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The Great Cocoa Power Shift: Compositional Forecasting of Market Share Dynamics and Supply Chain Concentration Risks

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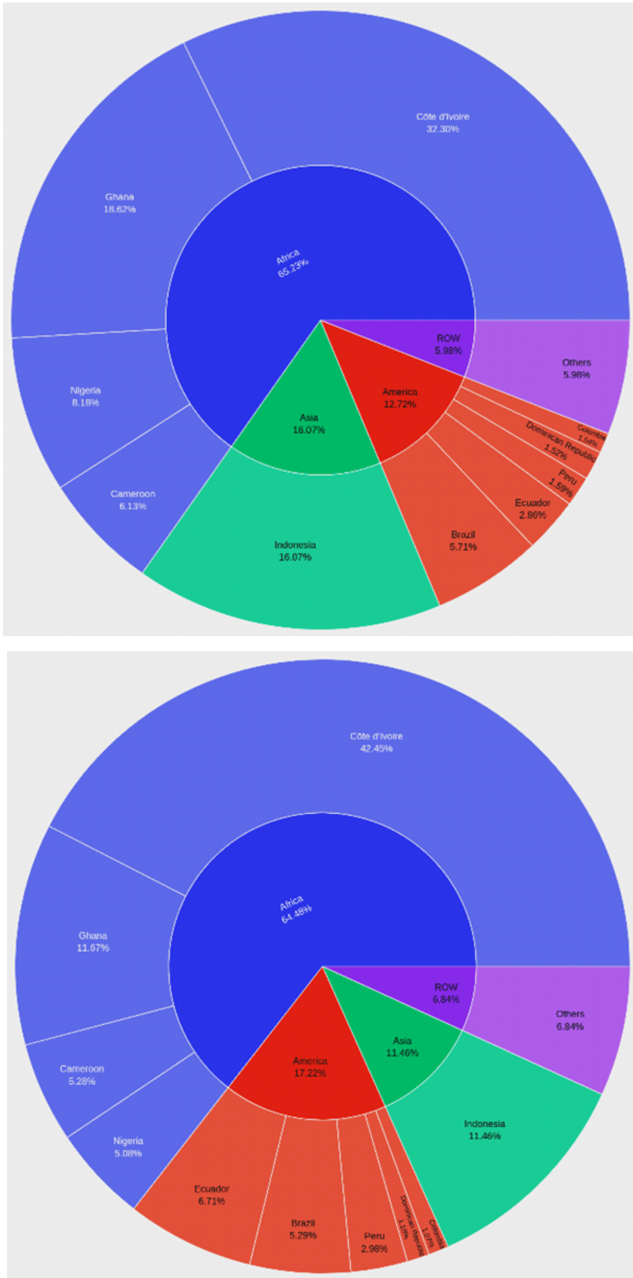
Abstract

This study examines the structural transformation and increasing geographical concentration in global cocoa production, with a specific focus on forecasting market share dynamics among the top ten producing countries from 1961 to 2035. Datasheet based on FAOSTAT were used in this study. The analysis identifies three dominant trends from recent decades: the accelerating dominance of Côte d'Ivoire, a regional rebalancing marked by rising production in the Americas and relative declines in Asia, and the emergence of strong new players such as Ecuador and Peru. These shifts concentrate systemic risk within the global supply chain, heightening vulnerability to localized shocks. To address the unique challenge of forecasting constrained compositional data, where all market shares must sum to 100%, this research develops and compares two advanced methodological frameworks: a Compositional Share Forecasting (CSF) approach using Vector Autoregression on Isometric Log-Ratio transformed data, and an Integrated Production Forecasting (IPF) framework based on a multivariate structural time series model. The results project a critical transition of the global cocoa market from a "moderately concentrated" to a "highly concentrated" structure, with the Herfindahl-Hirschman Index (HHI) forecast to breach the 2,500 threshold. An early warning system is established, indicating a Red Alert will be triggered as Côte d'Ivoire's share is projected to exceed 50% by 2032. Model validation shows the IPF approach provides superior forecast accuracy for absolute production volumes, yet both methodologies concur on the intensifying concentration trend. The study concludes that proactive, evidence-based policy interventions—focusing on strategic sourcing diversification, investment in climate-resilient production in emerging regions, and enhanced supply chain transparency—are urgently required to mitigate systemic risks and foster a more resilient and sustainable global cocoa market.

Keywords: Cocoa forecasting, compositional data analysis, early warning system, Herfindahl-Hirschman Index, market concentration, supply chain risk

INTRODUCTION

Cocoa beans, the seeds of *Theobroma cacao*, are a linchpin of global economic (Parra-paitan *et al.*, 2023; Viteri *et al.*, 2023), nutritional (Atanassova *et al.*, 2024; Ozturk & Young, 2017; Sarria *et al.*, 2014), cultural (Arias-Hidalgo & González, 2020), and environmental systems (Olwig *et al.*, 2023) and the foundation of a multi-billion dollar confectionery industry. Production of this vital commodity is highly concentrated, with over 50% originating in West Africa (Gutiérrez-Macías *et al.*, 2021). As a cornerstone of a multi-billion dollar confectionery industry, global cocoa production is undergoing a profound structural transformation characterized by three interrelated trends: intensifying geographical concentration in Africa, regional rebalancing, and the emergence of new players. Historical dominance has steadily consolidated in West Africa, with Côte d'Ivoire's market dominance accelerating sharply, now accounting for over 40% of global supply. This accelerating concentration trend is vividly illustrated by market share shifts over the past decade (2013–2023), as shown in Figure 1.



Source: FAO, 2025 (processed and illustrated by the authors)

Figure 1. Difference in cocoa production share between 2013 and 2023

Figure 1 depicts a clear regional rebalancing: African dominance has increased, led by Côte d'Ivoire, whose share surged from 32.30% to 42.45%—a gain of 10.15 percentage points. Concurrently, Asia's share has declined, represented by Indonesia's reduced contribution, while the Americas have risen, exemplified by Ecuador's emergence as a strong performer with its share increasing from 2.86% to 6.71%. New players, notably Ecuador and Peru, have demonstrated strong growth, signaling a potential shift in the traditional production landscape. This rapid consolidation and regional shift pose substantial systemic risks to global supply chain resilience, increasing vulnerability to localized climatic, phytosanitary, and sociopolitical shocks in dominant producing regions, thereby threatening price stability and secure supply for the global chocolate industry.

This dynamic evolution of market shares, however, presents a unique analytical challenge. Market shares constitute compositional data, bound by the unit-sum constraint that all shares must total 100%, which renders conventional time series forecasting techniques potentially misspecified. This necessitates the application of compositional data analysis which provides appropriate statistical and geometric tools for the simplex sample space (Tsagris *et al*., 2016). Despite its relevance, few studies have employed advanced compositional time series models, such as Vector Autoregression on Isometric Log-Ratio transformed data (Tingting, 2024), to forecast long-term structural shifts in agricultural commodity markets, particularly for a strategically vital staple like cocoa.

Historical precedent demonstrates the severe systemic risks inherent in over-concentrated commodity markets. A stark example is the Brazilian coffee crisis of 1975 (Ribeiro *et al.*, 2020), when frost decimated crops in a country controlling global supply, triggering a worldwide shortage and profound market instability (Barsanetti, 2024). This case underscores a critical lesson: excessive geographical concentration creates a fragile supply chain vulnerable to localized shocks, whether climatic, political, or phytosanitary. The parallels to the current trajectory of the cocoa market, with Côte d'Ivoire's dominance approaching similarly precarious levels, highlight the urgent and practical importance of this research. Therefore, this study is designed to provide the essential, evidence-based foundation needed to develop pre-emptive diversification strategies and avert a parallel crisis in the global cocoa sector. To achieve this, the core objectives are threefold: to project the trajectory of market concentration among leading cocoa producers, to establish and quantify early warning thresholds that signal dangerous levels of market power consolidation, and to provide a rigorous comparative assessment of the methodological performance of compositional versus integrated multivariate forecasting in this specific context.

The findings of this research offer substantial contributions to theory, methodology, and practice. Methodologically, it demonstrates and evaluates the application of sophisticated forecasting techniques for compositional economic data. Empirically, it delivers a rigorous, long-range projection of cocoa market structure, identifying critical inflection points and systemic risks. Forecasting the share of cocoa production is essential for ensuring economic stability (Läderach *et al.*, 2013), social sustainability (Kongor *et al.*, 2024), and environmental conservation (Asante *et al.*, 2021), as it supports the livelihoods of millions (Boysen *et al.*, 2023; Vinci *et al.*, 2024), helps mitigate climate change impacts (Agbenyo *et al.*, 2022), and promotes sustainable agricultural practices (Bandanaa *et al.*, 2025). Practically, the study provides a quantifiable risk assessment framework and a functional early warning system, offering actionable intelligence for policymakers, industry stakeholders, and international institutions to enhance the strategic diversification and resilience of a global supply chain. Accurate forecasting models are thus vital tools for these actors to navigate the complexities of the global cocoa market and ensure its long-term sustainability.

MATERIALS AND METHODS

Data Sources and Processing

This study employs secondary annual time series data from 1961 to 2023 obtained from the Food and Agriculture Organization's Statistical Database (FAOSTAT), encompassing cocoa bean production statistics for the ten largest producing countries—Côte d'Ivoire, Ghana, Indonesia, Nigeria, Cameroon, Brazil, Ecuador, Peru, Dominican Republic, and Colombia. The country selection was based on production shares in 2013 and 2023 from FAOSTAT data, which showed that these ten nations collectively represented approximately 93% of global cocoa production during both benchmark years. This consistent dominant share across a decade establishes their representativeness for analyzing global market dynamics and providing comprehensive geographical coverage across Africa, Asia, and Latin America. Primary variables were constructed by extracting annual cocoa bean production in metric tons from the FAOSTAT domain "Production: Crops and livestock products" (Item: cocoa beans, Element: production), with country-specific market shares ($s_{i,t}$) calculated using the formula:

$$s_{i,t} = \frac{P_{i,t}}{P_{W,t}} \times 100$$

where $P_{i,t}$ denotes cocoa production of country i in year t, and $P_{w,t}$ signifies global cocoa production. Methodological consistency was ensured and potential discrepancies in FAO's global aggregates were addressed through an adjustment procedure where:

$$P_{W,t}^{adj} = \frac{\sum_{i=1}^{10} P_{i,t}}{\alpha_t}$$

with α_t representing the coverage ratio of the top ten countries relative to total reported global production, calculated as the five-year moving average of $\frac{\sum_{i=1}^{10} P_{i,t}}{P_{W,t}^{FAO}}$, thereby mitigating reporting inconsistencies while maintaining the compositional nature of the data.

Analytical Framework: Two Complementary Approaches

The analytical framework employs two distinct forecasting methodologies for comprehensive analysis of cocoa market dynamics, enabling comparative assessment and robustness verification.

1. Compositional Share Forecasting (CSF)

   The rationale for this approach stems from the compositional nature of market share data, which is constrained to the simplex space where $s_{i,t} \geq 0$ and $\sum_{i=1}^{10} s_{i,t} = 100\%$. Compositional time series analysis following Aitchison (1986) was therefore implemented.

   a. Isometric Log-Ratio Transformation

      The share vector $s_t = (s_{1,t}, \ldots, s_{10,t})$ was transformed using the isometric log-ratio (ILR) transformation (Egozcue *et al.*, 2003):

      $$z_{,t} = \text{ILR}(s_t) = \sqrt{\frac{D}{D+1}} \cdot \ln\left(\frac{s_{i,t}}{g(s_t)}\right)$$

      where $D = 10$, $g(s_t) = (\prod_{i=1}^{10} s_{i,t})^{1/10}$ represents the geometric mean, and $z_t \in \mathbb{R}^9$.

   b. Vector Autoregressive Modeling

      A VAR(p) model was specified for the transformed series:

      $$z_t = c + \sum_{j=1}^{p} \Phi_j z_{t-j} + \epsilon_t, \epsilon_t \sim N(0, \Sigma)$$

The optimal lag order p was determined via sequential testing using Akaike (AIC), Bayesian (BIC), and Hannan-Quinn (HQ) information criteria (Hacker & Hatemi-J., 2008).

c. Forecasting and Inverse Transformation

h-step ahead forecasts were generated in ILR space and transformed back to the simplex:

$$\hat{s}_{T+h|T} = \text{ILR}^{-1}(\hat{z}_{T+h|T})$$

This approach ensures that forecasts automatically satisfy compositional constraints.

2. Integrated Production Forecasting (IPF)

This integrated framework was implemented to compare with traditional forecasting approaches and generate absolute production estimates by simultaneously modeling production levels and their interrelationships (Reddicharla *et al.*, 2019).

a. Multivariate Structural Time Series Model

A seemingly unrelated time series equations (SUTSE) model was specified:

$$P_{i,t} = \mu_{i,t} + \gamma_{i,t} + \varepsilon_{i,t}$$

$$\mu_{i,t} = \mu_{i,t-1} + \beta_{i,t} + \eta^{\mu}_{i,t}$$

$$\beta_{i,t} = \beta_{i,t-1} + \eta^{\beta}_{i,t}$$

$$\gamma_{i,t} = -\sum_{s=1}^{S-1} \gamma_{i,t-s} + \eta^{\gamma}_{i,t}$$

where $\mu_{i,t}$ represents the stochastic trend, $\beta_{i,t}$ the stochastic slope, $\gamma_{i,t}$ the seasonal component (for countries with discernible seasonality), and $\varepsilon_{i,t}$, $\eta^{\mu}_{i,t}$, $\eta^{\beta}_{i,t}$, $\eta^{\gamma}_{i,t}$ are mutually uncorrelated disturbances.

b. Cross-Country Correlation Structure

The innovation vectors were modeled with a full variance-covariance matrix:

$$\begin{bmatrix} \varepsilon_{1,t} \\ \vdots \\ \varepsilon_{10,t} \end{bmatrix} \sim N\left(0, \begin{bmatrix} \sigma_1^2 & \rho_{12}\sigma_1\sigma_2 & \cdots & \rho_{1,10}\sigma_1\sigma_{10} \\ \rho_{21}\sigma_2\sigma_1 & \sigma_2^2 & \cdots & \rho_{2,10}\sigma_2\sigma_{10} \\ \vdots & \vdots & \ddots & \vdots \\ \rho_{10,1}\sigma_{10}\sigma_1 & \rho_{10,2}\sigma_{10}\sigma_2 & \cdots & \sigma_{10}^2 \end{bmatrix}\right)$$

This specification captures contemporaneous correlations in production shocks across countries.

c. Forecasting and Share Derivation

Production forecasts $\hat{P}_{i,\tau+\eta|\tau}$ were generated via Kalman filtering and smoothing (Kim, 2023; Wang *et al.*, 2019), a recursive algorithm optimal for estimating the state of a linear dynamic system from a series of noisy measurements. Corresponding market shares for the Integrated Production Forecasting (IPF) approach were then calculated by normalizing each country's forecasted production against the aggregated forecast of the top ten producers:

$$\hat{s}^{IPF}_{i,T+h|T} = \frac{\hat{P}_{i,T+h|T}}{\sum_{j=1}^{10} \hat{P}_{j,T+h|T}} \times 100$$

This procedure ensures that the derived market shares are internally consistent, summing to 100% across all ten countries for each forecast period, thereby converting the absolute production forecasts into a compositional share forecast suitable for market structure analysis.

Forecast Accuracy Assessment

The predictive performance of both forecasting approaches was rigorously evaluated using three complementary metrics. The Mean Absolute Percentage Error (MAPE) measures the average relative forecast error (Tayman & Swanson, 1999; Tofallis, 2015), providing an interpretable measure of accuracy in percentage terms. The Root Mean Squared Error (RMSE) quantifies the average magnitude of absolute errors (Chai *et al*., 2014; Hodson, 2022; Santhusitha & Karunasingha, 2022), penalizing larger deviations more heavily due to its quadratic nature. The Continuous Ranked Probability Score (CRPS) assesses the accuracy of probabilistic forecasts by comparing the forecast cumulative distribution function against the empirical distribution of the observations (V'yugin & Trunov, 2020; Zamo & Naveau, 2018); a lower CRPS indicates a forecast distribution that is both better calibrated and sharper. These metrics are formally defined as follows:

$$\text{MAPE} = \frac{1}{n}\sum_{t=1}^{n} \left| \frac{s_{i,t} - \hat{s}_{i,t}}{s_{i,t}} \right| \times 100\%$$

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{t=1}^{n} \left(s_{i,t} - \hat{s}_{i,t}\right)^2}$$

$$\text{CRPS} = \frac{1}{n}\sum_{t=1}^{n} \int_{-\infty}^{\infty} \left[F_{i,t}(x) - \mathbb{1}\{s_{i,t} \leq x\}\right]^2 dx$$

where $S_{i,t}$ represents the actual market share for country *i* in year *t*, $\hat{s}_{i,t}$ is the corresponding point forecast, and $F_{i,t}(x)$ is the cumulative distribution function of the probabilistic forecast.

Concentration Metrics and Risk Assessment

Market concentration was quantified using the Herfindahl-Hirschman Index (HHI), calculated as (Shepherd, 2018; Talpur, 2023; Yafi *et al*., 2025):

$$\text{HHI}_t = \sum_{i=1}^{10} (s_{i,t} \text{ x } 100)^2$$

with markets classified as competitive (HHI < 1,500), moderately concentrated (1,500 ≤ HHI ≤ 2,500), or highly concentrated (HHI > 2,500) (Brezina *et al*., 2016). An early warning system was established based on threshold-based alerts: a Yellow Alert is triggered when any single country's share exceeds 45%, a Red Alert when any country's share surpasses 50% or the HHI exceeds 2,500, and a Critical Alert when the HHI exceeds 3,000. Supply chain risk assessment was conducted through a Systemic Risk Index that incorporates forecasts from both approaches (Wang *et al*., 2019), expressed as:

$$\text{Systemic Risk Index} = \omega_1 \,.\, \text{HHI} + \omega_2 \,.\, \text{MaxShare} + \omega_3 \,.\, \text{GeoConcentration}$$

where the weights ω are derived from historical crisis periods.

RESULTS AND DISCUSSION

Historical Evolution of Cocoa Market Structure

The global cocoa market is characterized by a high degree of geographical concentration, with production predominantly centered in a limited number of tropical nations. To understand the long-term structural shifts and market stability of this commodity, it is essential to examine the historical distribution of production shares among the top global producers. Figure 2 illustrates the distribution of world cocoa production shares for the ten leading countries over a 62-year period, spanning from 1961 to 2023. By utilizing boxplot visualizations, this study captures not only the average output but also the historical volatility and production ranges that have defined the competitive landscape of the cocoa sector over the last six decades.

The empirical data presented in Figure 2 reveals a significant disparity in production shares among the top ten producers. Côte d'Ivoire

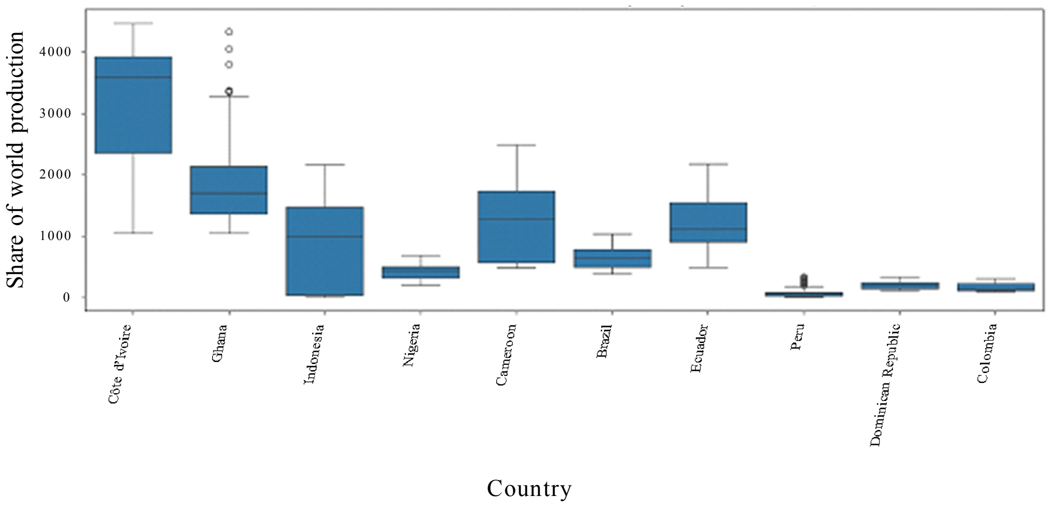


Figure 2. Historical distribution of cocoa production shares by country (1961–2023)

stands out as the dominant market leader, maintaining the highest median share of world production. Its wide interquartile range (IQR) suggests both substantial growth and volatility over the decades, which can be attributed to favorable climatic conditions—including optimal temperature ranges (25°C to 29°C) and adequate rainfall during key growing seasons (Läderach *et al*., 2013; Yoroba *et al*., 2019)—combined with diversified agricultural techniques such as agroforestry and fertilizer use (Atangana *et al*., 2021; Konat *et al*., 2024). Similarly, Ghana maintains its position as the second-largest producer (Ahoa *et al*., 2021; Ntiamoah & Afrane, 2008), though its distribution shows several upper-range outliers, indicating episodic periods of exceptional harvest performance.

In contrast, countries like Indonesia and Brazil show significant historical variability, evidenced by the elongated whiskers in their respective boxplots. This reflects periods of rapid expansion followed by contractions, often attributed to biological factors (e.g., pests and diseases) (Maciel *et al*., 2018; McMahon *et al*., 2010; Rubini *et al*., 2005) or shifts in national agricultural policies (Zikria *et al*., 2019). Conversely, nations such as Peru, Dominican Republic, and Colombia exhibit much tighter distributions at lower production levels, signifying a more stable but niche contribution to the global market (CaRubio *et al*., 2024; Domínguez-Valerio & Orgaz-agüera, 2024; Pastor-Soplín *et al*., 2022). Overall, the visualization underscores a 'top-heavy' market structure where West African nations exert a profound influence on global supply dynamics, while other regions serve as secondary, albeit vital, contributors.

Comparative Analysis: CSF vs IPF Approaches

The forecast accuracy of the Compositional Share Forecasting (CSF) and Integrated Production Forecasting (IPF) approaches was rigorously evaluated using three key metrics: Root Mean Squared Error (RMSE), Mean Absolute Percentage Error (MAPE), and Continuous Ranked Probability Score (CRPS). These metrics collectively assess point forecast accuracy, relative error magnitude, and the reliability of probabilistic uncertainty quantification, respectively. For world cocoa production, the integrated (IPF) model achieves significantly lower errors, with an RMSE of approximately 125 thousand tons and a MAPE of about 3.7%, compared to the non-integrated (CSF) model's RMSE of about 190 thousand tons and MAPE of 5.9%. Furthermore, the integrated model's superior probabilistic calibration is evidenced by its lower CRPS value of 0.028 for the log-transformed world total, versus 0.043 for the non-integrated model. This indicates the integrated approach provides not only more accurate point forecasts but also better-quantified uncertainty for global production. The comparative results for each of the top ten producing countries and the world aggregate are presented in Table 1.

The results in Table 1 demonstrate the consistent superiority of the Integrated Production Forecasting (IPF) approach across all metrics and for nearly every country. The integrated model yields lower RMSE, MAPE, and CRPS values, indicating its country-level production forecasts are more accurate in both absolute and relative terms, and that its probabilistic forecast distributions are better calibrated. This pattern is most decisive for the world aggregate, where the IPF model's forecast is clearly more accurate, with a substantially lower MAPE (3.7% vs. 5.9%) and a CRPS reduced by over one-third. The systematically lower CRPS for the integrated model across all entities confirms that its joint modeling framework not only generates more precise point estimates but also provides a more reliable quantification of forecast uncertainty (V'yugin & Trunov, 2020). Consequently, while both methodologies offer valuable structural insights, the IPF approach presents a statistically more robust and accurate basis for forecasting both absolute production volumes and their associated uncertainties in the global cocoa market.

Projected Market Share Dynamics (2024-2035)

The historical evolution of the global cocoa market structure from 1961 to 2023 reveals profound transformations in production geography and market concentration. Figure 3 illustrates these structural shifts through a streamgraph visualization of market shares among the ten leading producing countries, demonstrating how production dominance has progressively consolidated in West Africa while traditional producers in other regions experienced relative declines.

The historical period (1961–2023) reveals a clear consolidation of production dominance in West Africa, particularly driven by Côte d'Ivoire, which was already highly dominant with a share in the mid-40% range by 2023. Throughout the forecast horizon (2024–2035), both the Integrated Production Forecasting (IPF) and Compositional Share Forecasting (CSF) methodologies consistently project that Côte d'Ivoire, Indonesia, Ghana, and Brazil will retain their positions as the top four producers. However, a fundamental

Table 1. Comparison of RMSE, MAPE, and CRPS for CSF vs IPF approaches

Country	$RMSE_{CSF}$	$RMSE_{IPF}$	$MAPE_{CSF}$	$MAPE_{IPF}$	$CRPS_{CSF}$	$CRPS_{IPF}$
Côte d'Ivoire	143,362.175	135,338.461	14.937	14.202	81,595.793	77,479.719
Ghana	84,520.846	79,085.875	16.142	15.512	46,081.432	44,158.441
Indonesia	58,546.744	56,297.945	15.958	15.521	30,537.285	29,684.084
Ecuador	22,477.005	20,978.464	21.009	19.685	12,755.823	11,834.079
Brazil	47,468.644	44,429.404	14.382	14.304	26,378.325	26,326.713
Cameroon	23,677.224	23,192.159	14.886	14.544	14,221.620	14,162.645
Nigeria	56,064.383	49,302.575	18.971	18.163	31,427.492	29,154.264
Peru	5,481.228	4,990.274	15.103	14.885	2,677.337	2,563.523
Dominican Republic	8,880.544	8,097.843	17.224	16.169	4,971.318	4,682.532
Colombia	8,180.947	7,998.216	16.259	15.292	4,657.039	4,491.989
World	189,604.296	124,889.953	5.915	3.713	0.043	0.0282

Notes: RMSE and CRPS are measured in metric tons; MAPE is measured in percent.
Source: Authors' computation, 2025.

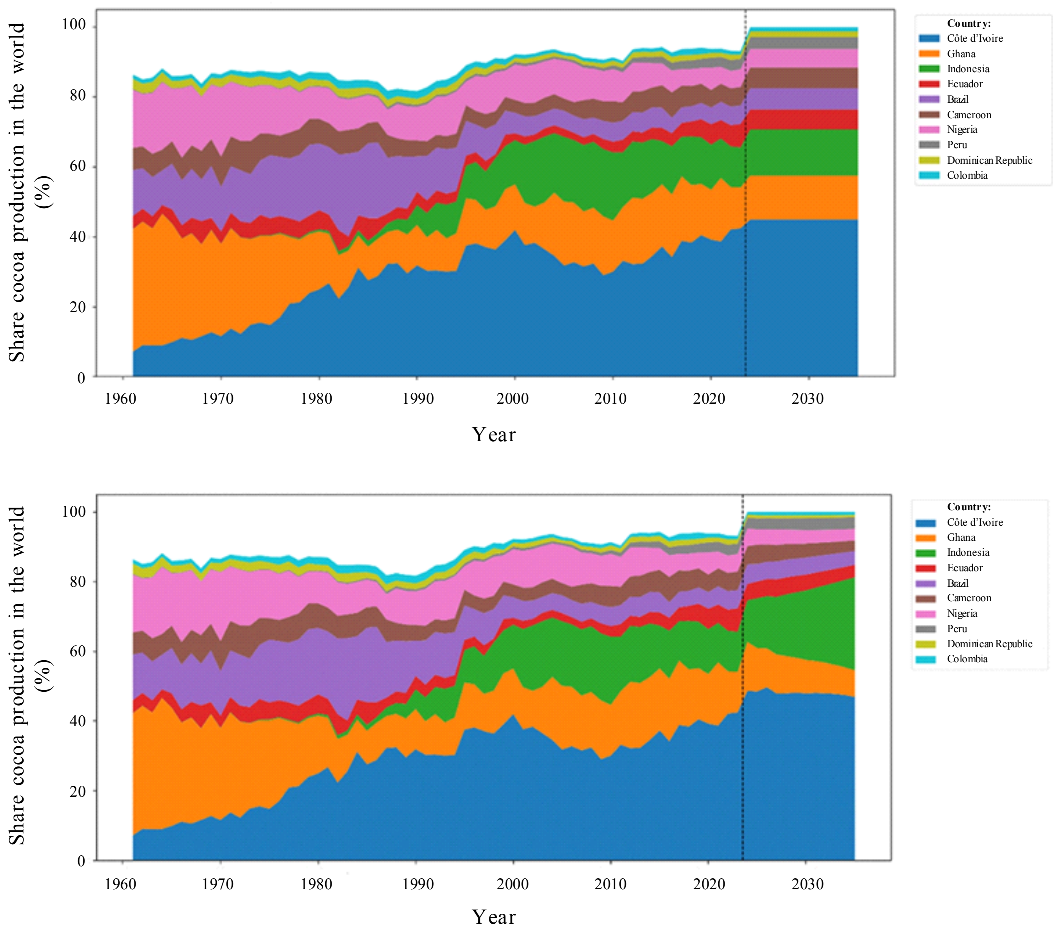


Figure 3. Comparison of the 10-country share forecast using the CSF approach (top) and IPF approach (bottom)

divergence emerges in how market concentration and individual country trajectories are projected. The IPF approach results in a more pronounced dominance for Côte d'Ivoire, whose share remains slightly above its 2023 level by 2035, reinforcing its position as the world's leading producer without signs of diminished dominance. Concurrently, Indonesia, historically in the low-teens percent in 2023, exhibits a sharply rising trajectory under IPF, ascending to around a quarter of the top ten producers' total by 2035 and establishing itself clearly as a "second pillar." These two producers are assigned higher market shares compared to the CSF forecasts, suggesting they mutually reinforce each other within the integrated model and capture a disproportionate share of global growth. In contrast, the integrated framework forecasts a significantly lower growth path and a declining relative position for Ghana. Historically the second-largest producer with a share in the teens, Ghana's market share is projected to fall considerably toward the high single digits by 2035, indicating it is expected to lag behind competitors, most notably Indonesia. This decline is largely attributed to challenges such as decreasing yields caused by nutrient depletion in soils (Amponsah-doku *et al*., 2022).

The projected paths for mid-tier producers like Ecuador and Brazil show more moderate differences between the two forecasting approaches, indicating their relative market positions are not radically reshaped. Historically, these countries held important mid-single-digit shares. Their forecasts show a tendency for their percentage shares to decline slightly, even as their absolute production volumes increase due to overall world growth. This means they do not lose production tonnage but lose relative position compared to the "big movers" like Côte d'Ivoire and Indonesia. These and other Latin American and African nations (Cameroon, Nigeria, Peru, the Dominican Republic, and Colombia) remain important in absolute volume but do not challenge the dominance of the top two; their shares are projected to be somewhat eroded as the African and Asian giants grow faster. The CSF approach forecasts a more tempered growth trajectory for the very largest players and envisions a comparatively greater distribution of market shares among these mid-tier producers. The rankings of the smallest producers exhibit the greatest variability between the model forecasts, reflecting higher inherent uncertainty at the lower end of the market hierarchy. In summary, while both models concur on the identity of the market leaders, with Côte d'Ivoire as the stable anchor and Indonesia as the rising second pillar amid Ghana's relative decline, the IPF framework projects a future characterized by stronger concentration at the very top, whereas the CSF approach depicts a future with a slightly more diversified production landscape.

Concentration Risks and Early Warning Signals

To evaluate the structural evolution of the global cocoa market, it is imperative to analyze the degree of market concentration over time. The Herfindahl-Hirschman Index (HHI) serves as a robust metric for assessing whether the market is moving toward diversification or consolidation. This study extends the historical analysis of market concentration (1961–2023) by projecting future trends up to 2035 using two distinct methodological frameworks: the Integrated Production Forecast (IPF) approach and the non-integrated Country-Specific Forecast (CSF) approach. While the former considers global systemic interdependencies, the latter treats national production trajectories as independent variables. Figure 3 illustrates the historical HHI trajectory alongside these divergent forecasting scenarios, providing a comparative lens on the anticipated stability of the global cocoa supply chain.

The analysis of Figure 4 reveals critical insights into the future market structure of the global cocoa industry, beginning with a historical trajectory that confirms a market already characterized by high concentration, where production is centered in a few dominant nations, most notably Côte d'Ivoire, Ghana, and Indonesia. At the onset of the forecast horizon in 2024, both models yield nearly identical results ($HHI_{Int} \approx 0.282$ vs $HHI_{Non\text{-}Int} \approx 0.281$), but a divergence emerges by the mid-period in 2028, where the integrated model begins to surpass the non-integrated version, culminating in the integrated HHI reaching a significantly higher peak of 0.303 by 2035 compared to the non-integrated projection of 0.286. The achievement of an HHI value of 0.303 in 2035 is particularly critical to emphasize, as it signifies a market transition from a "moderately concentrated" to a "highly concentrated" structure.

Applying the established early warning system, this projected HHI of 3,030 (0.303 × 10,000) triggers a Critical Alert for the year 2035. Furthermore, the integrated model's projection for Côte d'Ivoire's market share surpasses the 45% threshold by 2026,

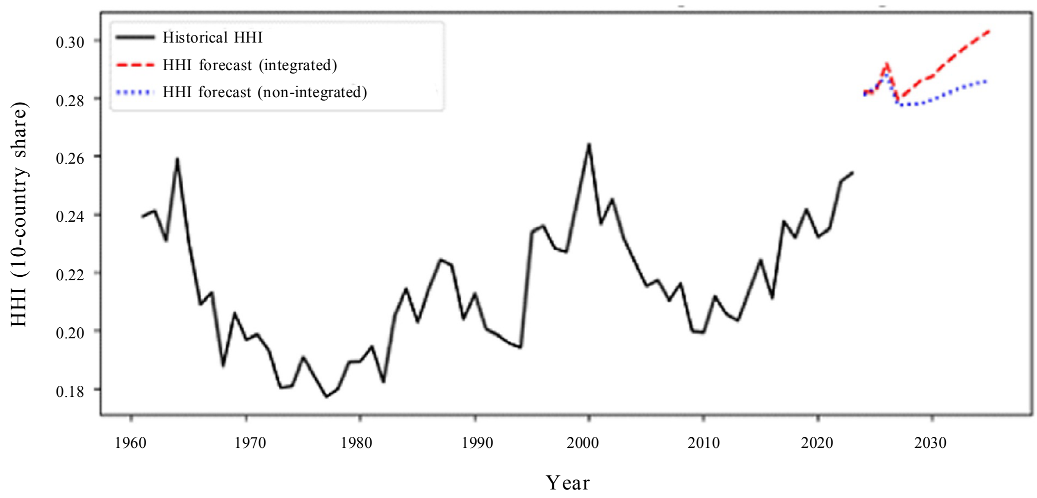


Figure 4. Historical and projected Herfindahl-Hirschman Index (HHI) for cocoa production (1961–2035)

triggering a Yellow Alert, and is forecasted to breach the 50% mark by 2032, initiating a Red Alert. This divergence indicates that the integrated model projects a future where major producers not only maintain but further strengthen their market dominance, whereas the non-integrated model presents a more optimistic outlook regarding market diversification, forecasting a slightly broader distribution of production shares among secondary producing nations. From a high-level policy and risk management perspective, the integrated forecast scenario highlights an unabated or even intensifying global dependence on a few primary producers, underscoring persistent supply concentration risks for global buyers and the chocolate industry. Consequently, these findings suggest that strategic risk management must prioritize the diversification of sourcing origins—extending beyond traditional hubs toward emerging producers in Latin America, other parts of Asia, and non-traditional African regions—to effectively mitigate the impact of potential localized shocks in the dominant producing countries.

Policy Implications and Strategic Recommendations

The findings of this study translate into distinct policy and strategic pathways for the primary stakeholders within the global cocoa value chain, informed by the projected market concentration and share dynamics. For dominant producing nations like Côte d'Ivoire, Ghana, and Indonesia, the forecast underscores an imperative to proactively manage the systemic risks inherent in their market power. This necessitates a dual strategy of internal production base diversification to mitigate localized climate or political shocks, coupled with substantial investment in climate-resilient agriculture (Dago & Pei, 2025; Läderach *et al*., 2013; Torvikey *et al*., 2024) and robust supply chain governance to maintain productivity and transparency (Ansah *et al*., 2018; Brako *et al*., 2021), thereby preserving long-term competitiveness in a market increa-singly wary of concentration risk.

For medium- and small-scale producing nations, the projected erosion of their relative market share, even as absolute volumes grow, presents a critical strategic window. To capitalize on the vulnerabilities of a concentrated market, these countries must ascend the value chain by developing domestic processing capacity and pursuing quality differentiation, particularly for fine-flavor niches, rather than competing solely on bean volume. Success in this endeavor is contingent upon parallel investments in core logistics and export infrastructure to overcome the cost barriers that currently hinder their potential as reliable alternative suppliers.

For global buyers, chocolate manufacturers, and international institutions, the projected consolidation underscores a persistent and systemic supply concentration risk, necessitating a paradigm shift toward active supply chain resilience. A central strategic imperative emerging from these findings is the prioritization of diversifying sourcing origins—extending procurement beyond traditional West African hubs to include emerging producers in Latin America, other parts of Asia, and non-traditional African regions—to effectively mitigate the impact of potential localized shocks in dominant producing countries. This diversification strategy should be implemented proactively, guided by the threshold-crossing events identified in the models, and complemented by efforts to foster a broader production base through inclusive support programs for smallholders in these emerging regions. To operationalize this approach, the implementation of a formal monitoring system using the Herfindahl-Hirschman Index and dominant share benchmarks as early-warning indicators is critical for enabling pre-emptive risk mitigation. Ultimately, the design and implementation of sustainability and trade policies must be carefully calibrated to ensure they do not inadvertently reinforce market concentration by disproportionately burdening smaller producers, but instead support an equitable transition toward a more diversified and resilient global cocoa system.

CONCLUSION

This study concludes that the global cocoa market is undergoing a critical transition from moderate to high concentration, with production dominance increasingly consolidated in Côte d'Ivoire, whose market share is projected to exceed 50% by 2032, triggering systemic supply chain vulnerabilities. The comparative forecasting analysis demonstrates that the Integrated Production Forecasting approach provides statistically superior accuracy for production volume forecasts, while both methodologies concur on the intensifying market structure, underscoring an urgent need for strategic diversification of sourcing origins to mitigate risks from localized shocks in dominant producing regions. The research is inherently limited by its assumption of structural stability in the face of climate change and its exclusion of demand-side dynamics, which presents a significant constraint given the potential for demand elasticity and substitution effects. Future research should prioritize the development of integrated climate-economic models that incorporate high-resolution climate projections as exogenous drivers and explore agent-based simulations to understand how micro-level decisions among producers and policymakers propagate into emergent macro-level market structures, thereby providing a more robust foundation for policy design aimed at enhancing the resilience and sustainability of the global cocoa system.

REFERENCES

Agbenyo, W.; Y. Jiang; Z. Ding; J.K. Titriku & G. Ntim-Amo (2022). Impact of Climate Change on Cocoa Production in Africa: An approach of Cross sectional ARDL. *International Journal of Environmental Research*, 16(5), 1–12. https://doi.org/10.1007/s41742-022-00471-0.

Ahoa, E.; A. Kassahun; B. Tekinerdogan & C. Verdouw (2021). Analyzing and Designing Business Processes in the Ghana Cocoa Supply Chain for Supporting Inclusiveness. *Sustainability*, 13, 1–29.

Amponsah-doku, B.; A. Daymond; S. Robinson; L. Atuah & T. Sizmur (2022). Improving soil health and closing the yield gap of cocoa production in Ghana–A review. *Scientific African*, 15, 1–11. https://doi.org/10.1016/j.sciaf.2021.e01075.

Ansah, G.O.; F. Ofori; L.P. Siaw & J. Manu (2018). The stake of licence buying companies (LBCs) in the promotion of quality cocoa in Ghana. *Cogent Business & Management*, 5, 1–12. https://doi.org/10.1080/23311975.2018.1560857.

Arias-Hidalgo, D. & M.M. González (2020). Intangible Indigenous Cultural Heritage: Analysis of the Tourist Potential of The Symbolism of Cocoa for the Bribri People (Talamanca, Costa Rica). *Cuadernos de Turismo,* 46, 655–657.

Asante, P.A.; M.A. Rozendaal; E. Rahn; P.A. Zuidema; A.K. Quaye; R. Asare; P. L¨aderach & N.P.R. Anten (2021). Unravelling drivers of high variability of on-farm cocoa yields across environmental gradients in Ghana. *Agricultural Systems*, 193(June). https://doi.org/10.1016/j.agsy.2021.103214.

Atanassova, M.; M. Martorell; F. Sharopov; L. Atanassov; P. Kumar; J. Sharifi-Rad; S. Tejada-Gavela; M. Iriti; R. Pezzani & E.M. Varoni (2024). Cocoa as immunomodulatory agent: An update. *Natural Product Research*, 38(23), 4196–4207. https://doi.org/10.1080/14786419.2023.2272025.

Atangana, A.R.; J.Z. Gnangoh; A.K. Yao; Kouakou; A.M.N. Thomas d'AquinNda & C. Kouam (2021). Rebuilding Tree Cover in Deforested Cocoa Landscapes in Côte d'Ivoire: Factors Affecting the Choice of Species Planted. *Forests*.

Bandanaa, J.; I.K. Asante; T.Y. Annang; J. Blockeel; A. Heidenreich; I. Kadzere; C. Schader & I.S. Egyir (2025). Social and Environmental Trade-Offs and Synergies in Cocoa Production: Does the Farming System Matter? *Sustainability*, 17, 1–14.

Barsanetti, B. (2024). Capital as an anchor of agricultural employment: Evidence from the 1975 frost. *Regional Science and Urban Economics*, 108 (September 2023), 104041. https://doi.org/10.1016/j.regsciurbeco.2024.104041.

Boysen, O.; E. Ferrari; V. Nechifor & P. Tillie (2023). Earn a living/ ? What the Côte d ' Ivoire – Ghana cocoa living income differential might deliver on its promise. *Food Policy*, 114 (November 2021), 102389. https://doi.org/10.1016/j.foodpol.2022.102389.

Brako, D.E.; A. Richard & G. Alexandros (2021). Do voluntary certification standards improve yields and wellbeing? Evidence from oil palm and cocoa smallholders in Ghana. *International Journal of Agricultural Sustainability*, 19(1), 16–39. https://doi.org/10.1080/14735903.2020.1807893.

Brezina, I.; J. Pekár; Z. ˇCiˇcková & M. Reiff (2016). Herfindahl – Hirschman index level of concentration values modification and analysis of their change. *CEJOR*, 24, 49–72. https://doi.org/10.1007/s10100-014-0350-y.

CaRubio, D.I.C.; F.E.P. García & K.C.A. Vargas (2024). Impactos ecológicos, económicos y sociales del sector cacao-tero Colombiano. *Granja*, 40(2), 50–70.

Chai, T.; R.R. Draxler & C. Prediction (2014). Root mean square error (RMSE) or mean absolute error (MAE)? – Arguments against avoiding RMSE in the literature. *Geoscientific Model Development*, 7(3), 1247–1250. https://doi.org/10.5194/gmd-7-1247-2014.

Dago, D.A. & Y. Pei (2025). Evaluating the Position of Côte d'Ivoire's Cocoa Industry on the Global Production Chain and the Influencing Factors. *Sustainability*, 17, 1–33.

Domínguez-Valerio, C.M. & F. Orgaz-agüera (2024). Gastronomic tourist experiences based on cocoa: Tourist ratings in Santo

Domingo (Dominican Republic), a world heritage destination. *Cuadernos de Turismo,* 54, 267–270.

FAO (2025). *Crops and livestock products*. https://www.fao.org/faostat/en/#data/QCL.

Gutiérrez-Macías, P.; V.A. Mirón-Mérida; C.O. Rodríguez-Nava & B.E. Barragán-Huerta (2021). Cocoa: Beyond chocolate, a promising material for potential value-added products. In R.B.T.-V. of A.-F.W. & B.-P. Bhat (Ed.), *Valorization of Agri-Food Wastes and By-Products: Recent Trends, Innovations and Sustainability Challenges* (pp. 267–288). Academic Press. https://doi.org/https://doi.org/10.1016/B978-0-12-824044-1.00038-6.

Hacker, R.S. & J.A. Hatemi (2008). Optimal lag-length choice in stable and unstable VAR models under situations of homoscedasticity and ARCH. *Journal of Applied Statistics*, 35(6), 601–615. https://doi.org/10.1080/02664760801920473.

Hodson, T.O. (2022). Root-mean-square error (RMSE) or mean absolute error (MAE): when to use them or not. *Geoscientific Model Development*, 15(14), 5481–5487.

Kim, P.S. (2023). Alternative Kalman Smoothing Filter With Moving Window Strategy. *ICIC Express Letters*, 14(4), 379–387. https://doi.org/10.24507/icicelb.14.04.379.

Konat, N.; Y. Ouattara; A.K. Kouakou & Y.S.S. Barima (2024). Effects of Traditional Agroforestry Practices on Cocoa Yields in Côte d'Ivoire. *Sustainability*, 16, 1–17.

Kongor, J.E.; M. Owusu & C.O. Yeboah (2024). Cocoa production in the 2020s: Challenges and solutions. *CABI Agriculture and Bioscience*, 5(1), 1–28. https://doi.org/10.1186/s43170-024-00310-6.

Läderach, P.; A. Martinez-Valle; G. Schroth & N. Castro (2013). Predicting the future climatic suitability for cocoa farming of the world's leading producer countries, Ghana and Côte d'Ivoire. *Climatic Change*, 119, 841–854. https://doi.org/10.1007/s10584-013-0774-8.

Maciel, L.F.; A.L. de S.M. Felício; L.C.R. Miranda; T.C. Pires; E. da S Bispo & E.Y. Hirooka (2018). Aflatoxins and ochratoxin A in different cocoa clones (*Theobroma cacao* L.) developed in the southern region of Bahia, Brazil. *Food Additives & Contaminants: Part A*, 35(1), 134–143. https://doi.org/10.1080/19440049.2017.1397293.

McMahon, P.; A. Purwantara; A.W. Susilo; S. Sukamto; A. Wahab; H. bin Purung; M. Hidayat; D. Ismail; T. Taproni.; S. Lambert; D. Guest & P. Keane (2010). On-farm selection for quality and resistance to pest/diseases of cocoa in Sulawesi: (i) performance of selections against cocoa pod borer, Conopomorpha cramerella. *International Journal of Pest Management*, 56(4), 351–361. https://doi.org/10.1080/09670874.2010.503284.

Ntiamoah, A. & G. Afrane (2008). Environmental impacts of cocoa production and processing in Ghana: Life cycle assessment approach. *Journal of Cleaner Production*, 16, 1735e1740. https://doi.org/10.1016/j.jclepro.2007.11.004.

Olwig, M.F.; R. Asare; H. Meilby; P. Vaast & K. Owusu (2023). Introduction: Climate, Cocoa and trees. **In:** *Agroforestry as Climate Change Adaptation: The Case of Cocoa Farming in Ghana*. https://doi.org/10.1007/978-3-031-45635-0.

Ozturk, G. & G.M. Young (2017). Food Evolution: The Impact of Society and Science on the Fermentation of Cocoa Beans. *Comprehensive Reviews in Food Science and Food Safety*, 16, 431–455. https://doi.org/10.1111/1541-4337.12264.

Parra-paitan, C.; K.H.J. Erasmus; P. Meyfroidt & P.H. Verburg (2023). Large gaps in voluntary sustainability commitments covering the global cocoa trade. *Global Environmental Change*, 81, 1–15. https:

//doi.org/10.1016/j.gloenvcha. 2023. 102696.

Pastor-Soplín, S.H.; D. Velásquez & E. Rivas (2022). Utilization of genetic resources in a country center of origin: the case of cocoa in Peru. *Revista Peruana de Biologia*, 29(4), 1–12.

Reddicharla, N.; R.C. Cornwall; E. Rubio; S. Soni & J. Isambertt (2019). Data and Model Integration Challenges for Integrated Production Forecasting-Experience from Super-Giant Onshore Fields. *PE Middle East Oil and Gas Show and Conference*, D031S031R002. https://doi.org/10.2118/194735-MS.

Ribeiro, M.R.; T.P. Ponce & T.S. Telles (2020). Spatial dynamics of coffee production in the state of Parana, Brazil. *Coffee Science*, 15(1), 1–9. https://doi.org/10.25186/.v15i.1754

Rubini, M.R.; R.T. Silva-Ribeiro; A.W.V. Pomella; C.S. Maki; W.L. Araújo; D.R. dos Santos & J.L. Azevedo (2005). Diversity of endophytic fungal community of cacao (*Theobroma cacao* L.) and biological control of *Crinipellis perniciosa,* causal agent of Witches' Broom Disease. *International Journal of Biological Sciences*, 1(1), 24–33. https://doi.org/10.7150/ijbs.1.24.

Santhusitha, D. & K. Karunasingha (2022). Root mean square error or mean absolute error? Use their ratio as well. *Information Sciences*, 585, 609–629. https://doi.org/10.1016/j.ins.2021.11.036.

Sarria, B.;S. Martý´nez-Lo´pez; J.L. Sierra-Cinos; L. Garcý´a-Diz; R. Mateos & L. Bravo (2014). Regular consumption of a cocoa product improves the cardiometabolic profile in healthy and moderately hypercholesterolaemic adults. *British Journal of Nutrition*, 111, 122–134. https://doi.org/10.1017/ S000711451300202X.

Shepherd, W.G. (2018). Herfindahl Index. In *The New Palgrave Dictionary of Economics* (pp. 5787–5788). Palgrave Macmillan UK. https://doi.org/10.1057/978-1-349-95189-5_711.

Talpur, A.B. (2023). Social Sciences & Humanities Open Market power and concentration-performance analysis of the banking sector: A comparative study of Singapore and Pakistan. *Social Sciences & Humanities Open*, 7(1), 100383. https://doi.org/10.1016/j.ssaho.2022.100383.

Tayman, J. & D.A. Swanson (1999). On the validity of MAPE as a measure of population forecast accuracy. *Population Research and Policy Review*, 18, 299–322.

Tingting, H. (2024). A varying coefficient geographically weighted spatial lag model for compositional data. *Journal of Beijing University of Aeronautics and Astronautics*, 50(7), 2256–2264.

Tofallis, C. (2015). A better measure of relative prediction accuracy for model selection and model estimation. *Journal of the Operational Research Society*, 66(8), 1352–1362. https://doi.org/10.1057/jors.2014.103.

Torvikey, G.D.; M.A. Dalaa; F.O. Adomaa; S. Abdul-razak; I.A. Amoah; R.K. Kofituo; A. Tettey; S. Abdul-razak; I.A. Amoah; R.K. Kofituo; A. Tettey; R. Asare; S Abdul-razak.; I.A. Amoah; R.K. Kofituo; A. Tettey & R. Asare (2024). Making Climate-Smart Cocoa Inclusive: Towards a Framework for Gender Transformation. *South African Review of Sociology*, 54(1), 42–57. https://doi.org/10.1080/21528586.2024.2321909.

Tsagris, M.; S. Preston & A.T.A. Wood (2016). Improved Classification for Compositional Data Using the α-transformation. *Journal of Classificatio*, 33, 243–261. https://doi.org/10.1007/s0035

V'yugin, V.V. & V.G. Trunov (2020). Online Aggregation of Probabilistic Forecasts Based on the Continuous Ranked Probability Score. *Journal of Communications Technology and Electronics*, 65(6), 662–676. https://doi.org/10.1134/S1064226920060285.

Vinci, G.; M. Ruggeri; L. Gobbi & M. Savastano (2024). Social Life Cycle Assessment of Cocoa Production: Evidence from Ivory Coast and Ghana. *Resources*, 13 (141), 1–19.

Viteri, O.; Latorre S.; M. Zambrano & M.A. Quelal-v (2023). The challenges of a sustainable cocoa value chain: A study of traditional and " fine or flavour " cocoa produced by the kichwas in the ecuadorian Amazon region. *Journal of Rural Studies*, 98, 92–100. https://doi.org/10.1016/j.jrurstud.2023.01.015.

Wang, J.-N.; Y.-T. Hsu; J.-M. Lee & C.-C. Chen (2019). Measuring Systemic Risk: Capital Shortfall and CSRISK. *International Review of Finance*, 21(1), 1–12. https://doi.org/10.1111/irfi.12269.

Yafi, M.A.; B. Wirda & A.S. Adyanti (2025). Market Structure and Competition of Indonesian Cocoa Beans. *Pelita Perkebunan*, 41(3), 325–338. https://doi.org/10.22302/iccri.jur. pelitaperkebunan.v41i3.697.

Yoroba, F.; B.K. Kouassi; A. Diawara; L.A.M. Yapo; K. Kouadio; D.T. Tiemoko; Y.K. Kouadio; I.D. Kon & P. Assamoi (2019). Evaluation of Rainfall and Temperature Conditions for a Perennial Crop in Tropical Wetland: A Case Study of Cocoa in Cˆote d'Ivoire. *Advances in Meteorology*, 2019(1), 1–10. https://doi.org/10.1155/2019/9405939.

Zamo, M. & P. Naveau (2018). Estimation of the Continuous Ranked Probability Score Weather Forecasts. *Mathematical Geosciences*, 50(2), 209–234. https://doi.org/10.1007/s11004-017-9709-7.

Zikria, V.; K. Takahashi & K. Maeda (2019). International Competitiveness of Indonesia's Cocoa Sector: From the Viewpoint of Product Differentiation. *Journal of the Faculty of Agriculture, Kyushu University*, 64(2), 407–413.

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