

Article

Responses of Cucumber Plants to Grafting and Calcium Foliar Application in Soil and Soilless Cultivation Systems

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Highlights

What are the main findings?

- Soilless cultivation significantly enhanced vegetative growth (plant length, leaf number, leaf area, and shoot fresh weight) compared to soil cultivation, regardless of grafting or calcium treatment.
- Grafting onto Saba/Routpower rootstock improved plant length and shoot fresh weight under soil conditions but provided limited benefits in the soilless system.
- Foliar application of nano-CaCO₃ and CaCl₂ did not significantly affect growth, yield, or fruit quality parameters across most graft × culture combinations.

What are the implications of the main findings?

- The benefits of grafting are context-dependent, with greater advantages observed under soil cultivation where root-borne stresses are more prevalent.
- In controlled soilless systems, rootstock selection may need to prioritize yield-related traits rather than stress tolerance to achieve productivity gains.

Abstract

Grafting and foliar calcium application are common practices for improving vegetable crops, but their interactions in soil and soilless cultivation systems are not well understood. To address these knowledge gaps for sustainable greenhouse cucumber production, this study investigated the effects of calcium foliar application (control, 200 mg/L as nano-CaCO₃ or CaCl₂) and grafting (no grafting, grafting on Ganate rootstock or Routpower rootstock) on the growth and yield of greenhouse cucumber cv. Saba in soil and soilless systems. It should be noted that the two cultivation systems differed in several management factors (pot size, substrate, irrigation frequency, and fertilization method), and this study compares complete production packages rather than isolating individual factors. The experiment was conducted in a greenhouse using a factorial design with four replications. The results showed that the cultivation system was the dominant factor. Soilless cultivation significantly increased shoot fresh weight (307–344 g), plant height (265–326 cm), number of fruits (36–54 per plant), and fruit yield (2.7–4.5 kg per plant) compared to soil cultivation (shoot fresh weight: 177–216 g; yield: 0.4–1.0 kg per plant). Conversely, plants grown in soil had higher leaf dry weight percentage, root dry weight percentage, chlorophyll, and carotenoids. The effects of grafting were system dependent, with non-grafted plants performing as well or better in soilless culture, while grafted plants (especially



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Saba/Routpower combination) showed some soil-based advantages, including greater root length. Foliar calcium did not significantly improve most parameters, indicating that standard nutrient management provided sufficient calcium or that the 200 mg/L concentration was insufficient. Under the conditions tested, ungrafted plants grown without foliar calcium supplementation in soilless culture achieved yields comparable to more complex treatments, suggesting a simpler and more cost-effective production strategy.

Keywords: Cucurbita rootstock; cultivation systems; greenhouse production; sustainable agriculture

1. Introduction

Cucumber (*Cucumis sativus* L.) is an annual plant of the Cucurbitaceae family and ranks fourth economically among global vegetables after tomato, cabbage, and onion. Global cucumber production reached approximately 98 million tons in 2022, with Iran producing about 400,000 tons, positioning it as the 13th largest producer worldwide [1].

Due to increasing vegetable consumption and limited arable land, greenhouse vegetable production, particularly cucumber, has become a significant agricultural model worldwide [2]. However, continuous and long-term greenhouse cucumber cultivation in soil-based systems can lead to increased soil-borne diseases, soil salinization, and ecological problems, ultimately reducing cucumber productivity [3]. To address these challenges, researchers have proposed various strategies, including soilless cultivation, the use of nanoparticles to balance nutrient uptake, biostimulant application, and grafting cucumber onto resistant rootstocks [4–6]. In soilless cultivation, soil is completely eliminated and instead cucumbers are grown in inert substrates (such as cocopeat, perlite, or rockwool) that are irrigated with a precisely controlled, complete nutrient solution [7]; this system offers higher yields (20–50% above soil), 70–90% water savings, no soil-borne diseases or weeds, and uniform root-zone conditions (pH 5.5–6.5, EC 1.8–2.5 mS/cm), but requires high initial investment, technical expertise, and constant monitoring due to low buffering capacity, where any pump failure or nutrient imbalance can rapidly damage crops [8]. Grafting commercial cucumber cultivars onto suitable rootstocks is a modern technique that enhances growth, yield, quality, disease resistance, mineral uptake, and stress tolerance, thereby solving many problems associated with soil cultivation in greenhouses [9]. Calcium (Ca) is an essential macronutrient for plant growth and development, acting as a crucial intracellular messenger in response to hormones, stress signals, and various growth processes [10,11]. However, calcium is immobile in plants, moving primarily through the xylem via transpiration flow without being transported from older tissues to growing points [12,13]. Consequently, calcium deficiency is one of the most common problems in greenhouse crop production, particularly in cucumbers. This deficiency primarily results from low transpiration rates (due to high humidity), irregular irrigation, ion antagonism (excess K^+ or Mg^{2+}), high salinity, poor root function, or insufficient calcium availability in the root zone. Rapid fruit growth further exacerbates the problem because calcium cannot be mobilized through the phloem [14].

For this reason, foliar application is considered an effective strategy for correcting calcium deficiency because it enables rapid nutrient delivery, uniform fertilizer distribution, and faster plant responses than soil application [15]. Nevertheless, the efficiency of conventional foliar calcium fertilizers is often limited by poor penetration through the cuticle and cell wall, resulting in relatively low nutrient absorption. Nanotechnology has emerged as a promising approach to overcome these limitations. Owing to their small particle size,

high specific surface area, and enhanced reactivity, calcium nanoparticles exhibit improved adhesion to leaf surfaces and greater potential for foliar uptake than conventional calcium formulations. Current evidence indicates that foliar-applied nanoparticles enter leaves primarily through stomatal openings, although penetration through cuticular aqueous pores and other discontinuities in the leaf surface may also occur depending on particle size and physicochemical properties. Following penetration, nanoparticles or the calcium ions released from them may be transported through apoplastic and symplastic pathways to metabolically active tissues, with uptake efficiency being influenced by particle size, surface charge, formulation characteristics, humidity, and temperature [16]. In addition to improved uptake, nano-calcium formulations generally exhibit greater colloidal stability and more controlled nutrient-release characteristics than conventional calcium fertilizers. Their gradual dissolution increases the availability of calcium at leaf surfaces, which is particularly important given the immobility of calcium in the phloem and its need for a constant external source to support fast-growing tissues such as young leaves and fruits [17]. Recent studies have shown the potential of nano-calcium in greenhouse vegetable production. In protected cultivation, foliar application of nano-calcium significantly improved cucumber growth, nutrient accumulation, fruit yield, and fruit quality compared with untreated plants, with the greatest responses observed at appropriate application rates [18]. Similarly, El-Mogy et al. (2025) reported that foliar application of calcium nanoparticles increased photosynthetic efficiency, antioxidant activity, osmolyte accumulation, and fruit quality in cucumber plants under drought stress [19]. Despite these promising findings, information remains scarce regarding the interactive effects of foliar nano-calcium application, grafting, and cultivation system on greenhouse cucumber performance. Therefore, evaluating these factors simultaneously under two commercially practiced greenhouse systems—soil-based and soilless—is essential to understand their combined effects on growth, yield, and fruit quality.

The two systems differed in multiple management components (pot size, substrate type, irrigation frequency, and fertigation method) reflecting their practical requirements rather than representing isolated experimental variables. Therefore, this comparison examines the overall performance of the complete production packages rather than isolating the effect of each single factor. Finally, we hypothesized that (1) grafting onto vigorous rootstocks would improve yield and quality primarily under soil cultivation, where root-borne stresses are more prevalent; (2) under soilless conditions, where root-zone factors are more controlled, the benefits of grafting would be diminished or absent; and (3) foliar nano-Ca application would enhance fruit quality and physiological performance, with the greatest effects observed in grafted plants under soil cultivation due to improved rootstock-mediated nutrient uptake and stress tolerance.

2. Materials and Methods

2.1. Location and Experimental Design

This experiment was conducted during the spring and summer seasons of 2023 in the research greenhouse of the Department of Horticultural Science and Engineering at Arak University (latitude 34°04'48" N, longitude 49°40'38" E, altitude 1700 m). A factorial experiment as a completely randomized design was used with four replications. The factors consisted of foliar application of 200 mg/L calcium in two forms (nano-calcium carbonate and conventional calcium chloride), graft combination at three levels (ungrafted, grafted on local Ganat pumpkin rootstock, and grafted on commercial Routpower rootstock), and cultivation system at two levels (soil and soilless culture).

2.2. Plant Material

In this study, seeds of the Saba greenhouse cucumber cultivar were used as the scion. The rootstock seeds consisted of the local Ghanat pumpkin landrace, which was originally collected from farmers in Markazi province and is distributed commercially by Ehsan Seed Company, Arak, Iran; and commercial seeds of the Rootpower (*Cucurbita maxima* × *Cucurbita moschata*) rootstock produced by Sakata Seed Company, Japan. For sowing the rootstock seeds, small paper pots were used. For sowing the scion seeds, 104-cell seedling trays filled with a 1:1 mixture of cocopeat and perlite were employed. The scion and rootstock seeds were sown simultaneously. The rootstock and scion seedlings, approximately two weeks after sowing at the stage of fully expanded cotyledons and the emergence of the first true leaf, were grafted using the ‘splice graft’ method [20], keeping one cotyledon on the rootstock. The grafted plants were then transferred to a grafting chamber maintained at 26–28 °C and approximately 95% relative humidity. After 10 days, upon confirmation of graft union success and completion of the acclimatization process, with sufficient natural light at 25–30 °C in day and 20–25 °C at night. The number of successful and unsuccessful links was counted in order to obtain a link acquisition rate.

2.3. Preparation of Growing Media and Nutrient Solution

In soil-based cultivation, each plant was grown in a 26 L pot. The pots were filled with a mixture of 50% garden soil, 25% manure, and 25% sandy soil. The garden soil used was collected from a natural field in Markazi province, and was not obtained from a continuous cucumber cropping system; therefore, pathogen build-up was not intentionally established or assessed. The soil texture was sandy loam (81.7% sand, 10.6% silt, and 7.7% clay) with 5.27% organic matter, electrical conductivity (EC) of 0.94 dS/m, and pH of 7.15. These plants were irrigated with half-strength Hoagland nutrient solution every 12 days. To maintain soil moisture, they were additionally irrigated with tap water every 4 days. In the soilless system, plants were grown in 10 L pots filled with a 50:50 (*v/v*) mixture of cocopeat and perlite (Figure 1). The plants were fertigated twice daily with half-strength Hoagland nutrient solution until 20% drainage was achieved. The nutrient solution had a pH of 5.8–6.5 and an EC of approximately 1.7–2.2 dS·m^{−1}. In the half-strength Hoagland nutrient solution, the macronutrients were provided by 589.5 mg/L Ca(NO₃)₂·4H₂O, 252.5 mg/L KNO₃, 68.1 mg/L KH₂PO₄, and 246.5 mg/L MgSO₄·7H₂O. Micronutrients were supplied as follows: 18.7 mg/L Fe-EDTA, 0.91 mg/L MnCl₂·4H₂O, 0.01 mg/L H₂MoO₄·H₂O, 0.11 mg/L ZnSO₄·7H₂O, 0.04 mg/L CuSO₄·5H₂O, and 1.46 mg/L H₃BO₃. The pH of the Hoagland solution was adjusted to 6.0–6.5 using H₂SO₄ or NaOH [21]. The two cultivation systems differed in pot size, substrate composition, irrigation frequency, and fertigation method, reflecting the practical requirements of each production approach. These differences are inherent to the respective systems and were maintained to represent realistic commercial production conditions. Consequently, the study compares complete production packages rather than isolating individual factors.

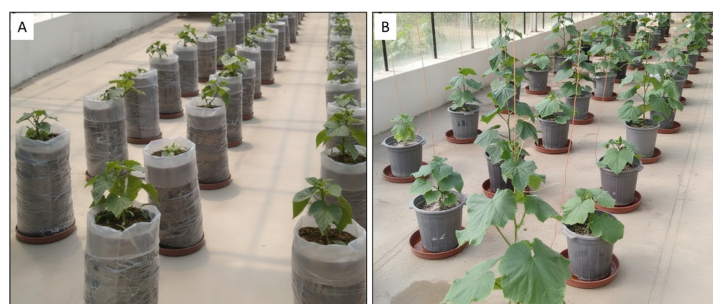


Figure 1. The two cultivation systems used in the experiment: soil-based (A) and soilless culture (B).

2.4. Preparation of Foliar Spray Solutions

To prepare a 200 mg/L calcium solution, 0.734 g of calcium chloride dihydrate (purity $\geq 99\%$, Merck, Darmstadt, Germany) was dissolved in one liter of distilled water. Separately, for the nano-calcium treatment, 0.50 g of calcium carbonate nanopowder (Nanoshel, Bengaluru, India) and two drops of Tween 20 (as a surfactant) were added to one liter of distilled water. The suspension was stirred using a magnetic stirrer until homogenized. Both solutions were then immediately used for foliar application. Approximately one month after grafting, at the flowering stage and first fruit formation, foliar application of calcium was performed four times at one-week intervals. Both nano- CaCO_3 and CaCl_2 solutions ($200 \text{ mg L}^{-1} \text{ Ca}$) were freshly prepared on the day of application and sprayed in the early morning until run-off to ensure complete leaf coverage. Although the exact volume varied according to plant size and canopy density, the spray volume was estimated to be approximately 20–40 mL per plant per application. At the applied calcium concentration ($200 \text{ mg L}^{-1} \text{ Ca}$), this corresponded to an estimated calcium dose of approximately 4–8 mg Ca per plant per application. The pH of the nano- CaCO_3 suspension was approximately 8–9, whereas the CaCl_2 solution had a pH of approximately 6–7. The stability of the nano- CaCO_3 suspension was evaluated through visual inspection and dynamic light scattering (DLS) analysis. No visible sedimentation was observed during the application period, indicating adequate suspension stability. DLS measurements of the freshly prepared suspension showed that most particles were within the 60–120 nm size range (Figure 2). Because the suspension was prepared immediately before use and applied without prolonged storage, the likelihood of substantial nanoparticle aggregation was minimized. The physicochemical characterization, particle size distribution, and SEM image of CaCO_3 nanopowder are shown in Figure 2.

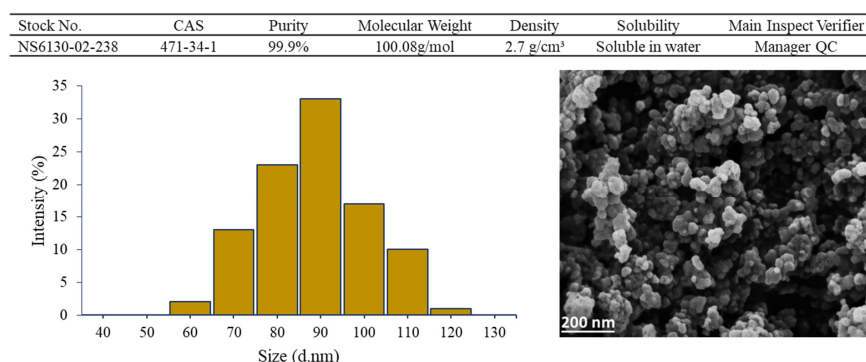


Figure 2. Physicochemical characterization, particle size distribution and SEM image of CaCO_3 nanopowder.

2.5. Morphological Growth Parameters

Morphological traits were evaluated two months after grafting, which corresponded to four weeks after the first fruit harvest. Leaf area was measured on three fully expanded, healthy leaves from each plant. Each treatment consisted of four biological replicates, with one plant per replicate. To minimize variation associated with leaf age and position, leaves were sampled from the middle canopy layer (nodes 5–8), where leaves were fully developed and physiologically active. For each replicate, the mean leaf area of the three sampled leaves was calculated and used for statistical analysis. Leaf area was measured using Digimizer image analysis software (version 4.6.1, MedCalc Software Ltd., Ostend, Belgium). Freshly collected leaves were placed on a flat white background adjacent to a calibrated scale ruler (1 cm). Each leaf was photographed using a digital camera mounted on a fixed stand at a constant height of 30 cm. Images were imported into Digimizer, and the spatial calibration was set using the scale ruler (pixels per cm). The leaf outline was

manually traced using the polygon tool, and the software automatically calculated the leaf area in cm². Plant height and root length were measured using a measuring tape or ruler, and stem diameter was measured above the graft union using a digital caliper. The number of leaves was also recorded on the day of plant removal (two months after grafting). Root volume was measured using a graduated cylinder. A specific amount of water was poured into the cylinder, and after placing the root inside, the change in water volume was measured to determine the root volume. To calculate dry weight percentage, leaf and root samples from each plant were oven-dried at 72 °C for 48 h. The dry weight percentage was then determined using the formula:

$$\text{Dry weight (\%)} = (\text{Dry Weight/Fresh Weight}) \times 100.$$

2.6. Fruit Yield Characteristics

Fruits with a minimum length of 13 cm from each plant were harvested daily, and their number and weight were recorded. Finally, the total fruit yield per plant was calculated. To measure fruit dry weight percentage, the fruits from each plant were sliced into rings, placed in Petri dishes, and weighed. They were then placed in an oven at 72 °C for 72 h and weighed again. Fruit dry weight percentage was calculated using the same formula applied to leaf and root samples.

2.7. Leaf Pigment Measurements

Leaf pigment measurements were performed on the third fully mature leaf from the top of each plant. To measure chlorophyll and carotenoids contents, 0.3 g of fresh leaf samples were ground in 80% acetone and centrifuged at 4800 rpm for 10 min. Using a spectrophotometer (Analytic Jena, model Specord 200 Plus, Jena, Germany), the absorbance of the extract was read at 663 nm, 646 nm, and 470 nm. Pigment concentrations were calculated using the Lichtenthaler equations [22] and expressed in mg per g fresh weight.

2.8. Statistical Analysis

Data were analyzed using a three-factor factorial ANOVA based on a completely randomized design (CRD) with four replications. The fixed factors included cultivation system (soil and soilless), rootstock treatment, and calcium treatment. The ANOVA model tested the main effects of each factor, all two-way interactions (cultivation system × rootstock, cultivation system × calcium treatment, and rootstock × calcium treatment), as well as the three-way interaction (cultivation system × rootstock × calcium treatment). Each treatment combination consisted of four biological replicates, with one plant per replicate; thus, each individual plant/pot represented one experimental unit. Minitab 17 software was used to analyze the data. Data normality and variance homogeneity were checked prior to analysis. Normality was verified using the Shapiro–Wilk test ($p > 0.05$) and homogeneity of variance was confirmed using Levene’s test ($p > 0.05$) for all variables prior to ANOVA. Significant differences among treatment means ($p < 0.05$) identified by ANOVA were further separated using Tukey’s HSD test. Results are shown as mean ± SEM. Multivariate pattern analysis, including principal component analysis (PCA) and heatmap clustering, was conducted using Origin Pro 2024 on standardized data.

3. Results

3.1. Grafting Success Percentage

As an observational measure of practical relevance, grafting success rates varied between rootstocks. The ‘Routpower’ rootstock showed higher survival (90–95% of grafted seedlings), while the ‘Ganat’ rootstock had lower success (70–75%). These values represent

descriptive observations from the grafting procedure and were not subjected to statistical analysis as no treatments were applied to affect grafting success.

3.2. Effect of Grafting on First Fruit Harvest

In both soilless and soil cultivation systems, all fruits were thinned up to the tenth node to promote vegetative growth during the early stages of plant development. In the soilless system, the first harvest from ungrafted plants occurred 29 days after transplanting seedlings to the greenhouse. Plants grafted onto Routpower rootstock were harvested one day later, and those grafted onto Ganat rootstock were harvested two days later than ungrafted plants. In the soil system, the first harvest from plants grafted onto Routpower rootstock occurred 36 days after transplanting. Plants grafted onto Ganat rootstock were harvested seven days later, and ungrafted plants were harvested ten days later than those grafted onto Routpower rootstock.

3.3. Shoot Traits

A three-way ANOVA followed by Tukey's HSD post hoc test ($p < 0.05$) revealed significant interactive effects of grafting, foliar spray, and culture system on plant length and shoot fresh weight (Figure 3). In the soilless system, all treatments resulted in significantly greater plant lengths (265.0–325.8 cm) compared to soil-grown plants (95.0–146.3 cm). The tallest plants were observed in soilless cultivation system with Saba/Routpower rootstock combined with either CaCl_2 (325.8 cm) or $\text{CaCO}_3\text{-NP}$ (324.0 cm). Ungrafted soilless cultivated plants treated with CaCl_2 (318.3 cm) and $\text{CaCO}_3\text{-NP}$ (314.5 cm), as well as Saba/Routpower control (317.8 cm), were not significantly different from the tallest group. Saba/Ganat rootstock in soilless system produced intermediate lengths (265.0–296.0 cm). In contrast, all soil-grown plants exhibited drastically reduced plant lengths (95.0–146.3 cm) and belonged to the lowest statistical groupings (d and e). Calcium supplementation did not significantly affect plant length in either system. In soilless, ungrafted plants had the highest shoot fresh weights (413.9–481.8 g), while grafted plants had lower weights (297.2–360.0 g). In soil, ungrafted plants had the lowest weights (172.6–213.1 g), and grafted plants intermediate values (251.2–303.6 g). Calcium application did not significantly increase shoot fresh weight within any graft $\times$ culture combination. Shoot fresh weight differed significantly among cultivation systems and grafting treatments, whereas the effects of calcium treatments had comparatively smaller effects.

Leaf length, leaf width, and stem diameter were affected by grafting, foliar treatment, and culture system (Table 1). For leaf length, soilless-grown plants (16.99–18.26 cm) produced significantly greater values than soil-grown plants (12.11–14.68 cm). In soil, leaf length ranged from 12.11 cm (Saba/Ganat + CaCO_3) to 14.68 cm (Saba/Ganat + Control). In soilless- and soil-grown plants, no significant differences were observed between grafting compounds or foliar treatments. For leaf width, soilless plants again exhibited superior values (21.49–23.28 cm) compared to soil plants (15.63–18.65 cm). In soilless system, the greatest leaf width was observed in Saba/Ganat CaCO_3 (23.28 cm). In soil, leaf width ranged from 15.63 cm (Saba/Routpower + CaCO_3) to 18.65 cm (ungrafted control) and no significant differences were observed among treatments. For stem diameter, the differences between soilless and soil systems were less pronounced. In soilless system, values ranged from 1.20 cm (Saba/Routpower + CaCO_3) to 1.43 cm (ungrafted control and ungrafted CaCO_3). In soil, stem diameter ranged from 1.17 cm (Saba/Routpower control) to 1.38 cm (Saba/Ganat + CaCO_3). Overall, foliar application of CaCl_2 or CaCO_3 had no significant effect compared to controls for any of the measured parameters.

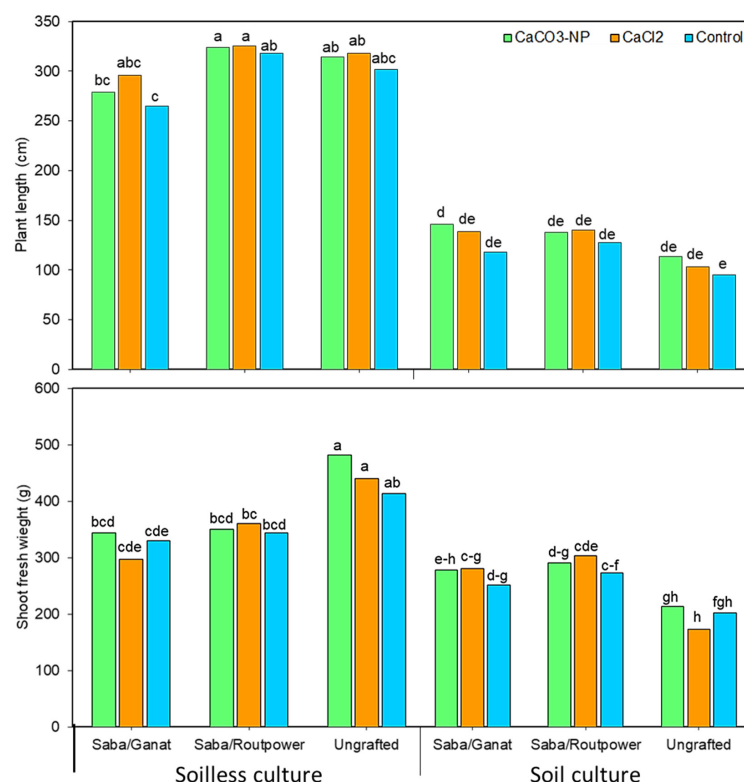


Figure 3. Interaction effects of grafting combination and foliar spray on plant length and shoot fresh weight of cucumber plants cultivated in soilless and soil culture systems. Different letters in each trait indicate statistically significant difference in the interaction effects among the three treatments, based on Tukey's HSD post hoc test at the $p < 0.05$ level.

Table 1. Interaction effects of grafting combination and foliar spray on leaf length, leaf width, and stem diameter of cucumber plants cultivated in soilless and soil culture systems.

Graft Combination	Spraying	Leaf Length (cm)		Leaf Width (cm)		Stem Diameter (cm)	
		Soilless	Soil	Soilless	Soil	Soilless	Soil
Ungrafted	Control	17.84 ^a	14.17 ^c	22.63 ^a	18.65 ^{bcd}	1.43 ^a	1.32 ^{a-d}
	CaCl ₂	18.26 ^a	13.31 ^c	21.74 ^{abc}	17.26 ^d	1.41 ^{abc}	1.29 ^{a-d}
	CaCO ₃	18.05 ^a	12.86 ^c	22.44 ^{ab}	17.08 ^d	1.43 ^{ab}	1.21 ^{a-d}
Saba/Routpower	Control	17.61 ^a	12.59 ^c	21.49 ^{abc}	16.20 ^d	1.25 ^{a-d}	1.17 ^d
	CaCl ₂	17.34 ^a	13.64 ^c	21.64 ^{abc}	17.19 ^d	1.27 ^{a-d}	1.25 ^{a-d}
	CaCO ₃	17.64 ^a	12.54 ^c	22.27 ^{ab}	15.63 ^d	1.20 ^{cd}	1.19 ^{cd}
Saba/Ganat	Control	17.61 ^a	14.68 ^{bc}	22.50 ^a	18.35 ^{cd}	1.27 ^{a-d}	1.33 ^{a-d}
	CaCl ₂	16.99 ^{ab}	13.23 ^c	22.49 ^{ab}	16.68 ^d	1.21 ^{bcd}	1.34 ^{a-d}
	CaCO ₃	17.90 ^a	12.11 ^c	23.28 ^a	15.73 ^d	1.26 ^{a-d}	1.38 ^{a-d}

Different letters within each column indicate significant differences according to multiple comparison test of Tukey ($p < 0.05$).

Soilless culture produced substantially higher leaf numbers (45.0–52.3 leaves) compared to soil culture (25.0–36.0 leaves). In the soilless system, the highest leaf number was observed in Saba/Routpower rootstock treated with CaCl₂ (52.3 leaves), which was significantly greater than the lowest soilless treatments (ungrafted control and Saba/Ganat + CaCO₃-NP, 45.0 and 45.3 leaves respectively). However, other soilless treatments were not significantly different from the highest or lowest soilless groups. In soil culture, leaf numbers ranged from 25.0 leaves (ungrafted + CaCl₂) to 36.0 leaves (Saba/Ganat + CaCl₂). Most soil treatments were not significantly different from each other. Ungrafted plants in

soil produced the lowest leaf numbers (28.7–25.0 leaves). Foliar application of calcium did not significantly increase leaf number compared to controls within any graft combination or culture system. A clear separation was observed between soilless and soil culture systems in terms of leaf area, with all soilless treatments (306.7–344.3 cm²) falling into the highest statistical grouping (a) and all soil treatments (176.7–215.6 cm²) falling into the lowest grouping (b). Calcium supplementation and grafting did not significantly affect leaf area within either system (Figure 4).

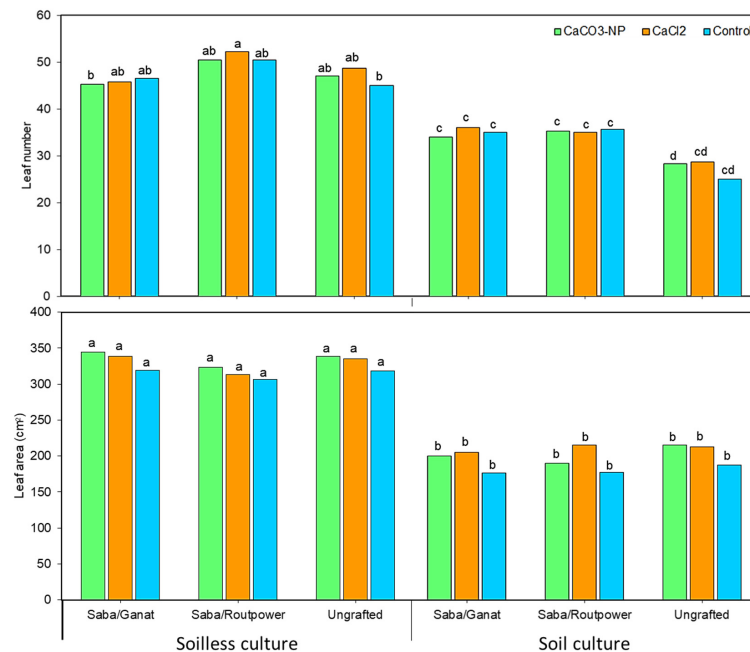


Figure 4. Interaction effects of grafting combination and foliar spray on leaf number and leaf area of cucumber plants cultivated in soilless and soil culture systems. Different letters in each trait indicate statistically significant difference in the interaction effects among the three treatments, based on Tukey's HSD post hoc test at the $p < 0.05$ level.

3.4. Root Traits

Ungrafted plants in soilless system produced the highest root fresh weight (116.8–170.3 g) and root volume (115.0–167.5 cm³). In contrast, all grafted plants in soilless system (root fresh weight 25.9–76.7 g; root volume 37.5–82.5 cm³) and all soil-grown plants regardless of graft or spray (root fresh weight 18.8–41.4 g; root volume 21.7–45.0 cm³) were not significantly different from each other. Notably, within the soil system, no significant differences were detected among any graft combinations or foliar treatments, as all nine soil treatments shared overlapping letters. Similarly, among grafted plants in soilless system (Saba/Routpower and Saba/Ganat), no consistent benefit from calcium application was observed. Ungrafted plants in the soilless system with CaCO₃-NP produced the greatest root fresh weight and root volume; while grafting and soil cultivation were associated with lower values for both parameters (Figure 5). In contrast to other root parameters (fresh weight and volume), the highest root lengths were observed in soil-grown plants, particularly those grafted onto Saba/Routpower (56.5–59.8 cm). These soil-grown, grafted treatments were not significantly different from several soilless treatments, including ungrafted with CaCO₃-NP (55.5 cm), ungrafted control (53.6 cm), and various Saba/Routpower soilless treatments (48.9–51.1 cm), all of which shared overlapping letters (a through d). The lowest root lengths were observed in Saba/Ganat control in soilless system (37.0 cm). Notably, ungrafted plants in soil produced relatively low root lengths (40.0–40.6 cm), which were significantly lower than grafted soil treatments

(Saba/Routpower and Saba/Ganat, 48.5–59.8 cm). Foliar application of CaCl_2 or $\text{CaCO}_3\text{-NP}$ did not consistently improve root length compared to controls within any graft or culture system, as indicated by overlapping letter groupings. Root length was greatest in grafted soil-grown plants (particularly Saba/Routpower), while soilless-grown and ungrafted soil-grown plants showed intermediate-to-lower values (Figure 5). Root morphology of cucumber plants under different grafting combinations (ungrafted, Saba/Routpower, Saba/Ganat) and calcium treatments (control, CaCl_2 , $\text{CaCO}_3\text{-NP}$) in soilless and soil culture is shown in Figure 6.

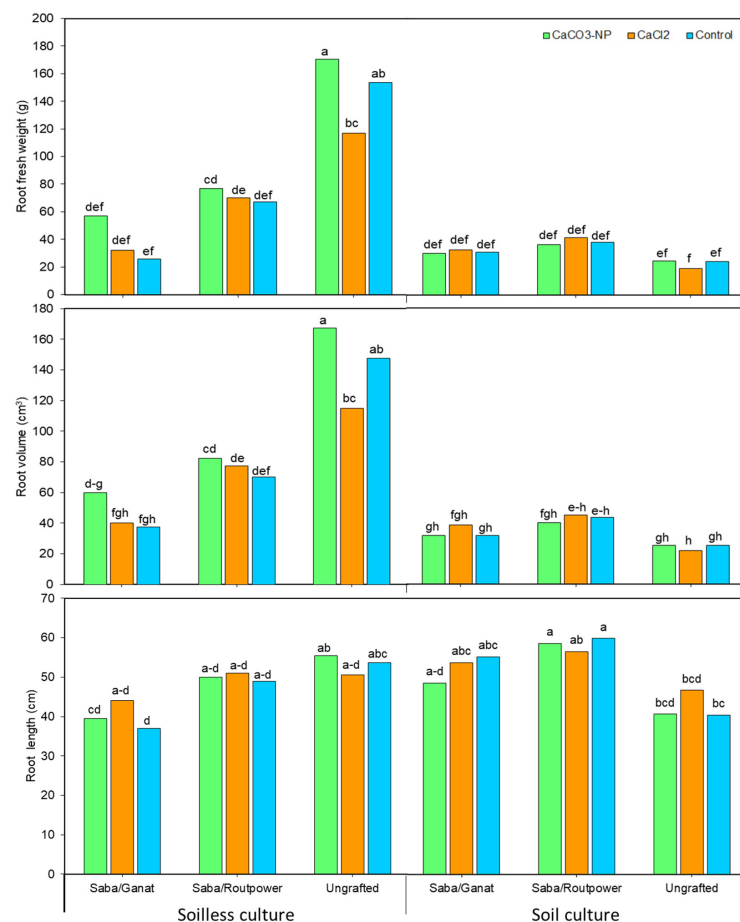


Figure 5. Interaction effects of grafting combination and foliar spray on root traits of cucumber plants cultivated in soilless and soil culture systems. Different letters in each trait indicate statistically significant difference in the interaction effects among the three treatments, based on Tukey's HSD post hoc test at the $p < 0.05$ level.

3.5. Yield Parameters

The number of fruits per plant and total fruit yield were significantly influenced by the interaction of grafting combination and culture system (Tukey HSD, $p < 0.05$). All soilless cultures produced significantly higher fruit number (36.0–53.8 fruits per plant) and yield (2.72–4.46 kg) than soil cultures (4.7–11.7 fruits; 0.37–0.98 kg). In soil cultures, no significant differences were observed between any grafting combinations or foliar treatments. In soilless system, the highest fruit number and yield were both recorded in Saba/Routpower with CaCO_3 NP (53.8 fruits; 4.46 kg), while grafting onto Ganat rootstock in soilless system reduced fruit number and yield relative to ungrafted plants (Figure 7).



Figure 6. Morphology of cucumber roots as affected by grafting combination (ungrafted, Saba/Routpower, Saba/Ganat) and calcium treatment (Control, CaCl₂, CaCO₃) in soilless and soil culture.

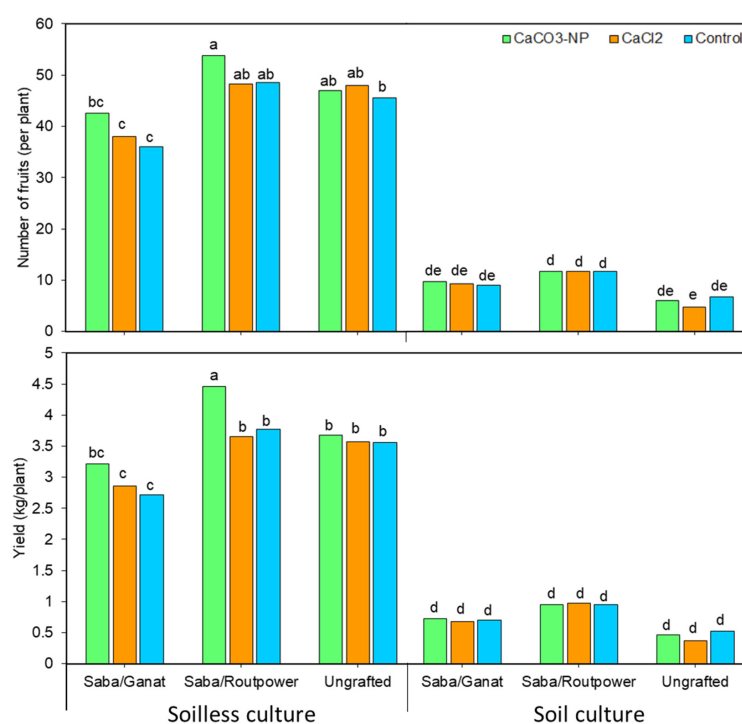


Figure 7. Interaction effects of grafting combination and foliar spray on fruit number and yield of cucumber plants cultivated in soilless and soil culture systems. Different letters in each trait indicate statistically significant difference in the interaction effects among the three treatments, based on Tukey's HSD post hoc test at the $p < 0.05$ level.

3.6. Dry Weight Percentage

The results presented in Table 2 clearly demonstrate that leaf dry weight percentage was significantly higher in soil-grown plants (19.2–24.2%) than in soilless-grown plants (11.5–13.4%). Within the soil system, the highest leaf dry weight percentages were recorded in Saba/Ganat with CaCO₃-NP (24.2%) and Saba/Routpower with CaCO₃-NP (23.2%). The lowest leaf dry weight percentage in soil was observed in ungrafted control (19.2%).

Within the soilless system, all treatments (range: 11.5–13.4%) fell into a single statistical grouping (c), with no significant differences detected among any graft combinations or foliar treatments. Similarly, soil-grown plants generally produced higher root dry matter percentages (range: 14.3–18.6%) than soilless-grown plants (range: 9.99–13.5%), although some overlap occurred in the intermediate groupings. The highest root dry matter percentage was recorded in ungrafted plants with CaCl_2 in soil (18.6%), which was significantly greater than most soilless treatments but not significantly different from several other soil treatments. Within the soilless system, the highest root dry matter percentage was observed in Saba/Ganat with CaCl_2 (13.5%). The remaining soilless treatments (range: 9.99–12.3%) were significantly lower than the top soil treatments (Table 2). Unlike those of leaves and roots, fruit dry weight percentages exhibited substantial overlap between the two culture systems. The highest fruit dry weight percentage was recorded in the Saba/Routpower control grown in soil (6.37%). Notably, one soilless treatment, Saba/Routpower with CaCO_3 NP in soilless system (5.47%), was not significantly different from the top soil treatments. The remaining soilless treatments (range: 4.55–5.00%) fell into the lower statistical groupings, with the lowest fruit dry weight percentage observed in the ungrafted control in soilless system (4.55%). Soil-grown plants had higher percentage dry weight in leaves, roots, and fruits than soilless-grown plants. Foliar application of CaCl_2 or CaCO_3 -NP did not significantly increase percentage dry weight compared to controls across graft and culture combinations (Table 2).

Table 2. Interaction effects of grafting combination and foliar spray on dry weight percentage of leaf, root and fruit of cucumber plants cultivated in soilless and soil culture systems.

Graft Combination	Spraying	Leaf Dry Weight (%)		Root Dry Weight (%)		Fruit Dry Weight (%)	
		Soilless	Soil	Soilless	Soil	Soilless	Soil
Ungrafted	Control	13.43 ^c	19.23 ^b	10.02 ^{fg}	16.03 ^{a-d}	4.55 ^c	5.39 ^{abc}
	CaCl_2	12.89 ^c	20.56 ^{ab}	12.29 ^{c-g}	18.63 ^a	4.79 ^c	5.50 ^{abc}
	CaCO_3	13.01 ^c	20.95 ^{ab}	10.42 ^{efg}	16.38 ^{abc}	4.79 ^c	5.50 ^{abc}
Saba/Routpower	Control	13.29 ^c	22.67 ^{ab}	11.09 ^{efg}	15.63 ^{a-d}	4.65 ^c	6.37 ^a
	CaCl_2	11.45 ^c	22.17 ^{ab}	10.56 ^{efg}	14.30 ^{a-f}	4.99 ^{bc}	6.13 ^{ab}
	CaCO_3	12.46 ^c	23.22 ^a	9.99 ^g	14.70 ^{a-e}	5.47 ^{abc}	5.64 ^{abc}
Saba/Ganat	Control	12.28 ^c	22.79 ^{ab}	12.02 ^{d-g}	15.93 ^{a-d}	4.77 ^c	5.06 ^{abc}
	CaCl_2	11.52 ^c	22.71 ^{ab}	13.55 ^{b-g}	17.43 ^{ab}	4.78 ^c	5.76 ^{abc}
	CaCO_3	12.60 ^c	24.16 ^a	11.10 ^{efg}	16.69 ^{ab}	4.96 ^{bc}	5.17 ^{abc}

Different letters within each column indicate significant differences according to multiple comparison test of Tukey ($p < 0.05$).

3.7. Leaf Pigment Content

Unlike many morphological parameters that showed a clear separation between soil and soilless systems, the results indicate that chlorophyll content has significant overlap between the two cultivation systems. The highest chlorophyll content was recorded in Saba/Routpower with CaCl_2 in soil (3.26 mg/g FW). The lowest chlorophyll values were observed in ungrafted control in soil (1.98 mg/g FW). Soilless treatments generally showed moderate values and no significant differences were observed between them. In contrast to chlorophyll content, carotenoid levels were significantly higher in all soil-grown plants (range: 0.66–0.92 mg/g FW) than in all soilless-grown plants (range: 0.46–0.49 mg/g FW). Within the soil system, the highest carotenoid content was recorded in Saba/Routpower with CaCl_2 (0.919 mg/g FW), and the lowest values were recorded in Saba/Routpower control (0.664 mg/g FW). In the soilless system, no significant differences were observed between any grafting combinations or foliar spray treatments, and all treatments had a

single statistical grouping (d). The results also showed that chlorophyll a/b ratios in all soil-grown plants (range: 3.55–4.47) were substantially higher than in all soilless-grown plants (range: 2.90–3.22). Within the soil system, the highest chlorophyll a/b ratio was recorded in Saba/Ganat with CaCO₃ NP (4.47), and the lowest was recorded in ungrafted plants with CaCO₃ NP (3.55). Within the soilless system, the highest chlorophyll a/b ratios were observed in Saba/Ganat control (3.22) and ungrafted control (3.22). The remaining soilless treatments (range: 2.90 to 3.16) were in lower statistical groups (Table 3).

Table 3. Interaction effects of grafting combination and foliar spray on leaf pigment content of cucumber plants cultivated in soilless and soil culture systems.

Graft Combination	Spraying	Chlorophyll (mg/g FW)		Carotenoids (mg/g FW)		Chlorophyll a/b	
		Soilless	Soil	Soilless	Soil	Soilless	Soil
Ungrafted	Control	2.56 ^{bcd}	1.98 ^d	0.48 ^d	0.73 ^{bc}	3.22 ^{bcd}	3.77 ^{a–d}
	CaCl ₂	2.45 ^{bcd}	2.18 ^{bcd}	0.49 ^d	0.75 ^{bc}	3.16 ^{cd}	3.85 ^{a–d}
	CaCO ₃	2.41 ^{bcd}	2.09 ^{cd}	0.49 ^d	0.75 ^{bc}	3.13 ^{cd}	3.55 ^{a–d}
Saba/Routpower	Control	2.45 ^{bcd}	2.08 ^{cd}	0.48 ^d	0.66 ^c	3.14 ^{cd}	4.07 ^{abc}
	CaCl ₂	2.52 ^{bcd}	3.26 ^a	0.49 ^d	0.92 ^a	3.07 ^{cd}	4.12 ^{abc}
	CaCO ₃	2.38 ^{bcd}	2.98 ^{abc}	0.49 ^d	0.86 ^{ab}	3.15 ^{cd}	4.19 ^{abc}
Saba/Ganat	Control	2.38 ^{bcd}	3.08 ^{ab}	0.49 ^d	0.82 ^{ab}	3.22 ^{bcd}	3.90 ^{a–d}
	CaCl ₂	2.48 ^{bcd}	2.55 ^{bcd}	0.48 ^d	0.80 ^{abc}	2.90 ^d	4.29 ^{ab}
	CaCO ₃	2.42 ^{bcd}	2.61 ^{bcd}	0.46 ^d	0.80 ^{abc}	2.93 ^d	4.47 ^a

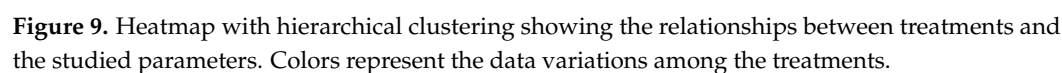
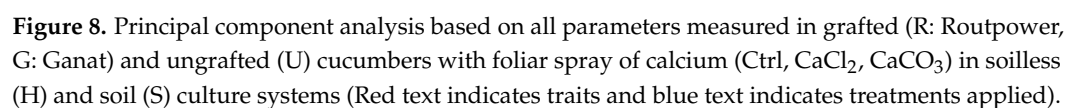
Different letters within each column indicate significant differences according to multiple comparison test of Tukey ($p < 0.05$).

3.8. Principal Component Analysis

The biplot diagram resulting from principal component analysis (PCA) of the studied traits is shown in Figure 8. PC1 explained 69.37% of the variance (positive with soilless, negative with soil-grown plants), while PC2 explained 14.81% (positive with ungrafted/soilless and grafted/soil plants; negative with ungrafted/soil and grafted/soilless plants). The distribution of treatments across the biplot revealed four distinct response regions. The first quadrant (positive PC1, positive PC2) contains ungrafted plants grown in soilless system, and was associated with most vegetative growth traits, fruit number, and yield. The second quadrant (positive PC1, negative PC2) includes grafted plants in soilless system, characterized by higher leaf length, leaf width, and leaf area. The third quadrant (negative PC1, positive PC2) shows higher leaf pigments, root length, and dry weight percentages of leaf and fruit in grafted soil-grown plants. The fourth quadrant (negative PC1, negative PC2) contains ungrafted soil-grown plants and is characterized by higher root dry weight percentage.

3.9. Heatmap with Hierarchical Clustering

Based on the heat map with cluster analysis, the standardized values of the measured traits across the eighteen experimental treatments are shown using different colors (Figure 9). The colors represent the relative magnitude of each trait within each treatment. The color gradient in the heatmap indicates the variation in trait values among the treatments. In our study, hierarchical clustering of the heatmap revealed that the primary division separated soilless from soil-grown plants, confirming culture system as the dominant factor. Within soilless system, grafted plants (Routpower and Ganat) clustered together and were distinct from ungrafted plants, indicating that grafting itself alters the trait profile regardless of calcium treatment. A similar pattern was observed in soil, where grafted plants also clustered separately from ungrafted ones.



4.1. Grafting Success Percentage

To reduce production costs, grafted seedling producers must achieve higher graft success rates. Although the factors influencing graft incompatibility are not yet fully understood, several fundamental studies have investigated hormonal, anatomical, and

physiological properties associated with graft success [23–25]. In our study, the grafting success rate of commercial rootstocks such as Rootpower was higher than that of local Ganat rootstocks. Reduced grafting success has been attributed primarily to differences in hypocotyl diameter between rootstock and scion, with greater differences leading to lower success rates. However, differences in diameter alone cannot fully explain graft outcomes; rather, stem anatomy and the number of vascular bundles is critical factors. Furthermore, environmental conditions after grafting, plant vigor, carbohydrate content, and the precise alignment of vascular bundles also play important roles in determining graft success [26–28].

4.2. Effects of the Cultivation System on Growth and Yield Parameters

A consistent finding across almost all parameters measured was the profound effect of the cultivation system. Soilless-grown plants exhibited significantly greater shoot fresh weight, plant length, leaf length, leaf width, fruit number, and fruit yield compared to soil-grown plants. However, because the two systems differed in multiple management factors simultaneously (pot size, substrate, irrigation frequency, and fertigation method), the observed differences represent the cumulative effect of the full production packages rather than the isolated effect of any single factor. This is in agreement with previous studies that soilless systems, as complete management packages provide optimal water and nutrient availability, eliminating soil-borne limitations and allowing for rapid vegetative growth and reproductive development [29,30]. Similarly, Roosta et al. [7] reported a significant enhancement in vegetative traits (i.e., plant height, number of nodes, leaf area) and reproductive traits (i.e., number of flowers, number of fruits, and yield per plant) in soilless-grown cucumber plants compared to that of soil-grown plants. An apparently contradictory response observed in this study is that under soil system ungrafted plants produced lowest leaf number while under soilless system they produced highest shoot biomass. This indicates that grafted and ungrafted plants respond differently under soil and soilless conditions to partition biomass and regulate source–sink balance. Soil-grown grafted plants on vigorous rootstocks likely extract more water and nutrient, with minimizing soil-borne limitations to promote leaf initiation, whereas under non-limiting conditions of soilless culture, ungrafted plants likely allocate more assimilates to aboveground parts than grafted plants. Other studies have also indicated greater benefit of grafting in soil-based than soilless cultivation systems [31,32].

Maintaining a non-pathogenic environment in the root zone is crucial for good plant growth in agricultural crops. Fortunately, the prevalence of soil-borne pathogens in soilless cultivation is very low [33]. One study investigated disease incidence in cucumbers grown in soilless systems versus traditional soil-based systems. In soilless systems, only downy mildew and anthracnose were observed, both with medium severity. In contrast, traditional systems recorded a wider range of diseases, including fungal, bacterial, viral, and nematode pathogens. Consequently, soilless systems produced nearly double the yield of traditional systems [34]. Comparison of yield and quality parameters of tomato cultivars grown in soil and soilless systems showed that plants in the soilless system developed faster and had higher total yield [35]. The most important chemical properties of growing media for plant production are pH, EC, CEC, and nutrient concentrations. For most plant species, including cucumber, the optimal pH range for nutrient availability in the root environment is between 5.5 and 6.0 [36]. In our study, the pH of the soilless growing medium (5.8–6.5) was lower than that of the soil medium (7.15), which may partially explain the enhanced growth of cucumber plants in the soilless system. It has also been reported that stem diameter and plant height of potato plants were greater in soilless cultivation media than in soil-based cultivation, attributed to better seedling growth resulting from the porosity

and suitable aeration of soilless media [37]. The addition of perlite to cocopeat in the root environment increases drainage capacity and improves root aeration, leading to greater root volume in the soilless medium. Furthermore, efficient nutrient uptake in soilless systems enhances photosynthesis and the carbohydrate supply to roots, which in turn increases leaf area through improved photosynthetic efficiency and root growth. However, soil-grown plants in the present study consistently produced higher dry weight percentage of both leaf and root compared to soilless-grown plants. The inverse relationship between observed fresh biomass and dry matter content is typically observed in soilless-grown plants likely due to continuous access to water; they accumulate more water and exhibit higher tissue hydration, while plants grown in soil experience mild water stress that promotes dry matter accumulation and more compact tissues [38]. The results aligned with the findings of a previous study in which hydroponically grown lettuce had 2.70% higher moisture content than soil-grown lettuce [39]. With regard to the earliness in fruit harvest, it was much earlier in grafted plants (particularly on Routpower than Ganat rootstocks) under soil conditions, which slightly delayed under soilless culture compared to ungrafted plants. This suggests that rootstock performance is strongly influenced by root-zone environment. It seems that under soil conditions, vigorous root system of grafted plants more efficiently extracts water and nutrients uptake and root-to-shoot hormone signaling, thereby promoting better reproductive development compared to ungrafted plants. Conversely, the benefit of rootstocks was lowered under non-limiting soilless conditions, where allocation of assimilates was likely diverted initially toward graft establishment and vegetative growth, thereby delaying the first harvest. The environment-influenced rootstock variable effects have been documented in grafted vegetables [32,40]. The delayed fruit harvest in grafted plants under soilless conditions while earliness under soil-grown condition were detected.

4.3. Effects of the Cultivation System on Leaf Pigments

The higher chlorophyll and carotenoid content observed in soil-grown plants may reflect an adaptive response to mild abiotic stress (e.g., uneven water and nutrient availability), which increases carotenoid biosynthesis as an antioxidant defense mechanism [41]. Additionally, the slower growth rate in soil produces denser, thicker leaves with higher pigment concentration per unit mass, while the rapid leaf growth and higher leaf water content in hydroponic systems dilute the pigment concentration. A recent study provided similar results, showing that lettuce grown in hydroponic systems exhibited lower levels of chlorophyll a, b, and total chlorophyll compared to lettuce grown in conventional soil [39,42].

4.4. Effects of Graft Composition on Measured Parameters

The response of cucumber plants to grafting was strongly dependent on the cultivation system, indicating a significant interaction between rootstock performance and the production environment. Under soil cultivation, grafted plants, particularly those grafted onto the commercial Rootpower rootstock, generally showed improved vegetative growth, earlier harvest, and greater yield-related performance compared with ungrafted plants. This response can be explained by the functional advantages of vigorous rootstocks under heterogeneous soil conditions, where plants frequently encounter spatial variation in water availability, nutrient distribution, salinity, and potential soil-borne stresses [43,44]. Rootstocks can enhance root system development, improve water and nutrient acquisition, and increase tolerance to unfavorable environmental conditions through improved root hydraulic properties and physiological regulation [43,45]. The greater benefit of grafting under soil cultivation may also be related to the particular root characteristics of cucumber. Compared with some other greenhouse vegetable crops, cucumber possesses a relatively

shallow and sensitive root system with high water and nutrient requirements, making it highly dependent on stable and efficient root-zone functioning. Recent study by Fanourakis et al. (2026) [46] emphasized that cucumber performance is strongly influenced by root-zone management, fertigation efficiency, grafting strategy, and environmental control because limitations in the root environment can rapidly affect plant water relations, nutrient uptake, and productivity. Therefore, under soil cultivation, where root-zone conditions are inherently more variable and difficult to regulate, vigorous rootstocks may provide a greater adaptive advantage by improving resource acquisition and buffering environmental fluctuations [46].

In contrast, the advantage of grafting was reduced under soilless cultivation, where root-zone conditions were maintained within optimal ranges through controlled nutrient supply, irrigation, and substrate properties. In such systems, many of the challenges that rootstocks are primarily selected to overcome, including soil-borne pathogens, nutrient heterogeneity, and restricted root development, are minimized. Consequently, the additional functional contribution of the rootstock may become less important, and the metabolic costs associated with maintaining a graft union and a highly vigorous root system may not necessarily result in increased reproductive performance [43,47]. Similar observations have been reported from grafting hybrid cucumber (Khasib F1) onto two local native rootstocks and five commercial *Cucurbita* hybrids in the greenhouse, where all rootstocks had similar or lower production than ungrafted plants in soilless culture. Therefore, these rootstocks may be more suitable for their resistance to soil-borne diseases rather than for their growth vigor. The use of local landraces as rootstocks could help reduce the cost of grafted plants, although the compatibility of the rootstock with the hybrid scion must be checked [48]. Interestingly, ungrafted plants frequently performed similarly to or better than grafted plants under soilless conditions. This response suggests that, when environmental limitations are minimized, the intrinsic efficiency of the scion root system may be sufficient to support plant growth and yield. Furthermore, highly vigorous rootstock may stimulate greater vegetative development by increasing water and nutrient uptake capacity, but this increased vegetative sink strength does not always translate into proportional improvements in fruit production. Excessive allocation of assimilates toward vegetative organs may alter source–sink relationships and reduce the relative investment in reproductive sinks under optimal conditions [49]. Therefore, rootstock vigor should not be considered the only criterion for selecting graft combinations; compatibility between rootstock and scion, resource partitioning, and the target production environment are also critical determinants of grafting success. The contrasting responses of Rootpower and Ganat pumpkin further demonstrate that rootstock effects are highly dependent on genotype and cultivation conditions. Although Rootpower generally enhanced plant performance, Ganat pumpkin did not consistently improve yield under all conditions, suggesting that superior root growth alone does not guarantee higher productivity. Previous studies have emphasized that successful graft combinations depend on vascular compatibility, hormonal interactions, and the ability of the rootstock to balance vegetative growth with reproductive development [43,49]. Therefore, grafting strategies for greenhouse cucumber production should be optimized according to the specific cultivation system.

4.5. Effect of Calcium Foliar Application

One of the most notable findings of this study was the limited response of cucumber plants to foliar calcium application. Neither nano- CaCO_3 nor conventional CaCl_2 significantly improved most measured growth, physiological, yield, or fruit quality parameters compared with the untreated control. This result suggests that calcium availability was likely not a major limiting factor under the experimental conditions. Both soil and soil-

less cultivation systems received sufficient calcium through the root-zone nutrient supply, which may have satisfied plant requirements and reduced the potential benefit of additional foliar calcium supplementation. Another possibility is that the calcium concentration in this foliar spray was too low and since calcium, unlike other nutrients, is immobile in the phloem tissue, the effectiveness of the foliar spray was limited [50]. Calcium deficiency is generally associated with restricted calcium transport to rapidly growing tissues rather than insufficient total calcium uptake alone. Because calcium is transported primarily through the xylem with the transpiration stream and has limited mobility through the phloem, developing organs such as young leaves and fruits are particularly vulnerable when transpiration is reduced or root-zone calcium uptake is impaired [51]. Environmental conditions such as high humidity, irregular water supply, salinity, and rapid fruit expansion can further restrict calcium delivery and increase the risk of physiological disorders [52]. However, when root-zone calcium availability and plant water relations are adequate, foliar calcium application may provide limited additional benefits. Although nano-calcium formulations may improve foliar retention, penetration, and nutrient-use efficiency compared with conventional calcium sources, their effectiveness depends strongly on plant calcium status, application conditions, nanoparticle characteristics, and the physiological demand for calcium [53]. In the present study, the absence of a significant difference between nano- CaCO_3 and CaCl_2 treatments indicates that calcium was probably not a growth-limiting factor under the applied greenhouse conditions. Therefore, the lack of response should not be interpreted as evidence that nano-calcium is ineffective but rather that its physiological benefits may become more apparent under conditions where calcium availability or transport is restricted.

Future studies should evaluate nano-calcium applications under experimentally induced calcium limitation or stress conditions, such as reduced root-zone calcium concentration, high humidity, salinity stress, or periods of rapid fruit development. Such conditions would provide a better opportunity to determine whether nano-Ca can improve calcium delivery to sink tissues and reduce calcium-related physiological disorders in greenhouse cucumber production.

5. Conclusions

In this study, soilless cultivation (frequent fertilization and irrigation, optimized nutrient supply) produces better vegetative growth and fruit yield in cucumbers (cv. Saba) compared to soil cultivation, although the dry weight percentage of leaf, root and fruit is lower. The benefits of grafting depend on the cultivation system: unnecessary in soilless system but potentially beneficial in soil culture, especially plants grafted on Routpower, which generally performed better than ungrafted plants, although the differences were often not statistically significant. Foliar application of calcium (both CaCl_2 and $\text{CaCO}_3\text{-NP}$) did not produce any significant increase in morphological traits or yield under these conditions, indicating that standard nutrient management provided sufficient calcium for plant needs, or that the foliar application concentration was too low. For soilless cucumber production, ungrafted plants without foliar calcium supplementation are a simple and cost-effective strategy that achieves yields comparable to more complex treatments under the conditions evaluated. Finally, because the two production systems differed in several management and environmental factors simultaneously, these findings should be interpreted as comparisons between integrated commercial production systems rather than evidence of a single causal cultivation-system effect.

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Writing—review and editing, M.B., H.R.R., P.K. and B.B.C.; Visualization, M.B.; Supervision, M.B. and H.R.R.; Project administration, M.B. and H.R.R.; Funding acquisition, M.B. and H.R.A. All authors have read and agreed to the published version of the manuscript.

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