

Farm management and yield gaps in Robusta (*Coffea canephora*) coffee production across the three largest Asian origins

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ABSTRACT

Robusta coffee is a key livelihood crop in Asia, and its productivity differs largely across main regions. However, the factors underlying these differences remain limited. This study examines yield variation across Vietnam, Indonesia, and India, the three largest Robusta-producing countries in Asia. Using 13,525 farm-level surveys, the study applied descriptive statistics, correlation analysis, and regression-based threshold methods to assess the relationships between yield and key management practices. The results show that median yields reach 2,643 kg GBE ha⁻¹ in Vietnam, compared with 1,359 kg ha⁻¹ in India-Karnataka, 509 kg ha⁻¹ in India-Kerala, and 383 kg ha⁻¹ in Indonesia. Correlation analysis shows that inorganic fertilizer use is positively associated with yield across the three countries, with coefficients ranging from 0.326 to 0.408. Pruning practices are also associated with higher yields in several regions, whereas shade levels are negatively related to yield in Vietnam. These findings indicate that yield gaps in Asian Robusta systems arise from different constraints across countries. Input scarcity appears to constrain productivity in Indonesia, while inefficiencies in nutrient management and structural characteristics of production systems play a larger role in Vietnam and India. The results highlight the need for context-specific strategies to improve productivity and sustainability in Robusta coffee production.

Key words: Yield differences; fertilizer efficiency; shade management; plantation rejuvenation; Robusta coffee.

1 INTRODUCTION

Coffee plays a vital role in rural economies in developing countries, supporting the livelihoods of over 12 million farming families (UN, 2015; Poncet, 2024). Global coffee consumption is projected to grow by 1–2% annually, further reinforcing the crop's economic importance (International Coffee Organisation - ICO, 2023). However, coffee production faces increasing threats from environmental degradation and climate change, which affect crop suitability, productivity, and the prevalence of pests and diseases (Pham et al., 2019; Koutouleas et al., 2022; Jawo et al., 2023).

Asia is a key region for global coffee production, led by Vietnam, Indonesia, and India. Vietnam is the largest producer in the region, contributing approximately 17.7% of global coffee output and generating around USD 5 billion in value, largely driven by Robusta production. Indonesia accounts for about 7% of global production, while India contributes roughly 3% and plays an important role in Robusta markets (ICO, 2023). While Vietnam's coffee sector is highly export-oriented, Indonesia and India maintain a more balanced approach between domestic consumption and international trade (Giang & Sarker, 2018). Despite their respective strengths, all three countries face persistent challenges, including the impacts of climate change, global price volatility, and significant productivity gaps (Byrareddy, 2021; Jawo et al., 2023).

Substantial yield gaps, commonly defined as the difference between potential yield under optimal conditions and

the actual yield achieved on farms, are present across producing regions (Lobell et al., 2009; Grassini et al., 2015). Yield gaps are not only determined by biophysical constraints such as soil and climate but also by management inefficiencies, input limitations, structural barriers, and knowledge gaps (Cassman et al., 2003; Lobell et al., 2009). Yield gap analyses have become a widely used framework to diagnose production inefficiencies and identify opportunities for sustainable intensification, particularly when based on farm-level data rather than experimental trials ((Grassini et al., 2015) et al., 2015).

In coffee systems, empirical evidence suggests that management practices play a particularly important role in explaining yield variation. In addition, fertilizer application, tree density, and shade management have also been identified as key determinants of coffee yields across different production contexts (Byrareddy et al., 2019; Tran et al., 2021). Shade trees, for example, can buffer temperature extremes, reduce erosion, and limit excessive radiation, but may also involve trade-offs with productivity depending on shade intensity and management (Piato et al., 2020; Hagggar et al., 2021; Koutouleas et al., 2022). Similarly, irrigation management has been shown to influence yield outcomes, especially in regions facing increasing climatic variability (Castanheira et al., 2019).

However, most previous studies rely on experimental trials or small regional datasets, while large-scale farm-level diagnostics of agronomic efficiencies across major Robusta-producing countries remain limited. In particular, few studies compare how management practices such as fertilizer use

efficiency, pruning, and shade systems shape yield outcomes across different Asian coffee systems. Understanding yield gaps, therefore requires a careful assessment of how current farming practices contribute to productivity differences under specific local conditions across the Asia region (Bacsi et al., 2022; Suárez et al., 2022).

Using 13,525 farm surveys collected across major Robusta-producing regions in Vietnam, Indonesia, and India, this study provides a large-scale comparative assessment of yield variation and its main agronomic drivers. By combining descriptive statistics, correlation analysis, and regression-based threshold methods, we examine how fertilizer use efficiency, pruning and rejuvenation practices, and shade management shape yield outcomes across contrasting production contexts. In doing so, the study contributes to the yield gap literature by extending farm-level diagnostics to perennial Robusta systems and by identifying distinct yield-gap archetypes that characterize the major Asian origins.

2 MATERIAL AND METHODS

2.1 Study area and Data collection

This study uses data from the 2023-2024 Enveritas Coffee Survey (ECS). The data collection methodology follows the ECS approach described by Tran et al. (2021). The survey collects information on social, environmental, and economic aspects of coffee farming, including farming practices, productivity, pricing, access to training and finance,

labor relations, health and safety, biodiversity, soil and water conservation, and chemical use. ECS employs machine learning and high-resolution satellite imagery to identify coffee-growing regions and randomly generate geo-referenced sampling points. Field enumerators visited these locations and randomly identified coffee-farming households within a 2 km radius of the assigned points. Selected households were interviewed in person using a mobile data collection application. Surveys were conducted during regional harvest periods to capture representative farming activities. All responses underwent quality control and outlier detection procedures, and approximately 5% of surveys were backchecked to ensure data reliability. Geographic, farm, and household characteristics are summarized in Table 1. Given the large dataset and the presence of skewed distributions, particularly when large estate-style farms are visited, the median was used for selected variables as a more robust measure of central tendency than the mean to avoid overrepresentation of statistical outliers.

Table 1 presents the main characteristics of the surveyed farms and households across the three countries. As mentioned earlier, Vietnam, Indonesia, and India are the three largest coffee producers, all dominated by Robusta. In total, 13,525 coffee farms were surveyed across eleven regions, representing the main Robusta-producing areas, as indicated in the Figure 1. The table reports key household and farm attributes, including farmer age, number of plots, farm size, and tree density. These variables provide an overview of the structural and management characteristics of coffee production systems represented in the survey sample.

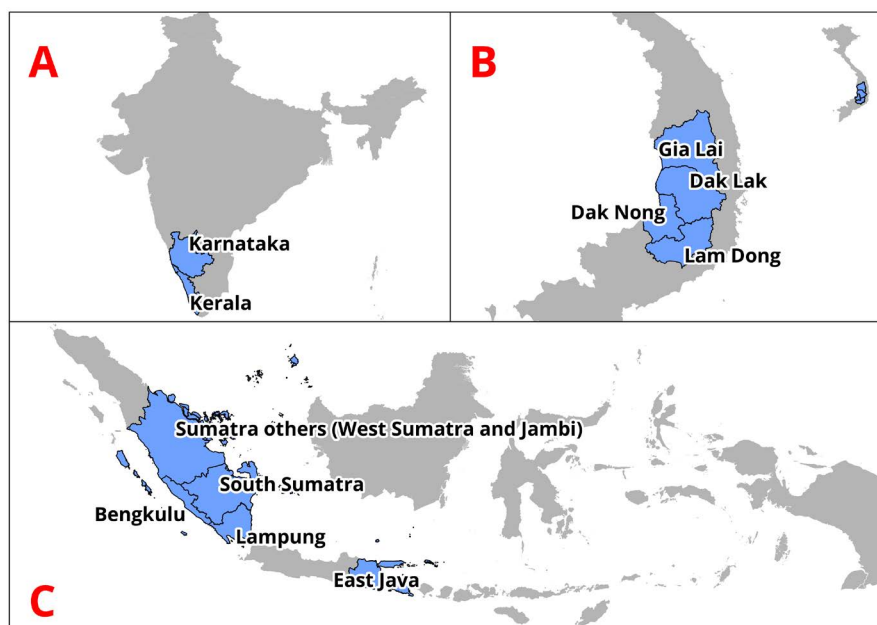


Figure 1: Geographical scope of the study. Data was collected from coffee farmers in the following regions: India (A) - Karnataka, Kerala; Vietnam (B) - Gia Lai, Dak Lak, Dak Nong, Lam Dong; Indonesia (C) - other Sumatra (West Sumatra and Jambi), Bengkulu, South Sumatra, Lampung, East Java.

Table 1: Overview of the farm and household characteristics.

Information	Vietnam	Indonesia	India
% of farmers who grow Robusta	96%	85%	72%
Total number of provinces visited	4	5	2
Total number of surveys collected	4626	7.306	1.593
Data collection period	Oct to Dec	May to Nov	Dec to Jan
Average survey length (minutes)	71	72	58
Average coffee farmer's age	50	49	52
Median farm size (ha)	1.0	1.0	0.8
Median number of plots	2	1	1
Median coffee trees per ha	1.000	2.333	1.112
% of female farmers interviewed	29%	27%	19%

2.2 Variable definitions and explanation

- Yield: Farmers were asked to report all forms of coffee harvested during the previous year. Reported amounts were converted to green bean equivalent (GBE). Conversion rates accounted for coffee type and country: in Vietnam, 4.5 kg of cherry or 2.25 kg of dry cherry equals 1 kg GBE; in Indonesia and India, 5 kg of cherry or 2 kg of dry cherry equals 1 kg GBE. Yield measurements are standardized to only include the productive area in calculations. We note that production volumes and farm sizes are self-reported by farmers and may be subject to recall bias or reporting errors.

- Inorganic fertilizer use: Data were collected by asking farmers and verifying fertilizer bags observed on farms. Total inorganic fertilizer use was calculated as the amount of fertilizer applied per round multiplied by the number of application rounds, recorded either per unit of area or per tree, and then converted to a per-hectare basis. Total fertilizer mass was reported rather than nutrient-specific rates, acknowledging that conversion to pure nutrient content is possible but beyond the scope of this study. Fertilizer use is reported in kg per hectare, with the number of trees per hectare provided in Table 1 for conversion to a per-tree basis. Fertilizer application volumes are based on farmer recall and may be subject to reporting inaccuracies.

- Fertilizer price: For regression analysis, fertilizer cost was based on the most commonly used fertilizer type in each country (India: NPK 17-17-17; Indonesia: NPK 15-10-12; Vietnam: NPK 16-16-8). Prices were standardized to 2023–2024 market rates: USD 0.18 kg⁻¹ (India), USD 1.20 kg⁻¹ (Indonesia), and USD 0.50 kg⁻¹ (Vietnam). Prices were collected by field team members from multiple agronomy input stores at each location and averaged for reporting. Limitations exist for regional variations in fertilizer prices that may have been overlooked due to budget or time constraints.

- Revenue: Revenue increases were estimated as yield increase (GBE ha⁻¹) × farmgate price, with price at USD

1.47 kg⁻¹ (India), USD 1.68 kg⁻¹ (Indonesia), and USD 1.10 kg⁻¹ (Vietnam). Farmgate price was reported by farmers and recorded at the time of the survey. We note that farmgate prices received are self-reported by farmers and may be subject to reporting errors.

- Pruning: Pruning practices were assessed through both farmer-reported questions and field observations by enumerators. Practices recorded included: dead or unproductive branch removal, replanting, stumping, desuckering, topping, selective pruning, skeletal pruning, and grafting.

- Tree Age: Farmers were asked to report the most common age of coffee trees on their farm.

- Shade level: Shade cover was assessed by enumerators and classified into five categories: no shade (0%), minimal (1–20%), light (21–40%), medium (41–60%), and heavy (61–100%). Shade levels were drawn from the literature (Wintgens, 2012) and classified internally into defined ranges.

- Farm income was estimated as coffee production volume multiplied by the price received, adjusted by the share of income from coffee (all = 1; more than half = 0.75; half = 0.5; less than half = 0.25; very small amount = 0.1).

2.3 Data analysis

All analyses were conducted in R, including descriptive statistics (median, standard error of the mean) and correlation/regression (R Core Team, 2023).

Farm data was grouped by country, except for India, where Karnataka and Kerala were grouped separately because of substantial differences in farming practices between the two regions. The relationship between yield and inorganic fertilizer use was tested using a generalized additive model (GAM) and 95% confidence intervals. Segmented analysis was also done to determine the linear relationship and change thereof, as well as the breakpoint at which the change happens. Additionally, differences in yield between farms with and without pruning, differences in yield and income between farms with and

without intercropping were assessed using Wilcoxon's rank-sum test ($p < 0.05$, 0.01, 0.005, and 0.001) (Wilcoxon, 1945). Furthermore, shade level effects on yield across countries were examined with Dunn's post-hoc tests, with p-values adjusted using the Benjamini–Hochberg method ($p < 0.0001$, 0.001, 0.01, 0.05) (Dunn, 1964; Benjamini & Hochberg, 1995).

3 RESULTS

3.1 The yield variation in Asia

Figure 2 presents an analysis of median coffee yields across different countries, measured in kilograms of GBE per productive hectare for Robusta. The density plots reveal clear differences in yield levels and variability among countries. Vietnam not only achieves higher productivity but also shows a yield distribution concentrated around higher yield levels. In contrast, both India and Indonesia display significantly lower productivity and more dispersed yield distributions, which indicate greater variability in yield outcomes. Overall, the figure highlights substantial cross-country differences in Robusta productivity. The large yield disparities highlight significant potential for improvement.

They further indicate that management practices, rather than biophysical constraints alone, are a key factor shaping productivity across countries.

3.2 Yield gaps in the main Robusta origins

3.2.1 Yield influencers

The theoretical framework proposed by Huang et al. (2014), Van Long et al., 2015; Le et al. (2022), and Ma'ruf et al. (2025) suggests that coffee yields are affected by a wide range of factors. These include (i) farm characteristics (e.g., tree age, shade presence and farm size); (ii) farming practices (e.g., fertilizer use, irrigation, pest and disease management, tree density, pruning, shade trees and weeding); (iii) topography (e.g., slope, altitude and soil conditions) and weather patterns (e.g., rainfall and temperature); and (iv) social factors (e.g., farmer education, training and group membership). In this study, Figure 3 highlights key practices with the most significant and quantifiable impacts. Among these factors, the correlation results indicate that fertilizer use, pruning, and shade management emerge as the most consistently influential factors across regions.

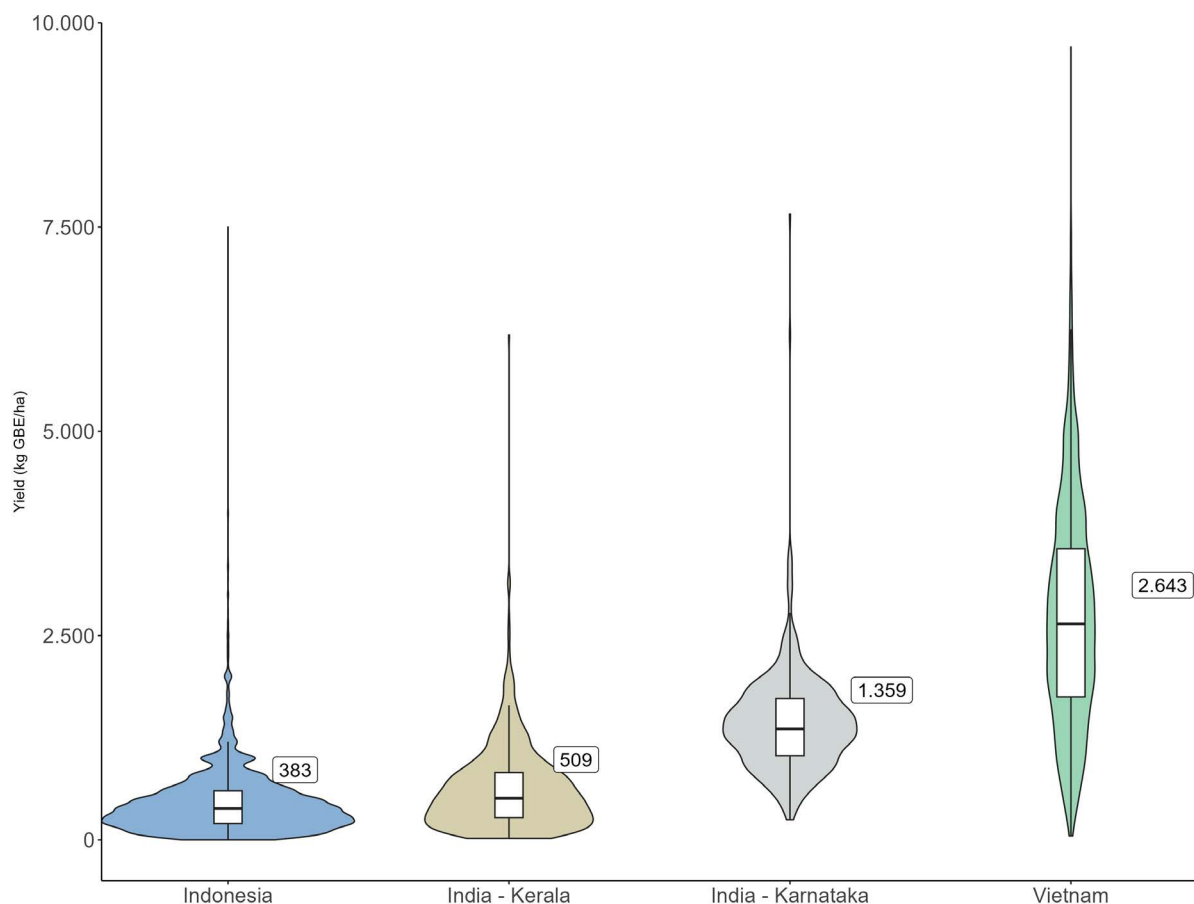


Figure 2: Median Robusta yield in selected Asian origins in kg green bean equivalent (GBE) ha⁻¹.

Source: *Enveritas Coffee Survey 2023/2024*.

Specifically, inorganic fertilizer had significant positive correlations to yield, observed in India-Kerala (0.348**), Indonesia (0.326**), and Vietnam (0.408**). These results indicate that fertilizer use plays an important role in productivity across the three countries. Regarding the pruning practice, it is also positively correlated with yield in India-Kerala (0.189**) and Indonesia (0.245**). It means that farms applying a greater number of pruning practices tend to achieve higher yields in these regions. Furthermore, in Vietnam, shade level shows a significant negative correlation with yield. This result contrasts with the patterns observed in the other origins and points to cross-country differences in the role of shade management. Overall, the statistical evidence from Figure 3 demonstrates that not all management factors exert the same influence on Robusta yields. Instead, a subset of practices, particularly inorganic fertilizer application, pruning, and shade, also impacted the Robusta coffee yield. On the other hand, among the variables assessed, inorganic fertilizer use, pruning practices, and shade level showed the most consistent

associations with yield and were therefore examined in greater detail in the following sections.

3.2.2 Inorganic fertilizer

In perennial crops such as coffee, fertilizer is applied to replace the nutrients removed during the harvest and address the nutrient needs during the following growth cycle (Byrareddy et al., 2019).

Figure 4 illustrates clear differences in fertilizer use patterns and their yield responses across countries. Vietnam stands out for its intensive fertilizer application, with a median of about 1,739 kg ha⁻¹, where additional inputs generate only modest gains in output, indicating diminishing returns at high input levels. In contrast, farmers in Indonesia apply extremely small amounts, with a median of roughly 6 kg ha⁻¹, yet yields respond strongly to increases in fertilizer, reflecting substantial untapped production potential. India shows a more heterogeneous pattern, with application levels varying by region and intermediate efficiency responses. Overall, these contrasts

	India - Kerala	India - Karnataka	Indonesia	Vietnam
Inorganic fertilizer (kg ha ⁻¹)	0,348**	0,077**	0,326**	0,408**
Organic fertilizer (kg ha ⁻¹)	0,308**	0,078**	0,043**	0,185**
Used weeding chemicals	0,052**	0,063**	0,163**	0,007**
Times used weeding chemicals	0,055**	0,063**	0,180**	0,001**
Used pest and disease chemicals	0,033**	-0,101**	0,217**	-0,021**
Water used for irrigation (m ³ ha ⁻¹)	-0,005**			0,062**
Faced pests and diseases	0,062**	-0,019**	0,105**	-0,097**
Area of farm used for all crops (ha)	0,129**	0,103**	0,073**	0,119**
Area of farm used for coffee (ha)	0,120**	0,110**	0,064**	0,129**
Tree density (trees ha ⁻¹)	0,560**	-0,008**	0,337**	0,282**
Intercropped food trees	-0,064**	-0,036**	-0,079**	-0,094**
Level of shading	0,063**	0,028**	-0,083**	-0,199**
Sufficient mulch and/or cover crop	0,005**	0,023**	0,073**	0,020**
Number of pruning techniques used	0,189**	0,094**	0,258**	0,061**
Number of IPM methods used	0,115**	0,012**	0,258**	0,047**
Had soil or leaf test	0,103**	0,092**	0,027**	0,045**
Received training in the past year	0,104**	0,036**	0,058**	0,063**
Member of farmer group/cooperative	0,063**	0,087**	0,069**	0,052**
Perceived severity caused by pests	0,059**	-0,019**	-0,049**	-0,218**

Figure 3: Spearman's Rank Correlation Heatmap between various factors and yield (kg green bean equivalent (GBE) hectare⁻¹) in India, Indonesia, and Vietnam.

Blue and orange cells represent positive and negative correlations, respectively. ** denotes significance at 1% level. Values in grey denote non-significance. Correlations between irrigation and yield in Karnataka and Indonesia were not available due to farmers not irrigating in those regions.

suggest that fertilizer-related yield gaps arise from different structural constraints, including overuse in Vietnam, underuse in Indonesia, and region-specific optimization challenges in India. This indicates that productivity improvements will require context-specific nutrient management strategies rather than uniform recommendations across countries.

The most common inorganic fertilizers are NPK and Urea, including NPK 16-16-8, NPK 20-5-6, NPK 16-8-16, or NPK 17-7-17 in Vietnam; NPK 15-10-12, NPK 15-15-15, NPK 16-16-16 in Indonesia; and NPK 17-17-17, NPK 15-15-15, or NPK 16-16-16 in India. Taken together, Figure 4 illustrates that underuse, as in Indonesia, results in lost income opportunities, overuse, as in Vietnam, and regional variation in India.

In parallel, Table 2 quantifies the marginal effects of inorganic fertilizer on yield and farm profitability. In Indonesia, fertilizer application generates strong yield gains before the threshold, while the marginal gains decline sharply beyond the threshold in Vietnam. In India, results differ by region: Kerala exhibits positive responses below the threshold but negative returns thereafter, while Karnataka shows weak or inconsistent responses, indicating potential input misallocation.

This combined evidence from Figure 4 and Table 2 strengthens the interpretation that fertilizer responses transition from input-limited to efficiency-limited regimes.

3.2.3 Pruning

Pruning is a critical agricultural practice in Robusta coffee management, as the species can grow into a tall, densely branched shrub that becomes less productive if left unmanaged (Dufour et al., 2019; Rohani et al., 2024). Fruiting mainly occurs on new branches, so unpruned trees accumulate old, unproductive branches and yield fewer cherries. By opening the canopy, pruning improves light penetration and air circulation, thereby reducing pest and disease incidence. For instance, previous studies confirm that the pruning benefits of moderate topping and thinning (removing around 30% of the canopy) increased yields by nearly 50% compared to unpruned controls (Gokavi et al., 2019; Rahman et al., 2024; Rohani et al., 2024). Systematic approaches such as stumping or maintaining a few stems of staggered ages can prolong the productive life of Robusta coffee and help stabilize yields across seasons.

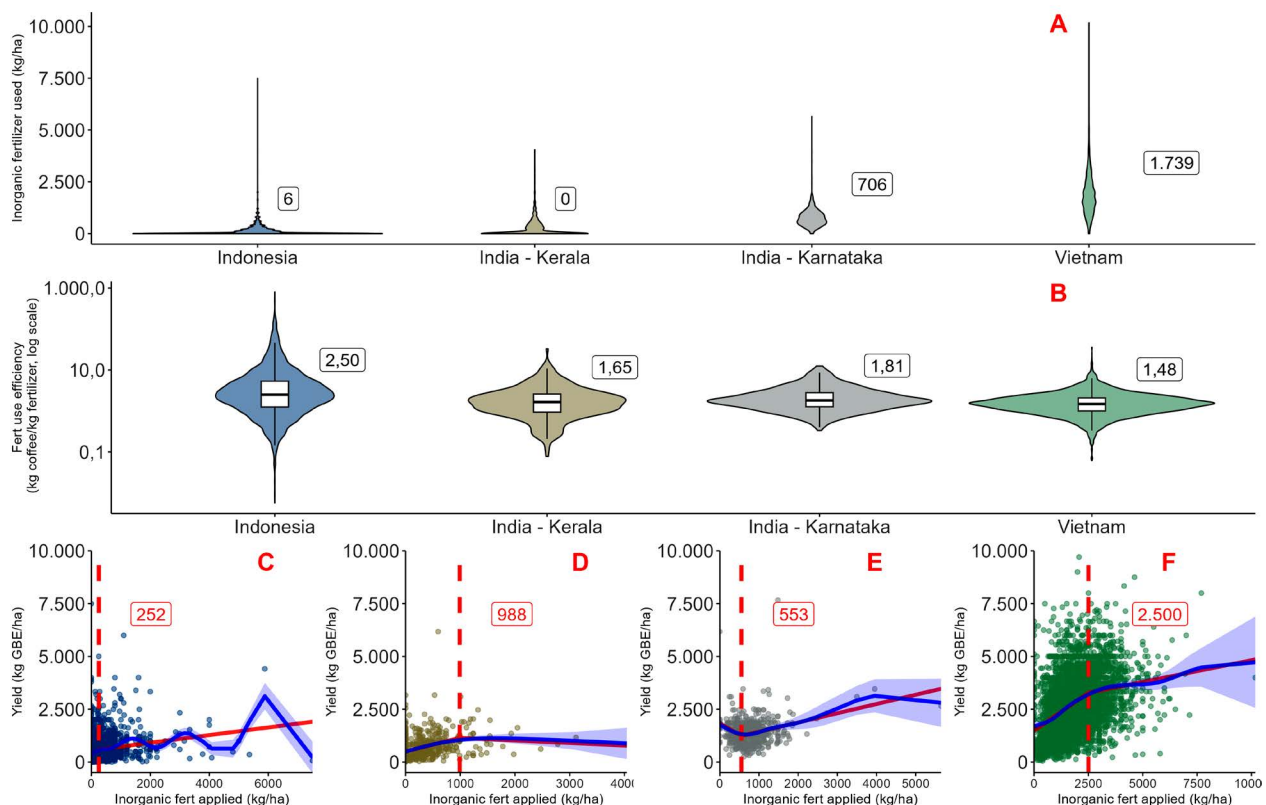


Figure 4: Relationship between yield and inorganic fertilizer in observed countries.

A - shows the distribution and median values of farms' inorganic fertilizer applied ($\text{kg ha}^{-1} \text{ year}^{-1}$); B - shows fertilizer use efficiency (kg of green coffee bean produced by 1 kg of inorganic fertilizer applied); C to F show the relationship between the amount of inorganic fertilizer applied and yield in the three countries. Red dashed lines represent calculated thresholds after which there is a change in fertilizer efficiency, while red solid lines represent the linear fits at both sides of each threshold, determined using segmented analysis. Blue solid lines and light blue areas represent the smoothed trend fitted by a generalized additive model (GAM), and each respective 95% confidence interval.

According to Enveritas' data, pruning is a common practice among farmers across the three countries, with 92–99% reported pruning among Robusta farmers surveyed (Table 1). This indicates the importance of pruning in annual farm management across almost all households. Dead or unproductive branch removal and desuckering were reported by at least 85% of farmers in all three countries. Topping was practiced by nearly two-thirds of farmers in India and Vietnam, while only about one in five farmers in Indonesia practiced topping. By contrast, rejuvenation practices such as stumping, grafting, or replanting were far less common, with only 12–28% of farmers applying these measures, with the lowest rates observed in Indonesia and India - Karnataka. Even in Vietnam, where pruning is nearly universal, less than one-third of farmers reported undertaking rejuvenation. Thus, while nearly all farmers manage the canopy each year through pruning, only a minority engage in the more intensive measures needed to renew or replace older coffee trees. Selective pruning, grafting, and skeletal pruning remained minimally practiced among farmers in all three countries, except for grafting in Indonesia (Table 3).

When comparing farmers who practiced pruning with those who did not, yields were higher among the pruning group. This difference was statistically significant in India and Indonesia. However, in Vietnam, yield differences between pruning and non-pruning farms were limited. This likely

reflects the already high and relatively uniform adoption of basic pruning practices among Vietnamese farmers, which reduces variation in pruning management and limits the statistical detectability of yield effects.

Specifically, in Kerala, farmers who reported pruning had median yields of 514.4 kg ha⁻¹ versus 280 kg ha⁻¹ for non-pruning farms, which we found to be statistically significant ($p < 0.01$). Moreover, the effect was strongest in Indonesia, where pruning farms produced a median yield of 400 kg ha⁻¹, substantially higher than the 100 kg ha⁻¹ recorded for non-pruning farms. On the contrary, pruning on Vietnamese farms showed a slightly higher yield (2,645 kg ha⁻¹) compared with non-pruning farms (2,500 kg ha⁻¹), but the difference was not statistically significant (Figure 5).

3.2.4 Shade

Robusta coffee naturally grows under forest canopy, and the use of shade trees or intercropping can benefit the environment to enhance sustainability under climate stress (Piato et al., 2020; Koutouleas et al., 2022). Shade trees help moderate the microclimate by reducing solar radiation and temperatures, lowering water evaporation, and conserving soil moisture (Van Long et al., 2015; Le et al., 2022). They can also buffer extremes of heat and drought, which is particularly valuable in marginal environments (Acosta-Alba et al., 2020). Beyond microclimatic regulation, shade contributes to soil

Table 2: The regression analysis predicts the yield increase when adding 100 kg of inorganic fertilizer ha⁻¹.

Country	Yield increase before cutoff (kg ha ⁻¹)	Fertilizer response threshold (kg ha ⁻¹)	Yield increase after cutoff (kg ha ⁻¹)	Fertilizer cost (USD per 100 kg)	Additional revenue (USD)	Net margin increase (USD)
Indonesia	90	252	18	120	643	523
India-Kerala	65	988	-12	18	748	730
India-Karnataka	-102	553	44	NA	NA	NA
Vietnam	71	2,500	21	50	2,907	2,857

Yield response is estimated from a piecewise regression model $y = ax + by = ax + by = ax + b$. The cutoff point represents the fertilizer application level at which the yield response changes. Additional revenue is calculated from the predicted yield increase and the farm-gate price of green bean coffee.

Source: Enveritas survey 2023/2024.

Table 3: Median most common tree age and share of pruning techniques used in three.

Pruning techniques	India (Karnataka)	India (Kerala)	Indonesia	Vietnam
Median most common tree age (years)	20	30	15	13
% of farmers who have pruned within the last year	98	91	92	99
% of farmers who removed dead or unproductive branches	96	85	85	98
% of farmers who removed suckers (desuckering)	95	85	88	86
% of farmers who cut off the top of the plant (topping or capping)	72	66	21	60
% of farmers who cut off some of the main stems	11	6	20	23
% of farmers that removed all foliage but left the main stem (skeletal)	2	0	1	7
% of farmers who practiced grafting (combining parts from two different trees)	0	0	38	26

fertility and biodiversity through nitrogen fixation, leaf litter, and habitat provision. However, excessive shade may reduce photosynthesis and limit yields, highlighting the need for balanced shade management (Teixeira et al., 2022).

Our study finds clear regional contrasts in shade management across Robusta systems. For instance, in India and Indonesia, farmers report shade levels beyond best practice levels, often at relatively high levels. More than half of farms in India - Karnataka (54%), over one-third in India-Kerala (35%), and nearly half in Indonesia (45%) reported maintaining shade cover above 40%. Vietnam presents the opposite, with 27% of farms reporting no shade at all, and the majority of shaded farms fall only within the 1 - 40% range (Figure 6). This reflects the country's intensive full-sun production model, which favors short-term yield gains but heightens risks to long-term sustainability under increasing heat and drought stress (DaMatta, 2004; Coltri et al., 2019; Piato et al., 2020). The most common shade trees are cassia (*Senna siamea*), silk cotton tree (*Ceiba pentandra*), and acacia hybrid in Vietnam; *albizia*, *leucaena*, and *mother of cocoa* in Indonesia; and silk oak (*Grevillea robusta*), teak (*Tectona grandis*), and black plum (*Syzygium cumini* Skeels) in India. Together, these results show that while India and Indonesia face potential trade-offs from overshading, Vietnam may be equally vulnerable due to the underuse of shade as a buffer against climate variability.

The different shaded levels between countries created the yield variabilities across countries in Figure 7. Our study shows that differences in median yield across shade levels are statistically significant in most countries. In detail, India-Kerala yields under no shade are lower than those under light and moderate shade ($p < 0.05$), although very heavy shade ($>60\%$) can reduce yields again. In India-Karnataka, yields are greatly higher under moderate shade (21-40%) compared with no shade or heavy shade. In Indonesia, plots with moderate shade (21-60%) yield more than unshaded plots. In Vietnam, yields are highest in full sun and decline consistently with greater shade. In other words, Vietnam tends towards under-shading, with over a quarter of farms lacking any shade, Indonesia and India lean towards excessive shading, with 42-44% of Robusta farms exceeding 40% canopy cover. It is possible that well-managed shade/intercrop systems can sustain coffee yields while providing additional benefits, but care is needed to manage shade intensity. If shade is too dense or competing trees are too crowded, coffee yields can decline due to insufficient light or competition for nutrients and water. Agronomists often recommend pruning shade trees to maintain dappled light (about 30-50% of full sun) for optimal Robusta production. These findings aligned with Hagggar et al. (2021) that moderate shade combined with good management practices can achieve high yields, challenging the perception that shade necessarily reduces productivity.

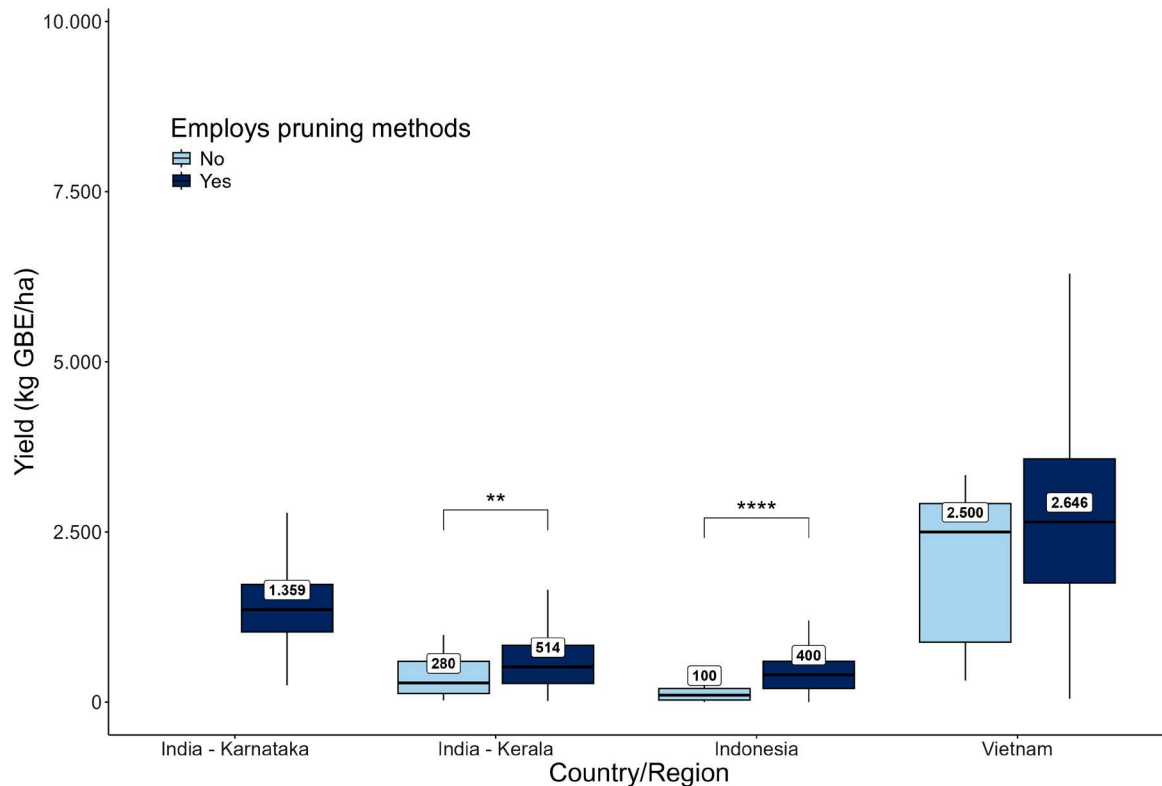


Figure 5: Median yield per productive area farms with pruning and no pruning.

Median yield per productive area for farms with and without pruning. Differences between pruning and no pruning were tested using Wilcoxon's rank-sum test. Asterisks (*, **, ***, ****) indicate significant differences ($p < 0.05$, 0.01 , 0.005 , 0.001 , respectively).

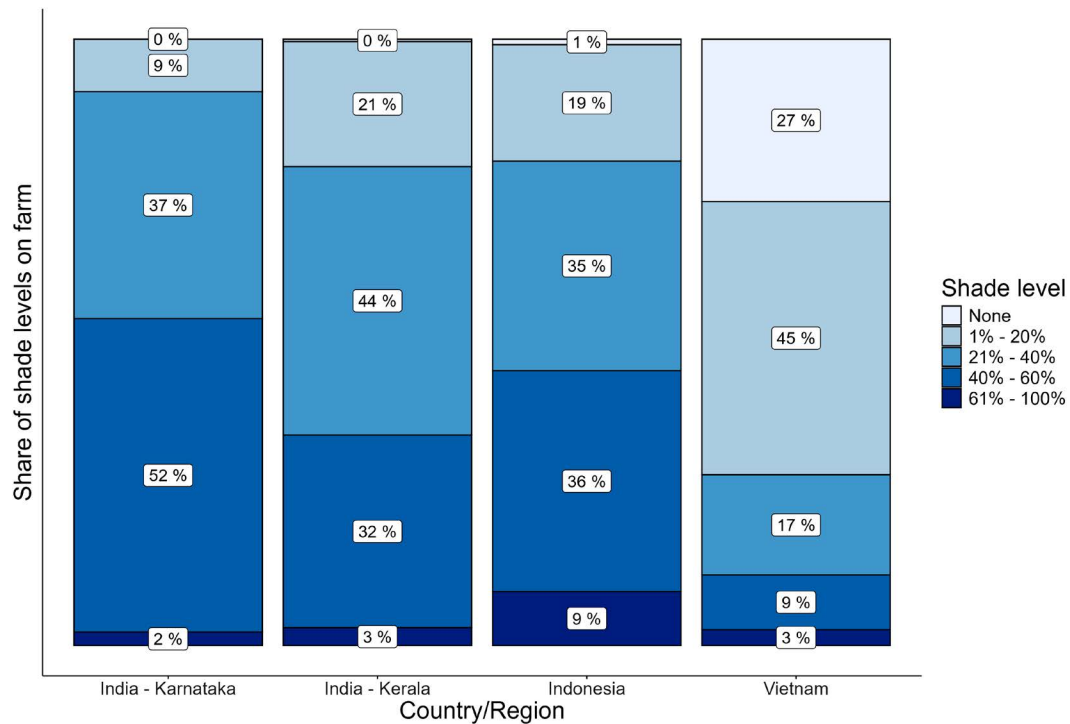


Figure 6: Share of shade level observed on farms in three countries.

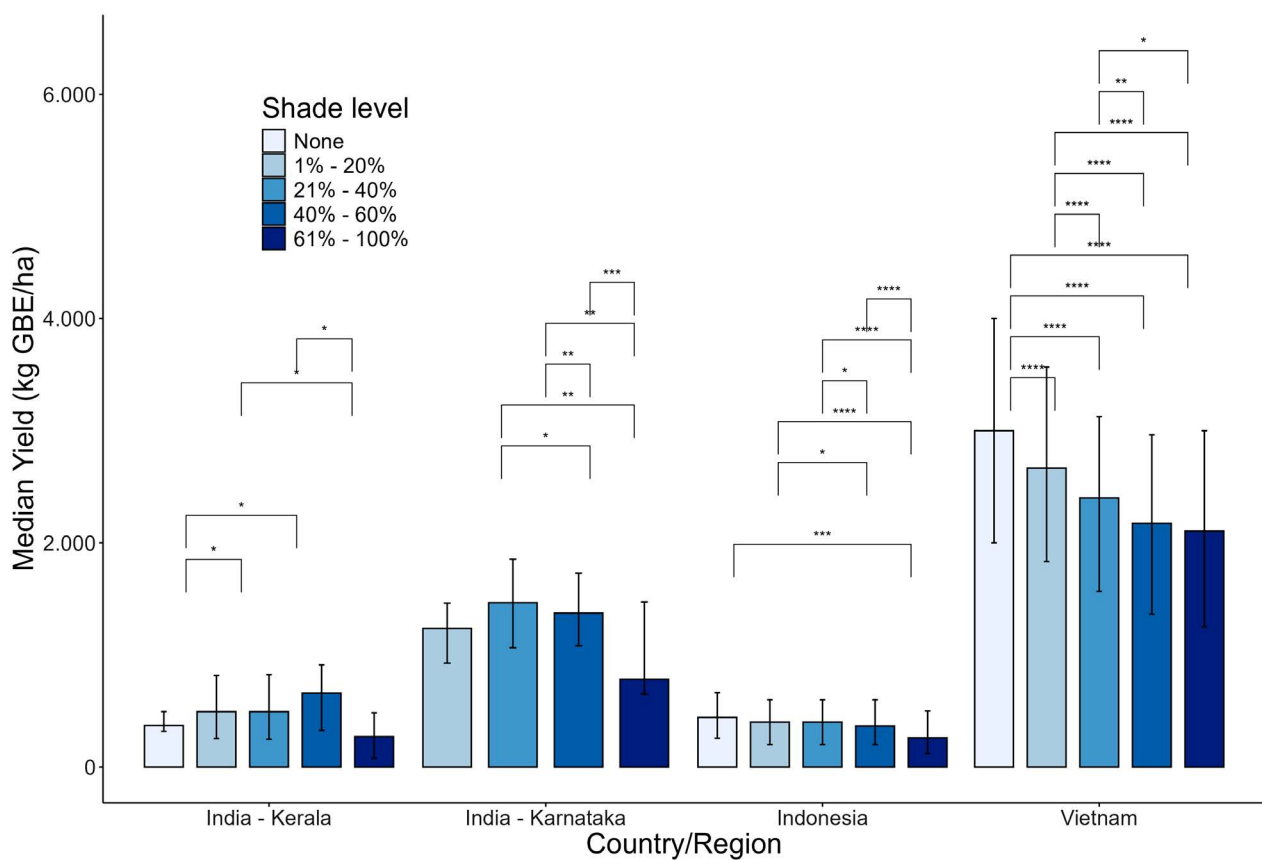


Figure 7: Median yield comparisons across different shading levels within each country.

(Dunn's post-hoc tests were performed separately for each country, with *p*-values adjusted using the Benjamini–Hochberg method. Significance levels are indicated as follows: **** *p* < 0.0001; *** *p* < 0.001; ** *p* < 0.01; * *p* < 0.05).

In addition to shade trees, intercropping represents another form of shade provision while also diversifying farm outputs. As shown in Figure 8, shade through intercropping has a complex relationship with coffee yield and household income, but is consistently linked to higher gross total income compared to monoculture coffee. Specifically, although intercropped farms in the three countries recorded slightly lower coffee yields than non-intercropped farms (Indonesia: 466.7 vs. 370 kg GBE ha⁻¹, $p = 5.93 \times 10^{-11}$, Vietnam: 2,977.2 vs. 2,500 kg GBE ha⁻¹, $p = 2.01 \times 10^{-10}$ - Figure 8A), their total annual income were significantly higher, specifically in India-Karnataka (USD 5,190.2 vs USD 12,624.7, $p = 6.94 \times 10^{-5}$) and Vietnam (USD 9,856.4 vs USD 10,102.8, $p = 1.53 \times 10^{-3}$) (Figure 8B). For Indonesia and India-Kerala, intercropped farms did not appear to achieve higher incomes, probably due to the small number of perennial crops on farms, which limited the effect to a non-significant level. This means that while coffee yields are somewhat reduced on intercropped farms, farmers may achieve higher overall revenue from other crops. In addition, intercropping helps protect household income against fluctuations in coffee prices by providing alternative sources of earnings. The most common intercropping trees

are *durian*, *black pepper*, and *avocado* in Vietnam; *banana*, *durian*, and *jengkol* in Indonesia; and *black pepper*, *arecanut*, and *coconut* in India.

4 DISCUSSIONS

The findings of this study suggest that yield gaps in Asian Robusta coffee systems arise via distinct pathways across Vietnam, Indonesia, and India. While overall productivity is evident, the underlying mechanisms vary substantially. In Indonesia, yield limitations appear primarily associated with input scarcity, particularly low fertilizer application and constrained access to agricultural inputs. In Vietnam, where fertilizer use is already intensive, yield gaps are more closely related to inefficiencies in nutrient management and diminishing marginal returns. In India, structural factors such as plantation age, canopy management, and shade systems appear to play a more important role in shaping the productivity outcomes. These contrasting patterns highlight that productivity differences in Robusta coffee cannot be attributed to a single constraint but instead reflect diverse management and structural conditions across production systems. Across

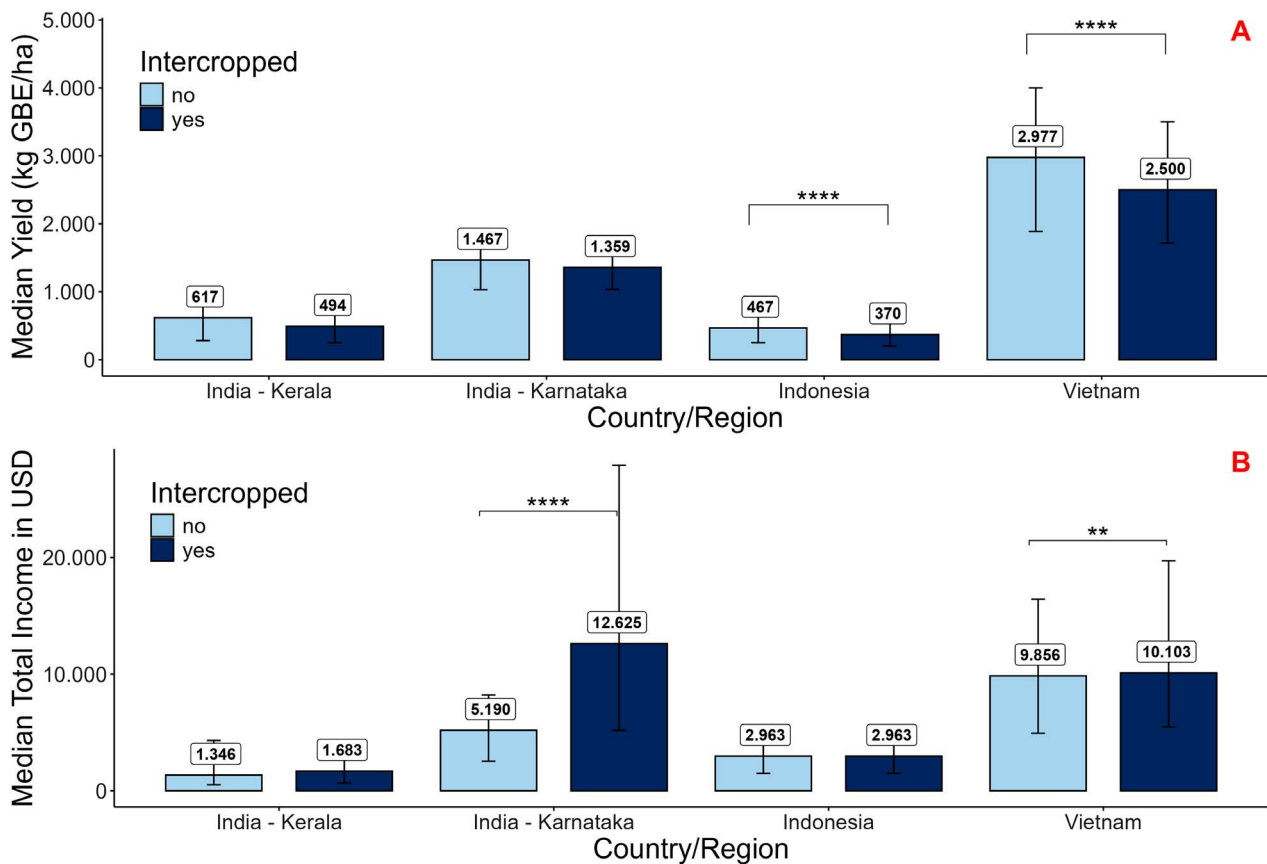


Figure 8: Comparison of coffee yield and total income of farms with and without intercropping other crops within coffee plots. Median yield (A) and median total income (B) of farms with and without intercropping. Differences between farms with and without intercropping were tested using Wilcoxon's rank-sum test. Asterisks (*, **, ***, ****) indicate significant differences ($p < 0.05$, 0.01 , 0.005 , 0.001 , respectively);

all three origins, agronomic response to nutrient input and shade management varies strongly, suggesting that nutrient management and shade regulation must be integrated with border farm management practices. In detail, fertilizer management emerged as a key factor influencing yield variance across the three countries. Specifically, in Vietnam, fertilizer application is already intensive, and additional inputs often generate only limited yield, indicating a decrease in marginal returns and inefficiencies in nutrient management. At these levels, the extra output adds little to farm income and can erode long-term soil quality. This pattern reflects an emphasis on maximizing yield rather than efficiency, and highlights the need for soil-testing services and training on balanced nutrient use (Byrareddy et al., 2019; Le et al., 2022). In contrast, many Indonesian smallholders reported applying only minimal amounts of fertilizer. This explains their low yields but also means that each additional unit of input brings a strong response in productivity. The problem appears to be less related to agronomic knowledge and more associated with limited access to inputs, high fertilizer prices, weak distribution networks, and limited credit availability. Therefore, addressing these constraints through micro-credit, targeted subsidies, and reliable supply chains would enable smallholders to raise application rates gradually (Nugroho, 2016). Within India, the picture is more complex and fertilizer responses vary between regions. Farmers in India - Kerala still operate below the economic threshold, while in Karnataka, fertilizer application is already relatively high but associated with limited yield gains beyond a moderate threshold. As a result, extra fertilizer often adds cost without much benefit. Fertilizer policy could be improved in India by treating both regions differently—farmers in India - Kerala need to increase fertilizer usage in a balanced way via soil testing, credit schemes, and access to NPK blends, while farmers in India - Karnataka need guidance to correct nutrient imbalance and avoid wasteful overuse (Smitha et al., 2010; Chand & Pavithra, 2015).

While fertilizer management provides the basic resources for growth, pruning determines how efficiently trees convert these inputs into productive branches and cherries. Our findings show that pruning had clear positive effects in Indonesia and India - Kerala, where adoption is less systematic and competition among branches is greater. In Vietnam, where pruning is already widespread, yield differences were not statistically significant, which reflects limited variation rather than a lack of benefit. This supports earlier studies showing that systematic pruning improves canopy structure, nutrient use efficiency, and overall tree vigor (Gokavi et al., 2019; Rahman et al., 2024). However, the benefits of pruning are constrained in aging plantations. In both India and Indonesia, many farms contain trees over 20-30 years old, where productivity is already in decline, even if pruning is practiced. This highlights the importance of coupling pruning with replanting and

grafting programs (Ho et al., 2017). These findings suggest that policy priorities should therefore differ, as Indonesia and India - Kerala need extension services that promote systematic pruning while also supporting rejuvenation, whereas Vietnam should focus on integrating pruning with balanced fertilization and soil management. In all cases, pruning acts as a bridge between nutrient management and broader farm resilience. Pruning practices influence canopy structure and are therefore closely related to shade management within coffee plantations. Shade management reflects a trade-off between productivity and resilience. It means that reduced shade can increase short-term yields by maximizing light interception, moderate shade can improve long-term resilience by stabilizing microclimatic conditions and reducing drought stress. Agricultural extension programs here should emphasize thinning excess shade and making use of the biomass as organic fertilizer, thereby addressing both shade and soil fertility constraints. Vietnam, in contrast, boosts short-term yields but increases vulnerability to climatic extremes (Van Long et al., 2015; Koutouleas et al., 2022). Suggested policy in Vietnam should encourage regulated shade levels of around 20-40% and promote intercropping with bananas, fruits, or timber. Our analysis shows that such systems, while slightly reducing coffee yields, increase household income and align with evidence that diversified agroforestry enhances both livelihoods and ecological resilience (Thuy et al., 2019; Rigal et al., 2023). Taken together, these results suggest that shading strategies must be country-specific in reducing excess canopy in India and Indonesia, while introducing more balanced shade and intercrops in Vietnam.

To summarize, the results highlight that yield gaps in Asian Robusta coffee systems are shaped by different constraints across countries. In Indonesia, improving access to agricultural inputs may offer the greatest potential for productivity gains. In Vietnam, improvements in nutrient management efficiency appear more important than further increases in input use. In India, structural features of shaded coffee systems and plantation age play a more prominent role in determining productivity. These differences indicate that productivity strategies must therefore be tailored to the specific production systems in each country rather than relying on a single universal approach. However, it notes that yield gaps in Robusta coffee systems cannot be understood through a single agronomic factor, but rather through the interaction between management practices, structural farm characteristics, and institutional constraints.

The study has several limitations, as it relies on farmer self-reports and enumerator observations rather than experimental measurements, which may introduce reporting inaccuracies. Key variables such as yield, farm size, fertilizer use, and farmgate prices are subject to recall bias, and fertilizer quantities were recorded as total volumes without conversion

to nutrient equivalents. Input prices were averaged from local suppliers, but regional variations may not be fully captured. Given the large and sometimes skewed dataset - particularly with the inclusion of large farms - the median was used for selected variables to reduce the influence of outliers. Despite these limitations, the large sample size supports the identification of overall trends.

5 CONCLUSIONS

This study revealed yield variation in Robusta coffee systems across Vietnam, India, and Indonesia, driven mainly by fertilizer use, pruning and rejuvenation, and shade management. Results indicate that productivity differences arise from distinct pathways across countries: limited access to inputs in Indonesia, inefficiencies nutrient management in Vietnam, and shaded systems and plantation age in India. These findings suggest that strategies to improve Robusta productivity should reflect the specific constraints across production systems rather than rely on a universal approach.

6 AUTHORS' CONTRIBUTION

Conceptual idea: Tran, H.T.M., Cao, L.N., Phan, T.T.; Methodology design: Tran, H.T.M., Cao, L.N.; Data collections: Tran, H.T.M., Cao, L.N., Phan, T.T.; Data analysis and Interpretation: Tran, H.T.M., Cao, L.N., Phan, T.T. and Writing and editing: Tran, H.T.M., Cao, L.N., Phan, T.T., Schenthal, J. and Patel, K.

7 DATA AVAILABILITY STATEMENT

Data available upon request to authors

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