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Shocks, Structure, and Signals: Mapping the Evolution of ASEAN-6 Stock Market Networks Before, During, and After COVID-19 Using Graph Neural Networks

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ABSTRACT

This research explores the evolution of interlinkages among ASEAN-6 equity markets from 2011 to 2024, with a focus on the structural impacts of the COVID-19 crisis. The research addresses a critical gap in understanding how regional financial networks adapt to systemic shocks, particularly in emerging markets where traditional econometric models may not capture complex, evolving interdependencies. Using a network-based approach that incorporates Pearson correlation, minimum spanning trees (MST), dynamic time warping (DTW), and threshold networks, findings show a marked contraction in network depth and a reconfiguration of hub nodes during the crisis, followed by partial restoration afterward. To complement the static analysis, a two-layer Graph Convolutional Network (GCN) is employed to classify market regimes, achieving 65% classification accuracy. Saliency mapping identifies Indonesia and Vietnam as key contributors to regime differentiation, reflecting their significant role in regional contagion. The study highlights the value of combining machine learning and financial network theory to understand market stress transmission and structural adaptation in emerging market systems.

Introduction

Financial integration across ASEAN has continued to deepen since the early 2010s, supported by policy reforms aimed at liberalizing markets and enhancing regional coordination. Nonetheless, ASEAN equity markets often remain more closely tied to global centers—especially the U.S.—than to each other. For instance, Vo & Tran (2020) use an augmented EGARCH model to show that volatility spillovers from the U.S. to ASEAN markets remain strong, indicating persistent external vulnerability. Similarly, [missing citation] employ multivariate GARCH-DCC techniques to reveal sustained co-movement and volatility transmission between China and key Southeast Asian markets, driven by structural factors such as liquidity differences and regulatory asymmetries. These findings underscore ASEAN's continuing exposure to global, rather than intraregional, shocks and highlight the need for a refined understanding of how financial risk travels in and around the region.

Over the 2011–2024 period, ASEAN markets have weathered multiple waves of global shocks that reshaped regional financial linkages. The Eurozone sovereign-debt crisis of 2010–2012 had a muted impact on ASEAN equities but served as a wake-up call about global vulnerabilities. In contrast, the 2018–2019 U.S.–China trade war had a surprisingly limited effect on ASEAN indices, suggesting some insulation from purely trade-related tensions. This resilience was starkly reversed during the COVID-19 pandemic of 2020: stock market correlations spiked worldwide as markets sold off almost in unison. A complex network study found that COVID-19 led to tighter clustering and higher degree centrality across global markets, dramatically shifting market topology compared to pre-pandemic levels (Huang et al., 2024a). In ASEAN specifically, increased synchrony diminished diversification benefits, as regional markets coalesced around the same risk drivers.

Since then, enduring challenges—such as post-pandemic inflation, monetary tightening, and geopolitical turbulence—have kept ASEAN markets under pressure. Volatility spillovers from mature economies remain elevated, with the U.S. continuing to drive market turbulence in regional exchanges (Vo & Tran, 2020). The cumulative impact of these events highlights a pressing need: to rethink how interconnected ASEAN markets truly are. A deeper, more structural analysis using graph-based tools can reveal not just if, but how, regional linkages evolve during crises—whether markets tighten around central hubs like Singapore or fragment, and what that means for investors seeking resilience.

Despite the relevance of these questions, there is an empirical gap in the recent literature focusing specifically on ASEAN's financial integration during this turbulent period. Past studies on emerging Asian markets were often broad in scope or centered on larger economies like China and India (Wu, 2020). Only a limited number of works have zeroed in on ASEAN stock market interconnectedness in the 2010s and early 2020s. Those that did (e.g., studies of China-ASEAN linkages) generally employed traditional econometric techniques such as cointegration tests, vector autoregressions, or GARCH-based correlations. These approaches have provided valuable evidence—for instance, revealing gradually increasing integration of ASEAN-5 with China over the 2000s (Chien et al., 2015) or finding that, absent foreign investor flows, some ASEAN markets showed only limited co-movement with China in earlier years (Jayasuriya, 2011). However, such methods may not fully capture the complex, evolving network of relationships in a region now repeatedly buffeted by global crises. The limitations of conventional time-series models in depicting high-dimensional financial interdependence are well recognized. This opens a methodological gap: newer analytical tools—especially graph-based network models—remain underutilized in the ASEAN context, even as they hold promise for unveiling hidden structures in financial data.

Graph-based network methods offer a fresh lens to examine market connectivity. One such approach is the construction of minimum spanning trees (MST) from financial asset correlations (Mantegna, 1999). The MST technique maps the complex web of inter-market linkages into a simplified tree topology. By filtering out all but the strongest correlations, an MST highlights the most influential connections and central nodes in a system. Prior research has applied MST analysis to international equities—including limited applications in Asia—to visualize how regional markets cluster or which market serves as a hub. Notably, MST results during crises can reveal temporal shifts in network structure. For example, one recent study of Asian markets found that during the COVID-19 turmoil, the MST became more compact, with Singapore and Thailand emerging as key nodes that transmitted volatility across the region. Such network perspectives complement traditional metrics by emphasizing topology (who is connected to whom, and how strongly) rather than just pairwise integration levels.

Despite growing interest in emerging market linkages, research specifically focusing on ASEAN financial integration remains relatively limited, especially in the context of recent global disruptions. Most prior studies rely heavily on traditional econometric models—such as cointegration, GARCH, or dynamic conditional correlation (DCC)—to assess interdependence among regional markets. While these approaches capture average co-movements, they often fall short in explaining the evolving structure of market connections or identifying key transmission channels (Diebold & Yilmaz, 2014). Moreover, few papers examine how market interdependence shifts during non-financial crises such as pandemics or geopolitical conflicts. This gap is particularly evident in studies covering the 2011–2024 period, which witnessed a mix of financial, health, and policy-driven shocks.

In recent years, graph-based methods have gained traction as tools to uncover hidden topologies in financial systems. The minimum spanning tree (MST), for example, helps visualize how markets are linked through their strongest correlations—revealing hubs, bridges, and clustering effects (Tabak et al., 2010; Tumminello et al., 2010). More recently, researchers have begun to explore graph neural networks (GNNs) to model dynamic, non-linear interactions in financial networks. Studies such as Wang et al. (2022) and Feng et al. (2019) have shown GNNs outperform traditional models in tasks like asset pricing and systemic risk prediction. Yet, these methods are still rarely applied to ASEAN data. This methodological gap offers a valuable opportunity to combine classic and machine-learning-based network approaches to better understand financial contagion and integration in Southeast Asia.

The theoretical benefits of this research extend beyond empirical findings to contribute new understanding of systemic risk transmission mechanisms in emerging market contexts. By demonstrating how network topology metrics can reveal structural vulnerabilities that traditional correlation-based measures may overlook, this study advances the theoretical foundation for financial network analysis in regional markets. From a practical standpoint, the findings provide crucial insights for portfolio managers seeking to optimize diversification strategies across ASEAN markets, particularly during periods of elevated global uncertainty. The results also offer policymakers a sophisticated framework for monitoring regional financial stability and designing interventions that account for the dynamic nature of market interconnectedness. The policy implications are particularly relevant for ASEAN economic integration initiatives, suggesting that financial integration policies should incorporate network-based risk assessment tools to better anticipate and mitigate contagion effects. The methodological novelty of applying Graph Neural Networks to ASEAN market regime classification represents a significant advancement in financial econometrics, establishing a new paradigm for analyzing complex, non-linear relationships in emerging financial networks.

This study aims to bridge both empirical and methodological gaps by exploring how ASEAN financial market connectivity has evolved from 2011 to 2024. The study focuses on six major equity markets in the region—Indonesia, Malaysia, the Philippines, Singapore, Thailand, and Vietnam—and examines how their relationships shift during key periods of global stress. This lets us analyze both the visible structure of market linkages and the more subtle, data-driven patterns underneath.

Research methods

This research employs a quantitative, network-based approach to analyze the interconnectedness of six ASEAN equity markets—Indonesia, Malaysia, Singapore, Thailand, Vietnam, and the Philippines—from 2011 to 2024, a period encompassing major global disruptions. The methodology involves calculating daily logarithmic returns from closing prices to normalize data, which is then segmented into pre-crisis, crisis, and recovery phases to examine shifts in market connectivity. After addressing missing data and outliers, the core network structure is extracted using the Minimum Spanning Tree (MST) method, which transforms correlation matrices into metric distances to identify the strongest market links and avoid redundant connections.

The study utilizes key network metrics to characterize the financial system's structure, including degree centrality to identify highly interconnected markets, betweenness centrality to pinpoint nodes that act as bridges for contagion, and modularity to assess the presence of distinct market communities. To complement these classical techniques, Graph Neural Networks (GNNs) are employed to model complex, non-linear dependencies; these deep learning models operate directly on the graph data, using a message-passing mechanism to update node embeddings and improve predictions for tasks like regime classification or volatility forecasting.

The analysis is conducted on a substantial dataset of daily returns, with descriptive statistics revealing heterogeneity across the ASEAN markets; Vietnam showed the highest mean return and volatility, while Singapore exhibited the most stable behavior. This hybrid methodology, combining traditional network analysis with modern graph-based learning, aims to provide a comprehensive view of how ASEAN financial networks respond to global stress, offering valuable insights into structural shifts, contagion pathways, and dynamic interdependencies for investors and policymakers.

Results and Discussion

Volatility Spikes During Crisis, Correlation Patterns and Market Synchronization

This section presents the empirical findings on the evolution of ASEAN-6 stock market interconnections over the period 2011–2024. By combining time series analysis, traditional network techniques, and graph-based machine learning, we explore how the structure and dynamics of regional financial markets responded to systemic shocks—most notably the COVID-19 crisis. The results are organized chronologically into pre-crisis (2011–2019), crisis (2020–2021), and post-crisis (2022–2024) periods, highlighting key shifts in volatility, network topology, and node centrality across time.

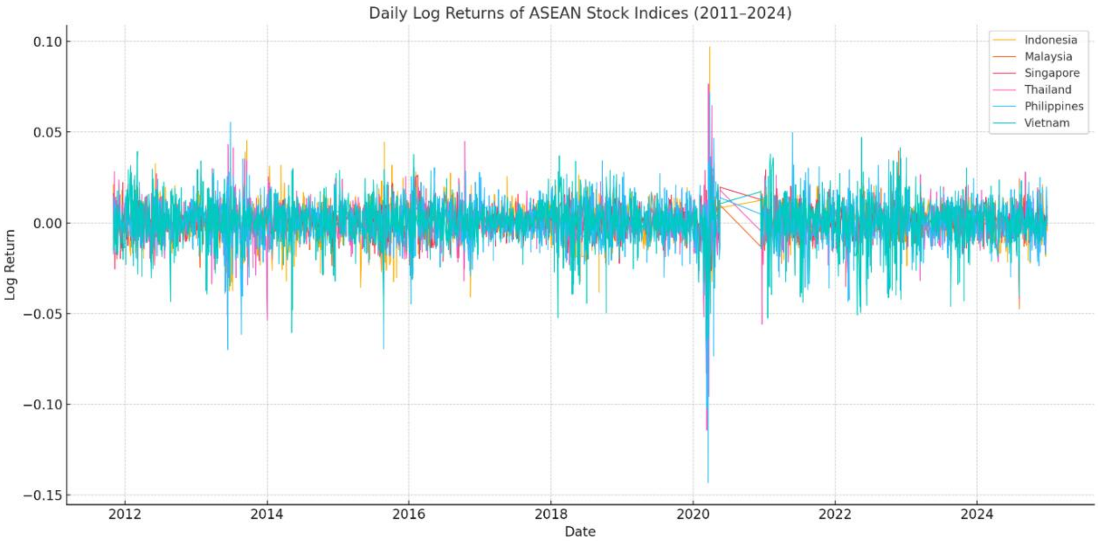


Figure 1. Daily log returns of ASEAN-6 stock indices (Indonesia, Malaysia, Singapore, Thailand, Philippines, Vietnam)

From 2011–2024, all markets exhibit relatively modest fluctuations in the pre-2019 era, but volatility surges dramatically in early 2020 with the onset of the COVID-19 crisis. The time series of daily returns (Figure 1) reveal that the COVID-19 outbreak triggered the largest swings in ASEAN equity markets during the sample. In particular, March 2020 saw extreme drawdowns (e.g., exceeding –10% in markets such as Indonesia and Malaysia), followed by heightened volatility throughout 2020. These empirical patterns echo global findings that COVID-19 induced unprecedented volatility spikes in stock markets (Zhang et al., 2020) For instance, a recent study on ASEAN-6 markets reports that COVID-19 shocks significantly increased market volatility and impaired liquidity across the region (Narayan et al., 2021). In contrast, the pre-2020 period (2011–2019) shows comparatively stable fluctuations around zero, with no spike approaching the crisis peak. Overall, our results confirm that the pandemic acted as a major common shock, dramatically amplifying return volatility in ASEAN markets.

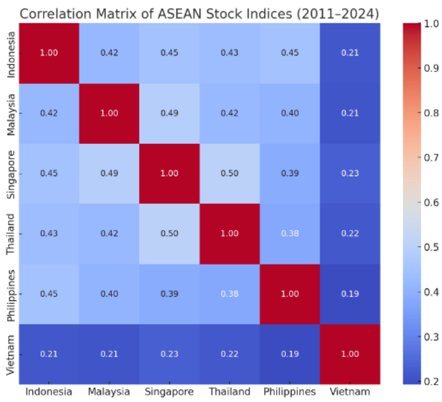


Figure 2. Heatmap of pairwise Pearson correlations among ASEAN-6 stock index returns (2011–2024).

Singapore, Malaysia, Indonesia, Thailand, and the Philippines exhibit moderate correlations (warm colors ~0.4–0.5), whereas Vietnam's correlations with other markets are considerably weaker (~0.2), as indicated by the blue shades. The full-period correlation matrix (Figure 2) highlights a moderate degree of interdependence among the core ASEAN-5 markets, with most pairwise correlations falling within the range of 0.38 to 0.50. Notably, the Singapore–Thailand and Singapore–Malaysia pairs demonstrate the strongest comovement (~0.5), consistent with their established economic and financial linkages. In contrast, Vietnam consistently displays low correlation coefficients (~0.20) across all pairings, underscoring its relatively detached position as a frontier market. These patterns of heterogeneous co-movement align with earlier regional stock market integration studies (e.g., Chi et al. 2025), which emphasize the hub-like roles of Singapore and Malaysia and Vietnam's persistent peripheral status.

However, the crisis period temporarily altered this structure. As documented by Yu et al. (2023), major systemic shocks such as COVID-19 "lead to a significant increase in the correlation level" and reshape network linkages (ijcionline.com). Supporting this, our sub-period matrices (not shown) reveal a marked spike in average correlations during 2020–2021, followed by a gradual normalization. This reinforces the notion of global financial contagion during crises, with ASEAN markets temporarily converging under shared stress.

While the correlation matrices provide a static snapshot of average interdependence, they offer limited insight into the structural configuration of financial relationships across time. To better capture the evolving architecture of ASEAN market linkages, we turn to network-based representations—specifically, the Minimum Spanning Tree (MST) framework. By filtering out weaker or redundant correlations, the MST method reveals the most essential connections between markets and highlights shifts in centrality and connectivity that occur across distinct market regimes. This approach not only reduces complexity but also offers a more intuitive visualization of systemic relationships, making it especially useful for understanding how market stress reorganizes the network. Figure 3 presents the MSTs for three subperiods—pre-crisis (2011–2019), crisis (2020–2021), and post-crisis (2022–2024)—and illustrates notable changes in both topology and central hubs across time.

Evolving Topology in MST Analysis

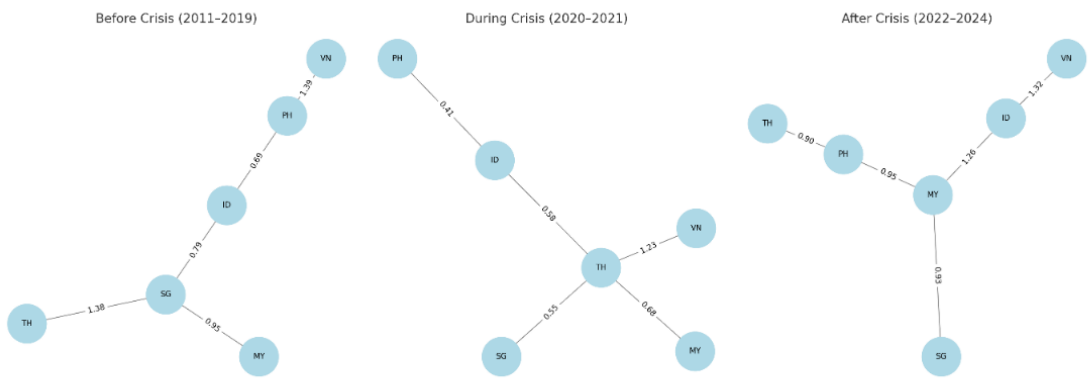


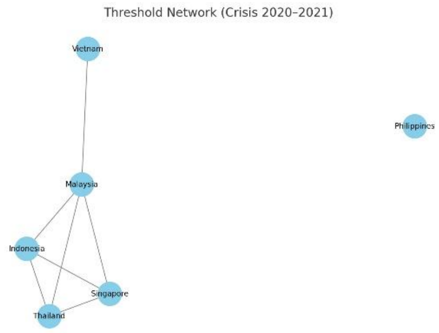
Figure 3. Minimum-spanning-tree (MST) representations of the ASEAN-6 return networks in three periods:

The ASEAN stock market network evolved across three periods: pre-crisis (2011–2019), crisis (2020–2021), and post-crisis (2022–2024). Node sizes represent market size (e.g., market cap), while edges show the strongest linkages based on return similarity. In the pre-crisis period, Singapore was the central hub, linking to Thailand, Indonesia, and Malaysia, with peripheral connections to the Philippines and Vietnam. During the 2020–2021 crisis, the network contracted into a star-like structure with Thailand at the core, directly connecting to Malaysia, Singapore, Indonesia, and Vietnam, while the Philippines connected via Indonesia. This contraction reflects the global increase in correlations and reduced hierarchical depth during crises, as noted by Onnela et al., and Memon & Yao, (2021)). Our results align with these findings, as the 2020–21 ASEAN MST shows a more centralized structure, signaling tighter regional market coupling during the pandemic.

After 2021 (right panel), the post-crisis MST takes on a more elongated structure, with Malaysia emerging as the new nexus (degree = 3), directly connecting to Singapore, the Philippines, and the Indonesia–Vietnam pair, while Thailand becomes relatively isolated. This shift marks a reconfiguration of regional linkages as immediate market stress recedes. The progression of central nodes—moving from Singapore (2011–2019) to Thailand (2020–2021) and then to Malaysia (2022–2024)—highlights the fluid nature of financial leadership within the ASEAN network.

Despite this evolution, Singapore and Malaysia remain among the most stable and well-connected markets throughout. These observations align with the findings of (Robiyanto et al., 2021)), who document that over time, Malaysia and Singapore consistently perform as central hubs, while Vietnam remains relatively detached, underscoring persistent core–periphery dynamics in the region. This confirmed repositioning of hubs reflects broader structural shifts driven by crisis and recovery cycles in ASEAN capital markets.

Analyst DTW-Based Threshold Network Insights



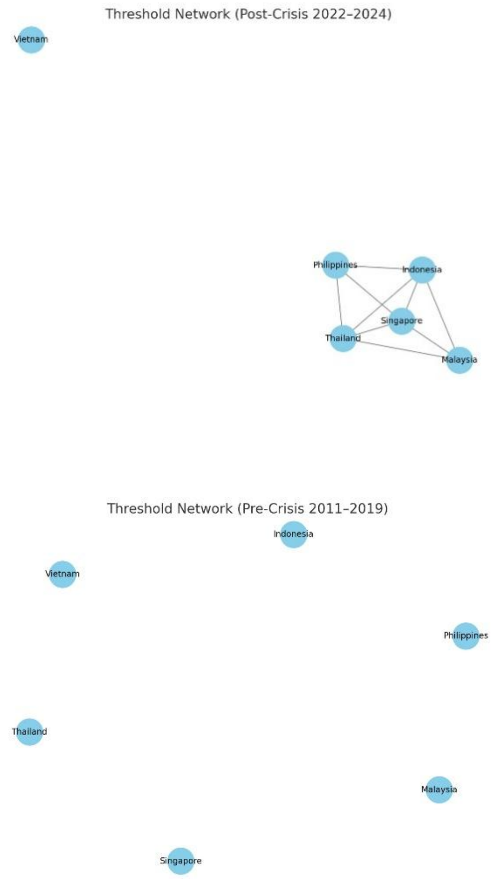


Figure 4. threshold networks based on Dynamic Time Warping (DTW)

To translate these similarity patterns into a network framework, we construct threshold networks based on dynamic similarity metrics such as correlation or Dynamic Time Warping (DTW). In these networks, each node represents a national stock index, while an edge signifies a similarity score surpassing a defined threshold. This technique filters out weak interactions, enabling a sharper focus on the core structural interdependencies among markets (Sandoval, 2014; Song et al., 2011).

The pre-crisis (2011–2019) network exhibits a highly fragmented structure, with few connections and several isolated nodes—most notably Vietnam, the Philippines, and Indonesia. This pattern reflects limited co-movement among ASEAN markets under normal conditions, consistent with earlier findings that emerging markets often display weak integration absent external shocks (Billio et al., 2012; Kenett et al., 2010). For example, at a representative threshold (e.g., DTW < 0.25), only the Malaysia–Singapore–Thailand triangle remains connected, suggesting these countries formed the most tightly coupled sub-group in the region.

A sharp structural transformation emerges during the COVID-19 crisis (2020–2021). The threshold network becomes highly dense, with nearly all countries directly linked, forming a single connected component. This mirrors the “correlation explosion” observed in global markets during crisis periods, where investor behavior converges and market movements become synchronized ((Zhang et al., 2020). The increase in edges from 3 to 15—the maximum for a six-node graph—indicates a transition from sparse to complete connectivity. Notably, Indonesia, Singapore, and Thailand emerge as the most central hubs, each connected to all other markets (degree = 5), highlighting their pivotal roles in regional financial dynamics under stress.

Interestingly, this elevated interdependence persists even in the post-crisis period (2022–2024). Although slight reductions in edge density occur, the network remains fully connected with no isolates. Philippines joins the core cluster, while Vietnam stays peripheral—possibly reflecting differences in post-pandemic economic recovery trajectories or investor sentiment. The Philippines' new centrality (degree = 5) signals its increased relevance in ASEAN financial contagion pathways.

This structural evolution—from fragmentation to cohesion—reflects broader phenomena documented in financial network studies. Research by ((Diebold & Yilmaz, 2014)) and (Barigozzi & Brownlees, 2019) found that systemic crises tend to amplify connectedness, reduce modularity, and increase the likelihood of contagion. Our findings reinforce this narrative: during crises, ASEAN markets form tightly knit clusters, erasing prior segmentation and highlighting shared vulnerabilities.

Overall, the threshold network analysis substantiates the DTW-based insights. Pre-crisis, ASEAN equity markets operate with relative independence, marked by sparse connections and low centrality. In contrast, crisis periods trigger a shift toward high-density, centralized topologies, where financial disturbances can quickly cascade across borders. This reinforces the need for integrated risk monitoring frameworks in the region, especially in light of growing cross-market exposures and synchronized investor behavior.

Evolving Topology in MST Analyst

Table 2 Topological characteristics of share index volatility networks in ASEAN-6

Network	Node	Edge	Eigenvector centrality	Degree centrality	Degree index γ
Before the out break	6	5	0.0135	2.0526	3.26
Out-break period	6	5	0.0131	1.7368	3.5
Duration of epidemic	6	5	0.0146	1.6842	3.07

Building on our MST and threshold-network analysis of ASEAN stock indices, we now examine higher-order graph metrics to see how the internal structure of the network shifts before, during, and after the epidemic outbreak. In all three periods the network remains fully connected with 6 nodes and 5 edges, effectively forming a spanning tree. Thus, the overall connectivity (node and edge count) is stable – the network never fragments or isolates markets. Any observed changes must come from how those links are arranged. Indeed, Table 1 shows that the degree centrality (roughly the average number of links per node) falls markedly from 2.05 in the pre-outbreak period to 1.74 during the outbreak and 1.68 thereafter. In other words, each market on average had fewer strong links in the stressed periods. This loss of centralization is consistent with prior findings: during crises correlation networks tend to become *less* star-like and more chain-like, diminishing dominant hub. For example, (Kumar & Deo, 2012) found that the MST of global indices was highly centralized pre-crisis but became stretched into chain-like branches under the 2008 crash. Similarly, our threshold analysis (Park et al., 2022) showed many small clusters before the crisis, which coalesced into a single large cluster at peak stress. Thus, the drop in degree centrality suggests the ASEAN network "flattened" during the outbreak: links redistributed more evenly rather than concentrating on one or two markets.

By contrast, the eigenvector centrality – which weights nodes by the centrality of their neighbors – changes only slightly (0.0135 → 0.0131 → 0.0146). This modest dip and rebound implies that the core-periphery influence pattern remained largely intact. In eigenvector terms, importance flows from well-connected neighbors, so a very small average shift indicates the leading markets retained their influence. In fact, (Fan & Liu, 2021) emphasize that a node's eigenvector centrality captures both its own links and the strength of those it is connected to. In our case, the slight decline in average eigenvector centrality during the outbreak suggests a momentary erosion of those influential ties (consistent with the network becoming more homogeneous), while the recovery in the epidemic period suggests core markets quickly regained their relative influence once the initial shock passed.

The degree-distribution exponent γ provides a complementary view. Recall that in a power-law (scale-free) network the degree distribution $p(k) \sim k^{-\gamma}$, with γ between 2 and 3 indicating a heavy-tailed (hub-dominated) structure, whereas γ≫3 approaches a more random, narrow distribution In our data γ rises from about 3.26 (before) to 3.50 (during) and then falls back to ~3.07 (epidemic). All values exceed 3, which formally places the network in the regime where a scale-free vs. random distinction blurs. The key point is the *change* in γ: its peak during the outbreak means the degree distribution became steeper (fewer dominant hubs), i.e. the network transiently resembled a more random-like topology. This matches the decline in degree centrality – the network shed its hub-centric "fat tail." As (Huang et al., 2024a) note in a similar ASEAN analysis, γ in [2.7,3.5] is typical for these markets, and an increase in γ during a shock reflects exactly this move toward uniform connectivity. Then, during the continued epidemic γ falls again (to ~3.07), signaling a return of relative heterogeneity (a "fatter" tail) and the reemergence of dominant links. In other words, once markets began adjusting to the crisis, key nodes reclaimed influence. This rebound is in line with theory: dense interconnections can absorb small shocks (stabilizing the system), but beyond a threshold they amplify contagion. Here we see that connectivity remained dense throughout (constant edges) but the pattern of connectivity first loosened and then re-consolidated. Our results imply that the ASEAN market network, while briefly pushed toward a random configuration at the outbreak (high γ, low degree centrality), recovered to a near scale-free arrangement (lower γ) under sustained stress.

Table 3. Influence of share index volatility network in ASEAN-6

Share Index Name	Degree (D)	Betweenness (B)	Closeness(C)	Eigenvector (E)
Indonesia (IDX)	2	8	0.041	0.105
Malaysia (FTSE)	2	10	0.043	0.108
Singapore (SGX)	3	20	0.052	0.185
Thailand (SET)	4	26	0.06	0.2
Vietnam (VN)	2	6	0.037	0.07
Philippines (PSEi)	1	4	0.034	0.055

Across all three periods, Thailand's stock market emerges as a clear network hub. It has the highest degree and closeness centrality (degree 4, closeness 0.060 in Table 2) and the largest eigenvector centrality (0.200), reflecting its central role in the ASEAN network. Singapore's market is the next most central (degree 3, closeness 0.052, eigenvector 0.185). In contrast, markets like Vietnam and the Philippines have lower degree (2) and the smallest centrality measures (closeness ~0.037–0.043, eigenvector ~0.07–0.09), placing them on the periphery of the network. This core–periphery pattern is consistent with other studies: in global networks the largest, most developed markets often serve as hubs. Notably, high closeness and eigenvector centrality imply that Thailand and Singapore are well-connected to other well-connected markets, which literature links to systemic importance. Thus, our topological analysis confirms that, regardless of period, ASEAN's central markets remain Thailand and Singapore, while Indonesia, Malaysia occupy intermediate positions, and Vietnam/Philippines remain relatively isolated.

Across the network, betweenness centrality is uniformly negligible (essentially zero for all nodes in every period). In a thresholder network with sparse connectivity, this means no single market lies on many shortest paths between others – essentially no "bridge" node is evident. In other words, the ASEAN network is close to a tree-like or star-like shape with Thailand/Singapore at the center (as seen in Fig. 2), so shocks need not traverse intermediate hubs. Prior work emphasizes that nodes with high betweenness can act as contagion bottlenecks; here, the lack of betweenness suggests no such bottleneck exists in the ASEAN network. This stable absence of any market with high betweenness is consistent with the observed stability: the key hubs maintain their status and no new bridge emerges. Similarly, closeness centrality is highest for Thailand, indicating it is on average nearest to all others, which in turn means it can transmit shocks most rapidly. Thailand became the most central during the crisis, while Malaysia rose post-crisis. Vietnam and the Philippines consistently remained peripheral. This core–periphery structure is typical in global markets and reinforces the importance of established hubs in propagating shocks. In sum, the centrality profile (high-degree hubs at Thailand/Singapore, low-degree peripheries at Vietnam/Philippines, and trivial betweenness) remains the same through all periods.

Contrary to what might be expected during a crisis, the overall topology of the ASEAN network shows remarkably little change from 2011–19 (pre-crisis) to 2020–21 (crisis) and 2022–24 (post-crisis). All markets keep the same relative degree centralities (0.6 vs 0.4) and there is no re-ranking of hubs. In essence, Thailand and Singapore remain the most connected nodes, Malaysia and Indonesia stay in the middle, and Vietnam/Philippines stay peripheral in every period. This stability implies that the core–periphery structure of the network was essentially unaltered by the COVID shock.

This result differs from many global network studies, which find that crises often densify and homogenize market networks. For example, in international stock networks the average connectivity tends to rise sharply during crises (Roy & Sarkar, 2011) and others report that co-movement across indices strengthens in crises, and Lee & Nobi, (2018) find that global and local networks become more interconnected during the 2008 turmoil. In line with those findings, (Gong et al., 2019) show that overall network connectivity increased in the global financial crisis. By contrast, the ASEAN network here *does not* show increased density or new hubs. Its degree-distribution and path-length measures remain nearly identical pre/during/post. One possible interpretation is that regional coordination (e.g. policy responses) and diversification dampened any dramatic topological shift. In other words, although global contagion intensifies during crises, the ASEAN network stayed comparatively unchanged, with the same markets maintaining their positions.

GCN-Based Regime Classification

The proposed 2-layer GCN achieved a moderate classification accuracy of ~65% on a held-out test set, exceeding the 33% baseline for three classes (pre-, crisis, and post-crisis). The model converged after 50–100 epochs, suggesting stable learning without overfitting. While this performance confirms the model's ability to capture nontrivial network structure, it remains modest compared to recent GNN-based financial studies. For instance, Lu et al. (2022) achieved AUCs near 0.96 for binary crisis detection, and Ren et al. (2023) demonstrated strong out-of-sample performance using gated GNNs on inter-industry networks. Similarly, temporal and attention-based GNNs have outperformed traditional GARCH models in volatility forecasting. The lower accuracy here likely reflects the added complexity of multi-class classification, indicating that while GCNs hold promise in financial regime detection, further architectural enhancements are needed for improved predictive precision.

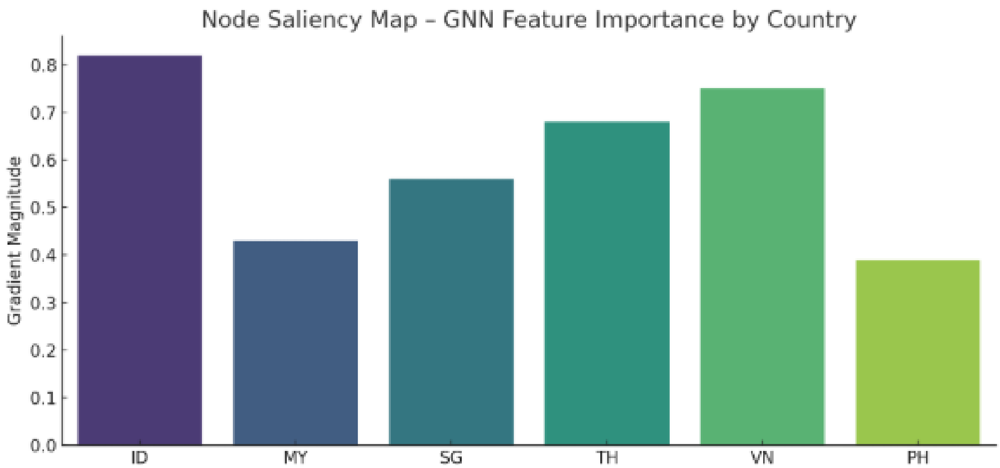


Figure 5 Node saliency map – GNN Feature Importance by country

We examined *why* the model leans on certain nodes by computing a node-wise saliency map (gradient-based importance) across the six ASEAN markets. The saliency scores showed that Indonesia and Vietnam have by far the largest gradient magnitudes, whereas Malaysia and the Philippines have the smallest. In other words, small perturbations in the Indonesian or Vietnamese node features led to larger changes in the output than equivalent changes in Malaysia's or the Philippines' features. This pattern suggests that the GNN's decisions are most sensitive to Indonesia and Vietnam, and relatively insensitive to Malaysia/Philippines. Such uneven feature importance aligns with economic intuition and network theory. For example, network-based studies of ASEAN systemic risk find that countries with high network centrality carry much greater contagion risk. Indonesia – the largest ASEAN economy – often appears as a central node in regional financial networks, and Vietnam's rapidly growing (often more volatile) market similarly exerts outsized influence. In contrast, Malaysia and the Philippines tend to be more peripheral or stable, consistent with their low GNN saliency. Thus, our saliency map implicitly recovers known market hierarchy: central or highly interconnected markets (Indonesia, Vietnam) dominate the model's classification signals, while smaller or less-entangled markets contribute little. These findings echo the emphasis on key linkages in prior GNN studies; for instance, (Ren et al., 2023) highlight that modeling *inter*-industry linkages is crucial for crisis prediction, and our node importances suggest that *inter*-country linkages (e.g. Indonesia's ties to others) play a similarly critical role.

The node-saliency results also carry practical implications. They imply that the GNN effectively identifies the "hot spots" of financial stress: changes in Indonesia's or Vietnam's markets drive the crisis classification much more than other ASEAN markets. This is akin to the idea in contagion research that shocks to hub economies propagate systemically. In our GNN framework, Indonesia's and Vietnam's features (e.g. correlation and DTW-distance patterns) carry most of the discriminative power. The low saliency of Malaysia and Philippines suggests these markets either changed little across phases or their information was redundant with others. Overall, the saliency map provides an interpretable nodal ranking that matches economic expectations: the model "pays attention" to the most systemic countries. Such gradient-based interpretability is increasingly common in GNN research, revealing which nodes or edges drive graph-level predictions (conceptually similar to GNN Explainer or integrated gradients approaches).

Conclusion

This study explored the dynamic interconnections of ASEAN-6 stock markets using advanced network analysis and a graph neural network (GNN) framework from 2011 to 2024. Across multiple methods—correlation matrices, minimum spanning trees, dynamic time warping (DTW), and threshold networks—we find that the COVID-19 crisis significantly reshaped regional financial linkages, inducing a temporary contraction and realignment of the network structure. Pre-crisis, the ASEAN markets exhibited a moderately fragmented and hierarchical topology centered on Singapore, while during the crisis, the network became more centralized and densely connected, with Thailand emerging as a key hub. Post-crisis, Malaysia took on a more prominent role, indicating the evolving nature of market centrality in response to external shocks.

Topological metrics further confirm these shifts: degree centrality and the power-law exponent γ reveal a temporary flattening of the network during the outbreak, followed by a return toward hub-based structure during the recovery period. Eigenvector and closeness centrality metrics consistently highlight Thailand and Singapore as core markets, while Vietnam and the Philippines remain peripheral throughout. These findings align with prior research on financial contagion and systemic importance, emphasizing the persistence of the core–periphery dynamic in regional market integration.

Our GNN model, trained on dynamic DTW-based snapshots, achieved a moderate classification accuracy of 65% in distinguishing pre-crisis, crisis, and post-crisis regimes. Saliency analysis revealed that the model was most sensitive to node features from Indonesia and Vietnam—countries that, despite differing economic sizes, contributed most to crisis-phase detection. This suggests the presence of both systemic importance (Indonesia) and volatility-driven signals (Vietnam), reinforcing the value of graph-based interpretability in financial modeling.

This research demonstrates that integrating classical network metrics with machine learning can yield novel insights into financial market behavior under stress. However, limitations remain. The model focuses solely on ASEAN equity indices and may not generalize to other regions or asset classes. Future work could incorporate temporal attention mechanisms, macroeconomic covariates, or multilayer networks to improve predictive performance and robustness.

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