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Market Integration and Price Transmission of Robusta Coffee in North Sumatra Province with the World Market

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Abstract. Previous coffee-market studies have linked domestic and international prices, but they have rarely examined long-run integration, short-run asymmetry, shock decomposition, predictive causality, and threshold adjustment in one empirical sequence for the North Sumatran robusta supply chain. This study addresses that gap by analysing farm-level or production-area prices (PFC), North Sumatra exporter-level prices (PEC), and world prices represented by London Robusta Futures (PWC) using 120 monthly observations from January 2016 to December 2025. The analysis applied unit-root testing, Johansen cointegration, VECM, FEVD, Granger causality, AECM, Wald tests, and Hansen-Seo threshold testing. All series were I(1), and the Johansen test identified two cointegrating equations, confirming long-run integration among farm, exporter, and world prices. VECM adjustment was significant for PFC (ECT = -0.426806; t = -5.07885) and PEC (ECT = -0.298370; t = -4.44265), while PWC behaved as the reference market. At the 10-month horizon, PWC shocks explained 51.15% of PFC variation and 40.50% of PEC variation, while PWC remained dominated by its own shocks (84.22%). Supporting four-market IRF evidence showed that the largest own-price responses occurred in the first period, were followed by sign reversals, and in several equations remained visible at period 10, indicating gradual rather than instantaneous stabilization. Granger causality was bidirectional between PFC and PEC and unidirectional from PWC to PEC. Short-run asymmetry was found mainly in the PFC-PEC relationship, whereas long-run asymmetry and threshold cointegration were not supported. These findings contribute to agricultural market-integration literature by showing that benchmark prices transmit risk to domestic actors through linear long-run adjustment and temporary short-run frictions. Policy should strengthen transparent price information, quality-based pricing, and farmer bargaining institutions.

Keywords: asymmetric adjustment; error correction; farm-export chain; futures benchmark; shock decomposition

1. Introduction

Robusta coffee is a strategic plantation commodity because it provides farm income, supports regional trade, and connects producing regions with international value chains (Vicol et al., 2018). For an export-oriented commodity, price formation cannot be explained only by local production conditions. Prices at the farm level are also affected by exporter prices, international benchmarks, exchange-rate conversion, product quality, transaction costs, and bargaining power along the supply chain. In this setting, price integration becomes a central issue because it indicates whether price information from a reference market is transmitted to other market levels in a timely and proportional manner.

In the robusta coffee trade, the world price formed through London Robusta Futures/ICE Futures Europe is commonly used as a benchmark for physical trade and risk management (Exchange, 2026). However, the existence of a global benchmark does not automatically imply complete pass-through to domestic or farm-level prices. International-to-local price transmission may be incomplete because domestic markets face transaction costs, institutional frictions, quality differentiation, policy changes, and heterogeneous market actors (Bekkers et al., 2017; Cramon-

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taubadel & Goodwin, 2021; Emediegwu & Rogna, 2024a).

Previous coffee studies provide evidence that coffee prices across international, export, and domestic markets do not always move in a perfectly symmetric and immediate manner. Asymmetric price transmission has been reported for Indonesian coffee, Vietnamese robusta coffee, Ethiopian coffee, and other global-domestic coffee chains (Huffaker et al., 2021; Hundie & Biratu, 2022; Kamaruddin et al., 2021; Mai et al., 2018). These findings imply that the vertical linkage between farmers, exporters, and world markets must be examined empirically rather than assumed from the existence of international trade.

North Sumatra is one of Indonesia's important coffee-producing and trading regions. In the provincial robusta coffee supply chain, the relationship among farm-level or production-area price (PFC), exporter-level price (PEC), and world price (PWC) is expected to influence how benefits and risks from global price movements are distributed. When world prices increase, farmers may benefit only if the increase is transmitted through exporters and local market channels. Conversely, when world prices decline, the speed and magnitude of adjustment may determine the vulnerability of producers and traders.

This study contributes to the literature by examining market integration, price transmission, asymmetry, and threshold adjustment within a single empirical sequence. The research specifically addresses three questions: whether PFC, PEC, and PWC share a long-run equilibrium relationship; whether price transmission between farm-exporter and world-exporter markets is symmetric or asymmetric; and whether nonlinear threshold adjustment is present in the price transmission process.

1.1 Market Integration and Price Transmission

Market integration refers to the degree to which prices in separate markets move together because information, trade, and arbitrage connect them. Classical market integration analysis argues that prices in related markets should not drift apart permanently when trade links and information flows are effective (Goodwin & Piggott, 2001; Ravallion, 1986). In agricultural markets, integration may be spatial, linking regions, or vertical, linking farm, trader, processor, exporter, and international markets. The presence of cointegration among price series indicates that they share a long-run equilibrium despite short-run fluctuations (Engle & Granger, 1987; Johansen & Juselius, 1990).

Price transmission explains how a price change at one market level affects another market level. Transmission may be symmetric when increases and decreases are passed through with similar speed and magnitude. Transmission may be asymmetric when market actors respond differently to positive and negative shocks. Asymmetry can arise from market power, search and adjustment costs, menu costs, inventory behavior, quality heterogeneity, and institutional barriers (Cramon-taubadel & Goodwin, 2021; Frey & Manera, 2007; Kinnucan, 2022; Meyer & von Cramon-Taubadel, 2004).

For export commodities such as coffee, world prices may function as a reference market. However, domestic prices can still be affected by transaction costs, product standards, logistics, exchange-rate movements, and bargaining structures. Recent studies highlight that international price transmission to domestic markets in developing countries can be incomplete and heterogeneous across commodities and market structures (Arnade et al., 2017; Emediegwu & Rogna, 2024b; Lan et al., 2022).

1.2 AECM and Threshold Adjustment

The Asymmetric Error Correction Model (AECM) extends conventional error-correction analysis by separating positive and negative shocks. This separation allows researchers to test whether price increases and price decreases are transmitted

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differently in the short run and whether positive and negative deviations from long-run equilibrium are corrected differently (Granger & Lee, 1989; von Cramon-Taubadel, 1998). The Wald test is then used to examine whether the positive and negative coefficients are statistically different.

Threshold cointegration assumes that price adjustment toward equilibrium may occur only when the deviation from equilibrium exceeds a certain threshold. This approach is relevant in agricultural markets because small deviations may not trigger adjustment when transaction costs, transportation costs, or search costs are larger than potential arbitrage gains. Threshold cointegration and TVECM, therefore, allow the speed of adjustment to differ across regimes (Balke & Fomby, 1997; Enders & Siklos, 2001; Hansen & Seo, 2002; Meyer & Cramon-taubadel, 2004).

1.3 Coffee Price Dynamics and Research Framework

Empirical studies show that international and domestic coffee prices are connected but often imperfectly transmitted. (Ghoshray & Mohan, 2021) identify asymmetric adjustment in the retail-international coffee price margin, whereas (Bohl et al., 2019) show that an emerging-economy coffee market can contribute to international price discovery. For Indonesia, (Kamaruddin et al., 2021) document asymmetric transmission from world to producer prices, while (Khumaira et al., 2016) identify price linkages between the Indonesian coffee market and major export destinations. Together, these studies indicate that the strength, direction, and symmetry of price transmission depend on the market level, institutional setting, and empirical specification.

The framework of this study positions PWC as the world reference market, PEC as the exporter-level market in North Sumatra, and PFC as the farm-level or production-area market. The empirical logic is that world price signals may influence exporter prices, and exporter prices may then transmit changes to farm prices. At the same time, local farm and exporter prices may also interact bidirectionally because of supply, procurement, and quality adjustments.

Based on the framework, four hypotheses were examined: H_1: PFC, PEC, and PWC have a long-run equilibrium relationship; H_2: price transmission occurs between PFC and PEC and between PWC and PEC; H_3: positive and negative price changes may be transmitted asymmetrically; and H_4: threshold adjustment may occur if price deviations exceed an economically relevant regime boundary.

2. Materials and Methods

2.1 Data and Variables

This study used secondary monthly time-series data from January 2016 to December 2025, resulting in 120 observations for each price variable. The analysis focused on three robusta coffee price series: farm-level or production-area price (PFC), exporter-level price in North Sumatra (PEC), and world price represented by London Robusta Futures/ICE Futures Europe (PWC). All prices were expressed in Indonesian rupiah per kilogram to maintain comparability across market levels.

PFC represents the price received in the production area and is used as a proxy for farm-level robusta coffee price. PEC represents the North Sumatra exporter-level price and was calculated from the ratio of export value to export volume. PWC represents the world robusta coffee price and was converted into rupiah per kilogram using the relevant exchange-rate conversion. The operational definitions are presented in Table 1.

2.2 Analytical Procedures

The analytical procedure followed the logic of time-series econometrics. First, descriptive statistics were used to assess price levels, volatility, relative growth, and price gaps. Second, the Augmented Dickey-Fuller (ADF) test was applied to determine whether each price series was stationary in levels or first differences. Third, the optimal lag length

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was selected using information criteria. Fourth, Johansen cointegration was used to test the existence of a long-run equilibrium among PFC, PEC, and PWC.

Table 1. Operational definitions of variables

Code	Variable	Unit	Explanation
PFC	Farm-level/production-area robusta coffee price	Rp/kg	Price series representing robusta coffee price in the production area.
PEC	North Sumatra exporter-level robusta coffee price	Rp/kg	Calculated from export value divided by export volume and converted into Rp/kg.
PWC	World robusta coffee price/London Robusta Futures	Rp/kg	London Robusta Futures/ICE Futures Europe price converted into Rp/kg.

When the variables were found to be I(1) and cointegrated, the Vector Error Correction Model (VECM) was used to estimate the short-run dynamics and the speed of adjustment toward long-run equilibrium. Forecast Error Variance Decomposition (FEVD) was employed to evaluate the contribution of shocks from each price series to the forecast error variance of other series. Granger causality tests were used to identify the direction of predictive relationships among PFC, PEC, and PWC.

To evaluate asymmetric price transmission, AECM was estimated by separating positive and negative price changes and positive and negative error-correction components. Wald tests were applied to examine whether the coefficients of positive and negative components differed significantly. Finally, the Hansen-Seo TVECM threshold cointegration test was conducted for the PFC-PEC and PEC-PWC relationships to determine whether nonlinear regime adjustment was statistically supported.

3. Results and Discussion

3.1 Descriptive Price Dynamics and Stationarity

The descriptive results show that PWC had the highest average price, followed by PEC and PFC. The average prices were Rp68,976/kg for PWC, Rp51,384/kg for PEC, and Rp37,843/kg for PFC. This pattern indicates a clear price hierarchy along the robusta coffee chain, where farm-level prices were lower than exporter and world prices. The difference reflects marketing costs, grading, logistics, quality adjustment, margins, and bargaining structures between market actors.

Relative volatility was higher in domestic/exporter markets than in the world reference market. PEC recorded the highest coefficient of variation at 55.63%, followed by PFC at 51.34%, whereas PWC recorded 25.31%. From the beginning to the end of the observation period, PFC increased by 348.85%, PEC increased by 287.21%, and PWC increased by 113.75%. These descriptive patterns suggest that local and exporter prices experienced sharper adjustment than the world price, especially during the post-2021 price escalation period.

The ADF results show that all variables were non-stationary at the level but stationary at the first difference. Thus, PFC, PEC, and PWC are integrated of order one, I(1), and are appropriate for Johansen cointegration testing. The summary of descriptive and stationarity results is presented in Table 2.

3.2 Long-Run Market Integration

The optimal lag-selection results for the three-variable PFC-PEC-PWC system indicated lag 1 as the dominant choice based on FPE, AIC, SC, and HQ, while the bivariate AECM transmission tests used lag 3 according to AIC and FPE. Johansen cointegration tests confirmed the presence of two cointegrating equations at the 5% level. Both trace statistics and maximum eigenvalue statistics reject the null hypotheses of no cointegration and at most one cointegrating relationship, but fail to

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reject the null of at most two cointegrating relationships.

These results show that farm-level prices, exporter prices, and world prices share a long-run equilibrium. The existence of cointegration implies that although short-run deviations occur, the three price series do not move independently over time. The findings are consistent with the theory of market integration and with previous coffee-market studies showing linkages between international and domestic prices. However, the strength and form of adjustment may differ across market levels. The Johansen results are summarized in Table 3.

Table 2. Descriptive statistics and ADF unit-root test summary

Indicator	PFC	PEC	PWC
Observations	120	120	120
Mean price (Rp/kg)	37,843	51,384	68,976
Coefficient of variation	51.34%	55.63%	25.31%
Initial-final percentage change	348.85%	287.21%	113.75%
ADF at level: statistic (p-value)	-1.286962 (0.6340)	-0.808487 (0.8127)	-2.276073 (0.1814)
ADF at first difference: statistic (p-value)	-13.60491 (0.0000)	-11.23706 (0.0000)	-16.06023 (0.0000)
Integration order	I(1)	I(1)	I(1)

Table 3. Johansen Cointegration Test Results for the PFC–PEC–PWC Model

Hypothesis	Trace stat.	Trace 5% CV	Trace p	Max-Eigen stat.	Max-Eigen p
None	41.81939	24.27596	0.0001	24.11296	0.0049
At most 1	17.70643	12.32090	0.0057	16.82586	0.0047
At most 2	0.880571	4.129906	0.4023	0.880571	0.4023

3.3 Speed of Adjustment, FEVD, and Granger Causality

The VECM results indicate that PFC and PEC are the main adjusting variables. In the first cointegrating equation, the error-correction coefficient for D(PFC) was -0.426806 with a t-statistic of -5.07885, indicating a significant adjustment of farm-level prices toward long-run equilibrium. In the second cointegrating equation, the error-correction coefficient for D(PEC) was -0.298370 with a t-statistic of -4.44265, indicating that exporter prices also correct deviations from equilibrium. By contrast, the world price equation had insignificant error-correction coefficients, supporting the interpretation that PWC acts more as a reference market than as an adjusting domestic variable.

FEVD at the 10-month horizon reinforces the dominant role of world prices. PWC shocks explained 51.15% of the variation in PFC and 40.50% of the variation in PEC. Meanwhile, PWC was largely explained by its own shocks, with an 84.22% contribution. These results suggest that world price dynamics strongly influence farm and exporter prices, whereas domestic price shocks have limited influence on the world benchmark.

Granger causality tests reveal a bidirectional relationship between PFC and PEC. PEC Granger-caused PFC at $p = 0.0151$, and PFC Granger-caused PEC at $p = 0.0190$. The test also shows one-way causality from PWC to PEC at $p = 0.0005$, while PEC did not Granger-cause PWC. This pattern supports a vertical transmission mechanism in which the world market affects exporters, and exporter-farm prices interact through procurement and local market adjustment. The adjustment, variance-decomposition, and causality results are summarized in Table 4.

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Table 4. VECM Adjustment, FEVD, and Granger Causality Summary

Analysis	Key result	Statistic/value	Interpretation
VECM ECT	CointEq1 in D(PFC)	-0.426806; t = -5.07885	Farm price adjusts significantly to long-run disequilibrium.
VECM ECT	CointEq2 in D(PEC)	-0.298370; t = -4.44265	Exporter price adjusts significantly to long-run disequilibrium.
VECM ECT	D(PWC)	Insignificant ECT coefficients	World price behaves as a reference market.
FEVD horizon 10	PWC contribution to PFC	51.15134%	World shocks are the largest source of farm-price variation.
FEVD horizon 10	PWC contribution to PEC	40.50096%	World shocks strongly explain exporter-price variation.
Granger causality	PEC -> PFC	F = 3.63730; p = 0.0151	Exporter price predicts farm price.
Granger causality	PFC -> PEC	F = 3.45639; p = 0.0190	Farm price also predicts exporter price.
Granger causality	PWC -> PEC	F = 6.34802; p = 0.0005	World price predicts exporter price.

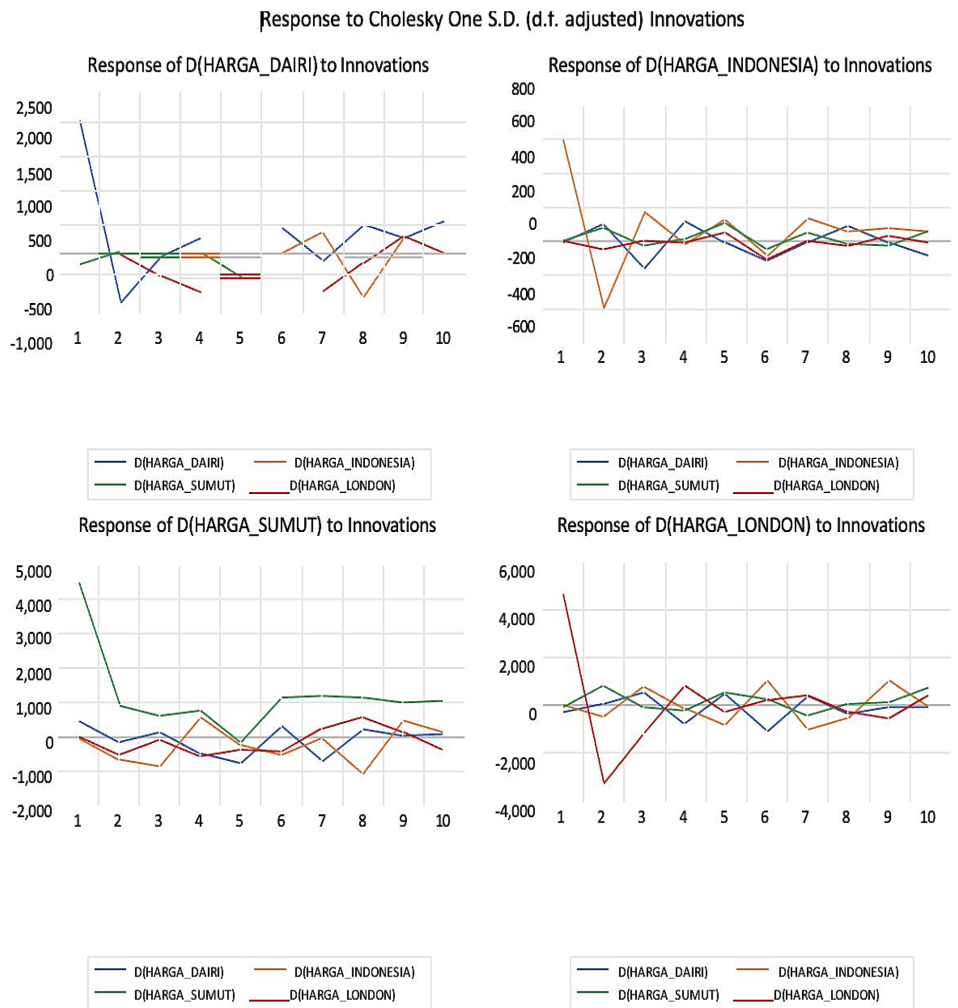

Figure 1. Impulse-response functions for the supporting Dairi-North Sumatra-Indonesia-London specification.

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Table 4 reports the available adjustment, decomposition, and causality results for the three-variable main model. Figure 1 presents complementary IRF evidence from the broader Dairi-North Sumatra-Indonesia-London specification. Because confidence bands are not shown, the IRF is interpreted in terms of direction, relative magnitude, and persistence rather than period-specific statistical significance.

Figure 1 shows that the response of Dairi prices to their own innovation was largest in period 1, reversed sharply in period 2, and then oscillated with smaller amplitudes through period 10. North Sumatra prices also displayed a very large initial own-price response, followed by a substantial decline; the response nevertheless remained positive at the end of the horizon, indicating slower dissipation than in the other domestic series. Indonesia and London prices showed pronounced sign reversals between periods 1 and 2 and thereafter fluctuated around the zero line. Cross-market responses were generally smaller than the initial own-price responses, changed sign several times, and remained visible in some equations at period 10. The overall pattern is therefore one of gradual, oscillatory stabilization rather than immediate convergence. Because the graph does not display confidence bands, the plotted paths are used to describe direction, relative magnitude, and persistence; they are not used to claim that individual period-specific responses are statistically different from zero. In addition, the four-market specification is treated as supporting evidence. It does not replace the exact PFC-PEC-PWC system used for the main cointegration, VECM, FEVD, and causality findings.

3.4 Asymmetric Price Transmission and Threshold Adjustment

The AECM and Wald test results show that asymmetric transmission was mainly a short-run phenomenon. In the PFC-PEC relationship, the Wald test for DPFC3_POS = DPFC3_NEG had F = 5.091568 and p = 0.0262, indicating short-run asymmetry at lag 3. However, the test for long-run asymmetry, ECT_POS = ECT_NEG, was not significant with p = 0.7072. This means that positive and negative deviations from long-run equilibrium were not corrected in a statistically different manner.

In the PEC-PWC relationship, the Wald test for DPWC3_POS = DPWC3_NEG had p = 0.0620, indicating only a weak short-run asymmetry at the 10% level. The long-run ECT asymmetry was again not significant, with p = 0.3959. Therefore, the evidence for asymmetric transmission is stronger in the farm-exporter relationship than in the world-exporter relationship, and the asymmetry is short-run rather than persistent in the long run.

The Hansen-Seo TVECM test does not support threshold cointegration. The PFC-PEC relationship had a SupLM statistic of 19.90959 with p = 0.667, and the PEC-PWC relationship had a SupLM statistic of 22.01281 with p = 0.394. Both statistics were below their respective critical values at the 90%, 95%, and 99% levels. Thus, nonlinear threshold adjustment was not statistically confirmed, and the linear VECM/AECM approach remains more suitable for explaining the robusta coffee price dynamics in this study. These asymmetry and threshold results are summarized in Table 5.

Table 5. AECM, Wald, and Threshold Cointegration Summary

Relationship	Short-run asymmetry	Long-run asymmetry	Threshold test	Main conclusion
PFC-PEC	Wald DPFC lag 3: F = 5.091568; p = 0.0262	ECT_POS = ECT_NEG: p = 0.7072	SupLM = 19.90959; p = 0.667	Short-run asymmetry exists; no long-run asymmetry; no threshold.
PEC-PWC	Wald DPWC lag 3: F = 3.563085; p = 0.0620	ECT_POS = ECT_NEG: p = 0.3959	SupLM = 22.01281; p = 0.394	Weak short-run asymmetry; no long-run asymmetry; no threshold.

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The difference between coefficient asymmetry and regime asymmetry can explain the absence of threshold cointegration despite short-run asymmetry. AECM-Wald tests ask whether positive and negative changes have different coefficients at certain lags. Hansen-Seo tests ask whether the whole error-correction process changes regime after deviations exceed a threshold. The data support the first mechanism mainly for PFC-PEC but not the second. Therefore, a linear VECM/AECM framework is more appropriate for the observed price dynamics than a threshold VECM.

Exchange-rate fluctuations are important in this system because the world Robusta price is quoted internationally and must be converted into rupiah. A depreciation of the rupiah can raise the rupiah value of a given USD-denominated world price, potentially strengthening the domestic price signal even when the foreign-currency benchmark does not change proportionally. Conversely, exchange-rate appreciation may dampen domestic transmission. For this reason, the conversion formula and exchange-rate source are not merely technical details; they are part of the economic mechanism through which PWC affects PEC and PFC.

The economic significance of the VECM results is as important as their statistical significance. The farm-level adjustment coefficient of -0.426806 implies that more than two-fifths of the relevant disequilibrium is corrected through the farm-price equation in the following month. In contrast, the exporter-level coefficient of -0.298370 implies a correction of almost one-third through exporter prices. These magnitudes are large enough to matter for market actors because they indicate that deviations from the long-run relation are not merely statistical artifacts. Farmers and exporters face real adjustment pressure when the system moves away from equilibrium, while PWC remains comparatively outside the domestic correction process.

The combined FEVD and IRF evidence also clarifies the difference between exposure to world-price risk and full price pass-through. A PWC contribution of 51.15% to PFC variation at the 10-month horizon means that world shocks are a major source of farm-price uncertainty, but it does not mean that every world-price increase is transmitted one-for-one to farmers. The supporting paths in Figure 1 show that responses are dynamic, sign-changing, and not fully dissipated in every market by period 10. This is compatible with a connected but imperfectly transmitted price system, especially when quality, moisture content, marketing costs, exchange-rate conversion, and trader relationships filter local prices.

3.5 Comparative Discussion with Previous Literature

The long-run integration result is broadly consistent with Indonesian evidence that domestic coffee prices are linked to external markets, but the present study locates the adjustment burden more precisely. (Khumaira et al., 2016) examined price transmission between the Indonesian coffee market and major export destinations, whereas (Kamaruddin et al., 2021) evaluated asymmetry between world and Indonesian producer prices. By estimating a three-level PFC-PEC-PWC system for North Sumatra, this study shows that PFC and PEC, rather than PWC, perform statistically significant error correction. The difference is partly methodological and partly institutional: national or bilateral models identify whether markets are connected. In contrast, the present vertical model identifies the farm and exporter nodes through which disequilibrium is corrected. The theoretical implication is that cointegration does not require equal adjustment across market levels; a common equilibrium can coexist with a reference market that is comparatively weakly adjusting and domestic actors that bear most of the correction.

The short-run asymmetry result is also comparable with, but narrower than, earlier Indonesian and Vietnamese evidence. Kamaruddin et al. (2021) reported asymmetric world-to-producer transmission

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for Indonesian coffee, and Mai et al. (2018) showed that vertical adjustment frictions shape the Vietnam robusta farm-export relationship. In North Sumatra, statistically supported asymmetry appears mainly at lag 3 in the PFC-PEC relation. At the same time, the PEC-PWC evidence is only weak at the 10% level, and long-run asymmetry is not supported. These differences can plausibly arise from the unit of analysis and data frequency. A regional monthly series averages many transactions, quality grades, and contract dates, whereas a national producer-world model or higher-frequency farm-export data can preserve different forms of adjustment. The 2016-2025 sample also covers the pandemic and the post-2021 commodity-price escalation, so its adjustment pattern need not reproduce findings from earlier periods.

The contrast with Ethiopia is more pronounced. (Hundie & Biratu, 2022) found dynamic and nonlinear responses of Ethiopian coffee prices to the world market, including evidence that positive and negative shocks were transmitted differently over the short and long run. The North Sumatra results support temporary short-run coefficient asymmetry but not long-run asymmetry or Hansen-Seo threshold cointegration. A plausible explanation is the difference in scale and market organization: the Ethiopian evidence is based on a country-level price system and distinct national marketing institutions, whereas North Sumatra combines decentralized farm procurement, exporter aggregation, quality deductions, and rupiah conversion of the London benchmark. In addition, the AECM-Wald and Hansen-Seo procedures used here distinguish coefficient asymmetry from a full change in the error-correction regime. Consequently, the absence of a threshold should not be read as evidence that frictions are absent; it indicates that the observed frictions do not form a statistically stable two-regime process in this sample.

The result also differs from (Huffaker et al., 2021), who detected endogenous instability in the global-exporter-processor-producer coffee chain in Papua New Guinea. In the present study, the joint evidence instead favors linear long-run correction, with temporary asymmetry and no statistically supported threshold. This difference may reflect both chain structure and empirical resolution. The Papua New Guinea analysis follows several commercial nodes and is designed to detect instability in the transmission mechanism, whereas the North Sumatra model uses three aligned monthly price aggregates. Monthly aggregation can smooth transaction-level changes in margins, inventories, and bargaining conditions, while differences in exporter concentration, processing arrangements, and producer-market access can alter the way shocks propagate. The comparison, therefore, suggests that nonlinear instability is an empirical property of a particular chain, not an automatic consequence of participation in the global coffee trade.

The location of asymmetry also differs from the downstream margin studied by Ghoshray & Mohan (2021). Their retail-international analysis emphasizes adjustment in a margin that includes processing, roasting, distribution, and retailing, where concentration among downstream firms may affect price behavior. The North Sumatra evidence places the clearer asymmetry upstream, between farm and exporter prices, while long-run correction remains symmetric. This contrast is consistent with the proposition that price-transmission frictions are segment-specific: market power, inventory costs, quality verification, and information delays may be concentrated at different points of the value chain. It also explains why evidence from retail coffee markets cannot be transferred directly to farm-exporter relations without considering the institutional position of the prices being compared.

The price-leadership result further contrasts with (Bohl et al., 2019), who showed that an emerging-economy coffee

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futures market can contribute to global price formation. North Sumatra farm and exporter prices do not display a comparable influence on the London benchmark; PWC remains largely explained by its own shocks and predicts PEC rather than the reverse. The difference is consistent with market structure. Brazil has a liquid domestic futures market capable of aggregating and transmitting local information to an international benchmark. In contrast, the North Sumatra series represents physical farm and export transactions without an equivalent regional futures platform. Thus, the findings are not contradictory: they show that the ability of a producing region to influence global price discovery depends on trading infrastructure, market scale, and the institutional channel through which local information enters futures markets.

Taken together, these comparisons refine the theoretical interpretation of market integration. Long-run cointegration, short-run coefficient asymmetry, and threshold-dependent regime change are related but distinct properties. A market may be integrated because prices share an equilibrium, yet still allocate adjustment unequally and transmit positive and negative changes differently for several months. Conversely, short-run asymmetry does not necessarily imply a persistent nonlinear regime. The North Sumatra evidence, therefore, supports a layered view of price transmission in which information connectivity, speed of correction, direction of predictive influence, and distribution of adjustment costs must be evaluated separately.

3.6 Implications

Within this layered structure, PWC functions as the external information anchor, PEC as the principal interface between the benchmark and the regional chain, and PFC as a domestic price that both responds to and predicts exporter prices. The one-way PWC-to-PEC Granger result is consistent with benchmark-led transmission. At the same time, the bidirectional PFC-PEC relationship indicates feedback between exporter purchasing decisions and local supply, quality, and procurement conditions. Because Granger causality measures predictive content rather than structural causation, these results should be interpreted as evidence about the direction of information flow within the estimated system, not as proof that a single market actor unilaterally determines prices.

The FEVD and IRF results reinforce this interpretation. World-price shocks explain a substantial share of PFC and PEC variation over ten months. Still, the sign-changing and gradually dissipating responses show that exposure to global risk is not equivalent to immediate or one-for-one pass-through. The gap between these concepts is economically important: a farmer can be highly exposed to world-price volatility while receiving only a filtered share of a particular price increase after exchange-rate conversion, quality grading, moisture deductions, logistics, and marketing margins are taken into account. The aggregate data do not identify the separate causal contribution of each filter, so these mechanisms are offered as economically plausible explanations rather than directly estimated effects.

The temporary PFC-PEC asymmetry points to the part of the chain where institutional improvement is most likely to matter. Delays in price information, non-standardized grading, working-capital constraints, inventory decisions, and unequal bargaining positions can make farm prices react differently to favorable and unfavorable movements over short horizons. However, the absence of long-run asymmetry indicates that these differences do not remain statistically distinct throughout the full adjustment process. Policy should therefore target short-run frictions without assuming permanent market segmentation.

A practical priority is a transparent price-information system that publishes the London benchmark, the relevant IDR/USD conversion, exporter reference prices, and production-area prices on a comparable date

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and quality basis. Such information should be accompanied by clear formulas for moisture, defect, and grade deductions so that farmers can distinguish legitimate quality adjustments from opaque margins. Strengthening cooperatives and farmer organizations can also improve collective marketing, record keeping, quality control, and negotiation with collectors and exporters.

For exporters and regional authorities, the results support exchange-rate-aware price monitoring and simple risk-management protocols. Export contracts and procurement rules can state how benchmark changes, currency movements, and verified quality differences are translated into purchase prices. These measures would not eliminate world-market risk, but they could reduce avoidable information asymmetry and make the distribution of gains and losses more predictable across the chain.

The study's theoretical contribution is therefore not the claim that one econometric result alone proves market efficiency. Instead, the combined evidence shows how different tests answer different questions: Johansen cointegration identifies a shared long-run relation; VECM identifies where correction occurs; FEVD and IRF describe shock exposure and persistence; Granger tests identify predictive direction; and AECM-Wald and Hansen-Seo tests distinguish temporary coefficient asymmetry from threshold-governed regime change. This integrated interpretation explains why an internationally connected market can still exhibit unequal adjustment burdens and temporary farm-exporter frictions.

4. Limitations and Future Directions

This study has five principal limitations. First, the monthly secondary series do not observe individual transactions, farm-level quality grades, moisture deductions, trader margins, informal credit relations, or contract mechanisms. Second, PEC is an export unit value derived from aggregate export value and volume, so changes in quality mix or destination composition may influence the series. Third, PWC is expressed in rupiah and therefore combines movements in the London benchmark with exchange-rate variation. Fourth, the IRF figure available for this analysis comes from a broader four-market supporting specification and does not include confidence bands; it is therefore used only to interpret directional, relative-magnitude, and persistence patterns. Fifth, the inferential scope is confined to the baseline outputs reported in the article; formal sensitivity to alternative lag lengths, sub-periods, structural breaks, residual behaviour, and alternative shock-identification schemes is not claimed. Future research should combine transaction-level prices with surveys of farmers, collectors, cooperatives, and exporters, model exchange-rate movements explicitly, and evaluate alternative lag structures and structural breaks using the complete reproducible dataset.

5. Conclusion

This study concludes that farm-level or production-area robusta coffee prices, North Sumatra exporter-level prices, and London world prices are integrated in the long run, with two Johansen cointegrating equations confirming equilibrium relationships among PFC, PEC, and PWC. The novelty of the study lies in reading integration, VECM adjustment, FEVD, IRF, Granger causality, AECM-Wald asymmetry, and Hansen-Seo threshold evidence in one empirical sequence for the North Sumatran robusta supply chain. PWC acts as a reference market, while PFC and PEC adjust significantly to disequilibrium; PWC shocks explain 51.15% of PFC variation and 40.50% of PEC variation at the 10-month horizon; Granger causality is bidirectional between farm and exporter prices but unidirectional from world price to exporter price; short-run asymmetry occurs mainly in the farm-exporter relationship; and threshold cointegration is not statistically supported. The supporting four-market IRF further shows large initial own-price responses, rapid sign reversals,

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and effects that remain visible in some markets at period 10, reinforcing the interpretation of gradual rather than instantaneous stabilization. The broader significance is that market integration does not automatically guarantee complete or equitable price transmission to farmers. Policy should therefore strengthen market-information systems, quality-based pricing, farmer organizations, transparent exporter-farm price formulas, and exchange-rate-aware price monitoring so that global robusta price signals can be translated into fairer and more predictable outcomes for producers and exporters.

Future research should incorporate primary data on transaction costs, quality grades, local trader behaviour, farmer organization, and contract mechanisms; estimate the exact PFC-PEC-PWC IRF with confidence bands; and test alternative lag structures, sub-periods, and structural breaks. These extensions would clarify why short-run asymmetry occurs and whether the principal adjustment pattern remains stable under alternative specifications.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation and revision of this work, the authors used OpenAI ChatGPT to assist with English-language refinement, structural organization, and reference-format consistency. The authors independently verified the scientific content, numerical results, interpretations, citations, and bibliographic details, reviewed and edited all AI-assisted output as needed, and took full responsibility for the accuracy, integrity, and final content of the publication.

Authorship Contribution Statement

Wahyunita Sitinjak: Conceptualization, methodology, visualization, and writing - original draft. Zulkarnain Lubis: Conceptualization, validation, and writing - review and editing. Muhammad Buhari Sibuea: Supervision, validation, interpretation, and writing - review and editing. Jef Rudiantho Saragih: Formal analysis, investigation, and supervision. Muhammad Reza Aulia: Supervision, validation, writing, review, and editing. Faiz Ahmad Sibuea: Data curation. All authors reviewed and approved the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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