

# Effect of biochar, yeast, silica and mineral fertilisers on cacao productivity and profitability in Piura, Peru

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## Research Article

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# Abstract

## Background and Objectives:

Cacao (*Theobroma cacao* L.) supports millions of Latin American smallholders. In Peru, over one hundred thousand families rely on this crop, with the Piura region widely recognized for its fine-flavor local variety, "Blanco de Piura." However, regional productivity is constrained by low yields. This study evaluated yield performance, its key driving factors, and the profitability of soil amendments and mineral fertilization in cacao, following the preliminary validation of a short-term harvest estimation index.

## Methods

The field trial was conducted in a cacao agroforestry system over two years using a completely randomized design with nine treatments: control, full and half doses of mineral fertilizer, biochar, yeast, humisil, and their combinations. The harvest index (HI) was validated with the actual harvest. In addition, predictive modelling and a cost-benefit analysis were performed across all treatments.

## Results

The HI was validated ( $R^2 = 0.71$ ). Although yield differences were not statistically significant, mean yield increased by approximately 29% with mineral fertilization, ~ 26% with yeast plus biochar, and ~ 25% with biochar plus half-dose fertilizer; conversely, humisil combined with fertilizer reduced yield by ~ 11% relative to the control. The individual applications of biochar and mineral fertilizer were the primary factors positively influencing yield performance. Under baseline experimental market conditions, the control was the most profitable treatment; however, net financial gains were realized for the other treatments under the 2024 price peak and in 2025.

## Conclusions

These findings highlight the importance of evaluating profitability alongside crop yield in field trials to justify their adoption by regional farmers.

## Highlights

- The Harvest Index (HI) serves as a reliable ( $R^2 = 0.71$ ) and cost-effective tool for estimating actual cacao yield and quantifying on-farm losses.
- Mineral fertilization and the combined use of biochar with yeast increased average yields by up to 29% and 27%, respectively, although these effects were not statistically significant.
- Economic profitability was highly sensitive to price volatility, proving viable only during exceptional market peaks.
- Under standard market prices, the control treatment proved to be the most profitable, as the yield gains did not offset the high input costs.

## Introduction

Cacao is a crop of global economic, social, and cultural importance with an estimated 5 and 6 million cacao farmers in Africa, Asia, Latin America, and Oceania (Kozicka et al., 2018; Voora et al., 2019). In Latin America the sale of cacao is the main source of income for hundreds of thousands of farmers (Meter et al.; 2019, Zug et al., 2019). According to the International Cocoa Organization (ICCO, 2025), world cacao production has been reported at approximately 4.698 million tonnes. By 2024, Peru accounted for around 159 thousand tonnes, making it the seventh-largest cacao producer in the world (Ministerio de la Producción, 2025).

In general, the productivity of cacao in smallholder farms is much lower than it could be, due to limited investment in external inputs, insufficient management, old plants and unproductive genotypes (Ocampo-Ariza et al., 2025, 2026), and more recently stress caused by climate change (Ceccarelli et al., 2021). The low use of external inputs may be attributable to the historically low market price of cacao that makes investment in external inputs uneconomical for smallholder farmers with limited income. In Peru, fertiliser and soil amendment use is not carried out systematically, partly because of a lack of informed technical assistance, but also because the cost of fertiliser is perceived to outweigh economic benefit (Instituto Nacional de Estadística e Informática (INEI), 2024)). The northern Peruvian department of Piura is home to the fine flavour landrace called Blanco de Piura (Thomas et al., 2023). Although Piura accounts for only about 1% of national production, it is well regarded internationally for high quality and interesting flavour profiles. The average cacao yield in the region is 600 kg dry beans ha<sup>-1</sup> (Ocampo-Ariza et al., 2025, 2026). The demand for Blanco de Piura cacao outstrips supply, leading to an incentive to improve yield (Thomas et al., 2026).

Improving nutrient availability for plants typically involves using fertilisers (macro and micronutrients) as well as combining them with soil amendments that may help increase or sustain nutrient cycling in the soil. An amendment increasingly promoted for its alleged potential in agriculture is biochar. Biochar is obtained from the thermochemical conversion of biomass in an oxygen-limited environment (Lehmann and Joseph, 2009). It has a range of applications that include soil improvement, improved resource use efficiency, remediation, protection against environmental pollutants, and carbon sequestration (IBI, 2015; Lehmann and Joseph, 2009). Biochar has been found to make macronutrients more available to the plant (Chan et al., 2007; Trupiano et al., 2017) and improve the physical and chemical properties of the soil (Biederman and Harpole, 2013; Mukherjee et al., 2014; Blanco-Canqui, 2017; K.C. and Mahat, 2024). A good relationship has also been found between biochar and biofertilisation, as it is suggested that the porous structure of biochar provides a favourable microhabitat for microbial establishment and proliferation (Lehmann et al., 2011; Steiner et al., 2016; Cargua et al., 2020; Liu et al., 2022; Song et al. 2025). Among such microbial communities are yeasts, some species or strains of which are recognized as plant growth-promoting microorganisms. Soil yeasts have been reported to enhance mineral solubilization, the production of phytohormones, siderophores, and enzymes, as well as to promote mycorrhizal colonization, pathogen suppression, and improvement in soil fertility and plant growth (Nassar et al., 2005; Cloete et al., 2008; Abdelaal, 2015). Studies with the yeast genus *Meyerozyma* have shown that they can promote plant biomass growth (Bilek et al., 2022) and, together with chemical fertilisation, improve yield (Nakayan et al., 2013). Another soil amendment with potential is silica (generally obtained from diatomaceous earth), the application of which can significantly improve soil fertility by improving chemical properties such as pH, soil carbon, cation exchange capacity, total nitrogen, phosphorus and potassium (Ali et al., 2025; Greger et al., 2018) and plant health (Mayzaitul-Azwa et al., 2025; Liang et al., 2007).

Quantifying the effectiveness of soil amendments on plant yield under field conditions is essential for understanding their relative utility. Although numerous studies have been carried out on annual crops to assess the effect of fertilisers on their yield (Zhang et al., 2023; Liu et al., 2025), for tree crops measuring potential productivity is costly and time-consuming, and the development of indicators is crucial to enable cost-effective data collection. In commercial crops such as mango and avocado with a single annual harvest, the yield is estimated by counting developing fruits on a number of trees in a farm and extrapolating this to plantation level. This approach is not commonly applied to cacao, but is increasingly trialled, mostly in scientific studies through the use of the Harvest Index (Orozco-Aguilar et al., 2024; Rahn et al., 2025). Having a robust approach to estimating yield enables economic analysis of the relative cost of different management actions, helping understand the effect on profit.

The objectives of this study are two-fold. First, we assess the validity of the harvest index (HI) over a two-year period by comparing cacao pod counts with the real harvest. Second, we use the HI data to assess potential productivity benefits of commercial biochar, yeast strains, humisil (silica from diatomaceous earth), and a mineral fertiliser package, both alone and in combination, in a field experiment, while accounting for the effect of external field variables. The yeast strains were applied in combination with biochar as this was expected to improve microbial survival (Kamaleshwaran et al., 2025) and, consequently, yield (Khalifa et al., 2026). Furthermore, we estimate the expected net profit of each amendment considering different cacao price scenarios. At the start of the experiment, we expected all amendments to substantially enhance cacao productivity compared to the control plots, but that only some would enhance net profit in the short-term due to the high investment costs of

several amendments. We believe our experimental approach can offer a straightforward way to direct technical assistance to small-holder farmers with limited resources to solutions that make economic sense.

## MATERIALS AND METHODS

### Study site

The field experiment was conducted in the village of El Partidor, Las Lomas district, in the northern Peruvian department of Piura (4° 45' 25" S and 80° 18' 54" W), at an altitude of 200 m above sea level. The farm comprised a ten-year-old cacao agroforestry where cacao trees planted at a spacing of 3 × 3 m were, intercropped with *Cedrela odorata* trees for timber production. Owing to the low annual rainfall in the region (10–200 mm year<sup>-1</sup>), cacao was grown under a flood-and-drain irrigation system.

### Experimental design

The experiment consisted of nine treatments each with eight replicates (Fig. 1). Each experimental unit (replicate) was composed of a block of nine trees surrounded by a row of untreated trees to reduce edge effects. The experiment was initiated in August 2018, and approximately 4-monthly measurements of the harvest index were carried out, starting in February and running over the years 2019 and 2020. The nine treatments included biochar, fertiliser plans, yeasts, and humisil, at different doses and in combination. Further details are shown in Table 1

Table 1  
Summary of the treatments applied each year of the experiment.

| N° | Treatment                    | Code      | Humisil (kg. tree <sup>-1</sup> ) | Biochar (kg. tree <sup>-1</sup> ) | Yeast (L. tree <sup>-1</sup> ) | Fertiliser plan (% suggested plan) |
|----|------------------------------|-----------|-----------------------------------|-----------------------------------|--------------------------------|------------------------------------|
| 1  | Control                      | C         | 0                                 | 0                                 | 0                              | 0                                  |
| 2  | Mineral Fertiliser           | F         | 0                                 | 0                                 | 0                              | 100                                |
| 3  | Humisil + fertiliser         | 3H_F      | 3                                 | 0                                 | 0                              | 100                                |
| 4  | Yeast + biochar              | Y_6B      | 0                                 | 6                                 | 5                              | 0                                  |
| 5  | Yeast + biochar + fertiliser | Y_6B_0.5F | 0                                 | 6                                 | 5                              | 50                                 |
| 6  | Yeast + biochar + fertiliser | Y_6B_F    | 0                                 | 6                                 | 5                              | 100                                |
| 7  | Biochar                      | 6B        | 0                                 | 6                                 | 0                              | 0                                  |
| 8  | Biochar + fertiliser         | 6B_0.5F   | 0                                 | 6                                 | 0                              | 50                                 |
| 9  | Biochar + fertiliser         | 6B_F      | 0                                 | 6                                 | 0                              | 100                                |

### Soil characterization

Soil characterization of each experimental unit involved determining particle size distribution (Bouyucos method); soil acidity in a 1:2 water extract (soil-to-water ratio); electrical conductivity in 1:2 water extract; and soil organic carbon (SOC) using the Walkley Black Method (Van Reeuwijk, 2002). These analyses were performed in duplicate for each sample at the Research Institute of the Peruvian Amazon (IIAP). Total soil Zn, and Mn were quantified by high-definition X-ray Fluorescence (XRF) using the E-max™ from Z-Spec, a low-power high-definition monochromatic X-ray fluorescence analyser. This method was selected due to its high performance, with an average limit of quantification (LOQ) of 0.2 mg Cd kg<sup>-1</sup> for soil samples, a strong correlation (R<sup>2</sup> = 0.9) with the traditional method requiring acid digestion and Inductively Coupled Plasma Mass Spectrometry (ICP-MS), and a coefficient of variation (CV) below 15% for most samples with Cd concentrations above the LOQ (Dekeyrel et al., 2024).

## Soil amendments

The biochar used was produced by the company Inkan Negro from chicken manure and municipal green waste from urban parks, which were pyrolysed at 600°C. This biochar is classified as Class 3 ( $10 \leq C \% < 30$ ) with a low C/N ratio of less than 25 and pH of 8.04 (IBI, 2015). The nutrient (Ca, Mg, P, K, N, Mn and Zn) and trace metals (Cd and Pb) concentrations are shown in Table S1. The yeast product was produced by Fertilev, developed as a biostimulant to optimise phosphorus availability and contained strains of *Meyerozyma* sp. and *Yarrowia* sp. The Humisil product from Feys comprised an organic complex of compost, humic acids and 70% silica ( $SiO_2$ ), developed to optimise nutrient uptake. In addition, a commercial mineral fertiliser plan was used, developed by Yara, which was applied at different phenological stages to meet the crop's needs (Table S2).

## Application of soil amendments in the field

The amendments were applied in August, December, and April for two years from 2018–2020, coinciding with the pre-pruning, fruit set and fruit filling stages corresponding to the peak harvest period.

### Biochar

Each tree received a total of 6 kg of the product over the two years, divided into six applications of 1 kg. For each application the product was applied via three evenly spaced holes of about 20 cm depth in the drip zone of the canopy

### Yeast

200 ml of the product was dissolved in 100 L of water. 5 L of this solution was applied to the soil uniformly within the circumference of the trees' canopy. Three applications were made in the first year only.

### Humisil

Each tree received a total of 3 kg of the product for two years, divided into three applications per year of 1 kg. For each application the product was applied via three evenly spaced holes of about 20 cm depth in the drip zone of the canopy.

**Mineral Fertilisers:** The fertiliser plan was applied via three evenly spaced holes of about 20 cm depth in the drip zone of the canopy alone and in combination with other inputs depending on the treatment. Additional Zinc was applied via a foliar drench. Fertilisers were applied for two years according to details of the plan (Table S2) in two different doses: high (100% of the fertiliser plan) and low (50% of the fertiliser plan).

## Productivity evaluation

### Harvest Index (HI)

The harvest index estimates the productive potential of the cacao per tree by counting all cacao pods in a tree that have passed the stage of physiological abortion, termed Cherelle wilt. For the Blanco de Piura variety this means pods that are over 8-10 cm long.

$$HI (kg \text{ dry beans}) = \frac{\text{Total count of pods bigger than cherelle wilt size (pods)}}{\text{Pod Index} \left( \frac{\text{pods}}{\text{kg}} \right)}$$

Where the Pod index (PI) is the number of pods needed to obtain one kilogram of dry cacao beans. This can be calculated by:

$$PI = \frac{1}{\text{Average dry weight of beans per pods} \left( \frac{\text{kg}}{\text{pod}} \right)}$$

In the first evaluation year, all harvested mature cacao pods were counted separately for each experimental unit, and the beans were extracted, weighed, air dried and weighed again to determine fresh and dry weights, respectively, thereby enabling the calculation of the pod index and relative humidity.

As cacao takes about four months to mature after passing the Cherelle stage, the harvest index was determined every four months, with three counts in the year. This ensures all pods are included, while limiting double counting and their sum provides an annual yield estimate. The HI is estimated per tree and then averaged to provide an annual potential yield estimate per hectare

The average HI per tree in each experimental unit was calculated based on the pod counts of all the trees in the unit over the two-year experiment. This was then scaled to provide the HI for 1 ha (using a plantation density of 1111 trees).

## Real Harvest (RH)

To assess the usefulness of the HI to provide a reliable estimate of the RH, the number of fruits harvested per tree was recorded over four harvests in 2019 (March, April, May, and June) and three harvests in 2020 (February, March, and May) and compared with the HI counts for the corresponding periods. These months corresponded to the peak harvest season, representing approximately 80% of the total yearly harvest.

## Economic estimate

Treatment costs (TC) were estimated as the sum of: (i) soil amendment costs, (ii) routine agronomic management costs (weed control, pruning, pest and disease management, irrigation, and harvesting) and (iii) additional labour costs associated with soil amendment applications. Local transportation costs of the amendments in Piura were not included, however the cost of transporting biochar, from Lima to Piura was added to the cost of this treatment.

Gross profit (GP) was calculated using the projected yield per hectare and the market price of dry cacao beans and under three price scenarios: (a) at the time of the experiment (2.30 USD kg<sup>-1</sup>) (b) at the peak price of 7.97 USD kg<sup>-1</sup> in 2024), and (c) at the most recent market price at the time of this publication (6.84 USD kg<sup>-1</sup> in 2025). Amendment and labour costs were also adjusted for scenario b and c by adjusting values to 2025 equivalents (biochar 333 to 400 USD t<sup>-1</sup>; fertilisers 521 and 502 USD ha<sup>-1</sup>; yeast 15.00 to 4.50 USD; humisil 0.914 to 0.355 USD per 50 kg bag for 2018 and 2025 respectively. Note that humisil was no longer commercially available by 2025, so the price was estimated using a comparable product marketed by the same company.

To better reflect actual on-farm conditions, net profit (NP) was evaluated under two scenarios: (1) including agronomic management costs, which approximated between 776 USD t<sup>-1</sup> and 1119 USD t<sup>-1</sup> and (2) excluding agronomic management costs. This distinction was established because many smallholders perform these operations using unpaid family labour.

## Data analysis

We conducted all data analyses in R (R Development Core Team, 2022). To evaluate whether there was significant difference in the yield between treatments, the R package nortest (Gross and Ligges, 2015) was used to perform the Anderson–Darling normality test, the R package car (version 3.0–10) was used for the Levene test to assess homogeneity of variances, and analysis of variance (ANOVA) was conducted using the aov function, at a significance level of 0.05. Constructed linear models evaluated the relationship between the response variable average Harvest Index of cacao and explanatory variables, which included soil properties, treatments (Biochar, Fertilization, Humisil, and Yeast application and combinations), terrain slope (%), elevation (m.a.s.l.), geographic coordinates (to account for spatial structure), counts of *Cedrela odorata* trees within circular neighbourhoods of 6- and 12-meter radii constructed around the centre of each experimental unit, and the distance from the centre of each experimental unit to the closest irrigation channel. To reduce multi-collinearity among explanatory variables, the variance inflation factor (VIF) was iteratively calculated, removing the variable with the highest VIF until all remaining variables

had VIF < 10. Continuous variables were scaled to facilitate coefficient comparison with binary variables (Barton, 2018; Gelman, 2008). Interaction terms between Biochar and Fertilization (B: F) were included. All possible combinations of explanatory variables were tested using the dredge function from MuMIn package, and models were ranked by Akaike information criterion (AIC). Competitive models were identified by  $\Delta AIC < 2$ , and model averaging was applied to estimate coefficients (Barton, 2018). Model assumptions were checked for linearity, absence of influential values, non-autocorrelated residuals, normality, homoscedasticity, and non-collinearity. Significant interactions were identified using marginal effect plots generated with ggpredict and ggplot functions, representing predicted changes in the response variable when only the focal predictor is varied.

## RESULTS

### Initial soil characteristics

Details of soil conditions at the cacao plantation are provided in Table 2. The pH was moderately acidic, the soil organic matter (SOM) content was low at  $1.24 \pm 0.46\%$ , electrical conductivity (EC) was  $543 \mu S.cm^{-1}$ , and the overall texture of the soil fell within the sandy clay loam category.

Table 2  
Summary statistics of soil parameters in the field site at the beginning of the experiment (n = 68).

| Parameter              | Value (mean $\pm$ SD) |
|------------------------|-----------------------|
| <b>Soil</b>            |                       |
| Sand (%)               | $52.68 \pm 6.82$      |
| Clay (%)               | $28.78 \pm 3.69$      |
| Silt (%)               | $18.55 \pm 4.71$      |
| pH                     | $6.13 \pm 0.38$       |
| SOC (%)                | $0.72 \pm 0.27$       |
| EC ( $\mu S.cm^{-1}$ ) | $543.01 \pm 264.23$   |
| <b>Terrain</b>         |                       |
| Slope (%)              | $10.09 \pm 3.44$      |
| Height (m.a.s.l.)      | $195.62 \pm 3.51$     |

### Validating of the harvest index methodology

We found a strong correlation between the harvest index and real harvest obtained for the different experimental units, averaged across the two study years ( $R^2 = 0.71$ ; Fig. 2). The unexplained 29% of variation in the data could be due to some double counting of pods and other methodological issues, losses from pests and diseases (estimated at 10%) and theft of pods. Given this good fit, the harvest index is used in subsequent analyses.

### Yield

Yield was averaged for each treatment and averaged across the two years (Table S3). Average yields per treatment ( $kg \cdot tree^{-1} \cdot year^{-1}$ ) met the assumptions of normality and homogeneity of variance, but did not show any significant difference between treatments based on an analysis of variance (Fig. 3A). However, in absolute terms the average yield of three treatments increased by at least 25% compared to the control: mineral fertiliser (+ 29%), yeast and biochar (+ 26%), and biochar with low fertiliser dose (+ 25%). The application of humisil combination with fertiliser showed a negative effect on yield (-11%).

Modelling the average harvest index of cacao for 2019 and 2020 resulted in 26 models with  $\Delta AIC < 2$ , explaining 28–34% of the variance (Fig. 4). Among the key predictors, higher harvests were positively associated with fertiliser and biochar applications. In contrast, negative relationships with harvest were observed for humus application, initial soil Mn content, higher topographic position of the experimental plots, and the interaction between biochar and fertiliser applications. Basically, analysis of the interaction term suggested that average cacao harvest tended to be highest either when the full mineral fertiliser package was applied without biochar, or when biochar was applied with lower fertiliser doses, as is also apparent from Fig. 3B.

## Profitability

Although most treatments showed non-significant increases in yield (Fig. 3a), the net profit analysis revealed that these gains were insufficient to offset the costs of the amendments at the time of the experiment (Fig. 5a), and the net profit was negative for most treatments. However, when the high cacao price of 2024 is used, 3.4 times higher than that during the trial, all treatments became profitable (Fig. 5c). A similar pattern is observed in Fig. 5e for 2025, where the cacao price was 2.9 times higher than during the trial. Across all figures, net profit improves when routine agronomic costs are excluded.

Figure 5. The economic performance of the treatments based on their average yield. The left column (a, c, e) shows net profit (USD ha<sup>-1</sup> yr<sup>-1</sup>), and the right column (b, d, f) shows the ratio of benefit to cost (ratio B:C), where values > 1 indicate net gain and values < 1 net loss. Comparisons are made across three periods: (i) the trial years (2019–2020; a, b), (ii) 2024, corresponding to the peak in cacao prices (c, d), and (iii) 2025 (e, f). Net profit and the benefit to cost ratio is evaluated under two scenarios: including routine agronomic costs (points) and excluding these costs (stripe). For the benefit to cost ratio, the control treatment is presented only under the scenario including the routine agronomic costs, as under the other scenario (zero cost) benefit to cost ratios would be infinite.

## Discussion

### Validating Harvest Index for cacao yield estimation

This study constitutes one of the first applications of the harvest index (HI) to cacao cultivation in Peru, drawing upon methodologies previously developed and validated in other countries (Santos Filho and Midlej, 2016; Santos Filho, 2018; Orozco-Aguilar et al., 2024). Furthermore, the pod index (PI) is widely utilized to compare the productive potential of cacao varieties (García, 2010; Rusinamhodzi et al., 2020). Previous work has indicated that the HI is a simple and useful tool for estimating yields based on counts starting from 21 days of fruit growth; dos Santos Filho and Midlej (2016) found a correlation coefficient of 0.95 and a margin of difference between 0.8% and 10.2% between estimated and actual yields. We also found similar results, exhibiting a strong correlation ( $r = 0.84$ ) (Fig. 2) thereby reinforcing the empirical support for the viability and applicability of this method. Notably, our findings demonstrate that the HI provides a robust approach to estimate annual potential production by counting pods larger than those that are likely to abort due to physiological issues. Additionally, comparing this index with actual harvest offers an approach to evaluate losses driven by pests, diseases, and other biotic and abiotic factors not directly linked to genotypic potential or fertilization (Armengot et al., 2023; Orozco-Aguilar et al., 2024).

### The effect of different soil amendments on cacao yield

Although no statistically significant differences in yield were detected between treatments ( $p > 0.05$ ), this result likely reflects the inherent variability not only of the field conditions but also of the individual trees themselves, rather than the complete absence of effects from the inputs applied. This variability is common in perennial crops such as cacao and can mask the effects of treatment (Wibaux et al., 2017; Asante et al., 2021). One possible explanation for the lack of statistical differences between treatments and the control in our case is that amendments had been applied annually prior to the start of the experiment. This previous management may have influenced the yield observed in the control treatment through eg effects; and may explain why the difference between treatments and control was greater during the second than the first year of the experiment, though also significantly so (Table S3).

The mineral fertiliser plan demonstrated its effectiveness by achieving the highest average yield increase in the trial, which is consistent with the literature recognizing fertilization as a key determinant of crop productivity (Macholdt et al., 2019; Havlin and Heiniger, 2020; Salazar, 2024). However, it is important to note that the fertilization scheme applied was not based on a soil characterization analysis of the experimental site; instead, it was formulated according to fertilization recommendations for cacao in the main cacao-producing areas of the country (e.g. San Martin). Hence, potentially higher yields might be obtained from fertiliser packages tailored to the specific growth condition in the study region.

The application of biochar alone did not result in substantial yield gains compared to the control. Similar results have been reported in wheat and maize, where biochar addition did not significantly enhance growth or yield (Wei et al., 2021). Biochar's direct nutrient contribution is limited, with its main agronomic benefits arising from improvements in soil physical and chemical properties (Yao et al., 2012; Burrell et al., 2016) and increased soil organic matter content (Tian et al., 2018). While biochar can contain nutrients within its structure, its high stability and persistence in soil may restrict the rapid release of these nutrients (Gwenzi et al., 2017; El-Naggar et al., 2019), which could explain the limited yield response despite its nutritional composition (Table S2, Table S1). Our results suggest there is an interaction between the use of fertiliser and biochar when applied together. The literature suggests that the interaction can lead to variable yield outcomes and a meta-analysis of 57 studies, found that the yield response to combined biochar and fertiliser application depends on biochar properties, soil characteristics, and experimental conditions (Bai et al. (2021).

Furthermore, previous studies have indicated that biochar can reduce nutrient losses due to its high adsorption capacity (Major et al., 2010; Zhang et al., 2016; Hamdani et al., 2017). Cations such as  $\text{NH}_4^+$ ,  $\text{K}^+$ , and  $\text{Ca}^{2+}$  are preferentially retained when fertilisers are applied, due to the “nutrient sponge” effect (Borchard et al., 2014), limiting the immediate availability of nutrients to crops. Further research is required to understand this relation.

Although the combined treatment of biochar and yeast did not result in a statistically significant difference, it led to a 27% increase in yield—comparable to the yield obtained with mineral fertiliser alone (+ 29%). However, the positive effect of the biochar-yeast combination appears to diminish with increasing levels of mineral fertiliser. Yeasts are known for their broad metabolic versatility and adaptability to diverse environments (Yurkov, 2018). As biostimulants, they can enhance plant growth by solubilizing nutrients and producing phytohormones and enzymes (Hernández-Fernández et al., 2021). For example, *Meyerozyma* spp. associated with maize have demonstrated plant growth-promoting properties (de Lima Targino et al., 2022), while the genus *Yarrowia* can solubilize inorganic phosphate (Hesham and Mohamed, 2011), produce indole-3-acetic acid, and stimulate plant defence responses (Mamaev and Zvyagilskaya, 2021). The interaction between yeast, biochar and mineral fertiliser also warrants further study.

Silicate-based fertilisers are increasingly used in agricultural systems, owing to its numerous reported benefits. However, field-based yield responses have been inconsistent. In a comprehensive review of 467 studies on Si-based fertilisers, Barão (2022) found that 69% reported yield increases, while 14% observed yield reductions which may depend on factors such as soil properties, fertilization regimes, and crop type. The yield reduction observed in this study for experimental units treated with humisil in combination with chemical fertilization likely falls within the broad variability reported in the literature. The underlying mechanisms driving these diverse responses remain insufficiently understood and warrant further investigation.

Additionally, our modeling results showed that higher topographic elevation was associated with lower cacao yields, while lower elevations were consistently linked to higher yields. As the field was on a slight hill, this may just be the consequence of nutrient movement down the slope. Thus, field conditions and agronomic management – as noted above – must be considered alongside fertilization strategies to ensure sustainable yield improvements. Notably, our analysis did not support the initial hypothesis that competition from *Cedrela odorata* timber trees intercropped with cacao would negatively affect cacao productivity.

The importance of plot variability and differences in agronomic management has been noted in other studies (FEDECACAO, 2000; Hernández-Bermúdez et al., 2025; Talero-Sarmiento et al., 2025) stressing that yield enhancement cannot rely solely on fertiliser application but rather requires the comprehensive implementation of recommended agronomic practices. Several authors have concluded that fertilization on its own is insufficient, but must be carried out in combination with improvements in

overall agronomic management to achieve significantly increases in yield (Uribe et al., 2001; Ruales Mora et al., 2011; Ocampo-Ariza et al., 2025, 2026).

## Profitability of using soil amendments

The economic analysis demonstrated that, despite yield increases, only the control and mineral fertilization yielded a benefit to cost (B:C) ratio greater than 1 (Fig. 5b), when routine agronomic costs were considered. This confirms that higher agronomic productivity does not guarantee superior financial returns when input costs exceed the marginal yield increase.

However, when cacao prices tripled in 2024 due to a global supply deficit driven by production declines in West Africa (ICCO, 2024), all treatments became financially viable, even after accounting for labour costs (Fig. 5c). Notably, mineral fertilization achieved returns up to eleven times higher than baseline conditions (Fig. 5d). However, net benefits declined once more in response to falling cacao prices in 2025, despite a marginal reduction in input costs (Fig. 5e). This fluctuation demonstrates that the economic viability of fertilization remains highly contingent upon cacao prices—an exogenous variable beyond the control of those smallholders selling to bulk commodity markets.

Consequently, assessing actual net profit is essential in field trials of cocoa cultivation, where plot variability, environmental factors, and market volatility greatly influence profitability (Hoffmann et al., 2020). In smallholder agriculture, investment in fertilisers does not systematically correlate with economic viability (Neizer et al., 2020; Vásquez-Zambrano et al., 2025). Furthermore, the analysis of labour costs (Fig. 5) explains why many small-scale cocoa farmers opt for direct family labour to minimize cash outlays (Neizer et al., 2020). Within this context, farmers' reluctance to adopt fertilization technologies or soil amendments represents a rational economic decision in the face of financial uncertainty. In the specific case of biochar, carbon credits could potentially incentivize adoption; however, under current conditions for Peruvian smallholders, this remains unfeasible in the short term. Accessing these markets is not a straightforward process, and the high costs of certification continue to exclude individual farmers from the carbon market.

## CONCLUSION

This study demonstrates that the Harvest Index (HI) is a practical and cost-effective tool for estimating cacao yield in the field. The strong correlation between HI and the real harvest reinforces its value for comparing treatment effects and identifying production losses, especially where direct yield measurements are logistically challenging. Although no statistically significant yield differences were detected between the treatments, several inputs produced meaningful average increases relative to the control. The mineral fertiliser and combinations yeast plus biochar and biochar with half the recommended fertiliser dose achieved similar average yields. From a practical perspective, profitability remains a primary concern for farmers. Using the cacao prices prevailing during the study period, yield gains were generally insufficient to offset input costs, making the control treatment the most profitable, when routine agronomic costs were considered. Only under the exceptional price conditions of 2024, and to a lesser extent, 2025, did fertilization become more attractive economically. These results highlight the importance of evaluating technologies based on net returns, rather than yield alone.

## Declarations

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## DECLARATION OF COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

## AUTHOR CONTRIBUTIONS

Rachel Atkinson, Brenton Ladd, Yerson Durán Ramirez and Evert Thomas contributed to the study conception and design. Field trial set up and data collection, were performed by Rachel Atkinson, Fredy Franco Yovera Espinoza, Karina Liseth Arango Ledesma, Franklin Aguilar, Sphyros Roomel Luciano Lastra Paucar, Carlos Medina Méndez and analysis were performed by Karina Arango, Rachel Atkinson, Manuel Gabriel Velasquez Ramirez, Evert Thomas. The manuscript preparation was written by Karina Liseth Arango Ledesma, Rachel Atkinson and Evert Thomas and the manuscript was reviewed by Rachel Atkinson, Brenton Ladd, Manuel Gabriel Velasquez Ramirez and Evert Thomas. All authors read and approved the final manuscript.

## DATA AVAILABILITY

The datasets generated during and/or analysed during the current study are available from Evert Thomas (e.thomas@cgiar.org) or Rachel Atkinson (r.atkinson@cgiar.org) upon reasonable request.

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# Figures

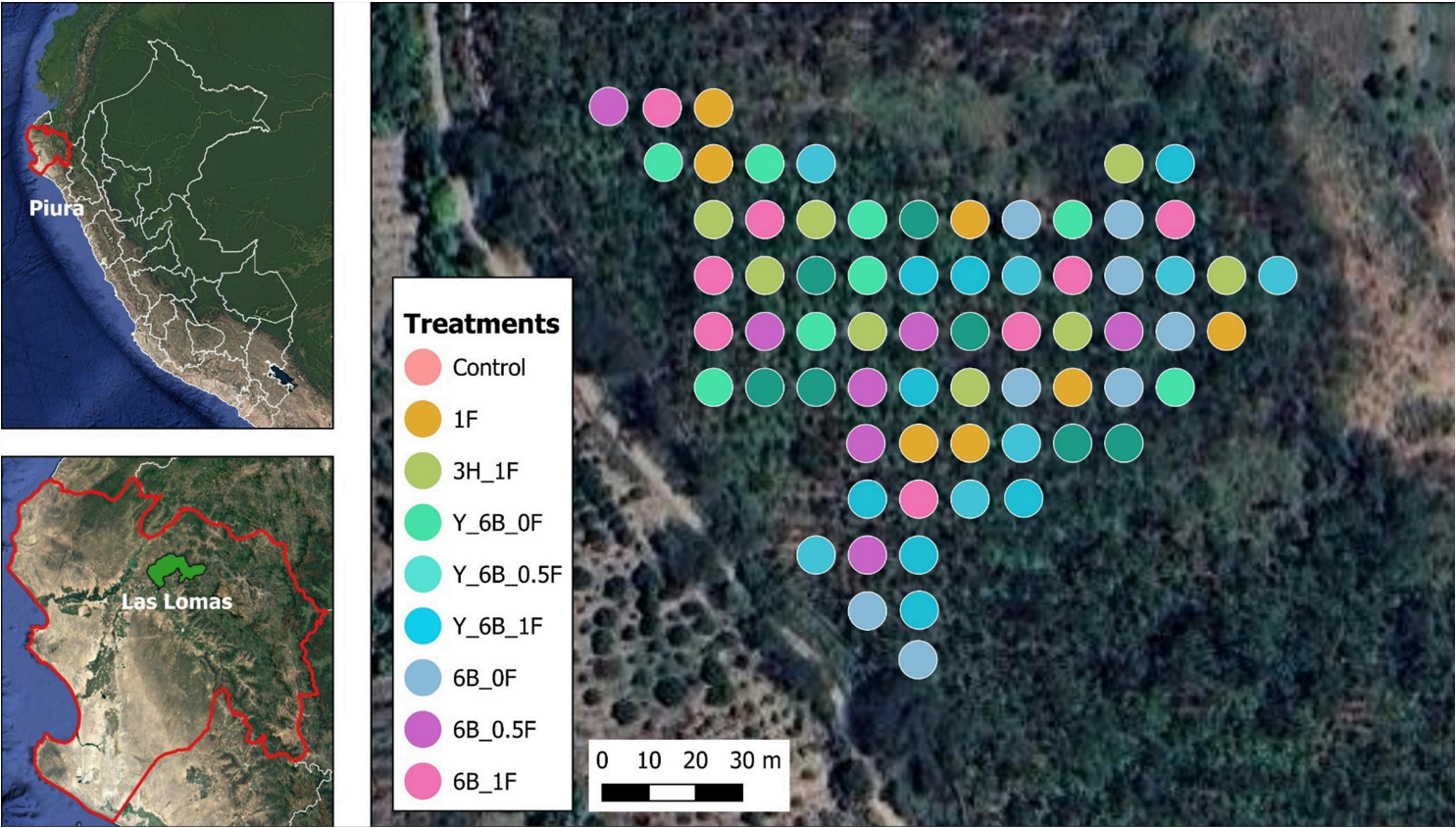


Figure 1

Location of the experiment in Peru and the Piura region, showing the layout of the experimental treatment plots. For abbreviations, please refer to Table 1.

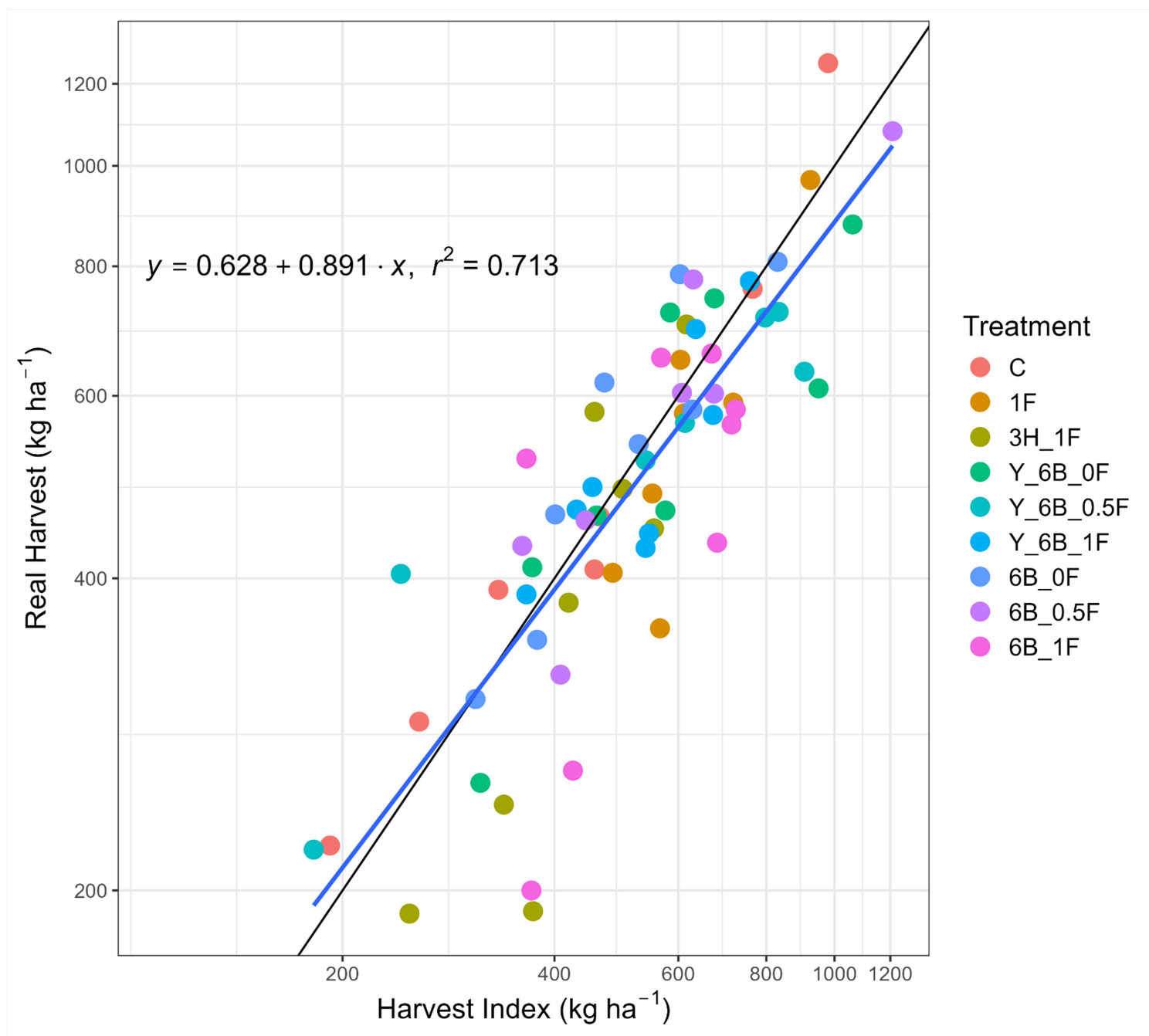


**Figure 2**

Linear regression between the Harvest Index (HI) and the real harvest (RH) obtained for each experimental unit, averaged across the two study years. Treatment codes are explained in Table 1.

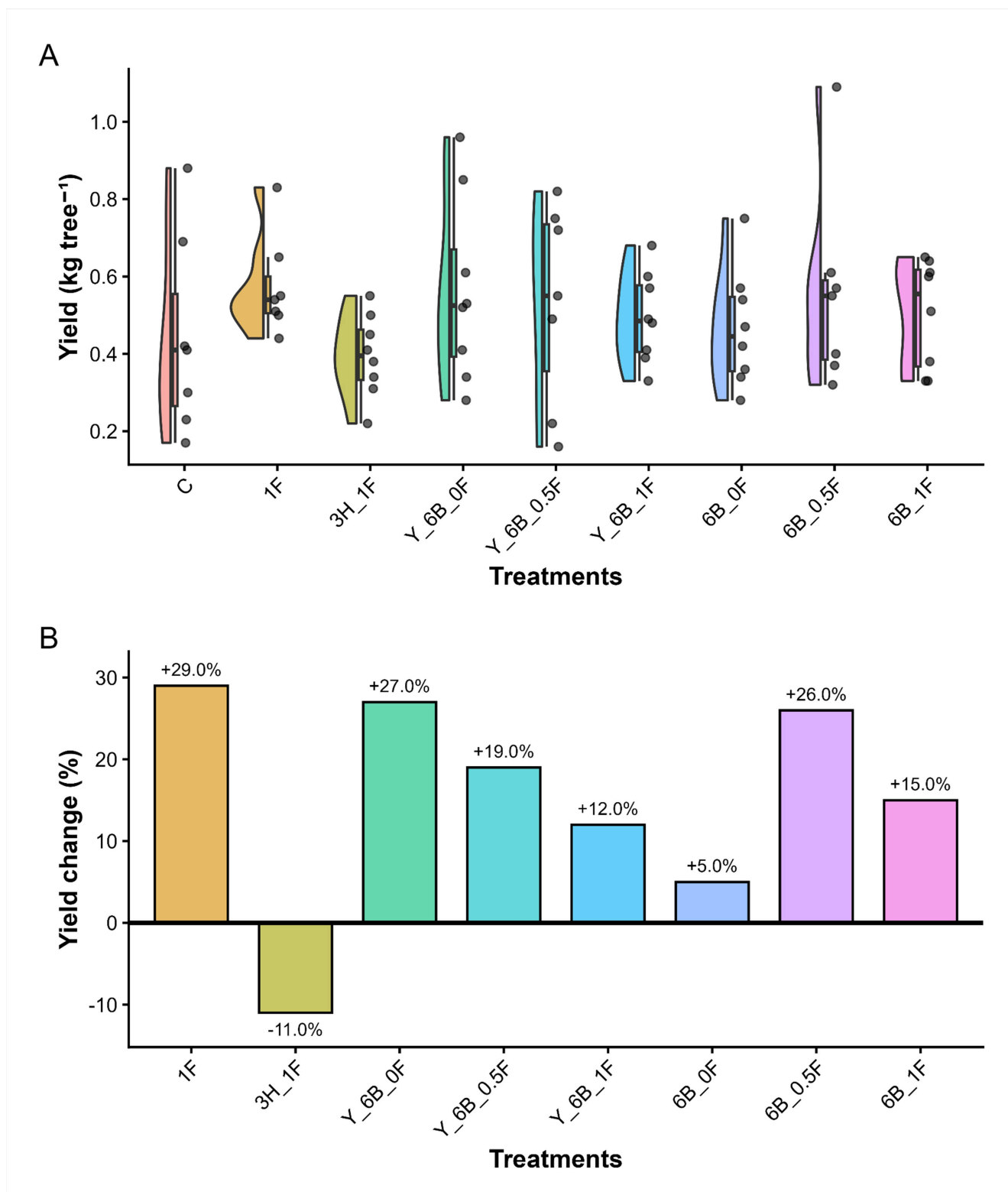


**Figure 3**

Average cacao yields (kg tree<sup>-1</sup> yr<sup>-1</sup>) in the experimental units by treatment (A) and percentage change in average annual cacao yield per tree relative to the control (B).

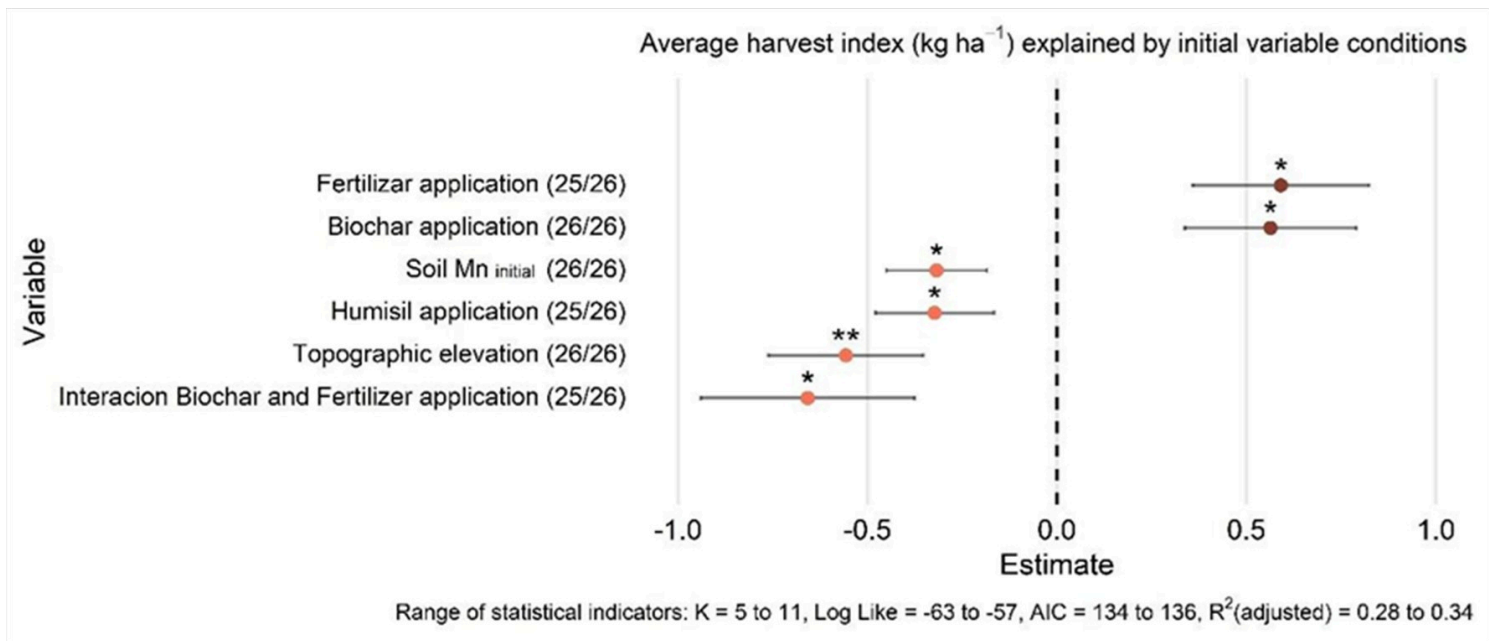


**Figure 4**

Effect sizes of the variables explaining the average cacao harvest index (HI) for 2019 and 2020. Orange points indicate a negative estimate for a predictor, meaning that, with all other predictors held constant, an increase in that predictor is associated with a decrease in the HI. Brown points indicate a positive estimate, meaning that an increase in the predictor is associated with an increase in HI. Therefore, negative values on the estimation axis should be interpreted as indicating an inverse relationship between the predictor and the response variable. Fractions in brackets following the variable names represent the frequency with which each variable was included across all models with  $\Delta\text{AIC} < 2$ .

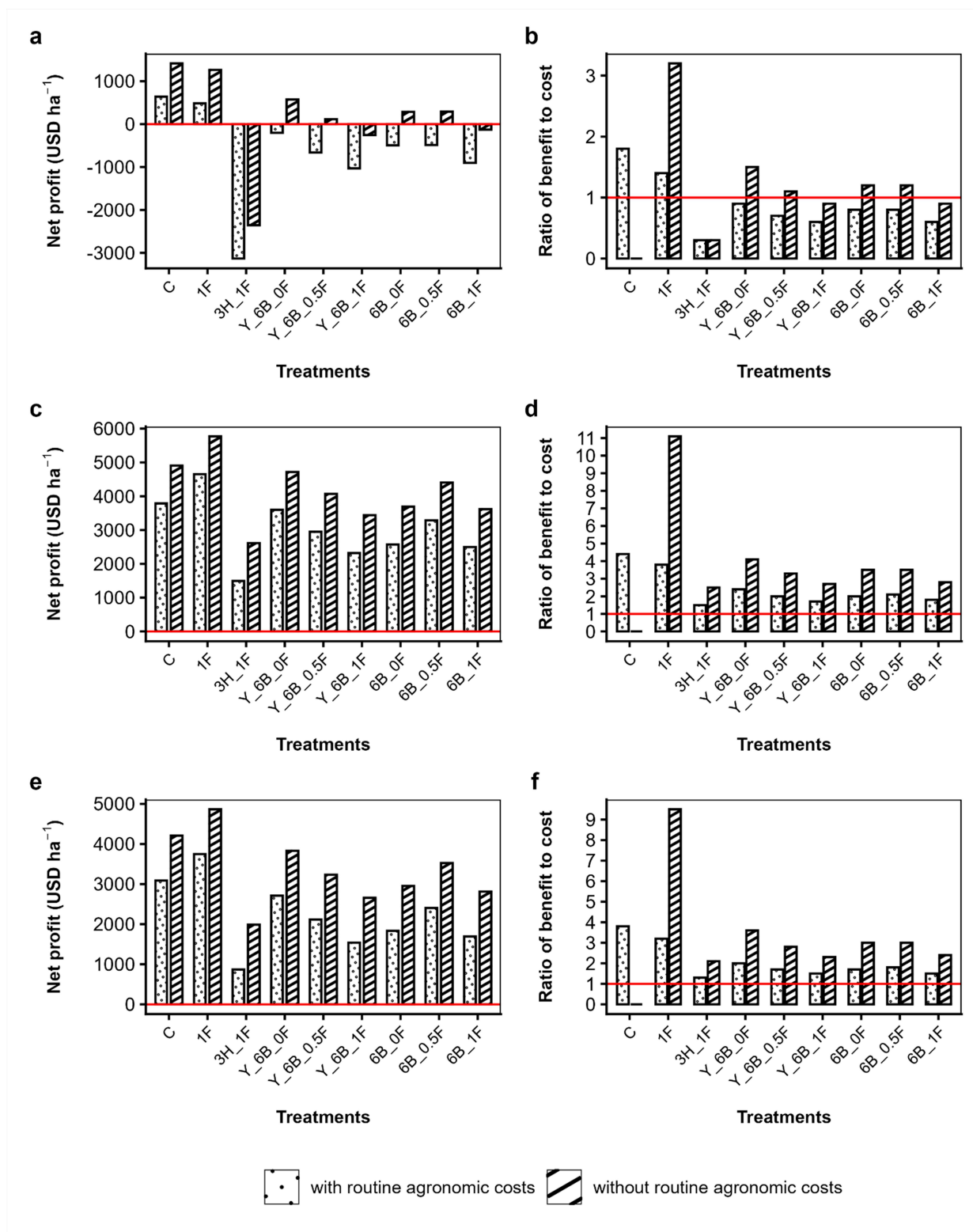


**Figure 5**

The economic performance of the treatments based on their average yield. The left column (a, c, e) shows net profit (USD ha<sup>-1</sup> yr<sup>-1</sup>), and the right column (b, d, f) shows the ratio of benefit to cost (ratio B:C), where values >1 indicate net gain and values <1 net loss. Comparisons are made across three periods: (i) the trial years (2019-2020; a, b), (ii) 2024, corresponding to the peak in cacao prices (c, d), and (iii) 2025 (e, f). Net profit and the benefit to cost ratio is evaluated under two scenarios: including routine agronomic costs (points) and excluding these costs (stripe). For the benefit to cost ratio, the control treatment is presented only under the scenario including the routine agronomic costs, as under the other scenario (zero cost) benefit to cost ratios would be infinite.

# Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryMaterial.docx](#)