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Effect of Pruning Systems on Vegetative Growth, Yield, and Fruit Quality of Key Lime (*Citrus aurantifolia* (Christm.) Swingle) Under Growing Conditions in the Piura Region

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Abstract

Key lime (*Citrus aurantifolia* (Christm.) Swingle) is an important fruit crop in northern Peru; however, inadequate canopy management can limit productivity and fruit quality. This study evaluated the effects of different pruning systems on vegetative growth, flowering, yield, and fruit quality of key lime under the growing conditions of the Piura region. The experiment was conducted during the 2024 and 2025 growing seasons in two commercial orchards using a randomized complete block design with four pruning systems, namely maintenance pruning (MP), thinning pruning (TP), maintenance pruning combined with thinning pruning (MP + TP), and no pruning (NP), with four replicates per system. Vegetative growth, flowering, yield, and fruit quality variables were evaluated. Data were analyzed using analysis of variance (ANOVA), Tukey's honestly significant difference (HSD) test ($p < 0.05$), principal component analysis (PCA), hierarchical cluster analysis, and correlation analysis. Pruning significantly affected vegetative growth, flowering, yield, and fruit physical attributes, whereas juice soluble solids, vitamin C content, and titratable acidity were not significantly affected. MP, TP, and MP + TP were associated with higher yields than NP, while MP also showed greater values for several fruit physical attributes. Some responses varied with growing season and/or study site. Overall, pruning modified vegetative and productive responses in key lime, and MP combined relatively high yield with greater values for several fruit physical attributes under the edaphoclimatic conditions of the studied orchards in Piura.

Keywords: canopy architecture; citrus production; fruit sizing; acid lime; yield efficiency

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1. Introduction

Key lime (*Citrus aurantifolia* (Christm.) Swingle), also known as acid lime, is a fruit tree of the family Rutaceae, native to Southeast Asia and widely cultivated in tropical and subtropical regions [1,2]. Global citrus production is approximately 21.52 million tonnes, with the Americas accounting for 42.7% of the total [3]. Owing to its demand for fresh

consumption and industrial processing, key lime is an economically important crop in many producing countries.

In Peru, the area cultivated with key lime has expanded in recent years because of its adaptability to diverse agroclimatic conditions, relatively simple agronomic management, and sustained domestic demand [4,5]. In 2024, national production reached approximately 359.8 thousand tonnes, with Piura as the leading producing region (216.8 thousand tonnes), followed by Tumbes and Lambayeque [6]. In Piura, key lime is an important crop for small- and medium-scale growers because it produces throughout the year and requires relatively simple agronomic management [4]. Despite the expansion of the cultivated area, however, yields have not increased substantially. Major constraints include water scarcity, orchard aging, inadequate canopy management, and pests and diseases, which can reduce productivity and fruit commercial quality [5,7].

These constraints highlight the need for agronomic practices that improve canopy management while sustaining crop productivity. Pruning is an important practice in citrus production because it regulates tree architecture and vegetative growth [8], influences light distribution within the canopy [9], and helps maintain a balance between vegetative and reproductive growth [10]. Appropriate pruning can also improve canopy aeration and facilitate nutritional and phytosanitary management [11,12].

Pruning and canopy management in citrus have been evaluated under different production systems and environmental conditions. Studies in several citrus species have shown that pruning severity can modify vegetative growth and productive responses in sweet orange [12], grapefruit [13], lemon [14], and mandarin [15], with the magnitude of these responses depending partly on the intensity of canopy removal [16]. Under Mediterranean conditions, different pruning strategies have also been associated with changes in canopy structure, vegetative growth, productivity, and fruit characteristics [10]. These findings indicate that pruning should not be considered a uniform management practice; its effects depend on the characteristics of the production system.

Similar responses to canopy manipulation have been reported in other perennial fruit crops. In mango (*Mangifera indica* L.), pruning increased the penetration of photosynthetically active radiation into the inner canopy compared to unpruned trees [17]. Pruning intensity can also alter canopy microclimate and reproductive development, with moderate pruning producing more favorable reproductive responses than severe or no pruning under the conditions evaluated [18]. In avocado (*Persea americana* Mill.), pruning and shoot tipping can modify canopy architecture by restricting primary shoot elongation and stimulating axillary branching [19]. This response is particularly relevant in high-density orchards, where progressive canopy closure can increase competition for light and ultimately constrain productivity [20]. Similar relationships among pruning, canopy structure, and light interception have been reported in apple (*Malus domestica* Borkh.). Summer pruning can substantially modify leaf area distribution and canopy light interception, both of which are closely associated with orchard productivity and fruit quality [21,22]. Overall, evidence from perennial fruit crops indicates that pruning responses are closely associated with changes in canopy architecture, light distribution, and the balance between vegetative and reproductive growth.

Nevertheless, responses to pruning vary among fruit crops and production environments. They may depend on species or cultivar, tree age and vigor, pruning type, timing and intensity, orchard architecture, and environmental and management conditions [10,16]. Therefore, pruning recommendations developed for other citrus species or for Mediterranean, subtropical, or other tropical environments cannot necessarily be extrapolated to key lime orchards in northern Peru.

Despite the economic importance of key lime in Piura, experimental evidence comparing pruning systems and their effects on vegetative growth, reproductive performance, yield, and fruit quality under local conditions remains limited. This study therefore addressed three questions: (i) How do different pruning systems affect vegetative growth and reproductive performance of key lime? (ii) How do these systems influence yield and fruit physicochemical quality? (iii) Do pruning responses vary between growing seasons and study sites in the Piura region? Accordingly, this study aimed to evaluate the effects of different pruning systems on the vegetative growth, flowering, yield, and fruit quality of key lime (*Citrus aurantifolia* (Christm.) Swingle) under the growing conditions of the Piura region.

2. Materials and Methods

2.1. Study Area and Plant Material

The experiment was conducted in commercial orchards located in the rural communities of Cieneguillo Sur (5°00′53.4″ S, 80°40′08.1″ W; 58 m above sea level) and Pachacútec (4°51′54.3″ S, 80°24′46.4″ W; 105 m above sea level), in the districts of Sullana and Tambogrande, respectively, Piura region, Peru (Figure 1). According to the Köppen–Geiger climate classification, both study sites have a BWh climate, characterized by high temperatures and low annual precipitation.

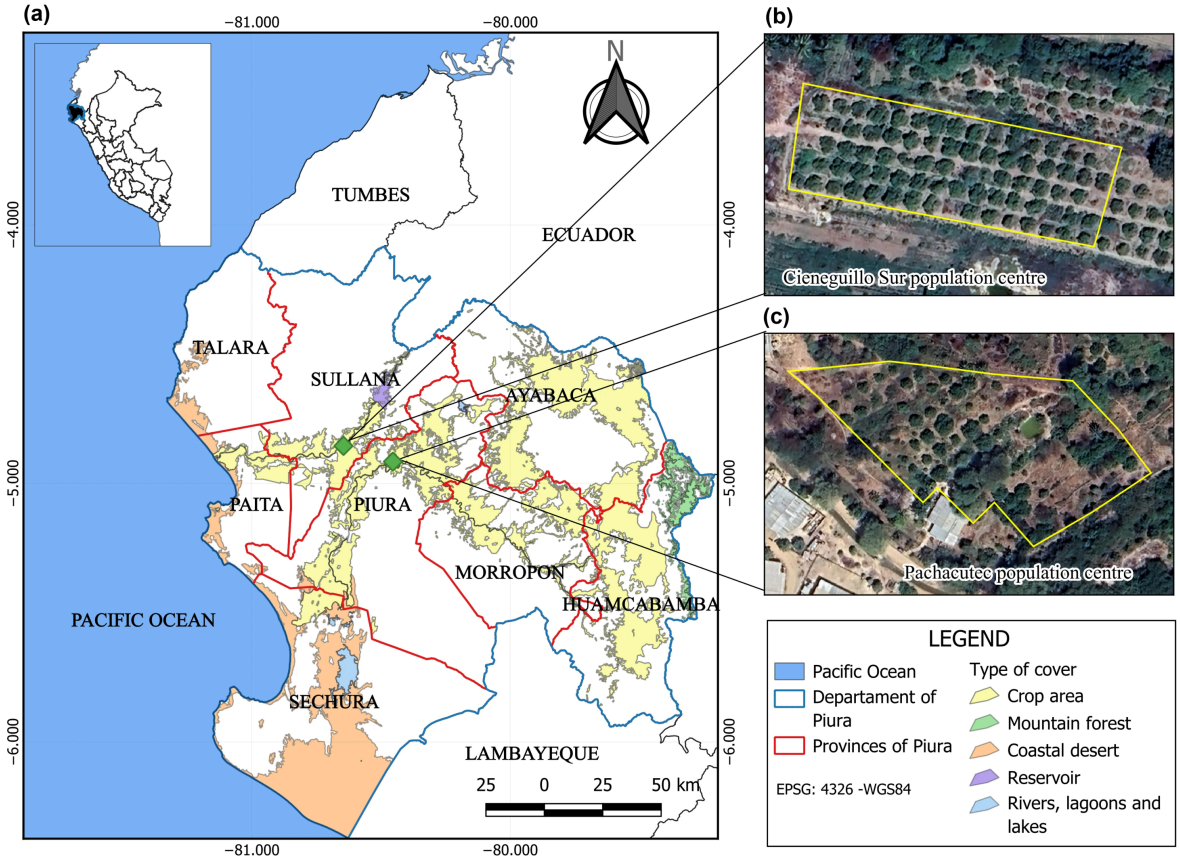


Figure 1. Location of the study sites in the Piura region, Peru. (**a**) Location of the study sites within the Piura region; (**b**) aerial view of the experimental key lime orchard at Cieneguillo Sur; (**c**) aerial view of the experimental key lime orchard at Pachacutec.

Climatic variables were recorded daily during the 2024 and 2025 growing seasons (Figure 2). At Cieneguillo Sur, maximum temperatures ranged from 27.2 to 37.2 °C, with the highest values recorded during the summer months (January–March 2025), whereas

minimum temperatures ranged from 13.8 to 24.8 °C. Rainfall was negligible throughout 2024, while sporadic rainfall events occurred in 2025, particularly in February and March, with a maximum daily rainfall of 46.8 mm. At Pachacutec, maximum temperatures ranged from 25.2 to 36.2 °C and minimum temperatures from 13.2 to 24.4 °C. Rainfall was also negligible during most of 2024 but increased in 2025, reaching a maximum daily value of 48.1 mm in March (Figure 2).

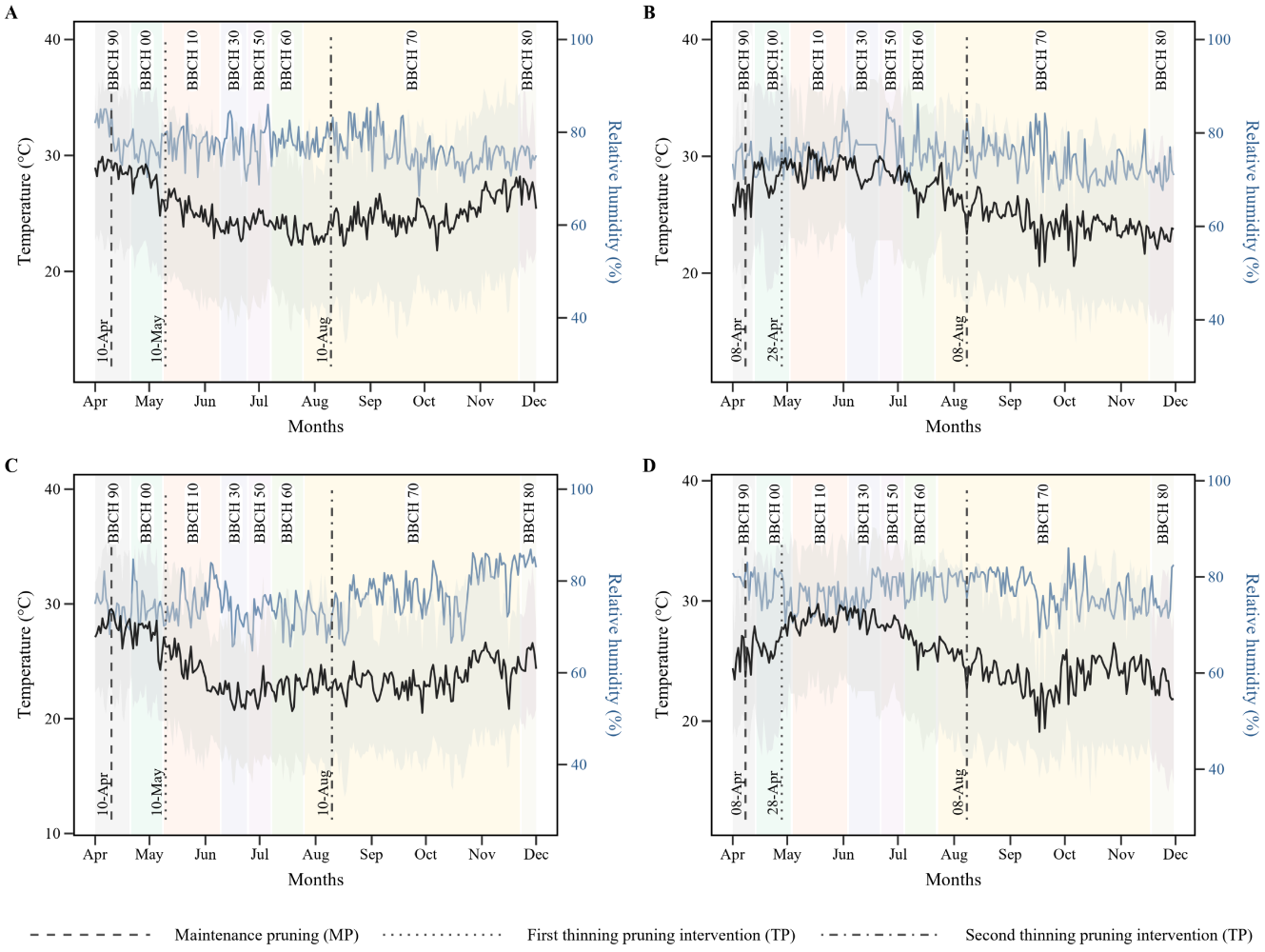


Figure 2. Climatic conditions and phenological development of key lime (*Citrus aurantifolia* (Christm.) Swingle) at the study sites during the 2024 and 2025 growing seasons. (**A**) Cieneguillo Sur, 2024; (**B**) Cieneguillo Sur, 2025; (**C**) Pachacutec, 2024; and (**D**) Pachacutec, 2025. Phenological stages were identified according to the BBCH scale for citrus: BBCH 00, bud development; BBCH 10, leaf development; BBCH 30, shoot development; BBCH 50, flower development; BBCH 60, flowering; BBCH 70, fruit development; BBCH 80, fruit ripening; and BBCH 90, vegetative dormancy. The black and blue lines represent mean air temperature (°C) and mean relative humidity (%), respectively. Vertical dashed lines indicate maintenance pruning (MP), whereas dotted and dash-dotted lines indicate the first and second thinning pruning (TP) interventions, respectively. Pruning dates are shown next to the corresponding vertical lines.

Soils at Cieneguillo Sur were classified as sandy clay loam, with 58.2–60.5% sand, 25.1–27.0% clay, and 14.4–14.8% silt. In contrast, soils at Pachacutec were classified as sandy loam, with higher sand (61.4–64.7%) and silt (20.2–22.2%) contents but lower clay content (15.1–16.4%). Soil pH ranged from 7.1 to 7.6 at Cieneguillo Sur, corresponding to neutral to slightly alkaline conditions, and from 7.9 to 8.0 at Pachacutec, corresponding to alkaline

conditions. Electrical conductivity ranged from 9.0 to 12.8 mS m^{-1}, indicating non-saline conditions at both study sites.

Soil organic matter content was low to moderate (2.1–2.6%) at both study sites, as is typical of arid coastal soils. Total nitrogen content was low (0.105–0.130%), whereas available phosphorus was high, particularly at Cieneguillo Sur, where concentrations reached 190.0 mg kg^{-1}. Potassium levels were high at Cieneguillo Sur (396–436 mg kg^{-1}) and moderate at Pachacutec (103.2–106.8 mg kg^{-1}). Exchangeable cation concentrations were within adequate ranges, with calcium exceeding 10 cmol(c) kg^{-1}, magnesium exceeding 2.0 cmol(c) kg^{-1}, and potassium exceeding 0.3 cmol(c) kg^{-1}, indicating adequate nutrient reserves at both study sites. In contrast, exchangeable sodium ranged from 2.3 to 2.9 cmol(c) kg^{-1}, suggesting a potential risk of soil sodicity. Calcium carbonate content was higher at Cieneguillo Sur (2.4%) than at Pachacutec (0.7%), consistent with the alkaline soil conditions.

Seven-year-old key lime (*Citrus aurantifolia* (Christm.) Swingle) trees from the same commercial plant material were used at both study sites. The trees were grafted onto rough lemon (Citrus jambhiri Lush.) rootstock propagated from botanical seed. Rough lemon has shown favorable physiological and biochemical responses under water-deficit conditions [23,24]. The plant material was obtained from the Hualtaco Nursery Experimental Center in Tambogrande, which belongs to the El Chira Agricultural Experimental Station of the National Institute for Agrarian Innovation (INIA), Peru. A separate set of 64 trees was evaluated for each study site × growing season combination. Thus, 128 trees were evaluated in each growing season and 256 trees in the entire study. Different trees were evaluated in 2024 and 2025. Trees were planted at a spacing of 7 × 7 m (204 trees ha^{-1}) and selected for uniform vegetative growth and good phytosanitary condition.

The orchards were surface-irrigated at 10-day intervals. Fertilization was based on crop nutritional requirements and the corresponding phenological stages of the BBCH scale for citrus [25]. Nutrient management included compost and synthetic fertilizers. Compost was applied after harvest during vegetative dormancy (BBCH 90), whereas synthetic fertilizers containing N, P, K, Ca, Mg, and B were applied during fruit development (BBCH 70). Pest and disease management followed the growers' conventional orchard practices.

2.2. Pruning Systems

The experiment followed a randomized complete block design with four pruning systems and four replicates per system at each study site. Each experimental unit consisted of four trees. Thus, 64 trees were evaluated for each study site × growing season combination, with 128 trees per growing season and 256 trees in the entire study. The experimental design and pruning-system allocation were established independently for each study site and growing season. The four pruning systems were maintenance pruning (MP), thinning pruning (TP), maintenance pruning combined with thinning pruning (MP + TP), and no pruning (NP; Figure 3).

At both study sites, MP was performed during vegetative dormancy (BBCH 91–97) on 10 April 2024 and 8 April 2025. This system involved the removal of dead, diseased, and poorly oriented branches [26,27]. TP was performed in two stages. The first intervention was conducted during bud development (BBCH 00–09), before flowering, on 10 May 2024 and 28 April 2025. Vegetative buds and emerging shoots were selectively removed to control excessive vegetative growth and canopy expansion [10]. The second intervention was conducted during fruit development (BBCH 71–79) on 10 August 2024 and 8 August 2025. Shoots and fruits were selectively removed to reduce competition between vegetative and reproductive sinks and promote fruit development [10,28]. The combined system

(MP + TP) consisted of MP at BBCH 91–97 followed by the two TP interventions at BBCH 00–09 and BBCH 71–79. Trees assigned to NP were not pruned during the production cycle.

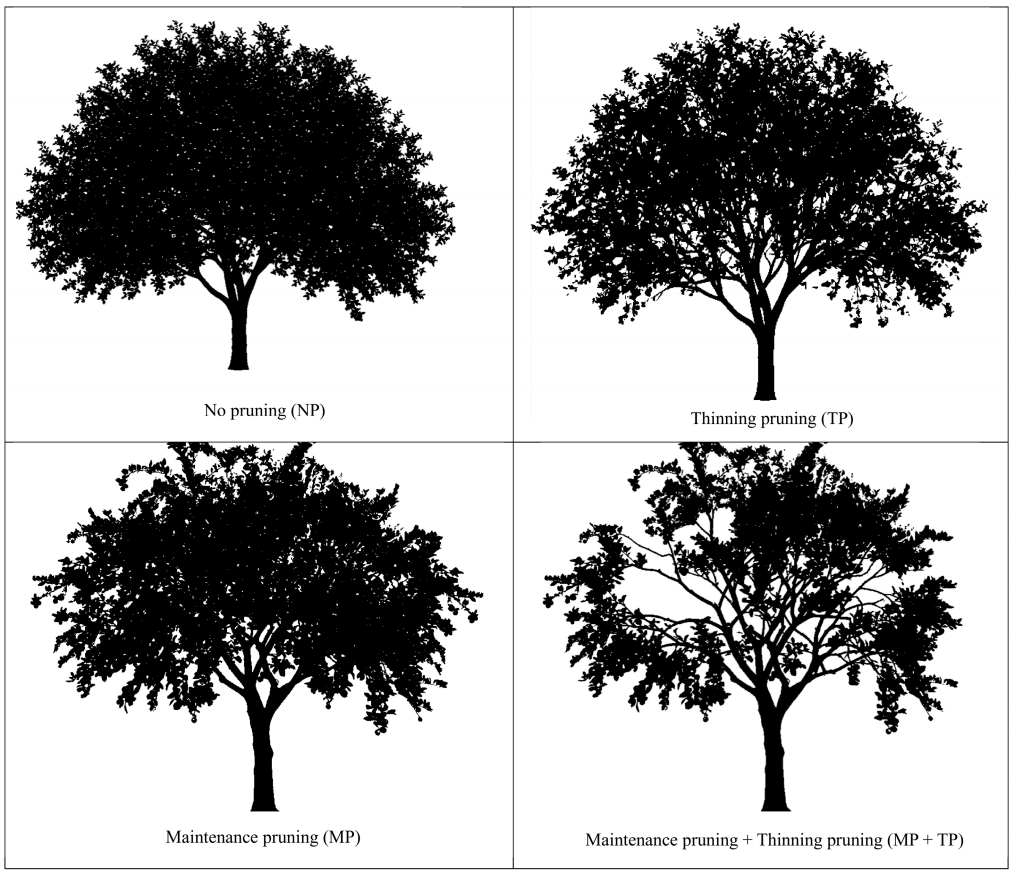


Figure 3. Representative key lime trees under the four pruning systems evaluated: no pruning (NP), thinning pruning (TP), maintenance pruning (MP), and maintenance pruning combined with thinning pruning (MP + TP).

To minimize variation in initial canopy architecture, the independent sets of trees evaluated in 2024 and 2025 were pruned to approximately 3.5 m during vegetative dormancy (BBCH 91–97) in 2023 and 2024, respectively. This pre-experimental pruning was performed approximately one growing season before each trial. Trees were subsequently selected for canopy uniformity and comparable vegetative development. During the experiment, pruning intensity was standardized according to the proportion of branches removed: 0% for NP, approximately 20% for TP (10% at BBCH 00–09 and 10% at BBCH 71–79), 40% for MP, and 60% for MP + TP (40% during MP and 10% during each TP intervention). The same pruning criteria and target removal proportions were applied to all trees within each pruning system.

Pruning operations followed the standardized technical guidelines for citrus described by Krajewski and Krajewski [16]. Hand pruners, loppers, and a pruning saw were used according to branch diameter. Hand pruners (18 cm) were used for branches <20 mm in diameter, whereas loppers (45 cm) and a curved pruning saw (40 cm) were used for branches >20 mm in diameter. Tools were disinfected between cuts by immersing the cutting blades in 70% isopropyl alcohol for 15 s. Immediately after pruning, a commercial wound sealant containing copper sulfate pentahydrate (50.0 g kg^{-1}), betaine (2.8 g kg^{-1}), zinc sulfate (7.0 g kg^{-1}), propanol (100.0 g kg^{-1}), and naphthaleneacetic acid (3000 ppm) was applied to all pruning wounds.

2.3. Plant Growth Variables

Plant growth variables included plant height, canopy volume, trunk cross-sectional area, and leaf area. Plant height (PH, m) was measured from the soil surface to the upper third of the canopy using a measuring tape attached to a wooden pole. Canopy volume (CV, m^3) was calculated according to the equation proposed by Castle [29], where b represents one-half of tree height and a represents the mean canopy radius measured in the east–west and north–south directions: $CV\ (m^3) = \frac{4}{3}\pi \times a^2 \times b$.

Trunk cross-sectional area (TCSA, cm^2) was estimated from trunk diameter measured in the east–west and north–south directions using a measuring tape. The mean trunk diameter (d) was used to calculate TCSA according to the equation proposed by Dubey and Sharma [30]: $TCSA\ (cm^2) = (\pi\frac{d}{2})^2$.

Leaf area (LA, cm^2) was estimated according to the equation proposed by Al-Saif et al. [12]: $LA\ (cm^2) = 0.49(L \times W) + 19.09$, where L and W represent leaf length and width, respectively. Leaf area was evaluated after BBCH 39 using fully expanded mature leaves [25]. Canopy volume, trunk cross-sectional area, and plant height were assessed after BBCH 50.

2.4. Flowering and Yield Variables

Flowering variables included the number of days to flowering (NDF) and the number of flowers per branch (NFB). NDF was calculated as the number of days from the reference date established for each pruning system to the appearance of the first flower bud. For MP and MP + TP, the reference date was the completion of maintenance pruning at BBCH 91–97. For TP, the reference date was the completion of the first thinning intervention at BBCH 00–09, before flowering. For NP, the reference date was the day of complete fruit harvest, which marked the onset of vegetative dormancy (BBCH 91–97) and the beginning of a new production cycle.

NFB was determined at full flowering (BBCH 65), approximately 15 ± 2 days after the appearance of the first flower bud. For TP and MP + TP, NFB was therefore recorded before the second thinning intervention at BBCH 71–79. Four branches were randomly selected from each tree, one in each cardinal direction (north, south, east, and west) at the middle third of the canopy. Flowers were counted on each branch, and the mean number of flowers per branch was calculated for each tree.

Yield variables included the number of harvested fruits per branch (NHFB), yield per tree (YT), and yield increase (YI). Fruits were harvested between BBCH 79 and 81. Harvest maturity was determined from the soluble solids-to-titratable acidity ratio (SSJ/TAJ) of randomly sampled fruits. Fruits were harvested when the mean SSJ/TAJ ratio reached approximately 8:1 [31].

NHFB was determined using the same branch position and sampling procedure described for NFB. Four branches were evaluated per tree, one in each cardinal direction at the middle third of the canopy. Yield per tree (YT, kg $tree^{-1}$) was determined by weighing all fruits harvested from each tree. Yield increase (YI, %) relative to NP was calculated as follows [32]: $\text{Yield increase}(\%) = \frac{\text{Yield(Pruning System)} - \text{Yield(No pruning)}}{\text{Yield(No pruning)}} \times 100$.

2.5. Fruit Physical and Chemical Variables

Twelve fruits were collected from each tree for the determination of physical and chemical variables. Fruits were sampled according to cardinal direction (north, south, east, and west) and canopy position (lower, middle, and upper thirds). Each fruit was analyzed individually for the physical variables, and the values were averaged per tree. The physical variables included fruit weight (FW, g), polar fruit diameter (PFD, mm), equatorial fruit

diameter (EFD, mm), fruit volume (FV, cm^3), peel thickness (PT, mm), and juice volume (JV, mL).

Fruit weight was measured using a digital balance (XY5000-1BF, Changzhou Xingyun Electronic Equipment Co., Ltd., Changzhou, China). Polar fruit diameter, equatorial fruit diameter, and peel thickness were measured using a digital caliper (®CALDI-6MP, 0–150 mm, Truper, S.A. de C.V., Mexico City, Mexico) and expressed in millimeters. Fruit volume was calculated as follows: $FV\ (\mathrm{cm}^3) = \frac{\pi}{6} \times (PFD \times EFD \times DFD)$, where *PFD* and *EFD* represent the polar and equatorial fruit diameters, respectively, and *DFD* represents the fruit diameter measured along the third orthogonal axis, perpendicular to both PFD and EFD. Juice volume was measured using a graduated cylinder and expressed in milliliters.

Chemical variables included juice soluble solids (SSJ, °Brix), juice pH (pHJ), titratable acidity (TAJ, % citric acid), and vitamin C content (VCJ, mg 100 mL^{-1}). SSJ, pHJ, and TAJ were determined individually for each of the 12 fruits, and the values were averaged per tree. For VCJ, juice from the 12 fruits collected from each tree was pooled to obtain sufficient volume for analysis. No additional technical replicates were performed for physical or chemical fruit-quality measurements.

Soluble solids and titratable acidity were measured using a digital soluble solids/acidity meter (ATAGO PAL-BX/ACID1, ATAGO Co., Ltd., Tokyo, Japan). For TAJ, 1.0 g of filtered juice was diluted with distilled water to a final mass of 50.0 g and analyzed by electroconductivity, with acidity expressed as citric acid (%). Juice pH was measured using a benchtop pH meter (MW151 MAX, Milwaukee Instruments, Inc., Rocky Mount, NC, USA). Vitamin C content was determined in the pooled juice by titration with 2,6-dichlorophenolindophenol (Merck KGaA, Darmstadt, Germany) according to the method of the Association of Official Analytical Chemists [33].

2.6. Statistical Analysis

Data from the four trees within each experimental unit were averaged before statistical analysis, and the resulting experimental-unit means were used as independent observations. Analysis of variance (ANOVA) was used to assess the effects of pruning system, growing season, study site, and their interactions on plant growth, flowering, yield, and fruit quality variables. Pruning system, growing season, and study site were included as fixed effects, whereas blocks were treated as a random effect nested within each study site × growing season combination.

Mean comparisons were performed using Tukey's honestly significant difference (HSD) test at $\alpha = 0.05$. Pruning systems were compared within each study site × growing season combination, whereas study site × growing season combinations were compared within each pruning system. Hierarchical cluster analysis and radar charts based on standardized values (Z-scores) were used to explore multivariate response patterns. Principal component analysis (PCA) was used to examine associations between pruning systems and agronomic variables. All statistical analyses were performed in Python version 3.13 [34] using the statsmodels, SciPy, scikit-learn, pandas, seaborn, and matplotlib libraries.

3. Results

3.1. Plant Growth Variables

Analysis of variance (ANOVA) showed significant effects of pruning system on plant height (PH), canopy volume (CV), trunk cross-sectional area (TCSA), and leaf area (LA) (Table 1; Figure 4). Significant pruning system × growing season interactions were detected for TCSA and LA, whereas the pruning system × study site interaction was significant only for TCSA.

Table 1. Summary of the analysis of variance (ANOVA) for plant growth, flowering, yield, and fruit quality variables of key lime (*Citrus aurantifolia* (Christm.) Swingle under different pruning systems.

Group	Variable	Meaning	Pruning Systems	Growing Season	Study Site	System × Season	System × Location
Growth	PH	Plant height	1.0589 (***)	0.0878 (ns)	0.6480 (***)	0.0217 (ns)	0.0351 (ns)
	CV	Canopy volume	102.7676 (***)	339.7110 (***)	55.8756 (*)	3.1000 (ns)	1.2104 (ns)
	TCSA	Trunk cross-sectional area	2856.7347 (***)	6703.5156 (***)	27.4314 (ns)	398.9786 (***)	138.5024 (*)
	LA	Leaf area	4.8794 (***)	1.1489 (ns)	0.5393 (ns)	1.2480 (*)	0.6431 (ns)
Flowering and performance	NDF	Number of days to flowering	352.1003 (***)	0.0156 (ns)	669.5156 (***)	9.8880 (***)	10.7786 (***)
	NFB	Number of flowers per branch	91.9786 (***)	0.8355 (ns)	1032.5176 (***)	19.1846 (ns)	76.6158 (***)
	NHFB	Number of harvested fruits per branch	2.6274 (***)	9.0940 (***)	0.3342 (ns)	0.1690 (ns)	0.8767 (ns)
	YT	Yield per tree	177.7386 (***)	3.0189 (ns)	3.2852 (ns)	3.4094 (ns)	28.8724 (ns)
Quality	FW	Fruit weight	542.2761 (***)	25.3449 (*)	49.6364 (**)	0.1499 (ns)	5.2060 (ns)
	EFD	Equatorial fruit diameter	138.6093 (***)	6.3620 (ns)	1.7468 (ns)	0.0093 (ns)	0.3203 (ns)
	PFD	Polar fruit diameter	169.2830 (***)	0.1954 (ns)	0.2754 (ns)	0.0003 (ns)	14.8811 (**)
	FV	Fruit volume	685.9314 (***)	1.4275 (ns)	0.5578 (ns)	0.0163 (ns)	0.1296 (ns)
	PT	Peel thickness	0.1870 (***)	0.0001 (ns)	0.0005 (ns)	0.0000 (ns)	0.0000 (ns)
	JV	Juice volume	160.2036 (***)	0.1028 (ns)	0.2705 (ns)	0.0014 (ns)	0.0369 (ns)
	SSJ	Soluble solids	0.3021 (ns)	0.0211 (ns)	0.2439 (ns)	0.0200 (ns)	0.0060 (ns)
	pHJ	Potential of hydrogen	0.1615 (ns)	0.0071 (ns)	0.0019 (ns)	0.0000 (ns)	0.0000 (ns)
	TAJ	Titratable acidity	0.2527 (ns)	0.0398 (ns)	0.0061 (ns)	0.0000 (ns)	0.0000 (ns)
	VCJ	Vitamin C content	5.4971 (ns)	3.1784 (ns)	11.5600 (*)	0.0001 (ns)	0.0187 (ns)

Note: Mean square (MS) values are presented for each source of variation. ns, not significant; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

For PH, significant differences among pruning systems were detected in several study site × growing season combinations (Figure 4A). At Cieneguillo Sur, a similar response was observed in both growing seasons. In 2024, MP, TP, and NP showed statistically similar PH values (3.16, 3.40, and 3.52 m, respectively), whereas MP + TP showed a significantly lower value (2.94 m). Similarly, in 2025, MP, TP, and NP did not differ significantly (3.01, 3.39, and 3.36 m, respectively), whereas MP + TP showed the lowest PH (2.91 m). At Pachacutec in 2024, TP and NP showed the highest and statistically similar PH values (3.38 and 3.61 m, respectively), followed by MP (3.30 m), whereas MP + TP showed the lowest value (2.89 m). These pruning systems formed three significantly different groups. At Pachacutec in 2025, TP and NP showed the highest and statistically similar PH values (3.64 and 3.80 m, respectively), whereas MP and MP + TP showed significantly lower and statistically similar values (3.47 and 3.21 m, respectively).

Comparisons among study site × growing season combinations within each pruning system showed significant differences ($p < 0.05$) for MP, MP + TP, and NP, but not for TP (Figure 4A). Under MP, PH was significantly higher at Pachacutec in 2024 and 2025 (3.30 and 3.47 m, respectively) than at Cieneguillo Sur in 2024 and 2025 (3.16 and 3.01 m, respectively). Under MP + TP, the highest PH was recorded at Pachacutec in 2025 (3.21 m), significantly exceeding the values recorded at Cieneguillo Sur in 2024 and 2025 (2.94 and 2.91 m, respectively) and at Pachacutec in 2024 (2.89 m), which did not differ significantly. Under NP, PH was significantly lower at Cieneguillo Sur in 2025 (3.36 m) than at Cieneguillo Sur in 2024 (3.52 m) and Pachacutec in 2024 and 2025 (3.61 and 3.80 m, respectively), which showed statistically similar values.

For CV, significant differences among pruning systems were detected only at Pachacutec in 2024 and 2025 ($p < 0.05$) (Figure 4B). No significant differences among pruning systems were detected at Cieneguillo Sur in either growing season. At Pachacutec, MP, TP,

and NP showed statistically similar CV values in both growing seasons and significantly exceeded MP + TP, which showed the lowest values (24.19 m^3 in 2024 and 31.23 m^3 in 2025).

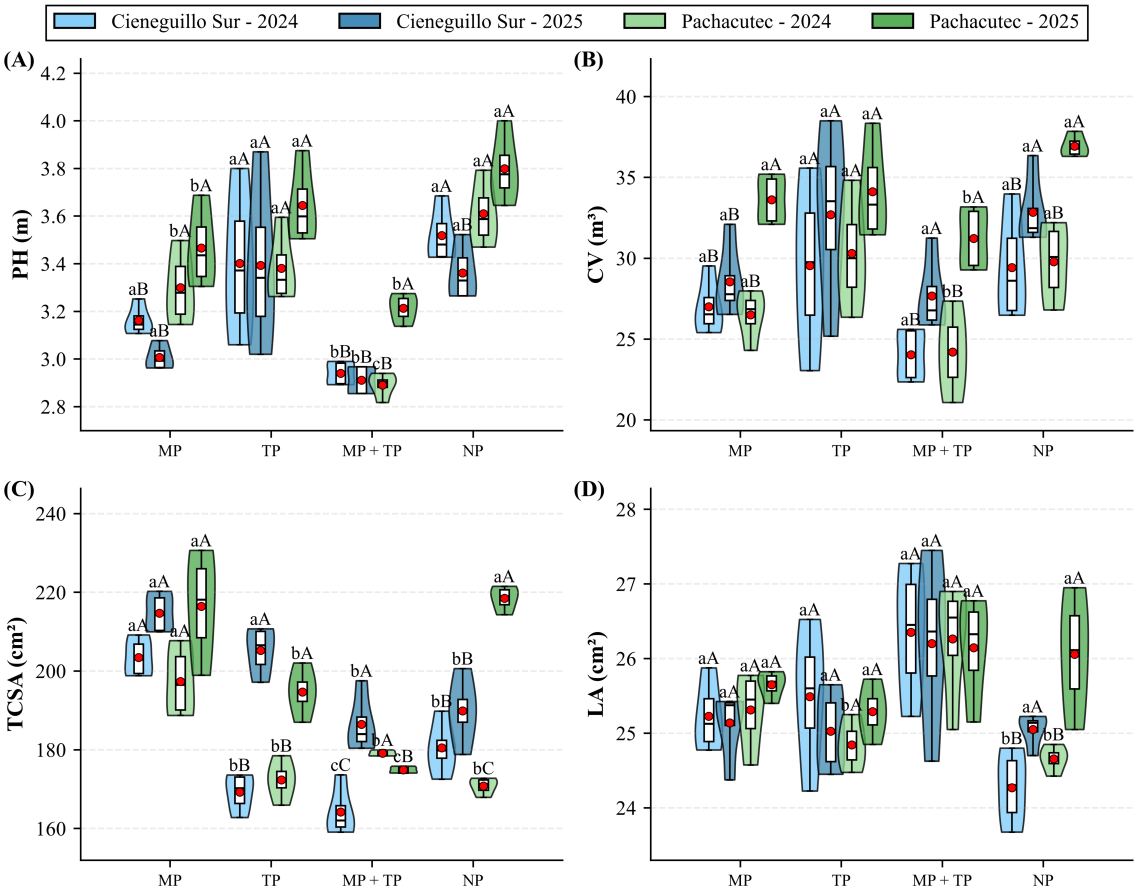


Figure 4. Plant growth variables as affected by pruning systems across study sites and growing seasons. (**A**) Plant height (PH), (**B**) canopy volume (CV), (**C**) trunk cross-sectional area (TCSA), and (**D**) leaf area (LA). Pruning systems: no pruning (NP), thinning pruning (TP), maintenance pruning (MP), and maintenance pruning combined with thinning pruning (MP + TP). White boxes represent the interquartile range, black horizontal lines indicate the median, and whiskers represent data dispersion. Different lowercase letters indicate significant differences among pruning systems within each study site × growing season combination, whereas different uppercase letters indicate significant differences among study site × growing season combinations within each pruning system, according to Tukey's honestly significant difference (HSD) test ($p < 0.05$).

Comparisons among study site × growing season combinations within each pruning system showed significant differences ($p < 0.05$) for MP, MP + TP, and NP, but not for TP (Figure 4B). Under MP, the highest CV was recorded at Pachacutec in 2025 (33.62 m^3), significantly exceeding the values recorded at Cieneguillo Sur in 2024 and 2025 (26.99 and 28.54 m^3, respectively) and at Pachacutec in 2024 (26.49 m^3), which did not differ significantly. Under MP + TP, CV was significantly higher in 2025 at both Cieneguillo Sur and Pachacutec (27.66 and 31.23 m^3, respectively) than in 2024 (24.03 and 24.19 m^3, respectively). Similarly, under NP, CV was significantly higher in 2025 at Cieneguillo Sur and Pachacutec (32.84 and 36.93 m^3, respectively) than in 2024 (29.41 and 29.78 m^3, respectively).

For TCSA, significant differences among pruning systems were detected in all study site × growing season combinations ($p < 0.05$) (Figure 4C). At Cieneguillo Sur in 2024, MP showed the highest TCSA (203.42 cm^2), whereas MP + TP showed the lowest value (164.19 cm^2). In 2025, MP and TP showed the highest and statistically similar values (214.69 and 205.25 cm^2, respectively). At Pachacutec in 2024, MP showed a significantly higher

TCSA than the other pruning systems, whereas in 2025, MP and NP showed the highest and statistically similar values (216.43 and 218.46 cm^2, respectively).

Comparisons among study site × growing season combinations within each pruning system showed significant differences ($p < 0.05$) for TP, MP + TP, and NP, but not for MP (Figure 4C). Under TP, TCSA was significantly higher in 2025 than in 2024 at both study sites. Under MP + TP, the highest values were recorded at Cieneguillo Sur in 2025 and Pachacutec in 2024, whereas under NP, the highest TCSA was recorded at Pachacutec in 2025 (218.46 cm^2).

For LA, significant differences among pruning systems were detected only at Cieneguillo Sur and Pachacutec in 2024 ($p < 0.05$) (Figure 4D). At Cieneguillo Sur, MP, TP, and MP + TP showed statistically similar LA values and significantly exceeded NP, which showed the lowest value (24.27 cm^2). At Pachacutec, MP and MP + TP showed significantly higher LA values than TP and NP, which did not differ significantly. No significant differences among pruning systems were detected at either study site in 2025.

Comparisons among study site × growing season combinations within each pruning system showed significant differences ($p < 0.05$) only for NP (Figure 4D). Under NP, LA was significantly higher at Cieneguillo Sur and Pachacutec in 2025 (25.05 and 26.06 cm^2, respectively) than in 2024 (24.27 and 24.66 cm^2, respectively).

3.2. Flowering and Yield Variables

Analysis of variance (ANOVA) showed significant effects of pruning system on the number of days to flowering (NDF), number of flowers per branch (NFB), number of harvested fruits per branch (NHFB), and yield per tree (YT) (Table 1; Figure 5). Significant pruning system × growing season and pruning system × study site interactions were detected for NDF, whereas NFB showed a significant pruning system × study site interaction. No significant pruning system × growing season or pruning system × study site interactions were detected for NHFB or YT.

For NDF, significant differences among pruning systems were detected in all study site × growing season combinations ($p < 0.05$) (Figure 5A). A consistent pattern was observed across study sites and growing seasons, with MP and MP + TP showing the highest and statistically similar NDF values, significantly exceeding TP and NP, which also did not differ significantly. At Cieneguillo Sur, NDF ranged from 29.44 to 38.50 days in 2024 and from 30.88 to 37.50 days in 2025. At Pachacutec, NDF was generally higher, ranging from 34.19 to 46.56 days in 2024 and from 35.94 to 45.69 days in 2025.

Comparisons among study site × growing season combinations within each pruning system showed significant differences ($p < 0.05$) for all pruning systems (Figure 5A). Under MP, TP, MP + TP, and NP, NDF was consistently higher at Pachacutec in both growing seasons than at Cieneguillo Sur.

For NFB, significant differences among pruning systems were detected only at Pachacutec in 2024 and 2025 ($p < 0.05$) (Figure 5B). In 2024, MP and MP + TP showed the highest and statistically similar NFB values (238.56 and 241.08 flowers per branch, respectively), significantly exceeding TP and NP (232.36 and 229.09 flowers per branch, respectively). In 2025, MP, TP, and MP + TP showed statistically similar NFB values, whereas NP showed a significantly lower value (231.25 flowers per branch). No significant differences among pruning systems were detected at Cieneguillo Sur in either growing season.

Comparisons among study site × growing season combinations within each pruning system showed significant differences ($p < 0.05$) for all pruning systems (Figure 5B). Under MP, TP, MP + TP, and NP, NFB was consistently higher at Pachacutec in both growing seasons than at Cieneguillo Sur.

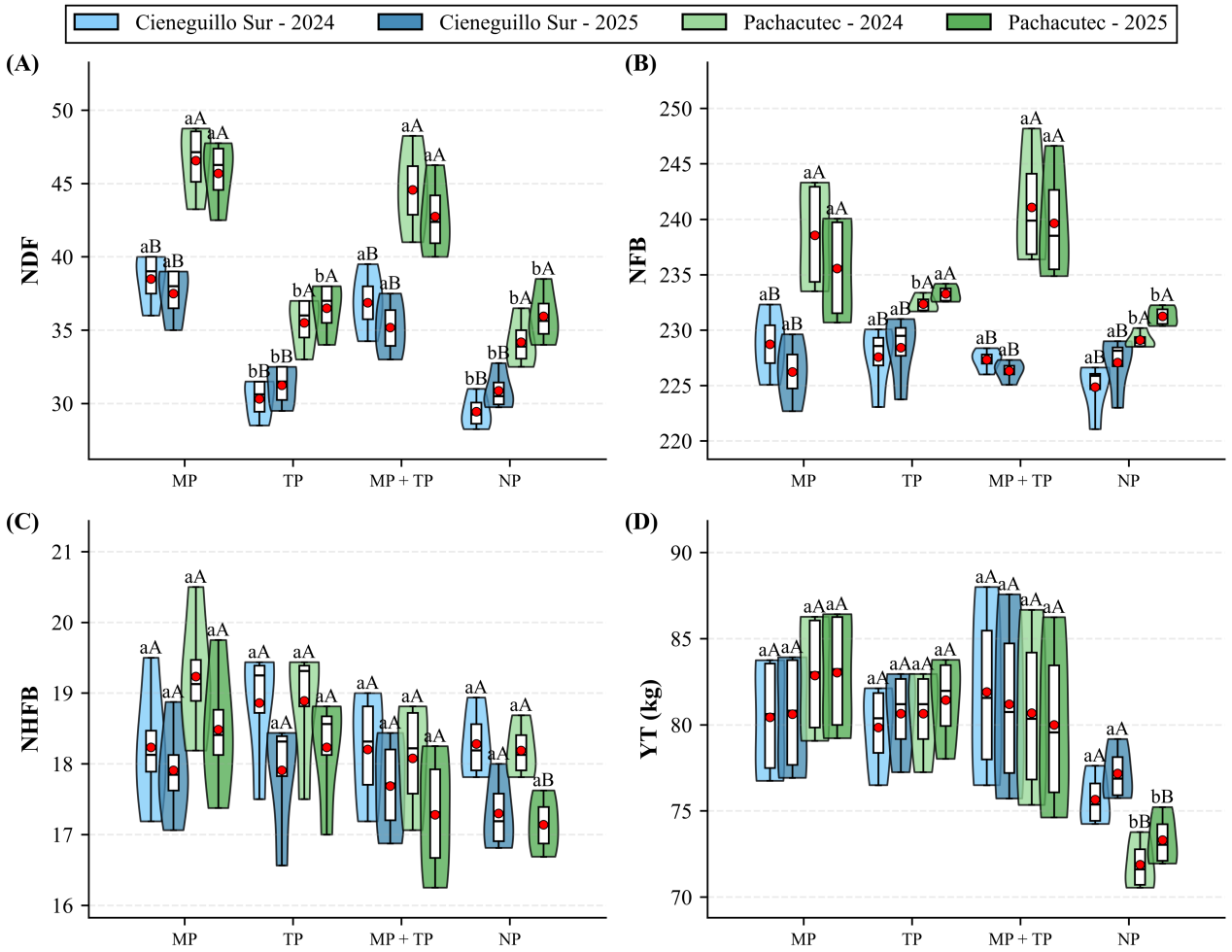


Figure 5. Flowering and yield variables as affected by pruning systems across study sites and growing seasons. (**A**) Number of days to flowering (NDF), (**B**) number of flowers per branch (NFB), (**C**) number of harvested fruits per branch (NHFB), and (**D**) yield per tree (YT). Pruning systems: no pruning (NP), thinning pruning (TP), maintenance pruning (MP), and maintenance pruning combined with thinning pruning (MP + TP). White boxes represent the interquartile range, black horizontal lines indicate the median, and whiskers represent data dispersion. Different lowercase letters indicate significant differences among pruning systems within each study site × growing season combination, whereas different uppercase letters indicate significant differences among study site × growing season combinations within each pruning system, according to Tukey's honestly significant difference (HSD) test ($p < 0.05$).

For NHFB, no significant differences among pruning systems were detected within any study site × growing season combination ($p > 0.05$) (Figure 5C). However, comparisons among study site × growing season combinations within each pruning system showed significant differences for NP. Under NP, NHFB was significantly lower at Pachacutec in 2025 (17.14 fruits per branch) than in the other study site × growing season combinations.

For YT, significant differences among pruning systems were detected only at Pachacutec in 2024 and 2025 ($p < 0.05$) (Figure 5D). In both growing seasons, MP, TP, and MP + TP showed the highest and statistically similar YT values, significantly exceeding NP, which showed the lowest yields (71.89 and 73.31 kg tree^{-1} in 2024 and 2025, respectively). No significant differences among pruning systems were detected at Cieneguillo Sur in either growing season.

Comparisons among study site × growing season combinations within each pruning system showed significant differences ($p < 0.05$) only for NP (Figure 5D). Under NP, YT was

significantly higher at Cieneguillo Sur in 2024 and 2025 (75.66 and 77.17 kg tree^{-1}, respectively) than at Pachacutec in the corresponding growing seasons (71.89 and 73.31 kg tree^{-1}, respectively).

Finally, the descriptive analysis of YI showed numerical increases in yield per tree relative to NP for all pruning systems (Table 2, Figure 5D). The increases were 9.70% for MP, 8.64% for MP + TP, and 8.24% for TP. These percentage differences were not statistically compared among pruning systems and should therefore be interpreted descriptively.

Table 2. Descriptive percentage increase in yield per tree (YI) relative to the no-pruning system (NP).

Pruning Systems	*n*	Mean (%)
TP	16	8.24
MP	16	9.70
MP + TP	16	8.64

Note: Pruning systems: no pruning (NP), thinning pruning (TP), maintenance pruning (MP), and maintenance pruning combined with thinning pruning (MP + TP).

3.3. Fruit Physical and Chemical Variables

Analysis of variance showed significant effects of pruning system on fruit weight (FW), equatorial fruit diameter (EFD), polar fruit diameter (PFD), fruit volume (FV), peel thickness (PT), juice volume (JV), and juice pH (pHJ) (Table 1; Figure 6). A significant pruning system × study site interaction was detected only for PFD, whereas no significant pruning system × growing season interactions were detected for any fruit quality variable. Soluble solids (SSJ), titratable acidity (TAJ), and vitamin C content (VCJ) were not significantly affected by pruning system, and no significant interactions with growing season or study site were detected for these variables.

For FW, significant differences among pruning systems were detected in all study site × growing season combinations ($p < 0.05$) (Figure 6A). A consistent pattern was observed, with MP showing the highest FW (42.51–45.97 g), followed by MP + TP (37.00–38.85 g), whereas TP (30.55–33.69 g) and NP (29.88–33.88 g) showed the lowest and statistically similar values. No significant differences among study site × growing season combinations were detected within any pruning system ($p > 0.05$) (Figure 6A).

For EFD, significant differences among pruning systems were detected in all study site × growing season combinations ($p < 0.05$) (Figure 6B). In all cases, MP and MP + TP showed the highest and statistically similar EFD values, significantly exceeding TP and NP, which showed the lowest and statistically similar values. Comparisons among study site × growing season combinations within each pruning system showed significant differences ($p < 0.05$) only for TP. Under TP, the highest EFD was recorded at Pachacutec in 2025 (37.66 mm), followed by Cieneguillo Sur in 2025 and Pachacutec in 2024 (37.00 mm in both cases), whereas the lowest value was recorded at Cieneguillo Sur in 2024 (36.45 mm). No significant differences among study site × growing season combinations were detected for MP, MP + TP, or NP.

For PFD, significant differences among pruning systems were detected in all study site × growing season combinations ($p < 0.05$) (Figure 6C). At Cieneguillo Sur, MP showed the highest PFD values in 2024 and 2025 (44.98 and 45.09 mm, respectively), followed by MP + TP (41.39 and 41.49 mm, respectively), whereas TP and NP showed the lowest and statistically similar values. At Pachacutec, MP, TP, and MP + TP showed statistically similar PFD values in both growing seasons and significantly exceeded NP (36.41 and 36.51 mm in 2024 and 2025, respectively). No significant differences among study site × growing season combinations were detected within any pruning system ($p > 0.05$) (Figure 6C).

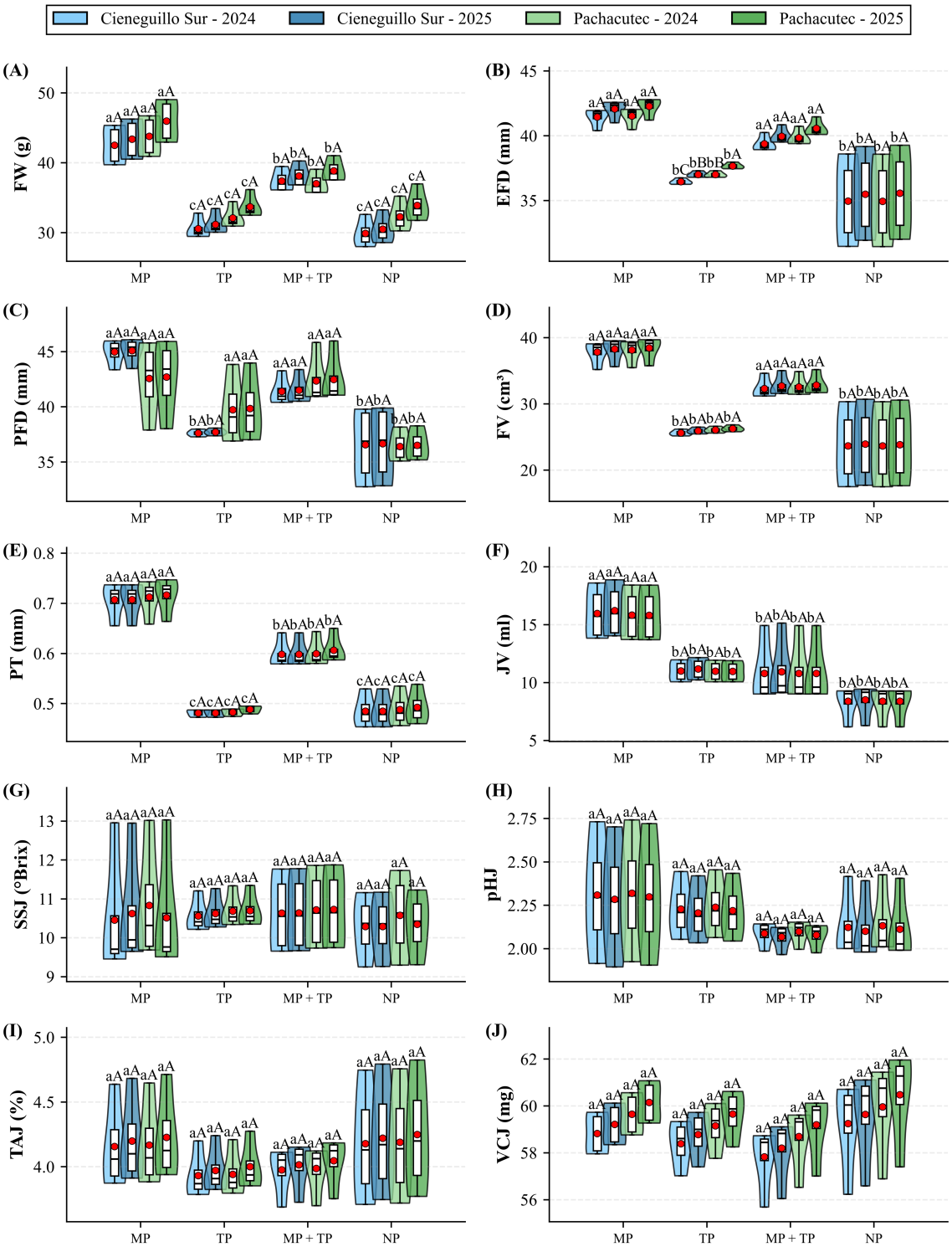


Figure 6. Fruit physical and chemical variables as affected by pruning systems across study sites and growing seasons. (**A**) Fruit weight (FW), (**B**) equatorial fruit diameter (EFD), (**C**) polar fruit diameter (PFD), (**D**) fruit volume (FV), (**E**) peel thickness (PT), (**F**) juice volume (JV), (**G**) juice soluble solids (SSJ), (**H**) juice pH (pHJ), (**I**) juice titratable acidity (TAJ), and (**J**) juice vitamin C content (VCJ). Pruning systems: no pruning (NP), thinning pruning (TP), maintenance pruning (MP), and maintenance pruning combined with thinning pruning (MP + TP). White boxes represent the interquartile range, black horizontal lines indicate the median, and whiskers represent data dispersion. Different lowercase letters indicate significant differences among pruning systems within each study site × growing season combination, whereas different uppercase letters indicate significant differences among study site × growing season combinations within each pruning system, according to Tukey's honestly significant difference (HSD) test ($p < 0.05$).

For FV, significant differences among pruning systems were detected in all study site × growing season combinations ($p < 0.05$) (Figure 6D). In all cases, MP and MP + TP showed the highest and statistically similar FV values, significantly exceeding TP and NP (Figure S1). Under MP, mean FV was 37.84 and 38.29 cm^3 at Cieneguillo Sur in 2024 and 2025, respectively, and 38.14 and 38.44 cm^3 at Pachacutec in the corresponding growing seasons. No significant differences among study site × growing season combinations were detected within any pruning system ($p > 0.05$) (Figure 6D).

For PT, significant differences among pruning systems were detected in all study site × growing season combinations ($p < 0.05$) (Figure 6E). In all cases, MP showed the highest PT values (0.707–0.717 mm), followed by MP + TP (0.598–0.607 mm), whereas TP (0.481–0.489 mm) and NP (0.485–0.493 mm) showed the lowest and statistically similar values. No significant differences among study site × growing season combinations were detected within any pruning system ($p > 0.05$) (Figure 6E).

For JV, significant differences among pruning systems were detected in all study site × growing season combinations ($p < 0.05$) (Figure 6F). MP showed the highest JV in all cases, with values of 15.97 and 16.20 mL at Cieneguillo Sur in 2024 and 2025, respectively, and 15.82 and 15.80 mL at Pachacutec in the corresponding growing seasons. These values were significantly higher than those recorded under TP, MP + TP, and NP, which did not differ significantly. No significant differences among study site × growing season combinations were detected within any pruning system ($p > 0.05$) (Figure 6F).

For SSJ, no significant differences were detected among pruning systems within any study site × growing season combination or among study site × growing season combinations within any pruning system ($p > 0.05$) (Figure 6G). Numerically, the highest SSJ was recorded under MP at Pachacutec in 2024 (10.83 °Brix), whereas the lowest value was recorded under NP at Cieneguillo Sur in 2025 (10.29 °Brix).

For pHJ, no significant differences were detected among pruning systems within any study site × growing season combination or among study site × growing season combinations within any pruning system ($p > 0.05$) (Figure 6H). Numerically, the highest pHJ was recorded under MP at Pachacutec in 2024 (2.32), whereas the lowest value was recorded under MP + TP at Cieneguillo Sur in 2025 (2.07).

For TAJ, no significant differences were detected among pruning systems within any study site × growing season combination or among study site × growing season combinations within any pruning system ($p > 0.05$) (Figure 6I). Numerically, the highest TAJ was recorded under NP at Pachacutec in 2025 (4.25%), whereas the lowest value was recorded under TP at Cieneguillo Sur in 2024 (3.93%).

Similarly, VCJ did not differ significantly among pruning systems within any study site × growing season combination or among study site × growing season combinations within any pruning system ($p > 0.05$) (Figure 6J). Numerically, the highest VCJ was recorded under NP at Pachacutec in 2025 (60.48 mg 100 mL^{-1}), whereas the lowest value was recorded under MP + TP at Cieneguillo Sur in 2024 (57.82 mg 100 mL^{-1}).

3.4. Multivariate Analysis

Multivariate response patterns among pruning systems were examined using a heatmap with hierarchical clustering of standardized variables, principal component analysis (PCA), and Spearman correlation analysis.

The heatmap and hierarchical clustering showed that MP and MP + TP clustered more closely than TP and NP, reflecting greater similarity in their standardized multivariate response patterns (Figure 7). MP showed the highest standardized values for TCSA (Z = 1.60), NDF (Z = 1.25), JV (Z = 1.61), FW (Z = 1.51), PT (Z = 1.50), FV (Z = 1.42), EFD

(Z = 1.30), PFD (Z = 1.27), and pHJ (Z = 1.39). In contrast, MP + TP showed the highest standardized values for LA (Z = 1.68), NFB (Z = 1.21), and SSJ (Z = 0.87).

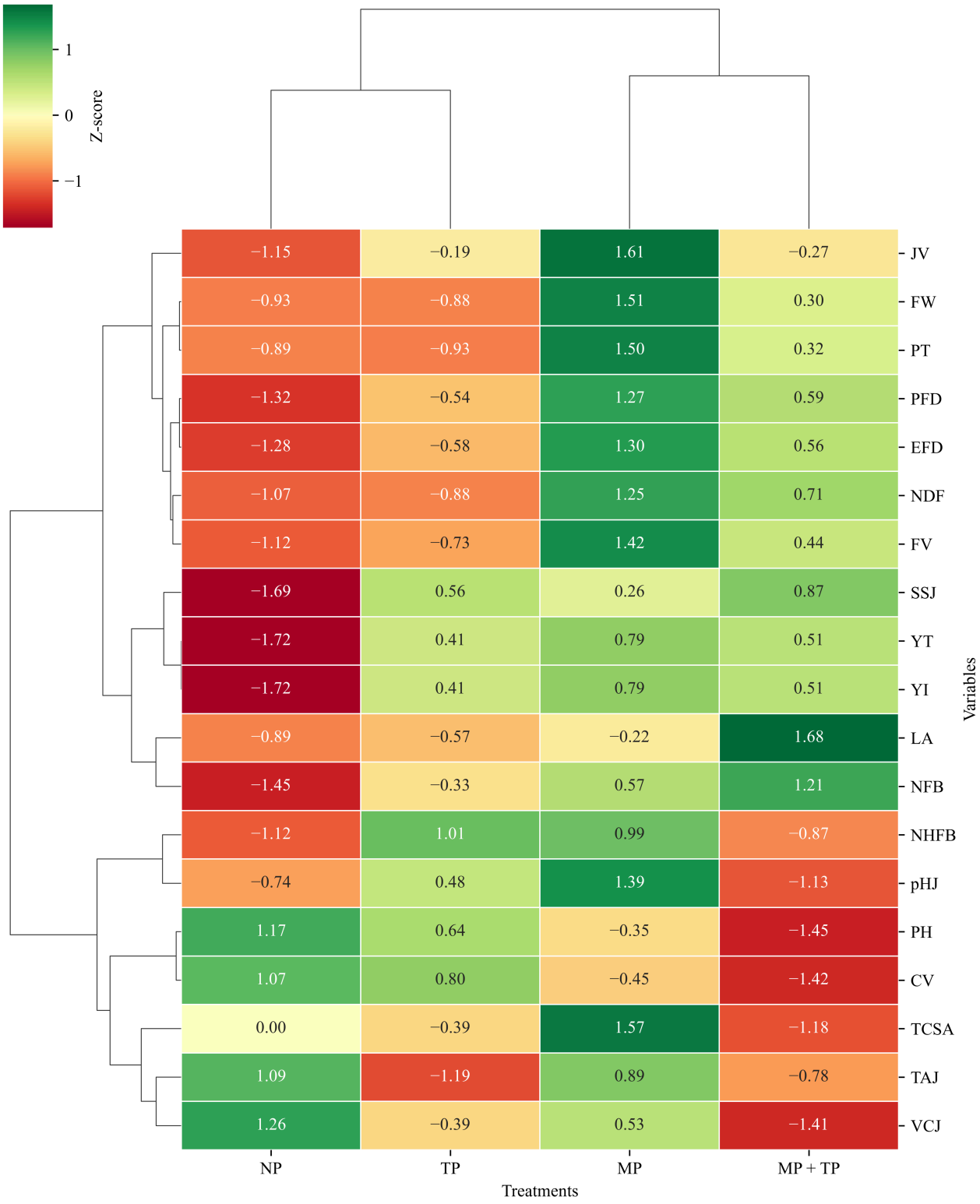


Figure 7. Heatmap and hierarchical clustering of plant growth, flowering, yield, and fruit physical and chemical variables under different pruning systems. Pruning systems: no pruning (NP), thinning pruning (TP), maintenance pruning (MP), and maintenance pruning combined with thinning pruning (MP + TP). Colors represent standardized values (Z-scores), with green indicating relatively high values and red indicating relatively low values. Dendrograms show hierarchical clustering among variables and pruning systems based on similarity in their standardized response patterns.

NP showed the highest standardized values for PH (Z = 1.17), CV (Z = 1.07), VCJ (Z = 1.26), and TAJ (Z = 1.09). TP showed an intermediate multivariate pattern, with relatively high standardized values for NHFB (Z = 1.01) and CV (Z = 0.80).

Hierarchical clustering of the variables identified three major groups (Figure 7). The first group comprised the fruit physical variables JV, FW, PT, PFD, EFD, and FV, which showed similar standardized response patterns. The second group comprised the fruit chemical variables SSJ, pHJ, TAJ, and VCJ. The third group comprised the vegetative growth variables PH, CV, LA, and TCSA, which formed a distinct cluster relative to the fruit physical and chemical variables.

The first two principal components explained 50.4% of the total variance, with PC1 accounting for 37.1% and PC2 for 13.3% (Figure 8). Given the proportion of variance explained, the two-dimensional PCA biplot was interpreted as an exploratory representation of the main multivariate patterns. PC1 was mainly associated with fruit physical traits and NDF. The largest positive loadings were observed for FV (0.368), PT (0.368), EFD (0.357), FW (0.356), PFD (0.329), JV (0.296), and NDF (0.290). The similar orientation of the fruit physical trait vectors in the PC1–PC2 space was consistent with positive associations among these variables. YT also showed a positive loading on PC1 (0.230). In contrast, PH (−0.200) and CV (−0.132) were projected toward the negative side of PC1, opposite to the direction of most fruit physical traits and YT.

PC2 was mainly associated with vegetative growth and fruit chemical variables. The largest positive loadings were observed for CV (0.459), PH (0.446), VCJ (0.437), TAJ (0.380), and TCSA (0.354). In contrast, YT showed a negative loading on PC2 (−0.220), whereas LA had a comparatively small negative loading (−0.080). Thus, the positive side of PC2 was primarily characterized by vegetative growth and some fruit chemical variables.

Spearman correlation analysis showed strong positive correlations among several fruit physical traits (Figure 9). FW was strongly and positively correlated with EFD (r = 0.95), FV (r = 0.93), and PT (r = 0.92). Similarly, FV was strongly correlated with EFD (r = 0.98) and PT (r = 0.98). Strong positive correlations were also observed between EFD and PT (r = 0.97) and between EFD and PFD (r = 0.80).

PH was negatively correlated with YT (r = −0.37), FW (r = −0.39), EFD (r = −0.45), PFD (r = −0.46), FV (r = −0.47), and PT (r = −0.46). CV also showed weaker negative correlations with FW (r = −0.15), EFD (r = −0.18), PFD (r = −0.24), FV (r = −0.25), and PT (r = −0.27). YT was positively correlated with JV (r = 0.56), whereas its correlation with SSJ was weaker (r = 0.21).

Within the PC1–PC2 space, MP was positioned on the positive side of PC1 and closer to FW, PFD, EFD, FV, PT, and TCSA, indicating a multivariate association with these traits (Figure 8). In contrast, NP was positioned mainly on the negative side of PC1 and the positive side of PC2, closer to PH and CV. TP and MP + TP occupied intermediate positions, and their confidence ellipses partially overlapped. MP + TP was positioned closer to NFB, NHFB, and pHJ. Given that PC1 and PC2 together explained 50.4% of the total variance, these associations should be interpreted as exploratory patterns within the two-dimensional PCA representation and considered together with the univariate and correlation analyses.

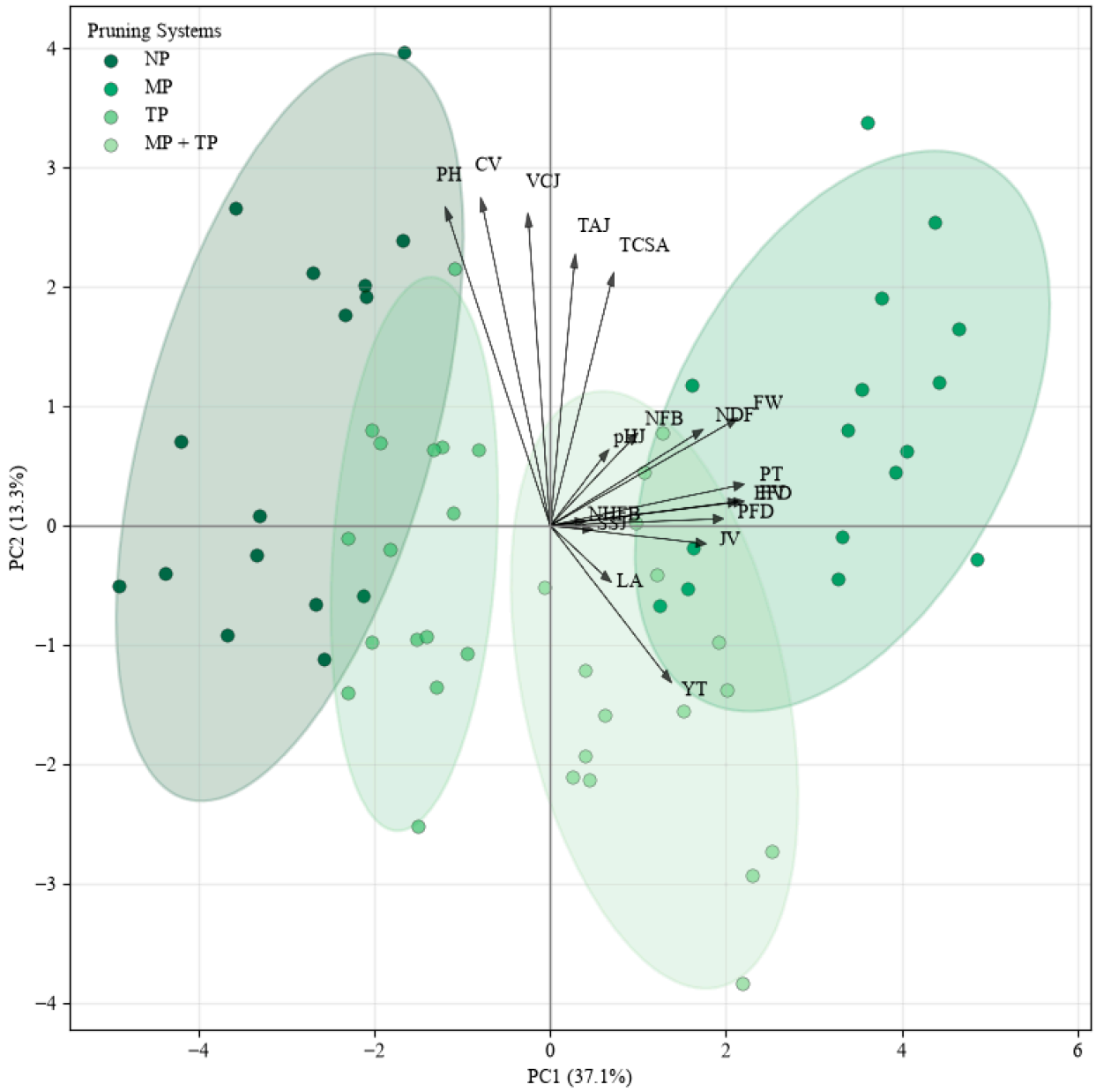


Figure 8. Principal component analysis (PCA) of plant growth, flowering, yield, and fruit physical and chemical variables of key lime (*Citrus aurantifolia* (Christm.) Swingle) under different pruning systems. Pruning systems: no pruning (NP), thinning pruning (TP), maintenance pruning (MP), and maintenance pruning combined with thinning pruning (MP + TP). Each point represents an experimental unit based on the mean of four trees within each block × pruning system combination for each study site and growing season. Ellipses represent the multivariate dispersion of experimental units within each pruning system. Arrows represent variable loadings, with their direction indicating associations with the principal components. PC1 and PC2 explained 37.1% and 13.3% of the total variance, respectively, accounting for 50.4% of the total variance.

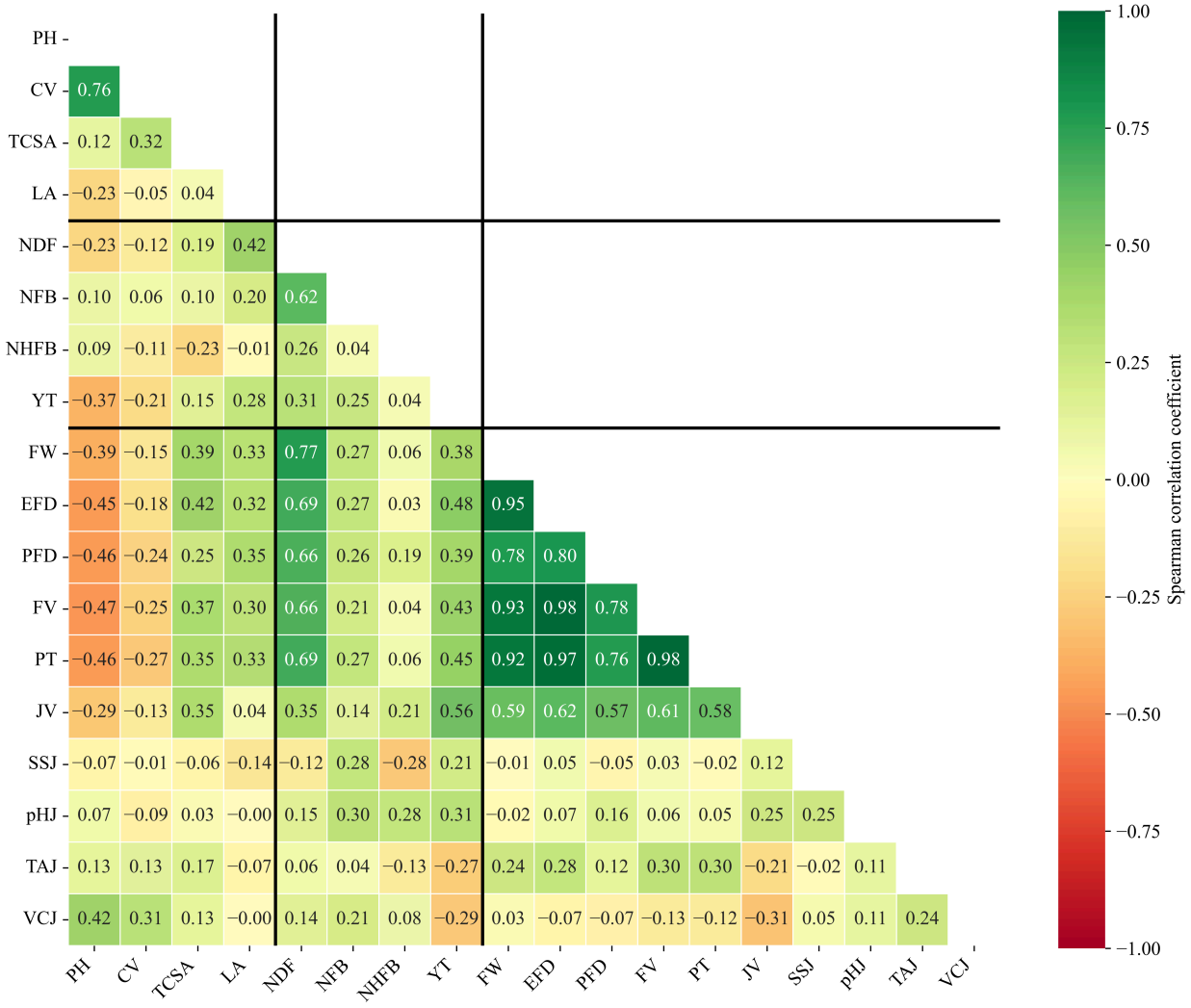


Figure 9. Spearman correlation matrix of plant growth, flowering, yield, and fruit physical and chemical variables of key lime (*Citrus aurantifolia* (Christm.) Swingle) under different pruning systems. Pruning systems: no pruning (NP), thinning pruning (TP), maintenance pruning (MP), and maintenance pruning combined with thinning pruning (MP + TP). Colors represent Spearman correlation coefficients, with green indicating positive correlations and red indicating negative correlations; color intensity reflects the magnitude of the correlation.

4. Discussion

4.1. Plant Growth Variables

Pruning is an important management practice in citrus production because it modifies canopy architecture, light interception, and the allocation of photoassimilates between vegetative and reproductive organs [35,36]. In the present study, pruning systems significantly affected PH, CV, TCSA, and LA, although some responses varied with growing season and study site. These results show that vegetative growth in key lime was influenced by both pruning and the conditions under which the pruning systems were evaluated.

The responses of PH and CV indicate that pruning intensity played an important role in regulating tree size and canopy development (Figure 4A,B). NP and TP generally maintained greater vertical growth and canopy expansion, whereas the more intensive MP + TP system tended to restrict these traits. The lower PH and CV observed after more intensive pruning may be associated with the removal of photosynthetically active tissues and changes in apical dominance and shoot growth [37,38]. Pruning-induced changes in hormonal regulation may also influence subsequent vegetative development [39–41].

However, pruning responses depend not only on the amount of tissue removed but also on pruning intensity [12] and the technique used [42].

Differences in PH and CV among study sites and growing seasons indicate that environmental conditions may also have contributed to vegetative growth responses. The relatively high PH and CV values recorded at Pachacutec in 2025 coincided with temperatures of approximately 25–29 °C during bud and shoot development (BBCH 00 and BBCH 30) (Figure 2). Temperatures below 24 °C have been reported to restrict vegetative growth in citrus [43] and can reduce photosynthetic activity [44], stomatal conductance [45], and CO_2 assimilation [44–46]. Goswami et al. [47] reported an optimum temperature range of 25–30 °C for vegetative growth in citrus. Thus, the temperature conditions observed at Pachacutec in 2025 may have favored vegetative development. Nevertheless, the contribution of temperature to the observed differences was not specifically evaluated in the present study.

TCSA responses depended on both pruning system and environmental conditions, as indicated by the significant pruning system × growing season and pruning system × study site interactions (Table 1; Figure 4C). MP generally maintained relatively high TCSA values, whereas MP + TP tended to show lower values, although the magnitude of these responses varied among study site × growing season combinations. Changes in TCSA after pruning may be associated with the redistribution of photoassimilates following partial canopy removal, which can influence biomass accumulation and cambial growth in woody tissues [48,49]. Conversely, intensive branch removal may reduce photosynthetically active leaf area and limit carbon availability for cambial development [50,51]. Partial canopy opening can also improve light distribution and leaf photosynthetic performance [52–54], which may contribute to differences in trunk growth. The variation in TCSA among study sites and growing seasons further suggests that environmental conditions may modulate cambial responses to pruning [55].

LA showed a different response from PH and CV. The relatively high LA values observed under MP + TP in some study site × growing season combinations may reflect compensatory vegetative growth after pruning (Figure 4D). Previous studies have associated post-pruning regrowth with the activation of latent buds and the development of vigorous shoots [37]. Changes in apical dominance and hormonal regulation, including cytokinin signaling, may contribute to this response [56,57]. Canopy opening may also improve light conditions for newly developing leaves [14,42]. However, bud activation, hormonal regulation, and leaf-level photosynthetic responses were not directly measured in the present study; therefore, these mechanisms should be considered possible explanations rather than demonstrated responses.

The multivariate analyses were generally consistent with the univariate patterns observed for vegetative growth (Figures 7–9). PH was negatively correlated with several fruit physical traits, including FW, EFD, PFD, FV, and PT, whereas CV showed weaker negative correlations with these variables. In the PCA, PH and CV were oriented toward the negative side of PC1, opposite to most fruit physical traits, which were associated with the positive side of this component. These patterns may reflect differences in the allocation of resources between vegetative growth and reproductive development [58,59]. However, because PC1 and PC2 together explained 50.4% of the total variance, the PCA should be interpreted as an exploratory representation of these multivariate relationships rather than as evidence of a definitive separation among pruning systems or groups of traits.

4.2. Flowering and Yield Variables

Flowering and yield in citrus depend on the balance between vegetative and reproductive growth, which is influenced by carbohydrate availability [60], hormonal regulation [61],

and environmental conditions during floral induction and fruit development [62,63]. In the present study, pruning system significantly affected NDF, NFB, NHFB, and YT, although the magnitude of these responses varied among study sites and growing seasons. NDF showed significant pruning system × growing season and pruning system × study site interactions, whereas NFB showed a significant pruning system × study site interaction. In contrast, no significant interactions of pruning system with growing season or study site were detected for NHFB or YT.

The response of NFB to pruning systems depended on study site, with differences being particularly evident at Pachacutec (Figure 5B). The relatively high NFB values observed under MP and MP + TP at this site suggest that canopy management before flowering may have influenced flowering intensity. Maintenance pruning removes part of the existing canopy and can alter source–sink relationships and photoassimilate distribution [16,64]. Subsequent regrowth and changes in canopy structure may also modify light distribution and the development of lateral shoots and buds [10,37]. Under MP + TP, flowering occurred after maintenance pruning and the first thinning intervention at BBCH 00–09. Therefore, the response observed under this pruning system may reflect the combined effects of canopy renewal and early regulation of vegetative growth.

Greater canopy openness can improve light penetration and photosynthetic activity, potentially favoring lateral bud development [42,65]. Changes in apical dominance and hormonal regulation after pruning may also contribute to bud break and floral differentiation [10,37]. However, these physiological processes were not directly measured in the present study and should therefore be considered possible explanations for the observed flowering responses.

The higher NDF and NFB values recorded at Pachacutec in both growing seasons may also reflect differences in environmental conditions between study sites (Figure 5A,B). Lower minimum temperatures during floral induction may slow plant metabolic activity and prolong the period preceding floral differentiation [62,63]. However, the specific contribution of temperature to the differences observed between study sites was not directly evaluated.

The exploratory PCA placed MP + TP closer to NFB and NHFB within the PC1–PC2 space (Figure 8), indicating a multivariate association with these reproductive traits. This pattern was generally consistent with the relatively high NFB values observed under MP + TP, particularly at Pachacutec (Figure 5B). Nevertheless, PC1 and PC2 together explained 50.4% of the total variance. Therefore, this pattern should be interpreted as complementary to the univariate results rather than as independent evidence of enhanced reproductive performance.

The higher YT values observed under TP, MP, and MP + TP relative to NP, together with the descriptive increases in YI (Figure 5D; Table 2), suggest a tendency toward increased productivity under pruning. This response may be associated with the selective removal of branches, which can reduce competition between vegetative and reproductive organs and modify photoassimilate allocation to developing fruits [10,26]. Canopy opening may also improve light distribution within the tree, potentially creating more favorable conditions for photosynthetic carbon assimilation during fruit development [52,66,67].

MP showed the largest numerical increase in YI relative to NP (9.70%), followed by MP + TP (8.64%) and TP (8.24%) (Table 2). However, these percentage differences were not statistically compared among pruning systems and should therefore be interpreted as descriptive trends rather than evidence of statistical superiority. The numerical response observed under MP may be associated with changes in the balance between vegetative growth and fruit production following partial canopy removal [10,27]. Removal of unproductive branches may also stimulate shoot renewal while maintaining sufficient photosyntheti-

cally active canopy [37]. In contrast, the absence of pruning may increase competition for photoassimilates between vegetative and reproductive sinks [27,28].

The multivariate analyses provided additional context for these responses. PH was negatively correlated with YT and several fruit physical traits, including FW and FV, whereas CV showed similar but weaker negative correlations with fruit physical traits (Figure 9). These relationships indicate that greater vegetative growth was not necessarily associated with higher yield or greater fruit size. Differences among study sites further indicate that productive responses were influenced by the conditions under which the pruning systems were evaluated. Temperature and soil nutrient availability have previously been identified as important factors affecting flowering and fruit production in key lime [62,68].

The heatmap also showed contrasting multivariate patterns among pruning systems (Figure 7). NP showed the highest standardized values for PH and CV, whereas MP showed high standardized values for TCSA and several fruit physical traits, including FW, FV, EFD, PFD, PT, and JV. This pattern was consistent with the correlation analysis and the PCA, in which PH and CV were oriented opposite to most fruit size-related traits along PC1. Thus, the greater canopy growth observed under NP was not accompanied by higher values for several fruit physical traits. These contrasting patterns may be related to pruning-induced changes in canopy architecture and light distribution, as canopy opening can improve light penetration and interception and thereby influence photosynthetic carbon assimilation and fruit development [10,52,66].

4.3. Fruit Physical and Chemical Variables

Fruit quality in citrus results from the interaction between fruit growth, water and photoassimilate accumulation, and biochemical changes during ripening [59,69]. These processes are influenced by tree photosynthetic capacity, carbohydrate allocation to reproductive organs, and environmental conditions during fruit development [70,71]. In the present study, pruning system significantly affected FW, EFD, PFD, FV, PT, and JV. In contrast, SSJ, TAJ, and VCJ were not significantly affected by pruning system, although a significant effect was detected for pHJ. Overall, pruning had a more pronounced effect on fruit physical attributes than on juice chemical attributes.

The generally higher FW, EFD, and FV values observed under MP, together with its relatively high PFD values, indicate that maintenance pruning was associated with greater fruit growth (Figure 6A–D). This response may be related to the selective removal of branches, which can reduce competition between vegetative and reproductive organs and improve light distribution within the canopy [26,27]. These changes may increase photoassimilate availability for developing fruits. Improved canopy light conditions can also enhance photosynthetic carbon assimilation and support cell division and expansion during fruit development [16,30].

The absence of significant pruning system × growing season and pruning system × study site interactions for FW, EFD, and FV indicates that the responses of these traits to pruning were relatively consistent across the evaluated conditions (Figures 6A,B,D and S1). In contrast, PFD showed a significant pruning system × study site interaction, indicating that its response to pruning depended partly on study site (Figure 6C). Environmental conditions during fruit development, particularly temperature, may also contribute to variation in fruit growth and final fruit characteristics [68,70]. However, their specific contribution to the responses observed in the present study was not directly evaluated.

The multivariate analyses supported the close relationships among fruit physical traits. FW, EFD, PFD, FV, PT, and JV formed a common hierarchical cluster in the heatmap (Figure 7), while the correlation analysis showed strong positive associations among several of these variables (Figure 9). In particular, FW was strongly correlated with EFD, FV, and

PT, while FV was strongly correlated with EFD and PT. These relationships are consistent with the coordinated changes in fruit dimensions and biomass that occur during fruit development through processes such as cell division and expansion [27,30].

MP also showed the highest PT and JV values across study sites and growing seasons (Figure 6E,F). These responses suggest that partial canopy removal may influence peel development and juice accumulation. Improved light interception after pruning can enhance canopy photosynthetic activity and carbohydrate availability [72], potentially supporting fruit tissue development and the accumulation of water and solutes in juice vesicles [27,28]. In contrast, NP showed the lowest JV values. Greater canopy density and self-shading under NP may have reduced light availability within the canopy and increased competition for photoassimilates between vegetative and reproductive organs [26]. However, canopy light interception and photoassimilate allocation were not directly measured in the present study, and these mechanisms should therefore be interpreted as possible explanations.

The absence of significant pruning system × growing season and pruning system × study site interactions for PT and JV indicates that their responses were relatively consistent across the evaluated conditions. The differences among pruning systems for these traits were therefore maintained across study sites and growing seasons (Figures 6E,F and S1).

Juice chemical attributes showed a different response from fruit physical traits. SSJ, TAJ, and VCJ were not significantly affected by pruning system (Table 1; Figure 6G,I,J). Although these variables showed some numerical variation among pruning systems, the differences were not statistically significant. Fruit maturity, genotype, and environmental conditions can influence citrus juice composition [12,16]; however, their contribution to the numerical variation observed in the present study was not specifically evaluated. Thus, the results indicate that SSJ, TAJ, and VCJ remained relatively stable across pruning systems under the conditions evaluated.

In contrast, the overall ANOVA detected a significant effect of pruning system on pHJ (Table 1). However, subsequent comparisons within individual study site × growing season combinations did not detect significant differences among pruning systems (Figure 6H). This result suggests that the overall pruning effect on pHJ was comparatively small and was not consistently expressed within individual study site × growing season combinations. Therefore, the pHJ response should be interpreted cautiously and should not be considered evidence of a consistent effect of pruning across environments.

The multivariate analysis further distinguished the response patterns of fruit physical and chemical attributes. In the heatmap, SSJ, pHJ, TAJ, and VCJ clustered separately from the main fruit physical traits, including FW, EFD, PFD, and FV (Figures 7 and S2). This pattern suggests that fruit physical and chemical attributes responded differently to the pruning systems. MP was characterized by relatively high standardized values for TCSA and several fruit physical traits, including FW, FV, EFD, PFD, PT, and JV, whereas the juice chemical variables showed less pronounced differences among pruning systems. Rather than indicating a uniform improvement across all traits, this multivariate profile suggests that MP was associated with a distinct balance between vegetative and reproductive responses. Such a pattern may be related to pruning-induced changes in canopy architecture and light distribution, which can influence photosynthetic activity and photoassimilate allocation between vegetative and reproductive organs [57,59]. However, these physiological processes were not directly measured in the present study. Therefore, the multivariate patterns should be interpreted as associations rather than evidence of the physiological mechanisms underlying the observed responses.

While the present study showed that pruning systems significantly affected vegetative growth, flowering, yield, and several fruit physical and chemical attributes in key lime, the

physiological mechanisms underlying these responses were not directly evaluated. Future studies should therefore incorporate measurements of photosynthetic rate and stomatal conductance to better elucidate the physiological processes associated with the observed responses. In addition, characterization of the internal canopy microclimate, particularly photosynthetically active radiation (PAR), would help clarify the relationships between pruning-induced changes in canopy structure and subsequent responses in fruit production and quality.

5. Conclusions

Pruning systems significantly affected vegetative growth, reproductive performance, yield, and fruit physical attributes in key lime under the edaphoclimatic conditions of the studied orchards in the Piura region. The evaluated pruning systems (MP, TP, and MP + TP) showed distinct vegetative and reproductive responses compared with the unpruned control (NP). MP was associated with relatively high yield and greater values for several fruit physical attributes, including fruit weight, diameter, volume, peel thickness, and juice volume, while most juice chemical attributes remained relatively stable across pruning systems. In contrast, NP generally maintained greater vegetative growth but lower yield. Some responses, particularly TCSA, LA, NDF, NFB, and PFD, depended on growing season and/or study site, highlighting the influence of environmental conditions on pruning responses. Under the conditions evaluated, MP combined relatively high yield with greater values for several fruit physical attributes; however, the descriptive yield increase should not be interpreted as evidence of statistical superiority over the other pruning systems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy16181790/s1, Figure S1: Representative key lime (*Citrus aurantifolia* (Christm.) Swingle) fruits under different pruning systems at Cieneguillo Sur and Pachacutec. Pruning systems: no pruning (NP), thinning pruning (TP), maintenance pruning (MP), and maintenance pruning combined with thinning pruning (MP + TP). Fruit images were scaled to their measured dimensions using a common graphical scale to allow direct comparison of fruit size among pruning systems and study sites. Scale bars represent 25 mm. Figure S2: Multivariate profile of plant growth, flowering, yield, and fruit physical and chemical variables of key lime (*Citrus aurantifolia* (Christm.) Swingle) under different pruning systems, expressed as stand-ardized values (Z-scores). Pruning systems: no pruning (NP), thinning pruning (TP), maintenance pruning (MP), and maintenance pruning combined with thinning pruning (MP + TP). Positive Z-scores indicate values above the mean for each variable, whereas negative Z-scores indicate values below the mean.

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Data Availability Statement: The dataset and Jupyter notebooks used to perform the statistical analyses in this study are publicly available in the GitHub repository: https://github.com/Hoseph22/pruning-systems-key-lime/tree/main (accessed on 3 August 2026).

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