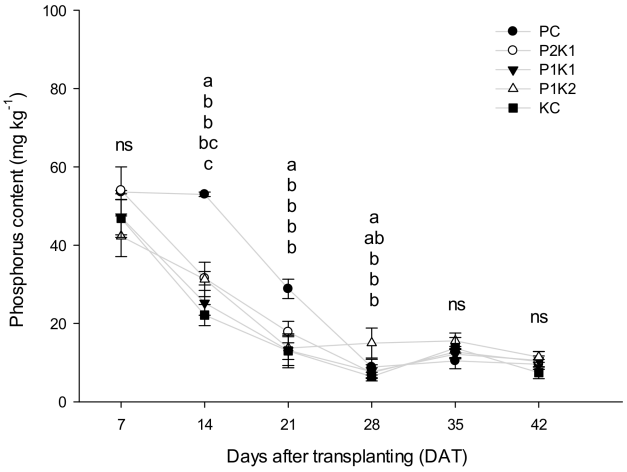


Figure 2. Changes in phosphorus content ($mg \cdot kg^{-1}$) in substrate as affected by companion cropping ratios of perilla and kidney bean during 42 days after transplanting (DAT) in containers under greenhouse conditions. PC, 12 perilla seedlings; P2K1, 8 perilla seedlings + 4 kidney bean seedlings; P1K1, 6 perilla seedlings + 6 kidney bean seedlings; P1K2, 4 perilla seedlings + 8 kidney bean seedlings; KC, 12 kidney bean seedlings. Values are mean ± standard error (SE) based on three replicates ($n = 3$). Different lowercase letters at each DAT indicate significant differences among treatments according to Duncan's multiple range test ($p < 0.05$), while "ns" denotes no significant difference.

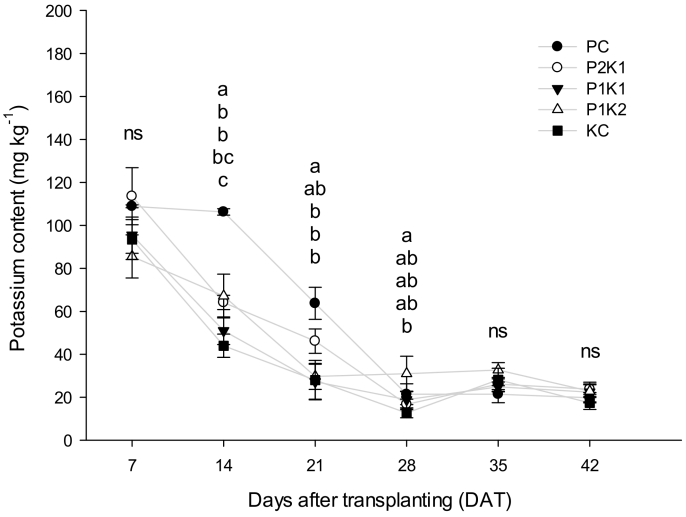
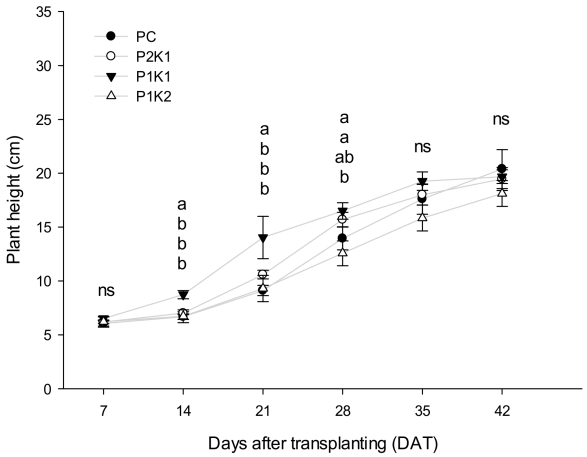
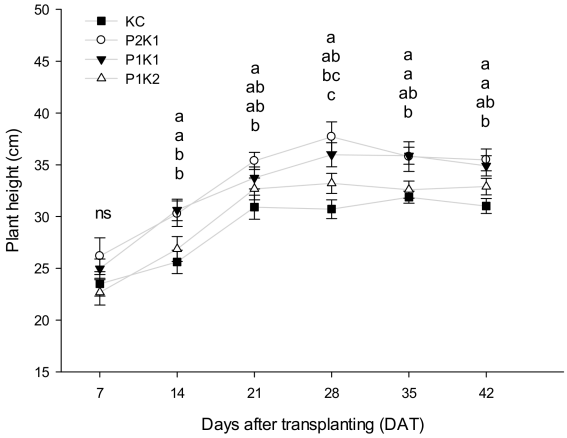


Figure 3. Changes in potassium content ($mg \cdot kg^{-1}$) in substrate as affected by companion cropping ratios of perilla and kidney bean during 42 days after transplanting (DAT) in containers under greenhouse conditions. PC, 12 perilla seedlings; P2K1, 8 perilla seedlings + 4 kidney bean seedlings; P1K1, 6 perilla seedlings + 6 kidney bean seedlings; P1K2, 4 perilla seedlings + 8 kidney bean seedlings; KC, 12 kidney bean seedlings. Values are mean ± standard error (SE) based on three replicates ($n = 3$). Different lowercase letters at each DAT indicate significant differences among treatments according to Duncan's multiple range test ($p < 0.05$), while "ns" denotes no significant difference.



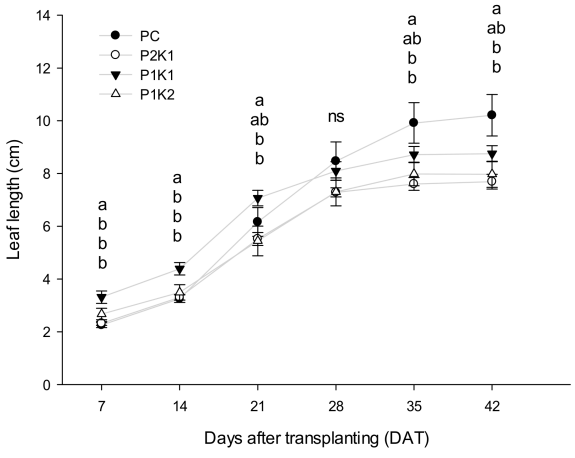
(**a**) Plant height of perilla.



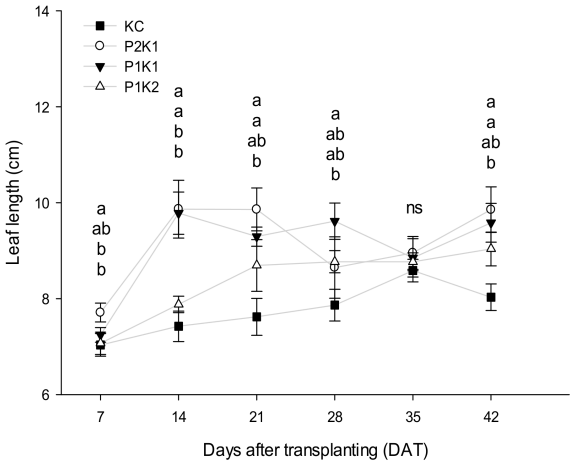
(**b**) Plant height of kidney bean.

Figure 4. Change in plant height of perilla (**a**) and kidney bean (**b**) by perilla–kidney bean companion cropping at different planting ratio during 42 days after transplanting (DAT) in containers under greenhouse conditions. PC, 12 perilla seedlings; P2K1, 8 perilla seedlings + 4 kidney bean seedlings; P1K1, 6 perilla seedlings + 6 kidney bean seedlings; P1K2, 4 perilla seedlings + 8 kidney bean seedlings; KC, 12 kidney bean seedlings. Values are mean ± standard error (SE) based on three replicates ($n = 3$). Different lowercase letters at each DAT indicate significant differences among treatments according to Duncan's multiple range test ($p < 0.05$), while "ns" denotes no significant difference.

Perilla leaf length responded differently to companion planting ratios. All perilla treatments followed a steady S-shaped increase over time, and the greatest leaf length was recorded at 35 DAT in the monoculture (PC), while the companion cropped treatments (P2K1, P1K1, and P1K2) tended to fall below it (Figure 5a). Kidney bean leaf length differed significantly with planting ratio, with the shortest leaves occurring in the kidney bean monoculture (KC). All mixed configurations (P1K2, P1K1, and especially P2K1, with its higher proportion of perilla) showed a rapid increase in leaf length by 14 DAT and maintained high values thereafter (Figure 5b).



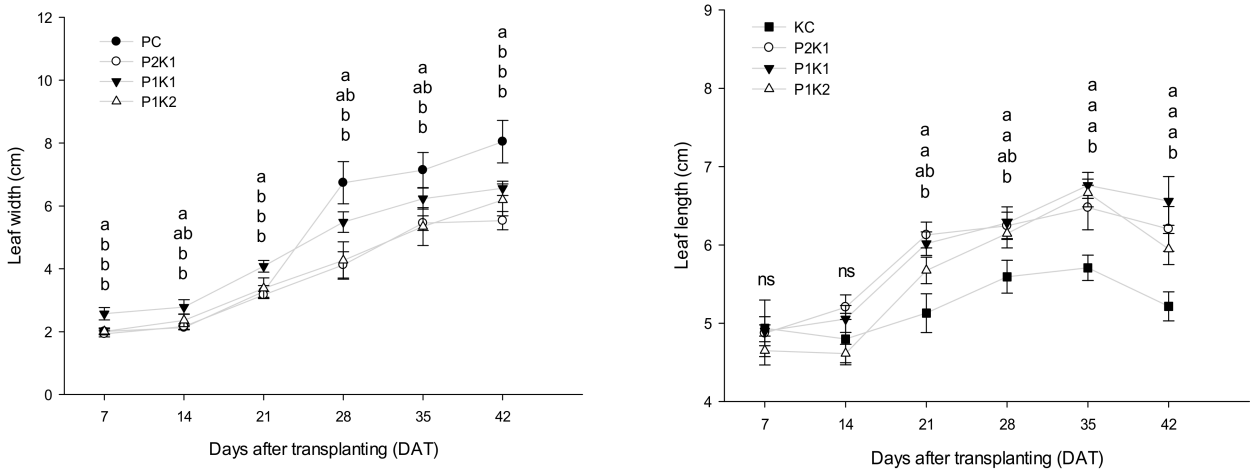
(**a**) Leaf length of perilla.



(**b**) Leaf length of kidney bean.

Figure 5. Change in leaf length of perilla (**a**) and kidney bean (**b**) by perilla–kidney bean companion cropping at different planting ratio during 42 days after transplanting (DAT) in containers under greenhouse conditions. PC, 12 perilla seedlings; P2K1, 8 perilla seedlings + 4 kidney bean seedlings; P1K1, 6 perilla seedlings + 6 kidney bean seedlings; P1K2, 4 perilla seedlings + 8 kidney bean seedlings; KC, 12 kidney bean seedlings. Values are mean ± standard error (SE) based on three replicates ($n = 3$). Different lowercase letters at each DAT indicate significant differences among treatments according to Duncan's multiple range test ($p < 0.05$), while "ns" denotes no significant difference.

Perilla leaf width confirmed that companion cropping with kidney bean was restrictive. Leaf width increased slowly during early growth (7–14 DAT) in all treatments and then rose sharply during the main vegetative period (28–35 DAT). At harvest (42 DAT), however, the monoculture (PC) reached a distinctly superior width of approximately 7.4 cm, whereas none of the companion-planted treatments increased further (Figure 6a). For kidney bean, leaf width followed the same trend as leaf length: width was significantly reduced in the monoculture (KC), reaching only about 5.7 cm at 42 DAT, whereas all companion cropped configurations (P2K1, P1K1, and P1K2) increased gradually to a final width of 6.6–6.8 cm (Figure 6b).



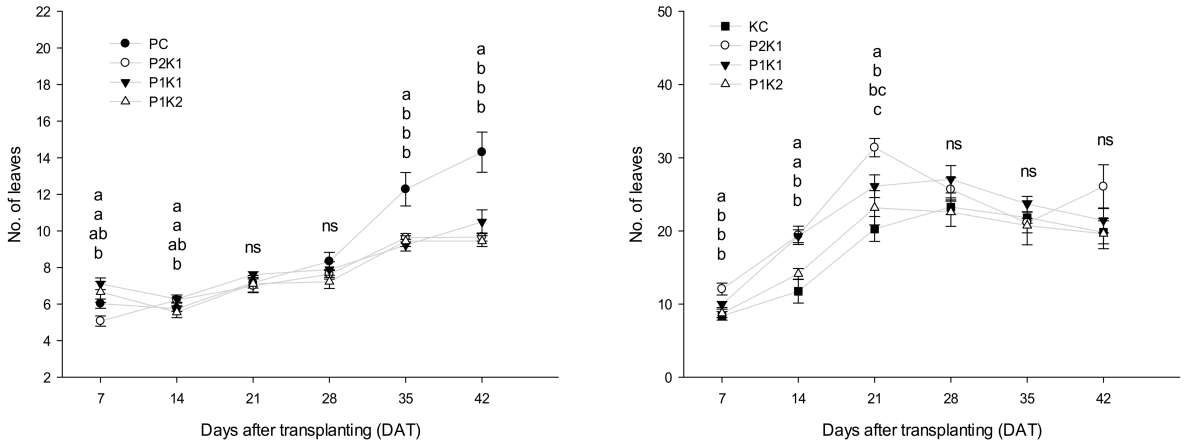
(**a**) Leaf width of perilla. (**b**) Leaf width of kidney bean.

Figure 6. Change in leaf width of perilla (**a**) and kidney bean (**b**) by perilla–kidney bean companion cropping at different planting ratio during 42 days after transplanting (DAT) in containers under greenhouse conditions. PC, 12 perilla seedlings; P2K1, 8 perilla seedlings + 4 kidney bean seedlings; P1K1, 6 perilla seedlings + 6 kidney bean seedlings; P1K2, 4 perilla seedlings + 8 kidney bean seedlings; KC, 12 kidney bean seedlings. Values are mean ± standard error (SE) based on three replicates ($n = 3$). Different lowercase letters at each DAT indicate significant differences among treatments according to Duncan's multiple range test ($p < 0.05$), while "ns" denotes no significant difference.

Perilla leaf number was profoundly suppressed by companion planting. Leaf number increased little in any treatment during the early stages (7–14 DAT), but a gradual upward trend appeared in all treatments from 21 DAT. At harvest (42 DAT), the monoculture (PC) carried approximately 12 leaves per plant, whereas all companion-cropped configurations (P2K1, P1K1, and P1K2) carried approximately 9.5 leaves, and these three did not differ significantly from one another (Figure 7a). Kidney bean leaf number, by contrast, rose rapidly in the early stage. In P2K1, the configuration with the highest proportion of perilla, kidney bean leaf number increased exponentially from 7 to 21 DAT and peaked at 21 DAT with an average of 30 leaves per plant, significantly more than in the kidney bean monoculture ($p < 0.05$). From 21 to 42 DAT, leaf number declined naturally in all treatments as the plants shifted from vegetative to reproductive growth, with no significant differences among treatments (Figure 7b).

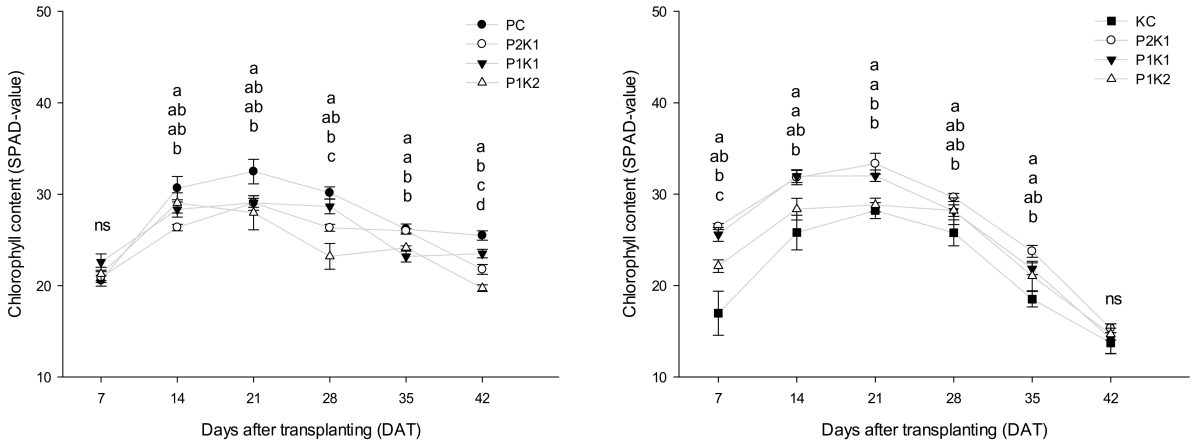
Chlorophyll content varied significantly with companion cropping ratio. The perilla monoculture (PC) reached the highest value (33.0 SPAD) at 21 DAT, and at harvest (42 DAT), it again recorded the highest value (26.2 SPAD), while the other treatments were significantly lower, and P1K1 was the lowest at 23.2 SPAD (Figure 8a). In kidney bean, chlorophyll content rose exponentially in all treatments from 7 to 14 DAT and then fell sharply from 21 DAT. The P2K1 and P1K1 configurations recorded the highest values at 21 DAT, approximately 33.0 and 32.0 SPAD respectively. At the final measurement (42 DAT), chlorophyll content

had fallen sharply overall, and the kidney bean monoculture (KC) reached the lowest value (18.8 SPAD) (Figure 8b).



(**a**) Number of leaves of perilla. (**b**) Number of leaves of kidney bean.

Figure 7. Change in number of leaves of perilla (**a**) and kidney bean (**b**) by perilla–kidney bean companion cropping at different planting ratio during 42 days after transplanting (DAT) in containers under greenhouse conditions. PC, 12 perilla seedlings; P2K1, 8 perilla seedlings + 4 kidney bean seedlings; P1K1, 6 perilla seedlings + 6 kidney bean seedlings; P1K2, 4 perilla seedlings + 8 kidney bean seedlings; KC, 12 kidney bean seedlings. Values are mean ± standard error (SE) based on three replicates ($n = 3$). Different lowercase letters at each DAT indicate significant differences among treatments according to Duncan's multiple range test ($p < 0.05$), while "ns" denotes no significant difference.



(**a**) Chlorophyll content of perilla. (**b**) Chlorophyll content of kidney bean.

Figure 8. Change in chlorophyll content (SPAD-value) of perilla (**a**) and kidney bean (**b**) by perilla–kidney bean companion cropping at different planting ratio during 42 days after transplanting (DAT) in containers under greenhouse conditions. PC, 12 perilla seedlings; P2K1, 8 perilla seedlings +4 kidney bean seedlings; P1K1, 6 perilla seedlings + 6 kidney bean seedlings; P1K2, 4 perilla seedlings + 8 kidney bean seedlings; KC, 12 kidney bean seedlings. Values are mean ± standard error (SE) based on three replicates ($n = 3$). Different lowercase letters at each DAT indicate significant differences among treatments according to Duncan's multiple range test ($p < 0.05$), while "ns" denotes no significant difference.

3.3. Leaf Color, Chlorophyll Fluorescence, Stem Diameter, and Biomass of Perilla as Affected by Companion Planting Ratios of Perilla and Kidney Bean in Container Cultivation

Leaf redness (a^* value) did not differ significantly among treatments and remained between −9.49 and −10.25. Lightness (L^*) and yellowness (b^*) were likewise similar in the

PC, P1K1, and P1K2 treatments; in P2K1, they were 41.24 and 17.63 respectively, slightly lower than in the other treatments but not significantly so. The perilla monoculture (PC) maintained the significantly highest maximum quantum yield of photosystem II(Fv/Fm), at 0.63 ($p < 0.05$). Companion cropping with kidney bean reduced this value to 0.57 in P2K1 and 0.56 in P1K1, and the lowest value, 0.55, was recorded in P1K2, the treatment with the highest proportion of kidney bean (Table 1).

Table 1. Leaf colorimetric parameters (L^*, a^*, and b^*) and chlorophyll fluorescence characteristics (Fv/Fm) of perilla leaves as affected by different companion planting ratio with kidney bean in containers under greenhouse conditions.

Treatments	Lightness (L^*)	Redness (a^*)	Yellowness (b^*)	Fv/Fm
PC [1]	42.55 ± 2.65 ns [2]	−9.61 ± 1.32 ns	18.05 ± 1.59 ns	0.63 ± 0.03 a
P2K1	41.24 ± 2.52	−10.25 ± 0.93	17.63 ± 1.15	0.57 ± 0.04 b
P1K1	42.65 ± 4.66	−9.49 ± 1.49	18.43 ± 1.96	0.56 ± 0.05 b
P1K2	44.03 ± 3.30	−9.78 ± 1.54	18.27 ± 0.97	0.55 ± 0.09 b

[1] PC, 12 perilla seedlings + 0 kidney bean seedlings; P2K1, 8 perilla seedlings + 4 kidney bean seedlings; P1K1, 6 perilla seedlings + 6 kidney bean seedlings; P1K2, 4 perilla seedlings + 8 kidney bean seedlings. [2] Values are mean ± standard error (SE) based on three replicates ($n = 3$). Different lowercase letters indicate significant differences among treatments according to Duncan's multiple range test ($p < 0.05$), while "ns" denotes no significant difference.

Mean stem diameter of perilla was 5.58 mm in the monoculture (PC) but only 4.50 to 4.81 mm under companion cropping with kidney bean, a significant reduction ($p < 0.05$). Stems were thinnest in P1K2, which suggests that raising the proportion of kidney bean adversely affects the physiological response of perilla. The reduction in stem thickness under companion cropping indicates that early nitrogen and potassium deficiency in the growing medium structurally inhibits vascular bundle development and can thereby limit leaf development. Biomass accumulation in both shoots and roots was influenced by the companion cropping ratio. In the perilla monoculture (PC), shoot fresh and dry weights were 9.70 and 2.09 g, respectively, and root fresh and dry weights were 16.43 and 3.98 g, respectively, generally higher than those in the companion cropping treatments. Among the mixed treatments, root fresh weight tended to increase with the proportion of kidney bean, reaching a maximum of 13.53 g in P1K2, but no significant differences were found in root dry weight (Table 2).

Table 2. Stem diameter and biomass of perilla as affected by different companion cropping ratio with kidney bean in containers under greenhouse conditions.

Treatments	Stem Diameter (mm)	Shoot Fresh Weight (g/plant)	Shoot Dry Weight (g/plant)	Root Fresh Weight (g/plant)	Root Dry Weight (g/plant)
PC [1]	5.58 ± 0.28 a [2]	9.70 ± 2.25 a	2.09 ± 0.48 a	16.43 ± 4.04 a	3.98 ± 1.10 a
P2K1	4.71 ± 0.18 b	4.93 ± 1.34 b	1.00 ± 0.38 b	9.21 ± 1.25 c	2.04 ± 1.06 b
P1K1	4.81 ± 0.15 b	5.75 ± 0.63 b	1.27 ± 0.41 b	10.53 ± 3.17 bc	2.15 ± 1.05 b
P1K2	4.50 ± 0.26 b	6.65 ± 2.21 b	1.16 ± 0.42 b	13.53 ± 5.94 ab	2.83 ± 0.30 b

[1] PC, 12 perilla seedlings + 0 kidney bean seedlings; P2K1, 8 perilla seedlings + 4 kidney bean seedlings; P1K1, 6 perilla seedlings + 6 kidney bean seedlings; P1K2, 4 perilla seedlings + 8 kidney bean seedlings. [2] Values are mean ± standard error (SE) based on three replicates ($n = 3$). Different lowercase letters indicate significant differences among treatments according to Duncan's multiple range test ($p < 0.05$), while "ns" denotes no significant difference.

3.4. Relative Yield (RY), Land Equivalent Ratio (LER), and Competitive Ratio (CR) of Perilla and Kidney Bean as Affected by Companion Cropping Ratio of Perilla and Kidney Bean in Container Cultivation

The RY of perilla was 0.6, 0.7, and 0.8 in P2K1, P1K1, and P1K2, respectively, increasing as the kidney bean cropping ratio increased, although the differences were not significant. The RY of kidney bean, in contrast, was 1.3, 1.0, and 0.7 in the same treatments, decreasing significantly as the perilla ratio decreased. The LER did not differ significantly among the treatments, although it increased numerically with the cropping ratio of perilla. The CR of perilla exceeded 1 only in P1K2, the treatment with the highest planting ratio of kidney bean. By contrast, the CR of kidney bean was significantly affected by the perilla ratio and was highest (4.6) in P2K1 ($p < 0.05$), indicating that kidney bean was more competitive than perilla (Table 3).

Table 3. Relative yield (RY), land equivalent ratio (LER), and competitive ratio (CR) of perilla and kidney bean as affected by different companion cropping ratios with kidney bean in containers under greenhouse conditions.

Treatments	$RY_{Perilla}$	$RY_{Kidney\ bean}$	LER_{Total}	$CR_{Perilla}$	$CR_{Kidney\ bean}$
P2K1 [1]	0.6 ± 0.06 ns [2]	1.3 ± 0.19 a	1.9 ± 0.23 ns	0.2 ± 0.03 b	4.6 ± 0.68 a
P1K1	0.7 ± 0.10	1.0 ± 0.13 ab	1.7 ± 0.20	0.8 ± 0.13 b	1.7 ± 0.30 b
P1K2	0.8 ± 0.10	0.7 ± 0.08 b	1.5 ± 0.15	2.2 ± 0.30 a	0.5 ± 0.05 b

[1] P2K1, 8 perilla seedlings + 4 kidney bean seedlings; P1K1, 6 perilla seedlings + 6 kidney bean seedlings; P1K2, 4 perilla seedlings + 8 kidney bean seedlings. [2] Values are mean ± standard error (SE) based on three replicates ($n = 3$). Different lowercase letters indicate significant differences among treatments according to Duncan's multiple range test ($p < 0.05$), while "ns" denotes no significant difference.

4. Discussion

Nutrients are essential for crop growth, and their availability varies among growing media [27]. Nutrient dynamics in all companion cropping treatments (P2K1, P1K1, and P1K2) closely resembled those in the kidney bean monoculture (KC) rather than those in the perilla monoculture (PC), indicating that kidney bean gained a competitive advantage over perilla. Crops require nitrogen in greater quantities than any other essential nutrient [5]. In the present experiment, substrate nitrogen content at the end of the experiment was several times lower than at the start. Although legumes can fix nitrogen, young plants may depend on inorganic soil nitrogen because rhizobial symbiosis lags during the early stages of root nodule formation [28]. Phosphorus is critical for early root morphogenesis and cellular energy transport [29]. The most rapid decline occurred in the kidney bean monoculture, suggesting that kidney bean had a greater capacity than perilla to absorb phosphorus. Nitrogen and potassium are indispensable macroelements for the structural integrity of the light-harvesting complex proteins and electron transport chain components of the chloroplast. Potassium content exceeded that of nitrogen and phosphorus because of the cocopeat and vermiculite that made up the artificial potting mix used as the container medium: cocopeat is naturally rich in potassium, and vermiculite enhances cation exchange capacity.

Kidney bean height, leaf length, leaf width, and leaf number all increased rapidly up to 21 DAT, which gave kidney bean an early competitive advantage over perilla. By contrast, the overall growth of perilla was limited under companion cropping. When substrate volume is restricted, temporal asynchrony in growth rates between companion species can convert potential facilitation into asymmetric competition [16]. The reduced growth of perilla may also reflect lower photosynthetic activity caused by shading from the taller kidney bean

plants. Lower L^* and a^* values generally correspond to darker green leaves, and as the proportion of kidney bean increased (P1K1 and P1K2), these values rose relative to the other treatments. Yellowness (b^*) also tended to increase, making chlorophyll deficiency visually apparent.

Photochemical efficiency is commonly used to assess the level of stress in plants; values typically range from 0.74 to 0.84, with lower values indicating stress; and healthy leaves of most plant species generally show a value of approximately 0.83 [19]. In the present study, the perilla monoculture exhibited an Fv/Fm value of 0.63, whereas the companion cropping treatments showed slightly lower values ranging from 0.55 to 0.57. This suggests that, under companion cropping, the upper kidney bean canopy reduced light transmittance relative to the perilla monoculture (PC), thereby lowering Fv/Fm. Furthermore, in leafy crops such as perilla, chronic macroelement starvation severely impairs chloroplast ultrastructure, causing premature chlorophyll degradation, loss of greenness, and functional downregulation of photosystem II photochemical efficiency, as diagnosed by maximum quantum yield (Fv/Fm) kinetics.

The fresh and dry weights of perilla shoots and roots at harvest represent accumulated biomass, which can serve as indicators of net photosynthetic efficiency and nutrient acquisition capacity over the life cycle. Perilla has strong adaptability, favors a warm and humid climate, and can grow in the shade [30]. However, the larger plant density can reduce leaf size and number of leaves due to shading and lower light interception, which decreases the aboveground biomass [18]. Companion cropping adversely affected the total fresh mass of perilla, which was lower than that of perilla grown in monoculture. Given that leafy vegetable cultivation aims to maximize production efficiency and achieve rapid weight gain, perilla monoculture may be more suitable than companion cropping with kidney bean for short-term container cultivation.

The LER expresses the land area that a monoculture system requires to produce the same yield as an intercropping system [18]. An LER of 1 indicates no advantage of intercropping; an LER >1 indicates cooperation or compensation between the intercrops, favoring the intercropping system; and an LER < 1 indicates mutual inhibition or compensation, reflecting a disadvantage of companion cropping relative to sole cropping [31]. Competitive ratio (CR) indicates how often one crop is more competitive than the other [14]. Likewise, CR values < 1, indicate a positive effect, reflecting limited competition among the associated plants, whereas values >1 indicate a negative level of competition in the association [26]. In the present study, the LER did not differ significantly among the companion cropping treatments, whereas the RY of kidney bean decreased significantly with decreasing perilla ratio. Similarly, the CR of perilla and kidney bean showed the highest values of 2.2 and 4.6 in P2K1 and P1K2, respectively, indicating that kidney bean was more competitive than perilla.

5. Conclusions

Overall, substrate macronutrients decreased more rapidly, as the kidney bean cropping ratio increased, although no significant difference remained among the treatments at the later growth stage. The growth of perilla, the main harvested crop, was negatively affected by companion cropping, and this effect intensified as the kidney bean cropping ratio increased. These findings suggest that, in volume-constrained container systems, the competitive advantage of a legume can directly inhibit the growth of the companion leafy vegetable, beyond its effect on the nutrients in the growing medium. Perilla monoculture is therefore more suitable than companion planting with kidney bean for short-duration container vegetable gardening. Future work should test a wider range of legumes in co-cultivation in

order to identify species that are genuinely complementary to container-grown horticultural crops and more effective, and more sustainable, than synthetic fertilizers.

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