The Pruning Paradox in Coffee Agroecosystems: Enhancing P Balance While Accelerating K Loss Under Different Fertilization Practices

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Abstract

This study evaluated the effects of canopy pruning, fertilizer type, fertilizer rate, and their interactions on nitrogen (N), phosphorus (P), and potassium (K) nutrient balances in an Arabica coffee agroforestry system. A 2 × 3 × 3 factorial experiments arranged in a completely randomized design with four replications (72 experimental units) was conducted at UB Forest, Malang, Indonesia (1,300 m above sea level) on an Inceptisol. The experimental factors consisted of pruning (pruned and unpruned), fertilizer type (organic, inorganic, and combined), and fertilizer rate (low, medium, and high). Nutrient balances were calculated as the difference between total nutrient inputs (initial soil nutrient stocks and fertilizer inputs) and outputs (final soil nutrient stocks, harvested yield, and litter), and analyzed using three-way analysis of variance (ANOVA) followed by Duncan's multiple range test at the 5% significance level.

Pruning exerted contrasting effects on nutrient balances by significantly increasing the P balance (244.50 vs. 225.03 kg ha^{-1}; $P < 0.01$) while decreasing the K balance (6,415.59 vs. 9,683.45 kg ha^{-1}; $P < 0.01$), whereas the N balance was not significantly affected. Fertilizer rate significantly influenced N and P balances, with the high fertilizer rate producing the greatest nutrient surpluses (911.40 kg N ha^{-1} and 466.55 kg P ha^{-1}), whereas the low fertilizer rate resulted in the only negative P balance (−32.28 kg ha^{-1}). Fertilizer type did not significantly affect the balances of N, P, or K. A significant pruning × fertilizer rate interaction was detected only for the P balance, indicating that the effect of pruning depended on fertilization intensity. These findings demonstrate nutrient-specific trade-offs associated with canopy pruning, improving P retention while accelerating K depletion. Integrating pruning practices with adequate K replenishment and balanced fertilizer application is therefore essential to maintain long-term soil fertility and nutrient sustainability in Arabica coffee agroforestry systems.

Keywords: Arabica coffee; agroforestry systems; canopy pruning; fertilizer management; nutrient balance; nitrogen; phosphorus; potassium; potassium depletion.

Introduction

Coffee production depends on adequate nutrient availability because coffee plants remove substantial amounts of nitrogen (N), phosphorus (P), and potassium (K) through harvested beans. According to FAO estimates, the production of one metric ton of coffee beans exports approximately 40 kg N, 2.2 kg P, and 53 kg K from the soil, emphasizing the importance of maintaining balanced nutrient cycling in coffee production systems (Salamanca-Jimenez et al., 2016). Among routine agronomic practices, canopy pruning is widely implemented to stimulate vegetative growth, rejuvenate productive branches, and sustain coffee yield (Dufour et al., 2019). Indonesia, the world's second-largest coffee-growing country with approximately 1.25 million ha of coffee plantations, relies predominantly on smallholder production systems, accounting for about 98% of the national coffee area, where canopy pruning is routinely practiced (Kurniawan et al., 2024).

Beyond its role in crop management, canopy pruning substantially modifies nutrient cycling within coffee agroecosystems. Pruning alters biomass allocation, litter production, decomposition dynamics, and root nutrient uptake, thereby changing both nutrient inputs and outputs at the field scale (Sauvadet et al., 2019). The magnitude of these changes depends not only on pruning intensity but also on fertilizer management, because fertilizer source and application rate determine the replenishment of nutrients removed through harvest and biomass export. Consequently, nutrient balance provides an integrated indicator of soil nutrient sustainability by quantifying the relationship between nutrient inputs and outputs.

However, nutrient depletion following pruning may not occur uniformly among essential macronutrients. Potassium is highly concentrated in vegetative tissues; therefore, removing pruning residues from the field can substantially increase K export and accelerate soil K depletion (Tully & Lawrence, 2016). In contrast, phosphorus may be partially recycled through litter decomposition and retained pruning residues, potentially improving P availability (Rahn et al., 2018). These contrasting nutrient pathways become particularly important in smallholder coffee systems, where fertilizer application rates are frequently below recommended levels, increasing the risk of negative nutrient balances and long-term soil fertility decline, especially for P and K (Haggar et al., 2011).

Previous studies have advanced the understanding of nutrient dynamics in coffee agroforestry, but important knowledge gaps remain. Kurniawan et al. (2024) evaluated the combined effects of pruning and fertilization on soil N dynamics in coffee agroforestry but focused exclusively on nitrogen without simultaneously assessing P and K balances. Sauvadet et al. (2019) demonstrated that shade trees improve soil nutrient availability in organic coffee systems, yet the specific contribution of coffee canopy pruning could not be separated from shade-tree effects. De Meersche et al. (2020) investigated nutrient cycling in coffee–*Erythrina* agroforestry systems in Central America, although their findings may not be directly transferable to Southeast Asian volcanic Inceptisols. Furthermore, the global nutrient balance database developed by Ludemann et al. (2024) provides valuable country-level estimates but lacks crop-specific and management-specific information, particularly regarding canopy pruning in coffee production systems.

Therefore, despite increasing interest in nutrient cycling within coffee agroforestry, it remains unclear how canopy pruning differentially affects N, P, and K balances under different fertilizer types and application rates. Addressing this knowledge gap is essential because nutrient-specific responses may require different nutrient management strategies to sustain soil fertility and crop productivity.

This study evaluated the effects of canopy pruning, fertilizer type (organic, inorganic, and combined), fertilizer rate (low, medium, and high), and their interactions on N, P, and K balances in an Arabica coffee agroforestry system. Unlike previous studies that focused on individual nutrients or single management factors, this research simultaneously quantified the balances of the three major macronutrients within a full factorial experimental design, enabling the assessment of nutrient-specific responses to pruning and fertilization. We hypothesized that canopy pruning would alter nutrient balances differently among N, P, and K because of their contrasting cycling pathways and that these responses would depend on fertilizer management.

2. Literature Review

Nutrient balance has become a widely adopted framework for evaluating the sustainability of agricultural production because it integrates nutrient inputs and outputs into a single measure of nutrient use efficiency and potential soil depletion (Ludemann et al., 2024). Within coffee agroecosystems, nutrient balance is commonly conceptualized as the difference between nutrients supplied through indigenous soil reserves and fertilization and those removed through harvested products, residual soil pools, and plant biomass (Tully & Lawrence, 2016). Although this framework is well established, most applications have emphasized the magnitude of nutrient surpluses or deficits rather than the ecological processes responsible for nutrient redistribution. Consequently, nutrient balance is frequently interpreted as a static accounting indicator, whereas management practices continuously reshape nutrient cycling through changes in biomass production, decomposition, and nutrient uptake. This limitation is particularly relevant because nitrogen, phosphorus, and potassium exhibit contrasting biogeochemical behavior in tropical soils. Nitrogen is characterized by rapid transformations and substantial losses through leaching and denitrification, making its balance highly responsive to fertilizer management (Kurniawan et al., 2024). Phosphorus follows a markedly different pathway, with its availability constrained by sorption processes involving aluminum and iron oxides under acidic tropical conditions (Salamanca-Jimenez et al., 2016). Potassium, despite often occurring in considerable quantities in volcanic soils, is readily exported through harvested biomass and pruning residues and may also be susceptible to leaching under unfavorable soil conditions (Tully & Lawrence, 2016). These differences suggest that management practices should not be expected to produce uniform responses across nutrients. Nevertheless, much of the existing literature continues to evaluate nutrient dynamics using aggregated indicators or single-nutrient approaches, limiting understanding of nutrient-specific responses.

Canopy pruning has generally been discussed as a practice that improves crop productivity and stimulates nutrient cycling through enhanced litter production and organic matter turnover. Experimental studies consistently demonstrate that pruning modifies soil biochemical properties, microbial activity, and nutrient availability (Kurniawan et al., 2024; Azizah et al., 2023; Rohani et al., 2024). However, these studies primarily assess changes in soil nutrient concentrations, microbial biomass, soil respiration, or plant growth, implicitly assuming that improvements in soil quality correspond to improvements in nutrient sustainability. Such an assumption deserves careful consideration because greater nutrient availability does not necessarily imply a favorable nutrient balance when nutrient export through harvested products or removed biomass simultaneously increases.

A similar pattern appears in studies examining nutrient cycling within coffee agroforestry systems. Research has shown that canopy structure and litter dynamics strongly influence nutrient return to the soil, decomposition processes, and soil organic matter accumulation (Smitha et al., 2022; Sauvadet et al., 2019). Yet these investigations generally emphasize the contribution of shade trees or litterfall to soil fertility without explicitly distinguishing the effects of coffee canopy pruning from other components of the agroforestry system. As a result, it remains difficult to isolate the specific role of pruning in regulating nutrient redistribution within coffee plantations.

The literature on fertilizer management reveals a comparable limitation. Long-term experiments demonstrate that increasing fertilizer application generally improves nitrogen and phosphorus balances, whereas potassium responses remain considerably more variable because they depend on harvest intensity, soil characteristics, and biomass removal (Sadeghian et al., 2020). At broader spatial scales, global nutrient balance assessments also indicate that potassium use efficiency is consistently lower than that of nitrogen and phosphorus across many tropical coffee-producing regions (Ludemann et al., 2024). Although these findings emphasize the importance of fertilizer management, they are largely derived from regional or national datasets that cannot adequately capture field-scale interactions among pruning, fertilizer source, and fertilizer rate.

Recent syntheses further recognize canopy management and fertilization as key determinants of soil fertility in coffee systems (Kiup et al., 2025). Nevertheless, the available evidence remains fragmented because pruning, fertilizer management, and nutrient dynamics are commonly investigated as separate processes rather than interacting components of a single nutrient cycling system. Likewise, studies that consider pruning frequently focus on individual nutrients, particularly nitrogen (Kurniawan et al., 2024), whereas broader agroforestry studies emphasize shade effects (Sauvadet et al., 2019) or regional nutrient budgets (Ludemann et al., 2024). Consequently, the literature provides limited understanding of how canopy pruning modifies the balances of N, P, and K simultaneously under different fertilization strategies. Addressing this conceptual gap is necessary to better explain nutrient-specific responses to management and to support the development of fertilization strategies that account for the contrasting ecological behavior of individual macronutrients rather than treating nutrient balance as a single integrated outcome.

3. Materials and Methods

3.1 Study site

The experiment was conducted in an Arabica coffee agroforestry plantation located in UB Forest, Sumbersari Hamlet, Tawangargo Village, Karangploso District, Malang Regency, East Java, Indonesia (7°49′27.2″ S, 112°34′41.0″ E). The site is situated at an elevation of approximately 1,300 m above sea level with an average annual rainfall of approximately 2,000 mm and a mean daily temperature of 23.61 °C. The agroforestry system consisted of 8–10-year-old Arabica coffee (*Coffea arabica* L.) grown beneath 35-year-old *Pinus merkusii* stands. The soil is classified as an Inceptisol (USDA Soil Taxonomy), corresponding to an Andic Humudepts subgroup, characterized by acidic pH, high cation exchange capacity, moderate base saturation, very low available phosphorus, silty clay loam texture, and bulk density below 1 g cm^{-3}. The experiment was conducted between July 2021 and December 2022, including field establishment, treatment application, sample collection, and laboratory analyses performed at the Soil Science Laboratory, Faculty of Agriculture, Universitas Brawijaya.

3.2 Experimental design

Most studies evaluating nutrient dynamics in coffee systems investigate either pruning or fertilization as independent management factors, making it difficult to distinguish their individual and interactive contributions to nutrient cycling. To overcome this limitation, the present study employed a fully factorial design that simultaneously evaluated canopy pruning, fertilizer type, and fertilizer rate under identical environmental conditions.

A three-factor factorial experiment was arranged in a completely randomized design (CRD) with four replications, resulting in 72 experimental units. The first factor consisted of canopy pruning with two levels: pruned and unpruned plants. Pruning included formative, production, and rejuvenation pruning, with the main stem maintained at approximately 1.5 m above ground level. The second factor comprised three fertilizer types: organic fertilizer (chicken manure), inorganic fertilizer (urea, SP-36, and KCl), and a combined treatment consisting of equal proportions of organic and inorganic fertilizers. The third factor was fertilizer rate, including low, medium, and high application rates. The medium rate represented farmers' common practice, the high rate followed the recommendation of the Indonesian Coffee and Cocoa Research Institute (ICCRI), whereas the low rate was determined from estimated nutrient removal through harvested coffee beans. The combination of these factors generated 18 treatment combinations.

Organic fertilizer was applied at 0.89, 11, and 17 kg $plant^{-1}$ for the low, medium, and high rates, respectively. For inorganic fertilization, the low, medium, and high application rates consisted of 0.14, 0.48, and 0.75 kg urea $plant^{-1}$; 0.07, 0.87, and 1.38 kg SP-36 $plant^{-1}$; and 0.13, 0.46, and 0.84 kg KCl $plant^{-1}$, respectively. The combined treatment received 50% of the corresponding organic and inorganic fertilizer rates. Fertilizers were incorporated into circular trenches approximately 1 m in diameter surrounding each coffee plant after shallow soil loosening.

3.3 Field management and sampling

Experimental plants were selected to minimize variability in age, canopy condition, slope position, and shade intensity. Each selected tree was permanently tagged before treatment application. The soil surface surrounding each plant was cleared of weeds and pre-existing litter within a circular area of approximately 1 m diameter. Litter traps (1 × 1 m) were installed 20 cm above the soil surface using bamboo supports to collect litterfall throughout the experimental period.

Soil samples for chemical analyses were collected before treatment application and twelve months after treatment from four points surrounding each coffee plant at a depth of 0–20 cm and composited into a single sample. Physical soil properties were determined before treatment, six months, and twelve months after treatment using intact core samples. Soil samples intended for biological analyses were collected after twelve months and transported under cooled conditions to preserve microbial activity.

Coffee cherries were harvested monthly during the harvesting season, while litterfall was collected monthly. Soil and air temperatures were recorded every seven days throughout the experiment.

3.4 Laboratory analyses

The nutrient balance calculations required quantification of nutrient pools in both soil and plant components. Soil total nitrogen was determined using the Kjeldahl method, available phosphorus using the Bray extraction method, and exchangeable potassium using flame photometry and atomic absorption spectrophotometry (AAS). Soil bulk density was measured using the core sampling method.

For plant materials, total nitrogen in coffee cherries and litter was analyzed using the Kjeldahl method, total phosphorus using the Olsen method, and total potassium using flame photometry and AAS. Fresh and dry biomass of harvested coffee cherries and litter were determined prior to nutrient concentration analyses. All laboratory analyses were conducted at the Soil Science Laboratory, Faculty of Agriculture, Universitas Brawijaya.

3.5 Nutrient balance calculation

Conventional assessments of fertilization frequently rely on changes in soil nutrient concentrations alone, which may underestimate nutrient depletion because nutrients removed through harvested products and plant residues are not explicitly considered. Therefore, this study adopted a nutrient balance approach integrating both nutrient inputs and outputs to quantify net nutrient accumulation or depletion under each treatment.

The nutrient balance for N, P, and K was calculated as:

Nutrient balance (kg ha^{-1}) = (initial soil nutrient + fertilizer input) − (final soil nutrient + harvested coffee nutrient + litter nutrient)

Soil nutrient concentrations were converted to kg ha^{-1} using soil bulk density and sampling depth (20 cm). Fertilizer inputs, harvested nutrient removal, and litter nutrient contents were converted to hectare-based values according to plant population and sampling area.

3.6 Statistical analysis

Data were analyzed using a three-way analysis of variance (ANOVA) to evaluate the main effects of canopy pruning, fertilizer type, fertilizer rate, and their interactions on N, P, and K balances. Prior to ANOVA, homogeneity of variance was evaluated using Levene's test, whereas residual normality was assessed using the Shapiro–Wilk, Anderson–Darling, D'Agostino–Pearson, and Kolmogorov–Smirnov tests. When treatment effects were significant ($P < 0.05$), mean separation was performed using Duncan's Multiple Range Test (DMRT) at the 5% significance level. Significant interactions were further explored using simple-effect analyses. All statistical analyses were conducted using SmartStatXL.

4. Results

4.1 Nitrogen balance

The three-way ANOVA showed that fertilizer rate had a highly significant effect on N balance ($P < 0.01$), whereas pruning, fertilizer type, and all interaction terms were not significant (Table 1). The coefficient of variation was 18.20%, indicating moderate variability among experimental units.

Table 1. Analysis of variance for nitrogen balance (kg ha^{-1}).

Source of variation	df	SS	MS	F-value	P-value	Significance
Pruning (P)	1	6,189.14	6,189.14	0.54	0.465	ns
Fertilizer type (F)	2	9,550.14	4,775.07	0.42	0.661	ns
Fertilizer rate (R)	2	5,757,328.86	2,878,664.43	251.67	<0.01	**
P × F	2	7,376.71	3,688.36	0.32	0.726	ns
P × R	2	19,704.12	9,852.06	0.86	0.428	ns
F × R	4	11,580.41	2,895.10	0.25	0.907	ns
P × F × R	4	41,729.23	10,432.31	0.91	0.464	ns
Error	54	617,674.78	11,438.42			
Total	71	6,471,133.41				

Note: ** = significant at $P < 0.01$; * = significant at $P < 0.05$; ns = not significant. CV = 18.20%.

Fertilizer rate produced a clear increase in N balance (Table 2). The high rate resulted in the greatest N surplus (911.40 kg ha^{-1}), followed by the medium rate (628.78 kg ha^{-1}), while the low rate produced the lowest N balance (222.44 kg ha^{-1}). All fertilizer rates maintained positive N balances, indicating that N inputs exceeded N outputs across treatments.

Table 2. Effect of fertilizer rate on nitrogen balance (kg ha^{-1}).

Fertilizer rate	Mean N balance
Low	222.44 a
Medium	628.78 b
High	911.40 c

Note: Means followed by different letters differ significantly according to Duncan's multiple range test at 5%.

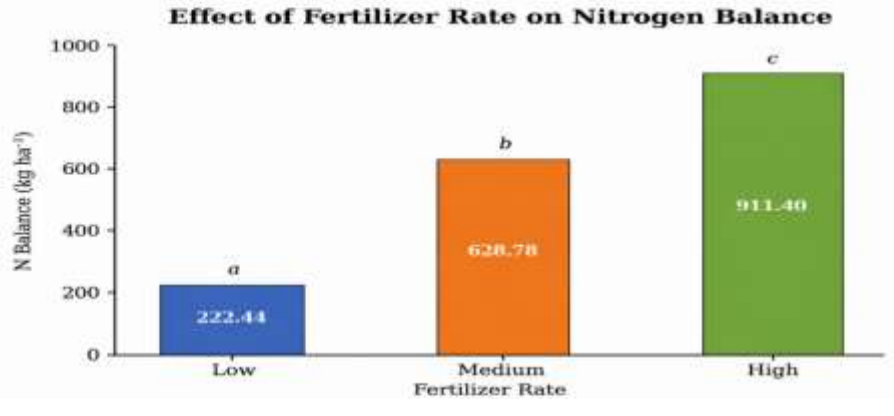

Figure 1. Effect of fertilizer rate on nitrogen balance. Different letters indicate significant differences according to Duncan's multiple range test at 5%.

4.2 Phosphorus balance

Phosphorus balance was significantly affected by pruning and fertilizer rate ($P < 0.01$), while the pruning × fertilizer rate interaction was also significant ($P < 0.05$) (Table 3). Fertilizer type and the remaining interaction terms were not significant. The coefficient of variation was 6.76%, indicating high experimental precision for this variable.

Table 3. Analysis of variance for phosphorus balance (kg ha^{-1}).

Source of variation	df	SS	MS	F-value	P-value	Significance
Pruning (P)	1	6,824.94	6,824.94	27.13	<0.01	**
Fertilizer type (F)	2	1,120.48	560.24	2.23	0.118	ns
Fertilizer rate (R)	2	3,030,724.21	1,515,362.11	6,023.52	<0.01	**
P × F	2	1,098.54	549.27	2.18	0.123	ns
P × R	2	1,942.62	971.31	3.86	0.027	*
F × R	4	901.48	225.37	0.90	0.473	ns
P × F × R	4	1,452.88	363.22	1.44	0.232	ns
Error	54	13,585.00	251.57			
Total	71	3,057,650.15				

Note: ** = significant at $P < 0.01$; * = significant at $P < 0.05$; ns = not significant. CV = 6.76%.

Pruned coffee plants showed a significantly higher P balance than unpruned plants (Table 4). The mean P balance under pruning was 244.50 kg ha^{-1}, compared with 225.03 kg ha^{-1} in unpruned plants.

Table 4. Effect of pruning on phosphorus balance (kg ha^{-1}).

Pruning treatment	Mean P balance
Unpruned	225.03 a
Pruned	244.50 b

Note: Means followed by different letters differ significantly according to Duncan's multiple range test at 5%.

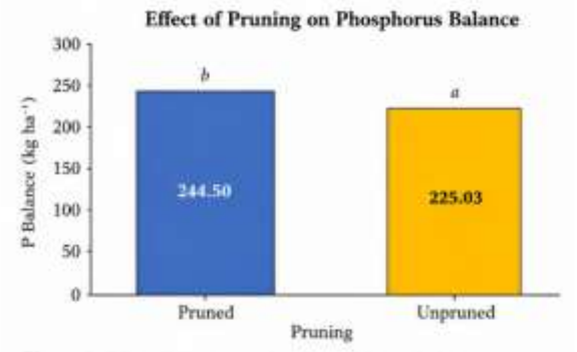

Figure 2. Effect of pruning on phosphorus balance. Different letters indicate significant differences according to Duncan's multiple range test at 5%.

Fertilizer rate also produced a strong response in P balance (Table 5). The high rate generated the highest P surplus (466.55 kg ha^{-1}), followed by the medium rate (270.02 kg ha^{-1}). In contrast, the low fertilizer rate resulted in a negative P balance (−32.28 kg ha^{-1}), indicating that P outputs exceeded P inputs at this rate.

Table 5. Effect of fertilizer rate on phosphorus balance (kg ha^{-1}).

Fertilizer rate	Mean P balance
Low	−32.28 a
Medium	270.02 b
High	466.55 c

Note: Means followed by different letters differ significantly according to Duncan's multiple range test at 5%.

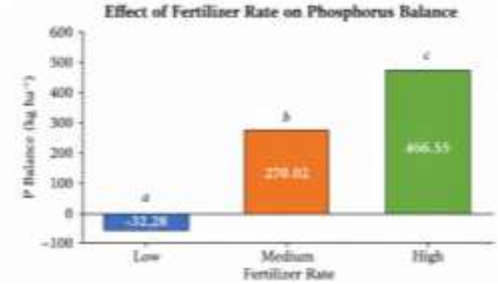

Figure 3. Effect of fertilizer rate on phosphorus balance. Different letters indicate significant differences according to Duncan's multiple range test at 5%.

The significant pruning × fertilizer rate interaction indicated that the effect of pruning on P balance depended on the level of fertilizer application (Table 6). At medium and high fertilizer rates, pruned plants had significantly higher P balances than unpruned plants. At the low rate, both pruned and unpruned plants showed negative P balances, with no significant difference between pruning treatments. Within each pruning treatment, the order of P balance was consistent: high > medium > low.

Table 6. Interaction between pruning and fertilizer rate on phosphorus balance (kg ha^{-1}).

Pruning treatment	Medium	High	Low
Pruned	280.20 bB	482.42 bC	−29.11 aA
Unpruned	259.85 aB	450.69 aC	−35.44 aA

Note: Lowercase letters compare pruning treatments within the same fertilizer rate; uppercase letters compare fertilizer rates within the same pruning treatment. Means followed by different letters differ significantly according to Duncan's multiple range test at 5%.

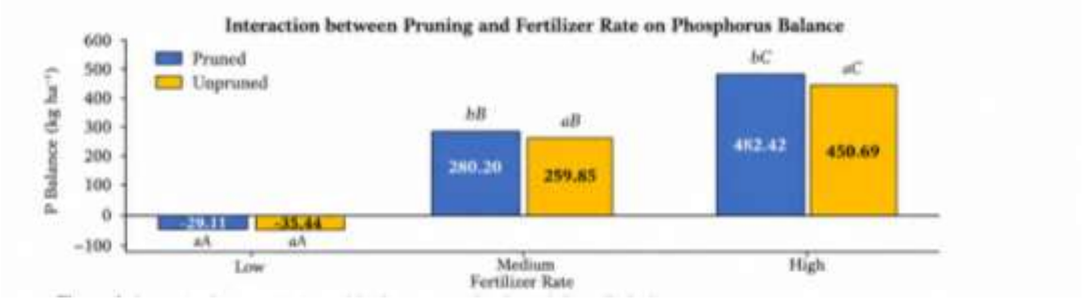

Figure 4. Interaction between pruning and fertilizer rate on phosphorus balance. Lowercase letters compare pruning treatments within the same fertilizer rate, while uppercase letters compare fertilizer rates within the same pruning treatment.

4.3 Potassium balance

Potassium balance was significantly affected only by pruning ($P < 0.01$), whereas fertilizer type, fertilizer rate, and all interaction terms were not significant (Table 7). The coefficient of variation was 52.11%, showing relatively high variability among experimental units.

Table 7. Analysis of variance for potassium balance (kg ha^{-1}).

Source of variation	df	SS	MS	F-value	P-value	Significance
Pruning (P)	1	192,220,133.94	192,220,133.94	10.93	0.002	**
Fertilizer type (F)	2	3,513.73	1,756.86	0.00	0.999	ns
Fertilizer rate (R)	2	9,478,136.14	4,739,068.07	0.27	0.765	ns
P × F	2	38,802.83	19,401.42	0.00	0.999	ns
P × R	2	3,841.19	1,920.60	0.00	0.999	ns
F × R	4	14,053.40	3,513.35	0.00	1.000	ns
P × F × R	4	16,034.46	4,008.62	0.00	1.000	ns
Error	54	950,006,991.69	17,592,722.07			
Total	71	1,151,781,507.39				

Note: ** = significant at $P < 0.01$; * = significant at $P < 0.05$; ns = not significant. CV = 52.11%.

Unpruned plants had a significantly higher K balance than pruned plants (Table 8). The mean K balance was 9,683.45 kg ha^{-1} in unpruned plants and 6,415.59 kg ha^{-1} in pruned plants. This pattern differed from the response observed for P balance, where pruning increased the nutrient balance.

Table 8. Effect of pruning on potassium balance (kg ha^{-1}).

Pruning treatment	Mean K balance
Pruned	6,415.59 a
Unpruned	9,683.45 b

Note: Means followed by different letters differ significantly according to Duncan's multiple range test at 5%.

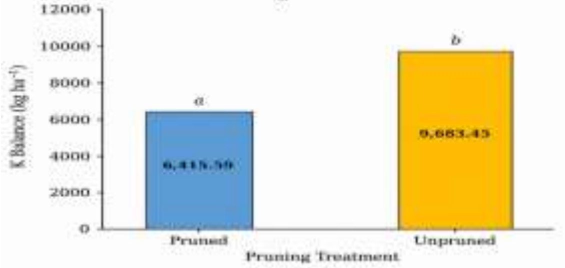

Figure 5. Effect of pruning on potassium balance. Different letters indicate significant differences according to Duncan's multiple range test at 5%.

Although fertilizer rate was not statistically significant, the mean K balance tended to increase from the low rate (7,617.37 kg ha^{-1}) to the medium rate (8,026.03 kg ha^{-1}) and high rate (8,505.17 kg ha^{-1}). However, this trend was not supported by statistical significance.

4.4 Summary of treatment effects on N, P, and K balances

The overall pattern of treatment effects differed among N, P, and K balances (Table 9). Fertilizer rate was the dominant factor affecting N and P balances, while pruning was the only factor affecting K balance. Pruning also affected P balance, but its effect depended partly on fertilizer rate, as shown by the significant pruning × fertilizer rate interaction. Fertilizer type did not significantly affect any of the three nutrient balances.

Table 9. Summary of treatment effects on N, P, and K balances.

Source of variation	**N balance**	**P balance**	**K balance**
Pruning (P)	ns	**	**
Fertilizer type (F)	ns	ns	ns
Fertilizer rate (R)	**	**	ns
P × F	ns	ns	ns
P × R	ns	*	ns
F × R	ns	ns	ns
P × F × R	ns	ns	ns

Note: ** = significant at $P < 0.01$; * = significant at $P < 0.05$; ns = not significant.

Figure 6. Comparison of pruning effects on N, P, and K balances. Different letters within each nutrient indicate significant differences according to Duncan's multiple range test at 5%.

Figure 7. Comparison of N, P, and K balances under different fertilizer rates. Potassium balance should be presented using a secondary Y-axis because its values are substantially higher than those of N and P.

Overall, N and P balances responded primarily to fertilizer rate, whereas K balance responded mainly to pruning. The low fertilizer rate maintained a positive N balance but produced a negative P balance, while all treatments showed positive K balances. The contrasting responses of P and K to pruning indicate that nutrient balance responses should be interpreted separately for each nutrient rather than as a single combined NPK response.

5. Discussion

The main finding of this study is that pruning did not produce a uniform response across N, P, and K balances. Instead, pruning increased the P balance, decreased the K balance, and did not significantly alter the N balance. This pattern suggests that canopy pruning should not be treated as a single agronomic practice with one generalized effect on soil fertility. Its effect depends on the nutrient being considered. This finding refines the conventional nutrient-balance framework, which often evaluates nutrient surplus or deficit as an aggregated outcome rather than as an element-specific process (Ludemann et al., 2024; Tully & Lawrence, 2011).

The absence of a significant pruning effect on N balance is consistent with the highly dynamic behavior of nitrogen in tropical agroecosystems. Nitrogen is easily transformed through mineralization, immobilization, nitrification, denitrification, and leaching, so changes in one N pool may not necessarily appear as changes in the total N balance. Kurniawan et al. (2024) reported that pruning increased soil total N and microbial biomass N in coffee agroforestry, but this does not automatically mean that the overall N balance becomes higher because N may also be redistributed into litter, microbial biomass, and plant uptake pathways (Kurniawan et al., 2024). Similar evidence from coffee agroforestry indicates that N dynamics are strongly affected by fertilizer management, litter quality, and microbial turnover rather than by canopy management alone (Azizah et al., 2023; Sauvadet et al., 2019; Salamanca-Jimenez et al., 2016).

The significant effect of fertilizer rate on N balance was expected because N input increased directly with fertilizer dose. The high fertilizer rate produced the largest N surplus, while the low rate still maintained a positive N balance. This result agrees with studies showing that coffee systems often require regular N inputs to sustain productivity, especially where harvest removes substantial nutrients from the system (Sadeghian et al., 2020; Haggar et al., 2011). However, a high N surplus should not be interpreted only as a positive outcome. Excess N can indicate inefficient nutrient use and possible risk of loss through leaching or gaseous emissions. Tully and Lawrence (2011) similarly showed that fertilized coffee agroforests may generate larger nutrient excesses than organic or unfertilized systems, implying that surplus nutrients require careful interpretation rather than automatic approval.

The response of P balance was different. Pruning significantly increased P balance, and this effect became clearer at medium and high fertilizer rates. This indicates that pruning may improve P retention only when enough P is supplied to the system. At the low fertilizer rate, both pruned and unpruned plants showed negative P balances, meaning that pruning alone could not compensate for insufficient P input. This result is consistent with the known behavior of P in acidic tropical soils, where P availability is strongly controlled by fixation with Al and Fe compounds (Salamanca-Jimenez et al., 2016). It also supports the argument that fertilizer rate, not fertilizer type, is the primary driver of P balance under these conditions.

The negative P balance at the low fertilizer rate is agronomically important. It suggests that low-input fertilization, which is common among smallholder coffee farmers, may gradually deplete soil P even when other nutrients appear sufficient. This finding aligns with broader studies showing that smallholder coffee systems often face soil fertility constraints because farmers apply fertilizers below crop demand due to limited capital, uncertain coffee prices, and weak access to technical support (Haggar et al., 2011; Adane & Bewket, 2021; Siles et al., 2022). In this sense, the P deficit observed here is not only a soil chemistry issue but also a smallholder management issue shaped by economic and institutional conditions.

The most contrasting result was observed for K. Pruning significantly reduced K balance, while fertilizer type and fertilizer rate had no significant effect. This suggests that the main K pathway affected by pruning was not fertilizer input but biomass removal. Potassium is highly concentrated in vegetative tissues and is more easily removed when branches, leaves, and pruning residues are taken out of the field (Tully & Lawrence, 2016). Smitha et al. (2022) showed that changes in canopy structure can reduce nutrient return through litter, especially for K, P, and Mg. Although their study focused on shade-tree composition, the mechanism is relevant here: modifying canopy biomass changes nutrient recycling.

The large reduction in K balance under pruning also agrees with global nutrient-balance evidence showing that K use efficiency is often lower and more variable than N and P in tropical agricultural systems (Ludemann et al., 2024). In this study, K balance remained positive, but the decline caused by pruning was substantial. Therefore, the issue is not immediate K deficiency, but the possibility of gradual K depletion if pruning is repeated over many years without returning biomass or increasing K replenishment. This interpretation is consistent with long-term coffee studies showing that K demand is strongly linked to harvest intensity, biomass cycling, and soil reserves (Sadeghian et al., 2020; De Meersche et al., 2020).

The finding that fertilizer type did not significantly affect N, P, or K balance should be interpreted carefully. It does not mean that organic, inorganic, and mixed fertilizers are functionally identical. Rather, under the conditions of this study, the total nutrient balance was more sensitive to fertilizer rate and pruning than to nutrient source. Organic and mixed fertilizers may still improve microbial biomass, soil structure, pH buffering, and organic matter turnover, as shown by Azizah et al. (2023), Rohani et al. (2024), and recent microbial studies in coffee agroforestry (Matondang et al., 2025). However, those improvements may not directly translate into short-term changes in NPK balance within one cropping cycle.

These results also contribute to the broader literature on coffee pruning. Pruning has long been recognized as a central practice in coffee cultivation, from early agronomic work by Iglesias (1936) to more recent studies showing that pruning time and system strongly affect growth, photosynthesis, yield, and plantation age dynamics (Morais et al., 2012; Somarriba & Quesada, 2022). However, much of this literature evaluates pruning mainly through productivity and canopy renewal. The present study adds a nutrient-balance perspective by showing that pruning may improve one nutrient balance while weakening another. This helps explain why pruning recommendations cannot rely only on yield response; they must also consider nutrient replacement.

The findings are also relevant to coffee agroforestry debates. Shade coffee systems are widely valued for biodiversity, carbon storage, microclimate regulation, and farmer livelihood benefits (Jha et al., 2011; Pinoargote et al., 2017; Siles et al., 2022; Miller & Stratford, 2025). Shade trees can also affect coffee leaf rust pressure at field and landscape scales (Avelino et al., 2023; Koutouleas, 2023). Yet agroforestry benefits depend on management. When pruning residues or litter are removed, the system may lose part of its nutrient-recycling advantage. This is why the ecological value of agroforestry should be evaluated together with actual biomass management, not only tree presence.

From a socioeconomic perspective, the results fit within a wider “coffee paradox”: coffee landscapes often produce environmental and market value, but smallholders do not always receive enough economic return to maintain soil fertility investments (Daviron & Ponte, 2008; Babin, 2015). Certification and value-chain systems may promote sustainability narratives, but they do not always solve the practical burden of labor, nutrient replacement, and farm-level risk (Mutersbaugh, 2004a, 2004b; Sirdey & Lemeilleur, 2021; Cano-González & Quiñones-Ruiz, 2025). Therefore, recommending pruning without addressing K replacement may transfer hidden ecological costs to farmers.

The practical implication is clear. Farmers who prune coffee should not only focus on canopy renewal but also manage the nutrient consequences of removed biomass. Returning pruning residues as mulch, composting pruned biomass, or increasing K fertilizer after pruning are possible strategies. McOsker (2026) similarly argues that coffee leaves and fruit residues may be monetized or reused to support regenerative agriculture, although such approaches must be adapted to local labor and market conditions. Evidence from root-pruning studies in perennial crops also shows that pruning can alter plant hydraulic and physiological status, reinforcing the need to view pruning as a whole-plant intervention rather than a simple mechanical operation (Knight et al., 2019).

The policy implication is that fertilizer recommendations for coffee should include pruning status as a management variable. Current recommendations often emphasize plant age, yield target, and soil test values, but this study suggests that pruning can change nutrient output pathways, particularly for K. In smallholder systems, this is especially important because farmers commonly modify recommended technologies according to local constraints, labor availability, and resource access (Kalanzi et al., 2022). Thus, extension programs should avoid rigid recommendations and instead provide flexible nutrient-management options after pruning.

This study also has limitations. First, the research covered one production cycle, so long-term nutrient depletion could not be fully assessed. Second, K balance showed high variability, suggesting strong spatial heterogeneity in soil K reserves. Third, leaching and runoff were not directly measured, although these pathways are important in sloping tropical agroecosystems. Fourth, the nutrient content of removed pruning biomass was not directly quantified, which limits precise estimation of K export through pruning residues. Future studies should use multi-year designs, lysimeter-based leaching measurements, direct biomass nutrient analysis, and economic evaluation of K replacement strategies.

Some broader references on “paradox” and methodological interpretation also help frame this study cautiously. In other fields, paradox is often used to describe tensions between intended benefits and unintended consequences, such as sustainability paradoxes in industry (Runfola et al., 2024), learning and knowledge paradoxes in the AI era (Oakley et al., 2025), or certification paradoxes in organic coffee systems (Mutersbaugh, 2004a, 2004b). However, in this study, the term "pruning paradox" should remain strictly agronomic: pruning improved P balance but reduced K balance. It should not be overstated beyond the measured nutrient-balance evidence. Similarly, references from outside coffee nutrient science, such as Cmelik et al. (2006), are not directly useful for explaining NPK cycling, although they remind us that crop-management evaluation often depends on the response variable chosen.

Overall, this study shows that nutrient balance in coffee agroforestry is nutrient-specific, not uniform. Fertilizer rate mainly controlled N and P balances, pruning mainly controlled K balance, and fertilizer type had no detectable effect on NPK balance within the study period. The main contribution is therefore conceptual and practical: pruning should be managed as both a canopy-renewal practice and a nutrient-export pathway. In sustainable coffee systems, maintaining productivity requires not only applying fertilizer, but aligning fertilizer rate, biomass return, and pruning management with the distinct behavior of N, P, and K.

Untuk standar **Q1 (Agriculture, Ecosystems & Environment, Field Crops Research, Nutrient Cycling in Agroecosystems)**, bagian **Conclusion** sebaiknya **bukan mengulang hasil**, tetapi **menegaskan implikasi konseptual**. Reviewer biasanya menyukai conclusion yang menjawab **"so what?"** daripada hanya mengulang angka.

Berikut versi yang lebih tajam, lebih kritis, dan bergaya profesor.

6. Conclusions

This study demonstrates that canopy pruning should not be interpreted as a universally beneficial management practice for nutrient conservation in coffee agroecosystems. Instead, its effects are nutrient-specific and operate through contrasting nutrient cycling pathways. While pruning significantly increased the phosphorus balance, it simultaneously reduced the potassium balance, whereas nitrogen balance remained unaffected. These contrasting responses challenge the common assumption that agronomic practices influence soil fertility uniformly across macronutrients. Rather, they indicate that nutrient balance should be evaluated as an element-specific process governed by the distinct biogeochemical behavior of N, P, and K.

Fertilizer rate emerged as the primary determinant of nitrogen and phosphorus balances, with progressively greater nutrient surpluses observed as application rates increased. In contrast, fertilizer source had no detectable influence on nutrient balance, suggesting that nutrient quantity was more influential than nutrient form under the conditions of this study. The occurrence of phosphorus deficit exclusively under the low fertilizer rate further indicates that fertilizer reduction below crop nutrient demand may compromise the long-term sustainability of coffee production, even when short-term crop performance appears acceptable.

The most important contribution of this study is not simply the identification of significant treatment effects, but the demonstration that a single management practice can simultaneously improve the balance of one nutrient while accelerating the depletion of another. This finding extends the conventional nutrient balance framework, which generally evaluates nutrient surpluses and deficits as aggregated indicators, by demonstrating that management effects cannot be generalized across nutrients. Consequently, sustainable nutrient management in perennial coffee systems requires moving beyond integrated NPK recommendations toward nutrient-specific strategies that explicitly account for the contrasting ecological behavior of individual macronutrients.

Practical implications and future research

From a management perspective, pruning should be accompanied by practices that compensate for potassium export, including increased K fertilization or the return of pruning residues to the field as mulch or organic amendments. Likewise, prolonged application of low fertilizer rates should be avoided because it consistently generated negative phosphorus balances, indicating progressive nutrient mining of the soil.

Future research should evaluate nutrient balances over multiple production cycles to determine whether the observed potassium decline represents a transient response or cumulative nutrient depletion. Quantifying nutrient losses through leaching and runoff, together with direct measurements of nutrient concentrations in removed pruning biomass, would substantially improve nutrient balance estimation. Expanding this work across contrasting soil types, climatic regions, and coffee agroforestry systems will also be essential to determine the extent to which the pruning paradox identified in this study represents a general ecological phenomenon rather than a site-specific response. Such evidence would strengthen the development of adaptive nutrient management strategies capable of simultaneously sustaining coffee productivity and long-term soil fertility.

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