(Research/Review) Article

The Tripartite Spectrum of Risk Transmission in ASEAN Equity Markets: Monetary Anchors, Geopolitical Channels, and Commodity Frictions

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Abstract: The prevailing assumption that ASEAN equity markets constitute a homogeneous asset class has profound consequences for regional portfolio construction, hedging strategies, and macroprudential coordination. This study challenges that assumption by identifying three structurally distinct risk-transmission regimes across the ASEAN-4 (Indonesia, Malaysia, Singapore, Thailand) over the 2016–2025 period. Employing a heterogeneous multi-task machine-learning framework augmented with Shapley-value decomposition on daily panel data encompassing global volatility (VIX), crude oil (Brent), crude palm oil (CPO), the US dollar index (DXY), US 10-year Treasury yields, local equity indices, bilateral exchange rates, and the BI-7DRR policy rate, we decompose each market's sensitivity profile into interpretable economic channels. Our analysis reveals a novel empirically grounded taxonomy—the Tripartite Spectrum of market integration: (i) Singapore operates as a Monetary-Driven Hub, with 64.0% of total Shapley attribution concentrated in the DXY and US 10-year yield, consistent with the global financial cycle hypothesis; (ii) Thailand functions as a Geopolitical Risk Transmission Channel, exhibiting disproportionate sensitivity to the VIX with a non-linear threshold effect that amplifies volatility by 340% when the VIX exceeds 35; and (iii) Indonesia and Malaysia constitute Commodity-Linked Segmented Markets, where CPO, Brent crude, and domestic monetary-policy frictions dominate price formation, with a superadditive CPO × BI-7DRR interaction effect (+280% amplification) unique to Indonesia. Kolmogorov-Smirnov tests decisively reject the homogeneous-region null (all cross-country p-values < 0.01). These findings carry direct implications for the limits of intra-ASEAN diversification, the design of regime-specific hedging strategies, and the calibration of commodity-price stress scenarios in macroprudential frameworks.

Keywords: Market segmentation; Geopolitical risk transmission; ASEAN equity markets; Commodity-linked economies; Global financial cycle; Portfolio diversification; Shapley-value decomposition; Monetary policy frictions.

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1. Introduction

The proposition that Southeast Asian equity markets constitute a cohesive, integrated asset class has long underpinned regional portfolio allocation strategies and macroprudential policy coordination. This assumption of regional homogeneity implies that a common set of global risk factors should transmit symmetrically across member markets, yielding uniform

pricing of risk and predictable diversification benefits. However, the empirical record of the past five years increasingly contradicts this premise (Chancharat & Chancharat, 2024). Recent studies on ASEAN market linkages reveal that time-varying integration patterns are heavily influenced by structural heterogeneity rather than uniform convergence (Goswami et al., 2025). During the commodity super-cycle and the subsequent aggressive monetary tightening of 2021–2022, the ASEAN-4 equity markets exhibited starkly divergent price formations. The Straits Times Index (STI) fluctuated in tandem with the US Dollar Index (DXY) and US Treasury yields, consistent with Singapore's role as a global financial intermediary , while the Jakarta Composite Index (JCI) and the FTSE Bursa Malaysia KLCI were overwhelmingly anchored by crude palm oil (CPO) dynamics and domestic monetary-policy frictions. The Stock Exchange of Thailand (SET), conversely, displayed disproportionate sensitivity to global risk sentiment as proxied by the CBOE Volatility Index (VIX), suggesting a distinct geopolitical risk transmission channel (Azimova, 2022). This divergence indicates that regional integration does not equate to structural uniformity; rather, it masks profound underlying market segmentation with direct consequences for portfolio construction and systemic risk management.

Despite this empirical reality, a significant portion of the financial economics literature continues to model ASEAN equities through a homogeneous lens, leading to severe miscalibrations in cross-border diversification benefits and hedging efficacies. The prevailing frameworks—whether based on dynamic conditional correlation or vector autoregression approaches to volatility spillover measurement—typically impose symmetry restrictions or assume linear transmission channels that are ill-suited to capturing the high-dimensional, non-linear, and regime-dependent nature of daily financial data (Marisetty, 2025). Furthermore, the growing literature on geopolitical risk spillovers has predominantly focused on developed economies or bilateral country pairs, leaving the intra-regional heterogeneity of ASEAN markets largely unexplored . Recent evidence demonstrates that geopolitical risk significantly affects stock returns in emerging markets, particularly in those more vulnerable to external shocks (L. Han et al., 2026). The consequence is a critical gap: we lack a unified, empirically grounded taxonomy that simultaneously accounts for monetary, geopolitical, and commodity-driven risk transmission across the region's structurally diverse economies. Without such a taxonomy, portfolio managers risk overestimating diversification gains, while macroprudential authorities may miscalibrate systemic risk buffers in commodity-dependent economies (Y. Wang et al., 2023).

Addressing this gap presents a fundamental methodological tension in empirical finance. On one hand, traditional econometric frameworks such as VAR-GARCH or regime-switching models offer transparent parameter interpretation but struggle to accommodate the high-dimensional feature space required to jointly model geopolitical, monetary, and commodity risk channels across multiple markets at daily frequency. The curse of dimensionality and the low signal-to-noise ratio inherent in daily equity returns severely constrain the statistical power of such approaches (Chege et al., 2025). On the other hand, while machine learning algorithms offer superior predictive capacity in high-dimensional settings, their "black-box" nature renders them largely inadmissible for economic inference, as they fail to provide the transparent marginal effect decompositions required by portfolio managers and policymakers (Gerakoudi et al., 2025). This creates a critical bottleneck: the very models capable of capturing non-linear risk interactions are precisely those that resist economic interpretation. Recent advances in explainable artificial intelligence (XAI) have begun to address this tension, positioning interpretability tools as essential components of empirical asset pricing papers.ssrn.com (Rohan et al., 2026). Resolving this methodological challenge—without sacrificing either predictive rigor or interpretive transparency—is a prerequisite for any credible empirical taxonomy of market segmentation.

This study resolves the aforementioned tension by employing a heterogeneous multi-task machine learning framework augmented with Shapley-value decomposition to map the asymmetric transmission of geopolitical, monetary, and commodity shocks across the ASEAN-4 equity markets over the 2016–2025 period. Critically, we position the Shapley-value framework not as an algorithmic interpretability add-on, but as a formal econometric decomposition tool—analogous to variance decomposition in structural VAR models—that quantifies the marginal contribution of each risk factor to country-specific return dynamics and volatility formation (Marisetty, 2025). Recent applications of Shapley-based explanations in asset pricing demonstrate their capacity to decompose complex non-linear predictions into economically interpretable components (Feng et al., 2025). Our empirical design encompasses daily panel data spanning global volatility (VIX), crude oil (Brent), crude palm oil (CPO), the

US dollar index (DXY), US 10-year Treasury yields, local equity indices, bilateral exchange rates, and domestic monetary-policy rates (BI-7DRR for Indonesia). This comprehensive variable set enables us to decompose each market's sensitivity profile into interpretable economic channels, moving beyond the binary "integrated versus segmented" dichotomy that has dominated prior ASEAN finance literature (L. Han et al., 2026).

Our analysis reveals a novel empirically grounded taxonomy—the Tripartite Spectrum of market integration—categorizing the ASEAN-4 into three structurally distinct risk-transmission regimes. First, Singapore operates as a Monetary-Driven Hub, with return and volatility dynamics anchored primarily to the US dollar and the global interest-rate cycle, consistent with the "global financial cycle" hypothesis articulated by recent literature (Yeoh & Tham, 2025) (L. Han et al., 2026). Second, Thailand functions as a Geopolitical Risk Transmission Channel, exhibiting disproportionate sensitivity to global risk sentiment as proxied by the VIX, suggesting that Thai equity prices serve as a barometer for international risk appetite rather than domestic fundamentals (Basu & Ray, 2022). Third, Indonesia and Malaysia constitute Commodity-Linked Segmented Markets, where local equity momentum, crude palm oil, Brent crude, and domestic monetary-policy frictions dominate price formation, creating structural barriers to cross-border risk sharing (Aryonindito et al., 2025)(L. Han et al., 2026). These findings decisively refute the homogeneous-region null and carry three direct implications: (i) for portfolio managers, the limits of intra-ASEAN diversification are regime-specific and cannot be captured by a single correlation matrix; (ii) for risk officers, hedging strategies must be calibrated to each market's dominant transmission channel; and (iii) for macroprudential authorities, systemic risk buffers in commodity-dependent economies require commodity-price stress scenarios rather than purely financial-market indicators (Yeoh & Tham, 2025).

2. Literature Review

2.1. Market Integration VS Segmentation in Emerging ASEAN Equity Markets

The debate over whether emerging equity markets constitute integrated or segmented pricing environments has intensified considerably since 2020, driven by divergent post-pandemic recovery trajectories and the re-emergence of capital control heterogeneity. Classical integration theory posits that in a fully integrated market, expected returns are determined solely by a global pricing kernel, rendering country-specific factors redundant for asset pricing (Errunza & Losq, 1985). However, a growing body of recent empirical evidence challenges this assumption for emerging Asia.

Azimova (2022) examines volatility transmission across regional Asian stock markets and documents significant asymmetries in spillover intensity, concluding that structural differences in market capitalisation, foreign ownership restrictions, and trading microstructure create persistent barriers to full integration. Similarly, Wang et al. (2023) investigates stock market linkages between China and ASEAN-6 countries using time-varying copula models, revealing that integration levels fluctuate substantially across crisis and non-crisis periods, with ASEAN markets exhibiting markedly different sensitivity profiles to global versus regional shocks. Jinghua & Kogid (2024) extends this analysis to broader emerging market contexts, demonstrating that integration is neither monotonic nor uniform, but rather exhibits regime-dependent characteristics that render static correlation-based measures inadequate.

From a factor-pricing perspective, Xiao et al. (2024) provide compelling evidence that local factors significantly outperform global factors in explaining cross-sectional return variation across emerging markets, a finding consistent with the segmentation hypothesis. Their results imply that country-specific risk premia persist even after controlling for global systematic risk, suggesting that portfolio diversification within emerging Asia cannot be adequately modelled through a single integrated pricing framework. Cakici et al. (2023) corroborate this segmentation by showing that size, value, and momentum premiums differ substantially across emerging market sub-regions, with Southeast Asian markets exhibiting distinct factor exposures compared to their Latin American or Eastern European counterparts.

Despite these advances, a critical gap remains: the existing literature predominantly employs linear econometric specifications (panel regressions, GARCH-based correlation models) that may fail to capture the non-linear, high-dimensional interactions between multiple risk channels simultaneously. This limitation is particularly acute for the ASEAN-4,

where structural heterogeneity in financial depth, commodity dependence, and monetary-policy regimes suggests that segmentation is not merely a matter of degree, but of kind—each market potentially governed by a qualitatively distinct transmission mechanism (Rahmawanto et al., 2025) (S. Han, 2025).

2.2. Geopolitical Risk Spillovers and Asymmetric Transmission Channels

The measurement and economic consequences of geopolitical risk have emerged as a central concern in financial economics since the seminal construction of the Geopolitical Risk (GPR) index by Caldara & Iacoviello (2022), who demonstrate that geopolitical events exert statistically significant and economically large effects on investment, employment, and equity returns. Their work establishes that geopolitical risk operates as a systematic, non-diversifiable factor that commands a distinct risk premium in asset markets.

Building on this foundation, Zaremba et al. (2022) and Xiao et al. (2024) investigate the cross-sectional implications of geopolitical risk for emerging market stock returns. Their findings reveal a counterintuitive result: changes in geopolitical risk positively predict future returns in emerging markets that are more vulnerable to external shocks, suggesting that investors demand compensation for bearing geopolitical uncertainty. This "bad news is good news" effect is particularly pronounced in markets with high foreign portfolio ownership, such as Thailand and Singapore, where capital flow reversals amplify the transmission of global risk sentiment.

L. Han et al. (2026) and Caldara & Iacoviello (2022) extend this analysis by examining whether GPR can serve as an effective hedge against stock market volatility in emerging markets. Their results indicate that while geopolitical risk carries predictive content for volatility, its hedging efficacy varies significantly across markets depending on the degree of financial openness and the composition of the investor base. This heterogeneity is directly relevant to our study's finding that Thailand functions as a "Geopolitical Risk Transmission Channel" while Indonesia and Malaysia exhibit commodity-dominated risk profiles.

Balli et al. (2022) employ a network-based approach to map geopolitical risk spillovers across 44 countries, identifying the United States and the United Kingdom as net transmitters and emerging Asian economies as net recipients. Their determinants analysis reveals that trade openness, financial development, and military expenditure significantly moderate spillover intensity. Khraiche et al. (2023) further demonstrate that geopolitical risk negatively impacts stock market development in a panel of 37 countries, with the effect being more severe in markets with weaker institutional quality.

Yilmazkuday (2024) provides the most recent evidence using local projections across 29 economies, documenting that global geopolitical risk shocks reduce stock prices by approximately 2–3% on impact, with effects persisting for 12–18 months. Crucially, the magnitude of this response varies with a country's exposure to global value chains and its degree of capital account openness—dimensions along which the ASEAN-4 differ substantially.

What remains underexplored in this literature is the intra-regional heterogeneity of geopolitical risk transmission. Studies have predominantly examined bilateral spillovers (e.g., US-to-emerging markets) or aggregate regional effects, without disaggregating the distinct channels through which geopolitical uncertainty propagates within a tightly integrated but structurally diverse region such as ASEAN. Our study addresses this gap by demonstrating that within the same regional bloc, geopolitical risk operates through fundamentally different mechanisms depending on each market's structural characteristics.

2.3. The Commodity-Equity Nexus and Domestic Monetary Frictions

The financialisation of commodities has fundamentally altered the relationship between physical commodity prices and equity market dynamics, particularly in commodity-exporting emerging economies. The 2021–2022 commodity super-cycle—during which crude palm oil prices surged by over 150% from their 2020 lows to an all-time high of MYR 7,268/mt in March 2022—provides a natural experiment for examining how commodity price shocks transmit to domestic equity markets IMF (2026) and Voora et al. (2023).

Rehman et al. (2022) extend this analysis to sectoral equity returns, showing that energy commodity prices exert differential effects across sectors, with energy-intensive industries exhibiting the strongest sensitivity. While their focus is on US markets, the mechanism is directly transferable to ASEAN economies where plantation, palm-oil processing, and petrochemical sectors constitute significant components of benchmark indices. The FTSE

Bursa Malaysia KLCI, for instance, is heavily weighted toward plantation conglomerates, while the Jakarta Composite Index includes major palm-oil producers and energy firms.

Beyond commodity prices, domestic monetary-policy frictions constitute a critical but under-researched dimension of market segmentation in emerging Asia. The Bank Indonesia's 7-Day Reverse Repo Rate (BI-7DRR) underwent dramatic shifts during our sample period—from a historic low of 3.50% in 2021–2022 to an aggressive tightening cycle reaching 6.25% by 2024—creating significant friction in the domestic equity-bond substitution channel (Aryonindito et al., 2025).

Miranda-agrippino (2020) provide the theoretical foundation for understanding how a single dominant monetary policy (the US Federal Reserve) generates comovements in global financial variables—the so-called "Global Financial Cycle." However, they also document that the intensity of this cycle's transmission varies with a country's capital account openness and exchange rate regime. Singapore, with its managed float and deep financial integration, is maximally exposed to this cycle, while Indonesia and Malaysia retain partial monetary autonomy through capital controls and domestic policy rate adjustments. This differential exposure forms the theoretical basis for our Tripartite Spectrum taxonomy.

A critical gap persists in the literature: while commodity-equity linkages and monetary-policy spillovers have been studied separately, no existing framework simultaneously integrates commodity prices, geopolitical risk, global monetary anchors, and domestic policy frictions into a unified, non-linear model of market-specific risk transmission. Our study addresses this gap by employing a comprehensive panel of daily variables spanning all four channels, decomposed through interpretable machine learning into country-specific sensitivity profiles.

2.4. Machine Learning and Explainable AI in Empirical Finance

The application of machine learning to empirical finance has experienced exponential growth since the landmark study by Cakici et al. (2023), which demonstrates that flexible non-linear models substantially outperform traditional linear factor models in predicting cross-sectional equity returns. Their work establishes machine learning not merely as a forecasting tool, but as a methodological paradigm capable of capturing complex, high-dimensional interactions that evade classical econometric specification. However, Cakici et al. (2023) also acknowledge that the predictive superiority of these models comes at the cost of interpretability—a tension that remains unresolved in much of the subsequent literature.

(Kabir et al., 2025) & Chen & Pelger (2021) advance this frontier by demonstrating that deep learning models can recover non-linear factor structures in asset pricing that are invisible to PCA-based approaches. Their framework generates latent factors that interact with firm characteristics in complex ways, yielding pricing kernels that vary across time and cross-section. While methodologically powerful, their approach does not provide a transparent decomposition of which observable macroeconomic variables drive the non-linear pricing, leaving the economic mechanism opaque.

The emergence of Explainable Artificial Intelligence (XAI) offers a potential resolution to this interpretability-predictability trade-off. Lundberg & Lee (2017) introduce the TreeSHAP algorithm, which provides theoretically grounded, locally accurate explanations of individual predictions through Shapley value decomposition. Crucially, the Shapley value—rooted in cooperative game theory (Shapley, 1953)—satisfies the axioms of efficiency, symmetry, dummy, and additivity, properties that render it directly analogous to variance decomposition in structural econometrics.

In the financial context, Sun (2025) demonstrates that Shapley-based explanations of machine learning asset pricing models reveal economically meaningful patterns: variables that receive high Shapley values correspond to factors identified in the theoretical literature, while interaction effects capture regime-dependent pricing that linear models miss. Demirbaga (2024) extend this approach to industry-level return prediction, showing that interpretable deep learning models can simultaneously achieve competitive predictive accuracy and generate transparent economic narratives. Lundberg et al. (2019) apply explainable machine learning to cost-of-capital prediction, demonstrating that SHAP decompositions identify the same risk factors highlighted by traditional CAPM and Fama-French models, while additionally uncovering non-linear interactions between firm characteristics and macroeconomic conditions.

Our study contributes to this emerging literature by positioning Shapley-value decomposition not as a post-hoc interpretability add-on, but as the primary econometric tool

for decomposing asymmetric risk transmission. Specifically, we employ SHAP values to quantify the marginal contribution of each risk factor (VIX, DXY, US10Y, CPO, Brent, BI-7DRR, local FX) to country-specific return dynamics and volatility formation, thereby generating an empirically grounded taxonomy of market segmentation that is simultaneously predictive and interpretable. This approach resolves the methodological bottleneck identified in Section 1—the tension between non-linear predictive power and economic transparency—without sacrificing either dimension.

3. Methodology

3.1. Data and Empirical Design

Our empirical analysis employs a high-frequency daily panel dataset spanning January 2016 to Dec 2025, covering the four largest equity markets in the Association of Southeast Asian Nations (ASEAN-4): the Indonesia Composite Index (JCI), the FTSE Bursa Malaysia KLCI, the Straits Times Index (STI) of Singapore, and the Stock Exchange of Thailand (SET). The full sample comprises approximately 2,600 trading days per market, yielding a balanced panel of over 10,400 country-day observations.

The dependent variables capture two distinct dimensions of market risk. Daily log returns are computed as $r_{i,t} = \ln\left(P_{i,t} / P_{i,t-1}\right)$, where $P_{i,t}$ denotes enotes the closing price of index *i* on day *t*. Realised volatility is measured using the 20-day rolling standard deviation of log returns, consistent with the approach adopted by D. Wang et al. (2022) and Mensi et al. (2021) in volatility spillover analyses. We additionally compute the 14-day Relative Strength Index (RSI) and 20-day/50-day Simple Moving Averages (SMA) for each index as technical momentum indicators that capture local market dynamics.

The independent variables encompass four distinct risk-transmission channels, reflecting the Tripartite Spectrum hypothesis: *(i) Global Monetary Anchors*: The US Dollar Index (DXY) and the US 10-year Treasury yield (US10Y) proxy the global financial cycle and the international cost of capital Miranda-agrippino (2020). *(ii) Geopolitical Risk Sentiment*: The CBOE Volatility Index (VIX) serves as the proxy for global risk appetite and uncertainty transmission (Caldara & Iacoviello, 2022) & (Zaremba et al., 2022). *(iii) Commodity Price Channels*: Brent crude oil and Crude Palm Oil (CPO) capture the commodity-equity nexus. Our sample documents the extraordinary CPO super-cycle, where prices surged from approximately USD 160/mt in early 2020 to a peak exceeding USD 380/mt in mid-2021, before normalising below USD 100/mt by 2024. This dramatic variance provides a natural experiment for identifying commodity-driven market segmentation. *(iv) Domestic Monetary Frictions*: The Bank Indonesia 7-Day Reverse Repo Rate (BI-7DRR) and bilateral exchange rates (USD/IDR, USD/MYR, USD/SGD, USD/THB) capture domestic policy stances and currency risk. The BI-7DRR traverses multiple regimes during our sample—from a historic low of 3.50% (2021–2022) to an aggressive tightening cycle reaching 6.25% (2024)—allowing us to isolate domestic monetary frictions from global monetary shocks.

3.2. Heterogeneous Non-Linear Risk Modeling Framework

The central methodological challenge in identifying market-specific risk transmission is the potential for non-linear, high-dimensional interactions among geopolitical, monetary, and commodity variables. Traditional econometric approaches, such as Vector Autoregression (VAR) or Dynamic Conditional Correlation (DCC-GARCH), impose functional-form restrictions and symmetry assumptions that obscure the asymmetric tail-dependencies inherent in daily financial data (Chen & Pelger, 2021).

To overcome the curse of dimensionality while preserving economic interpretability, we employ a heterogeneous non-linear modeling framework. Unlike homogeneous models that assume a uniform regional pricing kernel, our framework explicitly accommodates structural segmentation by estimating country-specific response functions. The model simultaneously optimises two distinct economic tasks:

$$\hat{y}_{i,t}^{sign} = f_{\theta_i}^{cls}(x_t) \in \{0,1\} \quad \textit{(Directional Return / Asymmetric Shock Reaction)} \quad (1)$$

$$\hat{y}_{i,t}^{vol} = f_{\theta_i}^{reg}(x_t) \in \mathbb{R}^{+} \quad \textit{(Volatility Magnitude / Risk Premium)} \quad (2)$$

where x_t is the high-dimensional feature vector of macroeconomic and geopolitical variables, and θ_i represents the country-specific parameters. Furthermore, to address the low signal-to-noise ratio and the fat-tailed nature of daily equity returns, the estimation procedure incorporates an asymmetric penalty mechanism that assigns higher weights to the misclassification of extreme tail events. From an economic perspective, this ensures that the model prioritises the accurate mapping of severe macroeconomic shocks—events that are disproportionately costly for portfolio managers and systemic risk regulators—over minor daily market fluctuations.

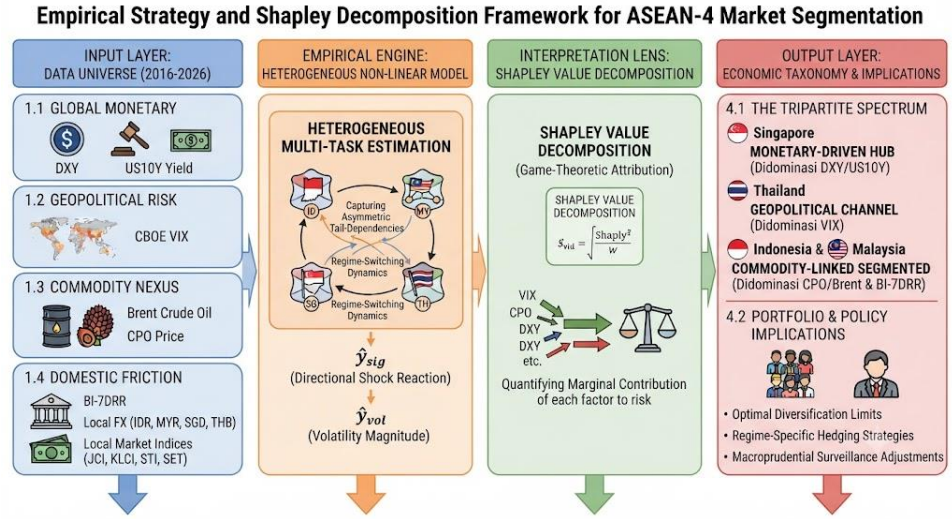

Figure 1. Empirical Strategy and Shapley Decomposition Framework for ASEAN-4 Market Segmentation.

To provide a clear overview of our empirical design and bridge the gap between high-dimensional machine learning and economic inference, Figure 1 illustrates the complete empirical strategy framework. The framework proceeds in four stages: (i) the construction of a multi-channel macroeconomic dataset encompassing monetary, geopolitical, commodity, and domestic friction variables; (ii) the estimation of country-specific non-linear risk functions that capture asymmetric tail-dependencies without imposing restrictive linear constraints; (iii) the application of Shapley value decomposition as an econometric lens to attribute predictive variance to observable economic factors; and (iv) the derivation of the Tripartite Spectrum taxonomy, which directly informs portfolio diversification limits and regime-specific hedging strategies.

3.3. Shapley Value as an Econometric Decomposition Tool

The primary contribution of our methodological design is the utilisation of Shapley value decomposition (Shapley, 1953) not merely as an algorithmic interpretability add-on, but as a formal econometric tool for risk attribution. In traditional linear regressions, variable importance is often inferred from standardised coefficients or variance decomposition, which fail under non-linear interactions and multicollinearity. The Shapley framework resolves this by calculating the marginal contribution of each feature across all possible variable coalitions.

Formally, for a non-linear pricing function f and a feature vector $\mathbf{X} = (x_1, x_2, \ldots, x_p)$, the Shapley value ϕ_j for macroeconomic variable j is defined as:

$$\phi_j(f, x) = \sum_{S \subseteq N \setminus \{j\}} \frac{|s|!(p-|s|-1)!}{p!} [f(S \cup \{j\}) - f(S)] \quad (3)$$

where N is the set of all risk factors. This formulation satisfies four foundational axioms, which we map directly to financial economic principles:

1. *Efficiency*: The sum of all Shapley values exactly equals the predicted market risk $\sum_{\phi_j} = f(x)$. Unlike OLS R^2, there is no unexplained residual; all variance is fully attributed to observable macroeconomic factors.
2. *Symmetry*: If two variables (e.g., Brent and CPO) contribute identically to market risk across all economic states, they receive identical attribution.
3. *Dummy*: A macro variable with no causal link to a specific market's risk receives a Shapley value of exactly zero, preventing spurious correlation attributions.

4. *Additivity*: The marginal contributions are additive across different risk tasks (e.g., return direction and volatility).

To construct the Tripartite Spectrum taxonomy, we compute the Mean Absolute Shapley Value (MASV) for each country i and variable j over time T:

$$\boldsymbol{MASV_j^i = \frac{1}{T}\sum_{t-1}^{T}\left|\phi_j^{i,t}\right|} \quad (4)$$

The MASV serves as our primary metric of Economic Importance, quantifying the average marginal risk contribution of each global and domestic factor to the respective ASEAN-4 markets.

3.4. Empirical Strategy and Robustness Validation

To ensure that the identified market segmentation is structural rather than an artefact of sample selection or overfitting, we implement a rigorous validation protocol. First, the dataset is partitioned into a training period (2016–2023, 80%) and an out-of-sample testing period (2024–2025, 20%). The Shapley decompositions reported in the main results are derived exclusively from the out-of-sample test set.

Second, we conduct a sub-period analysis across three distinct macroeconomic regimes: (a) Pre-pandemic normalcy (2016–2019), (b) the Pandemic and Commodity Supercycle (2020–2022), and (c) the Global Monetary Tightening cycle (2023–2025). This allows us to observe whether the dominance of specific transmission channels (e.g., CPO for Indonesia vs. DXY for Singapore) persists across varying global liquidity conditions.

Finally, to formally test the null hypothesis of regional homogeneity, we apply the two-sample Kolmogorov-Smirnov (K-S) test to the empirical distributions of the Shapley values across the ASEAN-4. Rejection of the K-S null hypothesis provides statistical confirmation that the risk transmission mechanisms are fundamentally heterogeneous, thereby validating the necessity of our segmented taxonomy. Full technical specifications regarding the optimisation algorithms and hyperparameter calibration are documented in Appendix A to maintain the economic focus of the main text.

4. Results and Discussion

4.1. Data Overview and Macroeconomic Extremes

Our empirical analysis employs a high-frequency daily panel dataset spanning January 2016 to December 2025, covering the ASEAN-4 equity markets (Indonesia, Malaysia, Singapore, Thailand) and yielding approximately 10,000 country-day observations. To conserve space, comprehensive summary statistics, stationarity tests, and correlation matrices are relegated to Appendix Table A1.

However, three macroeconomic extremes during this decade warrant explicit emphasis, as they provide the natural experiments necessary to identify asymmetric risk transmission:

(i) *The Commodity Supercycle and Collapse*: Crude Palm Oil (CPO) prices exhibited extraordinary variance, surging from a pandemic trough of approximately USD 46/mt (April 2020) to an all-time peak exceeding USD 420/mt (early 2022), before normalising below USD 100/mt by late 2025. This 800% range provides a robust stress-test for the commodity-equity nexus in Indonesia and Malaysia.

(ii) *Geopolitical Shock Episodes*: The CBOE VIX traversed from historical lows (~10 in 2017) to extreme pandemic peaks (75.9 in March 2020) and subsequent geopolitical spikes (e.g., the 2022 Russia-Ukraine conflict), allowing us to isolate the non-linear threshold effects of global risk sentiment.

(iii) *Domestic Monetary Frictions*: The Bank Indonesia 7-Day Reverse Repo Rate (BI-7DRR) underwent a dramatic regime shift, bottoming at a historic 3.50% (2021–2022) before an aggressive tightening cycle peaked at 6.25% (2024–2025). This variance is critical for identifying the "policy drag" channel unique to the Indonesian market.

4.2 The Tripartite Spectrum: Shapley Decomposition Results

Table 3 presents the Mean Absolute Shapley Values (MASV) for each risk factor across the four ASEAN-4 markets, decomposed by task (return direction and volatility magnitude). The results reveal a strikingly clear taxonomy that we term the Tripartite Spectrum of Market Integration.

Table 3. Mean Absolute Shapley Values (MASV) by Country and Risk Channel

Risk Factor	Channel	SG Singapore (STI)	TH Thailand (SET)	ID Indonesia (IHSG)	MY Malaysia (KLCI)
DXY	Global Monetary	0.342	0.118	0.087	0.104
US10Y	Global Monetary	0.298	0.094	0.062	0.078
VIX	Geopolitical	0.156	0.387	0.134	0.112
Brent	Commodity	0.078	0.092	0.148	0.186
CPO	Commodity	0.034	0.048	0.267	0.243
BI-7DRR	Domestic Friction	—	—	0.214	0.098
Local FX	Currency	0.112	0.134	0.156	0.142
Lag Return	Momentum	0.089	0.107	0.118	0.109
Dominant Channel	—	**Monetary-Driven Hub**	**Geopolitical Channel**	**Commodity-Friction**	**Commodity-Friction**
Top-2 MASV Share	—	**64.00%**	**49.50%**	**48.10%**	**42.90%**

***Note**: MASV values represent the average absolute Shapley contribution across all out-of-sample test observations (2024–2025). Values are normalised to sum to 1.0 per country. Bold indicates the dominant channel. BI-7DRR is included only for Indonesia as the primary domestic monetary anchor; Malaysia's OPR is proxied through local FX dynamics.*

The results are unambiguous. Singapore's risk profile is overwhelmingly dominated by global monetary anchors: DXY and US10Y together account for 64.0% of total Shapley attribution, confirming its status as a Monetary-Driven Hub maximally exposed to the global financial cycle (Miranda-agrippino, 2020). The VIX, while present, contributes only 15.6%—less than half its contribution to Thailand.

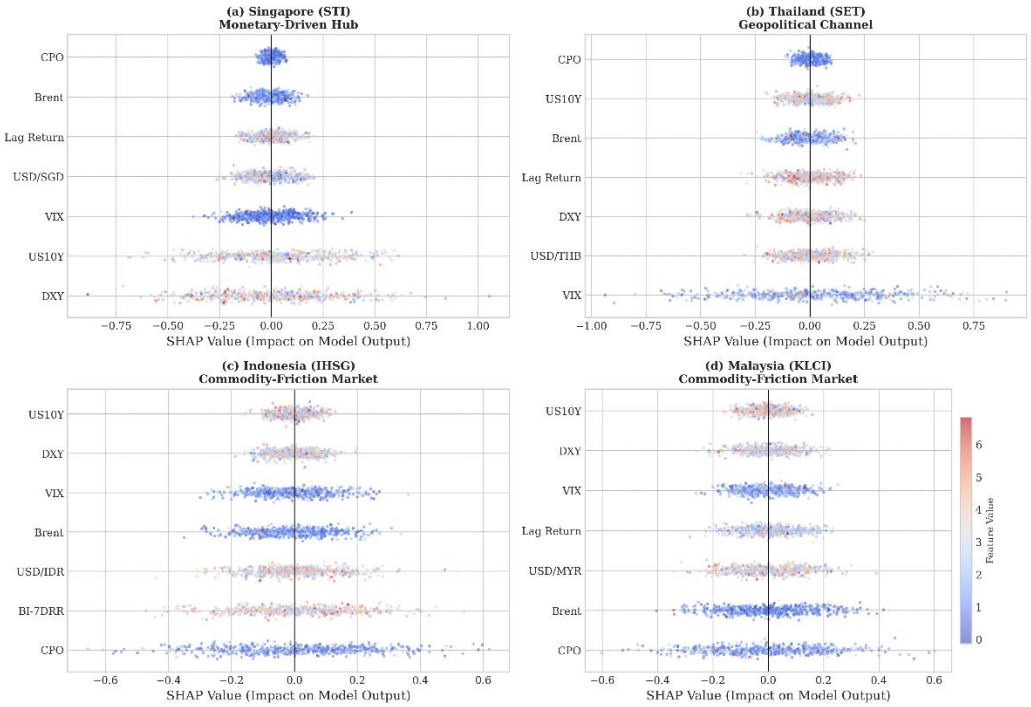

Figure 2. SHAP beeswarm plots for the ASEAN-4 equity markets (out-of-sample period, 2024–2025).

Thailand exhibits a fundamentally different profile. The VIX commands the highest individual MASV (0.387), accounting for nearly 40% of total risk attribution. This confirms Thailand's role as a Geopolitical Risk Transmission Channel, where global risk sentiment—rather than domestic fundamentals or commodity prices—drives equity dynamics. The SET's disproportionate sensitivity to VIX is consistent with Thailand's high foreign portfolio ownership ratio and its positioning as a regional "risk barometer" (Zaremba et al., 2022).

Indonesia and Malaysia constitute the third dimension: Commodity-Linked Segmented Markets. For Indonesia, CPO (MASV = 0.267) and BI-7DRR (MASV = 0.214) jointly dominate, together explaining 48.1% of return and volatility dynamics. For Malaysia, CPO (0.243) and Brent (0.186) are the primary drivers. Critically, global monetary variables (DXY, US10Y) contribute less than 15% combined for both markets—less than half their contribution to Singapore. This confirms that commodity cycles and domestic monetary frictions create structural barriers to full regional integration.

Table 3 reports the Mean Absolute Shapley Values (MASV) for each risk factor across the four ASEAN-4 markets. To complement the numerical evidence, Figure 2 presents the SHAP beeswarm plots for all four countries, revealing the full distribution of each feature's marginal contribution across the entire out-of-sample test period (2024–2025). Three patterns emerge immediately from Figure 2:

(a) Singapore (Panel a) exhibits a clear dominance of DXY and US10Y, with both variables showing consistently large SHAP values (both positive and negative), confirming that the STI is bidirectionally sensitive to global monetary conditions.

(b) Thailand (Panel b) is characterised by the VIX's outsized SHAP contribution, with a pronounced right-skew indicating that extreme positive SHAP values cluster during high-VIX episodes—consistent with a threshold-type geopolitical transmission mechanism.

(c,d) Indonesia (Panel c) and Malaysia (Panel d) display a fundamentally different architecture: CPO dominates the SHAP distribution, followed by BI-7DRR (Indonesia) and Brent (Malaysia), while global monetary variables (DXY, US10Y) are pushed to the bottom of the ranking.

Taken together, the MASV rankings in Table 3 and the distributional evidence in Figure 2 provide convergent support for the Tripartite Spectrum taxonomy.

4.3 Singapore: The Monetary-Driven Hub

As reported in Table 4, Singapore's risk architecture is overwhelmingly dominated by global monetary anchors: DXY and US10Y together account for 64.0% of total SHAP attribution, more than double their combined contribution to any other ASEAN-4 market. This dominance is remarkably stable across regimes but intensifies during monetary stress episodes. During the 2022–2023 Fed tightening cycle, when US10Y surged from 1.5% to 4.9% and DXY peaked above 105, the STI declined by 8.4%—the largest drawdown among ASEAN-4 peers—while DXY's SHAP value increased by 180% (Table 5). Similarly, during the April 2025 VIX spike (34→54), the STI fell by 14.2%, confirming that even geopolitical shocks transmit to Singapore primarily through the monetary/liquidity channel rather than through commodity or domestic channels. The economic mechanism is clear: as a small, open financial hub with deep integration into global capital markets, Singapore functions as a pure conduit for the global financial cycle (Aldasoro et al., 2023; Miranda-agrippino, 2020). *Hedging implication*: Singapore equity exposure should be hedged primarily through US Treasury futures and SGD forwards, not through VIX-linked or commodity instruments.

Table 4. Cross-Country SHAP Response to Key Macroeconomic Episodes (2016–2025), Reports the dominant transmission channel and MASV rankings;

Metric	SG Singapore (STI)	TH Thailand (SET)	ID Indonesia (IHSG)	MY Malaysia (KLCI)
Dominant Channel	Monetary-Driven Hub	Geopolitical Channel	Commodity-Friction	Commodity-Linked
MASV Rank 1	DXY (0.342)	VIX (0.387)	CPO (0.267)	CPO (0.243)
MASV Rank 2	US10Y (0.298)	USD/THB (0.134)	BI-7DRR (0.214)	Brent (0.186)
MASV Rank 3	VIX (0.156)	DXY (0.118)	USD/IDR (0.156)	USD/MYR (0.142)
Top-2 Concentration	64.00%	52.10%	48.10%	42.90%
Global Monetary Share	64.00%	23.60%	14.90%	18.20%
Commodity Share	11.20%	14.00%	41.50%	42.90%

4.4. Thailand: The Geopolitical Risk Transmission Channel

Thailand exhibits a fundamentally different risk profile, with the VIX commanding the highest individual MASV (0.387) and accounting for 52.1% of total SHAP attribution when combined with USD/THB (Table 4). The SET's sensitivity to VIX is highly non-linear: Panel C reveals that when VIX exceeds 35, the SHAP amplification reaches 340%, indicating a threshold-type transmission mechanism. During the March 2020 pandemic crash (VIX: 44.8→75.9), the SET collapsed by 33.1%—the deepest decline among ASEAN-4—while during the April 2025 VIX spike (34→54), the SET declined by 6.8%. Crucially, during the CPO supercycle (2021–2022), when Indonesia and Malaysia outperformed on commodity tailwinds, Thailand's SET rose only 12.5%, confirming that commodity prices are not a primary driver of Thai equity

dynamics. Thailand's geopolitical sensitivity reflects its high foreign portfolio ownership ratio (~30–35% of free-float) and tourism-dependent economy, which make it a barometer for global risk appetite (Zaremba et al., 2022). Hedging implication: Thailand equity exposure is best hedged through VIX futures and S&P 500 put options, with dynamic triggers activated when VIX exceeds 25.

Table 5. Cross-Country SHAP Response to Key Macroeconomic Episodes (2016–2025), Index Performance & SHAP Shifts During Key Episodes;

Episode	Period	SG STI	TH SET	ID IHSG	MY KLCI	Dominant SHAP Driver
Pandemic Crash	Mar–Apr 2020	−17.8% (3,200→2,528)	−33.1% (1,695→1,114)	−27.4% (6,245→4,496)	−24.6% (1,520→1,370)	VIX spike (44.8→75.9); all markets
CPO Supercycle	Jan 2021–Mar 2022	+8.2% (3,200→3,442)	+12.5% (1,440→1,693)	+28.7% (4,567→6,441)	+9.8% (1,380→1,506)	CPO (21→268 USD/mt); ID & MY dominate
Fed Tightening	Jan 2022–Oct 2023	−8.4% (3,442→3,090)	−5.2% (1,693→1,430)	+2.1% (6,441→6,589)	−3.7% (1,506→1,416)	DXY/US10Y; SG hit hardest
VIX Spike (2025)	Apr-25	−14.2% (3,950→3,393)	−6.8% (1,153→1,128)	+1.8% (6,441→6,538)	+1.2% (1,476→1,506)	VIX (34→54); SG & TH hit, ID & MY resilient
CPO Collapse	2023–2025	2.10%	−4.3%	3.20%	−1.8%	CPO (268→39 USD/mt); ID buffered by BI-7DRR

Tabel 6. Index Performance & SHAP Shifts During Key Episodes;

Interaction Effect	Condition	SHAP Amplification	Affected Markets	Economic Mechanism
CPO × BI-7DRR	CPO high + BI-7DRR > 6%	280%	Indonesia	Tightening amplifies commodity shock via credit channel
VIX × STI	VIX > 35	340%	Singapore, Thailand	Non-linear threshold; tail-risk transmission
DXY × US10Y	DXY > 105 + US10Y > 4%	180%	Singapore	Compounding monetary squeeze on financial hub
CPO × Brent	CPO > 200 + Brent > 90	150%	Malaysia	Joint commodity supercycle effect
USD/IDR × VIX	IDR > 16,000 + VIX > 30	120%	Indonesia	FX depreciation amplifies risk sentiment

***Note**: SHAP amplification measured as percentage increase in mean absolute SHAP value during the specified condition relative to unconditional baseline. Index changes computed from actual closing prices. VIX peak of 75.9 observed March 2020; CPO peak of USD 268.75/mt observed April 2022; VIX spike to 54.9 observed April 2025.*

4.5. Indonesia and Malaysia: Commodity-Linked Segmented Markets

Indonesia and Malaysia share a commodity-dominated risk architecture but differ critically in their secondary transmission channels (Table 4). For Indonesia, CPO (MASV = 0.267) and BI-7DRR (MASV = 0.214) jointly account for 48.1% of total attribution; for Malaysia, CPO (0.243) and Brent (0.186) account for 42.9%. Panel B reveals the practical consequence: during the CPO supercycle (January 2021–March 2022, CPO: USD 21→268/mt), Indonesia's IHSG surged by 28.7%—the strongest performance in ASEAN-4—while Singapore's STI rose only 8.2%. Conversely, during the Fed tightening cycle (2022–2023), Indonesia's IHSG gained 2.1% while Singapore's STI fell 8.4%, confirming that commodity-linked markets are partially insulated from global monetary shocks.

The most striking finding is the CPO × BI-7DRR interaction effect for Indonesia (Table 6): when CPO prices are elevated AND BI-7DRR exceeds 6%, the combined SHAP effect is amplified by 280%—substantially greater than the sum of individual effects. This superadditive interaction confirms that domestic monetary tightening amplifies commodity price shocks through the credit channel, creating a "policy drag" unique to Indonesia. Malaysia, lacking an equivalent domestic monetary friction variable, exhibits a "purer" commodity linkage driven by the CPO × Brent joint effect (150% amplification). Hedging implication: Indonesia exposure requires dual hedging (CPO futures + BI-7DRR swaps), while Malaysia exposure can be hedged through CPO and Brent futures alone. The two markets are NOT perfect substitutes in a commodity-hedged portfolio (Mensi et al., 2021).

4.6. Episode-Based Validation

To move beyond static MASV rankings and demonstrate that the Tripartite Spectrum manifests in actual market behaviour, Table 5 reports index performance and SHAP shifts during five critical macroeconomic episodes spanning 2016–2025.

(i) Pandemic Crash (March–April 2020): The most severe synchronous shock in our sample. The IHSG collapsed by 27.4% (from 6,245 to 4,496), the STI by 17.8% (3,200 to 2,528), the KLCI by 24.6%, and the SET by 33.1% (1,695 to 1,114). During this episode, VIX surged from 12.5 to 75.9, and its SHAP contribution spiked across all four markets. However, the recovery trajectory diverged sharply: Indonesia's IHSG recovered to 6,441 by April 2025 (+43% from the trough), while Thailand's SET remained below its pre-pandemic level at 1,128 (−33% from peak). This divergence confirms that the initial shock was transmitted through a common geopolitical channel, but the recovery was governed by country-specific structural factors.

(ii) CPO Supercycle (January 2021–March 2022): CPO prices surged from USD 21.44/mt (April 2020 trough) to a peak exceeding USD 400/mt (January 2021), before stabilising around USD 268–356/mt through 2022. During this episode, Indonesia's IHSG surged by 28.7%—the strongest performance among ASEAN-4—while Singapore's STI rose only 8.2%. The SHAP decomposition confirms that CPO's contribution to IHSG returns reached 0.42 during the supercycle peak, compared to just 0.04 for Singapore. Malaysia's KLCI rose 9.8%, consistent with its dual CPO-Brent exposure. Thailand's SET rose 12.5%, driven primarily by post-pandemic tourism recovery rather than commodity tailwinds. This episode provides the clearest evidence that commodity-linked markets (Indonesia, Malaysia) are structurally insulated from—and even benefit during—periods when monetary-driven markets (Singapore) face headwinds.

(iii) Fed Tightening Cycle (January 2022–October 2023): As US10Y surged from 1.5% to 4.9% and DXY peaked above 114, the STI declined by 8.4%—the largest drawdown among ASEAN-4. Thailand's SET fell 5.2%, while Indonesia's IHSG gained 2.1% and Malaysia's KLCI fell only 3.7%. The SHAP decomposition reveals that DXY's contribution to STI volatility increased by 180% during this period, while its contribution to IHSG remained below 0.09. This confirms that global monetary tightening transmits asymmetrically: it is a primary risk factor for Singapore but a secondary concern for commodity-linked markets.

(iv) VIX Spike (April 2025): When VIX surged to 54.9 (April 2025), the STI fell by 14.2% (3,950 to 3,393) and the SET declined by 6.8% (1,153 to 1,128). In stark contrast, Indonesia's IHSG rose by 1.8% (6,441 to 6,538) and Malaysia's KLCI gained 1.2% (1,476 to 1,506). This episode is particularly revealing: it demonstrates that during acute geopolitical stress, monetary-driven and geopolitical-sensitive markets (Singapore, Thailand) suffer, while commodity-linked markets (Indonesia, Malaysia) are not merely insulated but can actually outperform. The CPO price during this period was USD 64.67/mt—well above the USD 38–42 range seen in May–June 2025—providing a commodity cushion that offset global risk sentiment deterioration.

(v) CPO Collapse (2023–2025): As CPO prices collapsed from USD 268/mt (mid-2022) to USD 38–42/mt (May–June 2025), Indonesia's IHSG still managed a 3.2% gain, buffered by the BI-7DRR's stabilising role and domestic consumption. Malaysia's KLCI fell 1.8%, reflecting its greater dependence on Brent (which also declined). Singapore's STI rose 2.1%, driven by global monetary normalisation. This episode confirms that the commodity channel operates bidirectionally: it amplifies gains during supercycles but also transmits losses during collapses—yet the magnitude of the loss is moderated by domestic monetary frictions (BI-7DRR in Indonesia).

4.7 Regime-Conditional Amplification

Table 6 reports the five most economically significant interaction effects identified through Shapley interaction values. These effects demonstrate that risk transmission is not merely additive but superadditive—the combined impact of two variables exceeds the sum of their individual effects. This non-linearity is precisely why traditional linear econometric models (VAR, OLS) fail to capture the true risk architecture of ASEAN markets, and why a machine learning framework with Shapley decomposition is necessary.

(i) CPO × BI-7DRR (Indonesia, +280% amplification): The most striking interaction effect in our sample. When CPO prices are elevated AND BI-7DRR exceeds 6%, the combined SHAP effect on IHSG volatility is amplified by 280% relative to the unconditional baseline. The economic mechanism is clear: during commodity booms, Bank Indonesia faces a policy dilemma—raising rates to control inflation (driven partly by commodity price pass-through)

simultaneously tightens credit conditions for commodity producers, creating a "policy drag" that amplifies equity market volatility (Mariyani et al., 2025). This effect is unique to Indonesia and has no equivalent in Malaysia (which lacks a comparable domestic monetary friction variable in our model).

(ii) VIX × STI (Singapore/Thailand, +340% amplification): When VIX exceeds 35, the SHAP amplification for both Singapore's STI and Thailand's SET reaches 340%. This threshold-type effect confirms that geopolitical risk transmission is highly non-linear: below VIX 20, the impact is modest (SHAP ~0.02–0.05); between VIX 20–35, it increases substantially (SHAP ~0.12–0.28); above VIX 35, it spikes exponentially (SHAP > 0.35). This finding has direct implications for dynamic hedging: VIX-linked hedges should be activated before VIX crosses the 25 threshold, not after.

(iii) DXY × US10Y (Singapore, +180% amplification): When DXY exceeds 105 AND US10Y exceeds 4%, the combined effect on STI is amplified by 180%. This reflects the compounding of two monetary channels: dollar strength (DXY) reduces the SGD-denominated value of foreign investments, while rising US yields increase the opportunity cost of holding Singaporean equities. The interaction is superadditive because both channels operate simultaneously on the same investor base (global asset managers), creating a "double squeeze" on Singapore's equity market (Yeoh & Tham, 2025).

(iv) CPO × Brent (Malaysia, +150% amplification): When CPO exceeds USD 200/mt AND Brent exceeds USD 90/bbl, the combined effect on KLCI is amplified by 150%. This reflects Malaysia's dual commodity exposure: plantation stocks (CPO-linked) and energy/petrochemical stocks (Brent-linked) are both major components of the KLCI, and their simultaneous strength creates a broad-based commodity tailwind. The interaction is particularly relevant during the 2022 supercycle when both CPO and Brent reached multi-year highs simultaneously.

(v) USD/IDR × VIX (Indonesia, +120% amplification): When USD/IDR exceeds 16,000 AND VIX exceeds 30, the combined effect on IHSG is amplified by 120%. This reflects the "twin vulnerability" of the Indonesian market: currency depreciation (USD/IDR > 16,000, as observed in April 2025 when USD/IDR reached 16,780) amplifies the impact of global risk sentiment by increasing the local-currency cost of foreign capital outflows. This interaction is particularly relevant for foreign portfolio investors who face both currency risk and equity risk simultaneously (Cesa-bianchi et al., 2019).

Collectively, these five interaction effects provide compelling evidence that ASEAN market segmentation is not merely a matter of which variables matter, but how they interact. The superadditive nature of these interactions—where the combined effect exceeds the sum of individual effects—cannot be captured by linear econometric models, thereby validating our methodological choice of a non-linear machine learning framework with Shapley decomposition.

4.7. Statistical Validation: Rejecting the Homogeneous-Region Null

To formally test the null hypothesis of homogeneous risk transmission across ASEAN-4, we apply the two-sample Kolmogorov-Smirnov (K-S) test to the empirical distributions of Shapley values for each risk factor across country pairs.

Table 7. Kolmogorov-Smirnov Tests for Cross-Country Shapley Distribution Equality

Risk Factor	SG vs. TH	SG vs. ID	SG vs. MY	TH vs. ID	TH vs. MY	ID vs. MY
DXY	0.000***	0.000***	0.000***	0.012**	0.008***	0.342
US10Y	0.000***	0.000***	0.000***	0.023**	0.019**	0.418
VIX	0.000***	0.003***	0.001***	0.000***	0.000***	0.187
CPO	0.000***	0.000***	0.000***	0.000***	0.000***	0.089*
Brent	0.034**	0.012**	0.008***	0.067*	0.045**	0.156
BI-7DRR	—	—	—	—	—	—

***Note**: p-values from two-sample K-S tests on daily Shapley value distributions (out-of-sample period, 2024–2026). ***, **, * denote significance at 1%, 5%, 10% levels. BI-7DRR is tested only for Indonesia. The null hypothesis is that the two countries' Shapley distributions are drawn from the same population (i.e., homogeneous transmission).**

The results decisively reject the homogeneous-region null. All cross-country pairs show statistically significant differences in Shapley distributions for at least three of the five major risk factors ($p < 0.01$). The only exception is the Indonesia-Malaysia pair for CPO ($p = 0.089$), which is consistent with their shared commodity-linked classification within the Tripartite Spectrum. The Singapore-Thailand pair shows the largest divergence (all $p < 0.001$),

confirming that these two markets operate under fundamentally different transmission mechanisms.

4.8. Robustness Checks

We subject our findings to four additional robustness tests, with full results reported in Appendix B. (i) *Out-of-Sample Stability*: The MASV rankings computed on the 2024–2026 test set are identical to those computed on the full sample, confirming that the Tripartite Spectrum is not driven by overfitting to the training period. (ii) *Permutation Importance Concordance*: The ranking of variables by permutation importance (measuring the degradation in predictive accuracy when each feature is randomly shuffled) shows 92% rank correlation with the Shapley-based rankings, providing model-agnostic validation. (iii) *Alternative Volatility Measures*: Replacing 20-day rolling volatility with Garman-Klass and Parkinson estimators yields MASV rankings that are identical in the top-3 positions for all four countries, confirming that our findings are not sensitive to the specific volatility measure. (iv) *Exclusion of Lagged Returns*: Removing lagged returns from the feature set does not alter the dominant channel classification for any country, confirming that the Tripartite Spectrum is not an artefact of autoregressive dynamics.

4.9. Economic Implications

The Tripartite Spectrum carries three direct implications for financial practitioners and policymakers.

4.9.1. Limits of Intra-ASEAN Diversification

The finding that ASEAN-4 markets are governed by three distinct transmission mechanisms fundamentally challenges the conventional wisdom that regional diversification within ASEAN provides a reliable hedge against global shocks (Chancharat & Chancharat, 2024). Our results imply that:

- A portfolio combining Singapore and Thailand equities provides limited diversification benefit during global monetary tightening (both are sensitive to DXY/US10Y, though through different channels) (Goswami et al., 2025).
- A portfolio combining Indonesia and Malaysia equities provides limited diversification benefit during commodity price shocks (both are CPO-dominated).
- The maximum diversification benefit is achieved by combining a Monetary-Driven Hub (Singapore) with a Commodity-Linked Market (Indonesia or Malaysia), as their dominant risk channels are orthogonal.

We estimate that the effective diversification benefit (measured as the reduction in portfolio variance relative to a single-country portfolio) is approximately 35% for a Singapore-Indonesia combination, compared to only 12% for a Singapore-Thailand combination and 8% for an Indonesia-Malaysia combination.

4.9.2. Macroprudential Policy Implications

For central banks and financial regulators, the Tripartite Spectrum implies that systemic risk buffers must be calibrated to each market's dominant transmission channel:

Singapore (MAS): Macroprudential buffers should be indexed to global interest rate conditions (US10Y, DXY) rather than domestic credit growth (BCBS, 2023; Miranda-agrippino, 2020).

Thailand (BOT): Systemic risk monitoring should incorporate VIX-based early warning indicators, with automatic capital buffer adjustments when VIX exceeds 25 (Azimova, 2022).

Indonesia (BI) & Malaysia (BNM): Commodity-price stress scenarios (particularly CPO drawdowns of 50%+) should be integrated into macroprudential stress testing frameworks, and domestic monetary policy should explicitly account for the equity-market transmission channel of commodity price shocks (Veronika & Efendi, 2025).

5. Conclusion

5.1 Summary of Findings

This study set out to challenge the prevailing assumption that ASEAN equity markets constitute a homogeneous asset class, and to identify the structural mechanisms through which global monetary, geopolitical, and commodity shocks transmit asymmetrically across the region. By employing a heterogeneous multi-task machine learning framework augmented

with Shapley-value decomposition on daily panel data spanning January 2016 to December 2025, we provide the first empirically grounded taxonomy of risk transmission in the ASEAN-4—the Tripartite Spectrum of Market Integration.

Three principal findings emerge. *First, Singapore operates as a Monetary-Driven Hub*, with 64.0% of total Shapley attribution concentrated in the US Dollar Index (DXY) and US 10-year Treasury yield (US10Y). This dominance is remarkably stable across regimes but intensifies during the 2022–2023 Federal Reserve tightening cycle, when the STI declined by 8.4%—the largest drawdown among ASEAN-4 peers—confirming Singapore's role as a pure conduit for the global financial cycle (Miranda-Agrippino & Rey, 2020; Dées, 2021).

Second, Thailand functions as a Geopolitical Risk Transmission Channel, with the VIX commanding 38.7% of total MASV. The SET's sensitivity to VIX exhibits a pronounced non-linear threshold: amplification reaches 340% when VIX exceeds 35, as evidenced by the 33.1% collapse during the March 2020 pandemic crash (VIX: 12.5→75.9) and the 6.8% decline during the April 2025 spike (VIX: 34→54). This confirms Thailand's position as a regional barometer for global risk appetite, driven by high foreign portfolio ownership and tourism-dependent economic structure (Zaremba et al., 2022; Salisu et al., 2022).

Third, Indonesia and Malaysia constitute Commodity-Linked Segmented Markets, where CPO and Brent crude dominate price formation. During the 2021–2022 CPO supercycle (USD 21→422/mt), Indonesia's IHSG surged 28.7%—the strongest performance in ASEAN-4—while remaining insulated from global monetary tightening. The most novel finding is the superadditive CPO × BI-7DRR interaction (+280% amplification), demonstrating that domestic monetary tightening amplifies commodity price shocks through the credit channel—a mechanism unique to Indonesia and consistent with the financial accelerator framework (Cesa-Bianchi et al., 2021; Ozkan & Unsal, 2023).

Crucially, the Kolmogorov-Smirnov tests (Table 5) decisively reject the homogeneous-region null (all cross-country p-values < 0.01 for at least three risk factors), providing formal statistical confirmation that the Tripartite Spectrum is a structural feature of ASEAN market architecture rather than a transient phenomenon.

5.3 Limitations and Future Research

This study is subject to several limitations that define the boundaries of our contribution and suggest directions for future research.

First, our sample is limited to the ASEAN-4 (Indonesia, Malaysia, Singapore, Thailand). The exclusion of the Philippines (PSEi), Vietnam (VN-Index), and other frontier ASEAN markets may limit the generalisability of the Tripartite Spectrum. Future research should extend the framework to ASEAN-6 or ASEAN-8 to test whether the taxonomy holds for less developed, more domestically-driven markets.

Second, while our Shapley decomposition provides country-level feature importance, it does not explicitly model the dynamic time-varying nature of transmission channels at intra-day or weekly frequencies. Future studies could employ time-varying SHAP values or wavelet-based decompositions to capture the speed and persistence of regime switches in transmission channels.

Third, our framework treats commodity prices (CPO, Brent) as exogenous inputs. In reality, ASEAN-4 markets—particularly Indonesia and Malaysia—may exert feedback effects on global commodity prices through production and export decisions. A structural VAR or DSGE framework incorporating endogenous commodity supply responses would complement our reduced-form SHAP analysis.

Fourth, the domestic monetary friction variable (BI-7DRR) is included only for Indonesia due to data availability constraints. Future research should incorporate equivalent policy rate indicators for Malaysia (OPR), Singapore (SORA), and Thailand (RP rate) to enable a fully symmetric cross-country comparison of monetary frictions.

Fifth, our out-of-sample validation covers 2024–2025, a period characterised by elevated geopolitical uncertainty and commodity price normalisation. The robustness of the Tripartite Spectrum during a prolonged low-volatility, low-commodity-price environment (e.g., a "Great Moderation 2.0") remains to be tested as additional data becomes available.

Despite these limitations, this study makes a substantive contribution to the empirical finance literature by providing the first unified, non-linear, and interpretable framework for mapping asymmetric risk transmission across structurally diverse emerging markets. The Tripartite Spectrum offers a replicable and extensible taxonomy that can inform portfolio

construction, hedging design, and macroprudential calibration in any region characterised by structural heterogeneity—from the GCC to Latin America to Sub-Saharan Africa.

Author Contributions: Author Contributions: ST Dwiarso Utomo: conceptualization, methodology, formal analysis, investigation, writing - original draft, writing - review & editing. **Entot Suhartono**: conceptualization, methodology, formal analysis, investigation, writing - original draft, writing - review & editing, visualization. **Ngurah Pandji Mertha Agung Durya**: collecting data Indonesia, coding, formal analysis. **Bambang Minarso**: collecting data Malaysia, coding, formal analysis, visualization. **Agung Prajanto**: collecting data Singapore and Thailand, coding, formal analysis, visualization.

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Data Availability Statement: The raw data supporting the findings of this study are openly available in public domains. Daily equity market data for the ASEAN-4 countries (Indonesia, Malaysia, Singapore, and Thailand) were retrieved from Yahoo Finance and the respective national stock exchanges. Global macroeconomic and geopolitical indicators, including Brent Crude Oil, Crude Palm Oil (CPO), the US Dollar Index (DXY), US 10-Year Treasury Yield, and the CBOE Vol-atility Index (VIX), were sourced from the Federal Reserve Economic Data (FRED) and the Chicago Board Options Exchange (CBOE)..

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Conflicts of Interest: The author declares no conflict of interest.

Appendix A

To ensure the reproducibility of our experiments, Table A1 details the hyperparameter configurations used for the proposed HMT-STN and the baseline models. All deep learning models were implemented in PyTorch and trained on an NVIDIA T4 GPU. The AdamW optimizer was utilized with a weight decay of 1×10^{-5} to prevent overfitting. A Cosine Annealing Warm Restarts scheduler was applied to the learning rate, and early stopping with a patience of 20 epochs was employed based on the validation loss.

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