# Volatility Spillovers Across Fintech, Digital Economy, and ESG Indices in India: A Quantile Time-Frequency Connectedness Analysis

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**Abstract**

This study investigates the volatility spillovers among India's sustainability-linked and technology-driven financial indices, spanning the digital economy, ESG investments, electric vehicles, and energy. Using a Quantile Time-Frequency Connectedness framework, we examine five key indices of Nifty100 Enhanced ESG, Nifty India Digital, Nifty EV & New Age Automotive, MSX iCOMEDEX Energy, and Gold from April 2018 to December 2024. The research captures connectedness across quantiles and time, especially during times of global stress such as COVID-19 pandemic and geopolitical tensions. Results show short-term connectedness accounting for a substantial portion of total connectedness, with ESG and Digital indices emerging as persistent net transmitters, while Gold and Energy act as volatility absorbers. Long-term spillovers are weaker but suggest underlying structural linkages that intensify under prolonged economic uncertainty. Notably, the Nifty100 Enhanced ESG index shows the highest spillover, highlighting its systemic influence. Portfolio optimization further underscore the stabilizing role of Gold and ESG-linked assets, offering risk-averse strategies in turbulent markets. This study fills a key gap by integrating quantile and frequency-domain connectedness in the Indian context and provides novel insights into asymmetric risk transmission for policy and portfolio design.

**Keywords:** India-Digital, Fintech, ESG, Electric Vehicle & New Age Automotive, Quantile connectedness, Multivariate Portfolio Construction.

**JEL Codes:** G11, O16, Q56, Q02

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# Introduction

In the contemporary landscape of financial markets, two parallel yet converging trends are reshaping investment strategies: the rise of the digital economy, fuelled by advancements in Fintech, and the increasing prominence of sustainable finance, driven by Environmental, Social, and Governance (ESG) principles, alongside growing capital flows into electric vehicles (EVs) and clean energy. These independent but increasingly intertwined trends are transforming portfolio construction, redefining how investors perceive risk, return, and long-term value. Once viewed as a niche ethical strategy, ESG investing has become mainstream, with evidence suggesting superior risk-adjusted returns, particularly during market stress (Nofsinger & Varma, 2014; Henke, 2016). In parallel, India is blooming into a Fintech hub (Migozzi et al., 2020), and extant literature highlights how the Fintech ecosystem is facilitating financial services and driving inclusion (Mehrotra, 2019; Asif et al., 2023). The Digital India initiative, launched in 2015, has been a catalyst for digital transformation, strengthening financial inclusion through the biometric ID system of Aadhaar and the Unified Payments Interface (UPI), which has enabled a thriving tech-driven economy (PIB, 2024). Beyond finance, digital expansion has enabled progress in e-governance, and rural connectivity through national broadband initiatives. Programs such as India Stack, BharatNet, and Common Service Centres (CSCs) underscore the country's accelerating digital adoption and integration into the global digital economy. In parallel, the rise of ESG-focused investments signals a structural shift toward integrating environmental considerations into capital allocation. Together, these trends reflect a growing convergence of technological innovation and sustainability-linked capital flows.

## 1.1 Overall Conceptual Framework: Interplay between Digital and Sustainability

The study's conceptual framework is illustrated in Figure 1, comprising the dynamic relationships among the digital economy, sustainability-focused sectors, and their collective dynamics within modern financial markets. The five selected indices provide insights into emerging investment strategies that balance financial performance, technological advancement, sustainability goals, and risk management in the contemporary Indian market. The Nifty100 Enhanced ESG Index reflects India's growing integration of ESG principles into mainstream investments. Complementing this, the Nifty EV & New Age Automotive Index tracks companies integral to the EV ecosystem and advanced automotive technologies. The Nifty India Digital Index represents India's growing digital economy, reflected in the performance of companies leading digital innovation and transforming financial services through technology. These indices provide a framework to study the intersection of India's Fintech transformation, and the increasing prominence of sustainability-focused investments such as ESG and EVs. The interplay between these modern asset classes reveals important dynamics that could inform portfolio construction strategies in a rapidly evolving financial landscape. To strengthen this framework, traditional safe-haven assets like Gold and Energy commodities were included to assess their role in providing stability during market volatility. The MCX iCOMDEX Gold Index, represents the enduring importance of gold in stabilizing portfolios, while the MCX iCOMDEX Energy Index, based on crude oil and natural gas futures, reflects conventional energy sector trends. These indices serve as benchmarks for hedging and portfolio diversification, reinforcing the importance of commodity markets in uncertain economic conditions. As India's leading commodity exchange, MCX facilitates the majority of the country's commodity futures trading.

Several theoretical perspectives help anchor this study's conceptual framework. Financial contagion theory suggests that asset linkages deepen during crises, amplifying volatility across sectors (Forbes & Rigobon, 2002). This is particularly relevant when examining co-movement across ESG, EV, digital, and commodity-linked indices. Safe haven theory explains how assets like gold or ESG-aligned securities may preserve value in downturns, providing a buffer against shocks (Baur & Lucey, 2010). Meanwhile, diversification theory highlights the value of blending traditional and emerging asset classes to improve portfolio resilience (Reboredo, 2013). Together, these reinforce the rationale for using quantile time-frequency connectedness to capture the intensity and asymmetry of spillovers across different investment horizons.

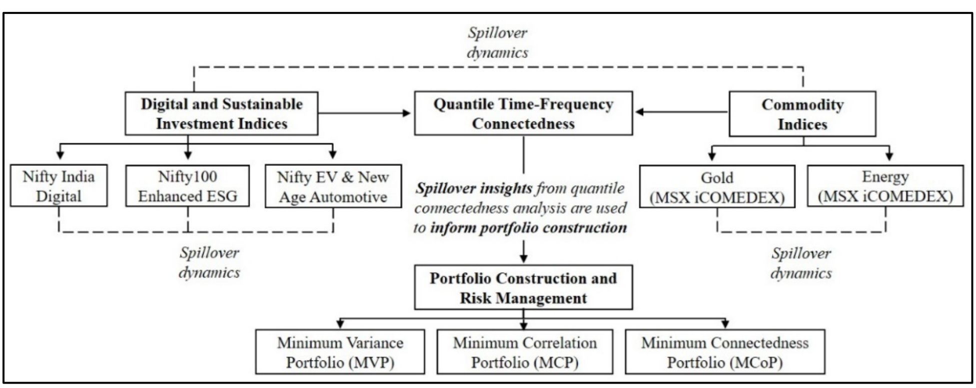


**Figure 1: Overall Conceptual Framework**

## 1.2 Research Questions and Scope of the Study

This study explores spillover dynamics across a broad spectrum of asset classes, spanning modern (digital, ESG, EVs) and traditional (Gold, Energy). Using quantile time-frequency connectedness, we uncover asset interlinkages, contributing to literature on portfolio management, sustainable finance, and Fintech-driven investments. We assess whether these indices enhance resilience through hedging or diversification, particularly during market stress. The findings inform investors aligning with technological and sustainability trends and guide policymakers fostering financial innovation and environmental responsibility. Table 1 presents the research questions and the corresponding methodological approach to address them.

**Table 1: Research Questions and methodological approach followed to answer these**

| S.No. | **Research Question** | **Methodology and Approach** |
|---|---|---|
| RQ1 | How do volatility spillovers among Digital, ESG, EV-focused investments, and traditional assets like Gold and Energy vary across time horizons and market conditions? | Frequency quantile connectedness framework employed to examine interaction and volatility spillovers under varying market conditions. |
| RQ2 | How do traditional assets like Gold and Energy contribute to portfolio stability? Do these act as hedging instruments in the presence of spillovers from new-age asset classes? | Portfolio construction techniques (MVP, MCP and MCoP) examine how traditional assets such as Gold and Energy may hedge risk and enhance portfolio stability |
| RQ3 | How can the connectedness among Digital and ESG investments inform regulatory policies/frameworks. | Spillover analysis provides insights into how digital and ESG investments interact, helping shape regulatory policies to foster sustainable finance. |

The rest of the paper is structured as follows. Section 2 presents a literature review, Section 3 discusses the methodology, Section 4 describes the data, Section 5 presents the empirical results and discussion, and Section 6 presents the conclusion.

## 2. Literature Review

ESG investing is emerging as a widely adopted investment strategy, combining competitive financial performance with ethical alignment. Prior research has established that ESG-focused portfolios may outperform traditional ones during market downturns, benefiting from downside risk mitigation, though they may underperform in stable periods (Nofsinger & Varma, 2014). Exclusion-based ESG approaches maintain comparable risk-adjusted performance while improving sustainability scores, with smart beta strategies enhancing this effect (Alessandrini and Jondeau, 2019). Meanwhile, the strong returns observed in green bonds and stocks in recent years, evidenced in the widening 'greenium', aligning with theoretical expectations of lower returns for green assets compared to brown ones (Pástor et al., 2022). In bond markets, ESG integration boosts performance during recessions by excluding issuers with poor CSR activities (Henke, 2016). In equity markets, ESG activity demonstrates a modest but positive influence on financial performance of firms, highlighting ESG metrics' role in aligning sustainability and financial outcomes (Huang, 2019). The growing significance of ESG indices in financial markets is reflected in their ability to navigate market disruptions effectively. In the Indian context, companies with strong ESG characteristics outperform their conventional counterparts during black swan events, supporting the notion that ESG practices can provide stability during market volatility (Deshmukh et al., 2020). Recent studies also examine ETF and commodity market behaviour during turbulent periods, highlighting how Indian equity ETFs responded actively to COVID-19, oil markets reacted to the Russia-Ukraine conflict, and ETF splits influenced returns and liquidity through market structure shifts (Saini et al., 2023; Saini & Sharma, 2023; Saini, Sharma & Verma, 2024). Additionally, evidence from gold ETFs, spot, and futures markets points to strong spillover transmission across asset classes, particularly in volatile conditions (Saini & Sharma, 2024a, 2024b). Empirical evidence from India suggests that governance criteria play a pivotal role in shaping investor decisions, while ESG-aligned investments provided downside protection and reduced return volatility during the COVID-19 crisis, reinforcing their role in strengthening portfolio resilience amid market disruptions (Sood et al., 2023; Beloskar & Rao, 2022).

Fintech stands for financial technology. For investors, it is represented by companies in financial markets, that focus on transforming financial services through innovation and technology. Its impact on sustainable investment performance has been extensively examined, particularly in relation to investor sentiment and clean energy stocks. Evidence suggests that Fintech can enhance the appeal of green assets, improving their market resilience, particularly during periods of financial stability (Dong & Huang, 2024). Additionally, studies highlight Fintech's role in driving efficiency within banking sectors, reinforcing its contribution to financial market performance (Dwivedi et al., 2021). The interconnectedness between Fintech, ESG, and broader financial markets has also been a subject of empirical inquiry. Research indicates that Fintech indices exhibit strong co-movements with equity markets, particularly in times of financial distress (Rabbani et al., 2023). The Indian financial landscape has witnessed a rapid evolution of Fintech, supported by digital innovation and shifting market structures. The effectiveness of Machine learning in predicting stock prices of Indian Fintech firms has been evidenced, reflecting the sector's growing analytical sophistication (Meher et al., 2023).

Fintech has also played a pivotal role in promoting access to financial services among underbanked and middle-income populations, aligning with India's broader financial inclusion agenda (Asif et al., 2023). The Digital India initiative has been a key driver in reshaping India's financial geography. Research highlights that Bengaluru and New Delhi have emerged as Fintech hubs, complementing Mumbai's established financial dominance (Migozzi et al., 2020). Additionally, government policies aimed at promoting digital payments and financial trust have reinforced this transformation. The Unified Payments Interface (UPI) and mobile banking initiatives have significantly enhanced financial accessibility, solidifying India's position as a leading digital economy (Kandpal & Mehrotra, 2019). While Digital, Fintech and ESG themes have been studied individually, such as digitalization's impact on firm-level ESG disclosures (Singhania et al., 2025), their combined influence on market-level connectedness and volatility spillovers remains largely unexplored in the Indian financial market context. This study fills that gap, and it is the first to examine the interaction between digital and sustainable investment strategies in India. It explores connectedness among Nifty India Digital, Nifty100 Enhanced ESG, Nifty EV & New Age Automotive, Gold, and Energy indices. Using quantile time-frequency analysis, it tracks volatility spillovers across quantiles and horizons, offering fresh insights into risk behaviour and diversification in India's evolving financial landscape.

# 3. Methodology

We analyse spillover dynamics based on the foundation by (Diebold & Yilmaz, 2012) framework and a Quantile Vector Autoregressive (QVAR) model of order $p$ to capture time-varying, quantile-specific risk transmission (Ando et al., 2018; Chatziantoniou et al., 2021) represented as:

$$y_t = \mu(\tau) + \sum_{j=1}^{p} \Phi_j(\tau) y_{t-j} + \epsilon_t(\tau), \qquad \textbf{(1)}$$

$y_t$ is a vector of returns of the five indices, $\mu(\tau)$ represents quantile-specific deterministic components, $\Phi_j(\tau)$ denotes the lagged coefficient matrix at quantile $\tau$, and $\epsilon_t(\tau)$ is the error term which follows a quantile-dependent covariance structure $\Sigma(\tau)$.

For connectedness analysis, we apply Generalized Forecast Error Variance Decomposition (GFEVD), adjusted for quantile settings (Koop et al., 1996; Pesaran & Shin, 1998), measuring how shocks from variable $j$ influence forecast error variance of $i$ given horizon $H$:

$$\psi_{ij}^{(\tau)}(H) = \frac{\sum_{h=0}^{H-1} (e'_i \psi_h(\tau) \Sigma(\tau) e_j)^2}{\sum_{h=0}^{H-1} (e'_i \psi_h(\tau) \Sigma(\tau) \psi_h(\tau)' e_i)^2} \qquad \textbf{(2)}$$

Where $\psi_h(\tau)$ represents the impulse response functions derived from the QVAR model, and $e_i$, $e_j$ are selection vectors for the respective variables. Each entry $\psi_{ij}^{(\tau)}(H)$ captures the quantile-specific impact of shocks from $j$ on $i$ over $H$ steps. To ensure interpretability, each variance decomposition element $\psi_{ij}^{(\tau)}(H)$ is normalised by sum of all contributions:

$$\tilde{\psi}_{ij}^{(\tau)}(H) = \frac{\psi_{ij}^{(\tau)}(H)}{\sum_{j=1}^{N} \psi_{ij}^{(\tau)}(H)} \qquad \textbf{(3)}$$

Directional connectedness quantifies shock transmission (*TO*) and (*FROM*) as follows:

$$TO_i^{(\tau)} = \sum_{j\neq 1} \tilde{\psi}_{ij}^{(\tau)}(H), \text{ and } FROM_i^{(\tau)} = \sum_{j\neq 1} \tilde{\psi}_{ji}^{(\tau)}(H). \qquad \textbf{(4)}$$

'Net connectedness' is defined as the difference between *TO* and *FROM*, providing insight into whether a variable transmits or receives shocks. We calculate Total Connectedness Index (TCI) based on (Chatziantoniou & Gabauer, 2021) across all variables:

$$TCI^{(\tau)} = \frac{\sum_{i,\ j=1,\ i\neq j}^{N} \tilde{\psi}_{ij}^{(\tau)}(H)}{N-1}, \qquad \textbf{(5)}$$

where $N$ represents number of variables. Higher TCI values indicate greater system-wide connectedness and potential market contagion. Extending our analysis, we adopt a frequency-domain connectedness approach (Barunik & Křehlík, 2018; Marco et al., 2023). Using a spectral decomposition, we examine short- and long-term spillovers by isolating specific frequency bands within the forecast error variance. This decomposition captures distinct temporal spillover dynamics and enhances our understanding of connectedness over different investment horizons. Further, we implement three portfolio construction approaches based on variance-covariance matrix, derived from the TVP-VAR model. These include:

i. Minimum Variance Portfolio (MVP) (Markowitz, 1959) widely used for constructing portfolios that target to minimise volatility across assets. Portfolio weights are calculated by minimising variance as follows:

$$w_t = \frac{{V_t}^{-1}\,\mathrm{I}}{\mathrm{I}^t.{V_t}^{-1}\,\mathrm{I}} \tag{6}$$

where $w_t$ is the portfolio weight vector of dimension $m \times 1$, $I$ is an $m$ dimensional vector of ones, and $V_t$ denotes conditional variance-covariance matrix at time $t$.

ii. Minimum Correlation Portfolio (MCP) (Broadstock et al., 2022; Christoffersen et al., 2014) which uses an $m$×$m$ conditional correlation matrix $R_t$ to get portfolio weights.

$$R_t = diag(V_t)^{-\frac{1}{2}}\, V_t\, diag(V_t)^{-\frac{1}{2}} \tag{7}$$

where weights are calculated as:

$$w_t = \frac{{R_t}^{-1}\,\mathrm{I}}{\mathrm{I}^t.{R_t}^{-1}\,\mathrm{I}} \tag{8}$$

iii. Minimum Connectedness Portfolio (MCoP) aims to reduce interconnectedness among assets and therefore reduce spillover effects, so that the portfolio becomes more resilient to market shocks. It uses pairwise connectedness indices ($PCI_t$) to calculate the weights as follows:

$$w_t = \frac{{PCI_t}^{-1}\,\mathrm{I}}{\mathrm{I}^t.{PCI_t}^{-1}\,\mathrm{I}} \tag{9}$$

where $PCI_t$ captures inter-asset spillovers, I is the identity matrix (Broadstock et al., 2022).

# 4. Data

Daily data for Nifty indices was sourced from https://www.niftyindices.com, and for commodity indices from https://www.mcxindia.com/market-data/mcx-icomdex-indices. Duration of data was from April 2, 2018 to December 6, 2024. Unit root tests of stationarity conducted at level confirmed non-stationarity. Consequently, daily log-differenced prices were used to transform the data into return series. Figure 2 depicts return series and Table 2 presents descriptive statistics. The ADF tests confirm stationarity at conventional levels (with p-values < 0.01), indicating suitability for time-series analysis.

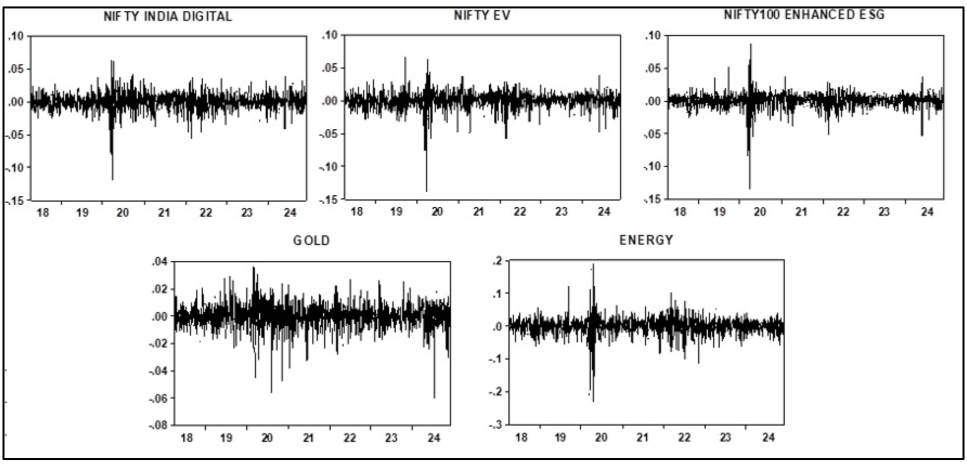


**Figure 2: Returns**

**Table 2: Descriptive Statistics and Tests for Stationarity**

| | Nifty India Digital | Nifty100 Enhanced ESG | Nifty EV | Gold | Energy |
|---|---|---|---|---|---|
| Mean | 0.000599 | 0.000563 | 0.00069 | 0.00039 | -0.00035 |
| Median | 0.000877 | 0.001156 | 1.49E-03 | 0.0006 | 0.00125 |
| Maximum | 0.063267 | 0.08679 | 0.06786 | 0.036 | 0.18882 |
| Minimum | -0.11874 | -0.13477 | -0.13852 | -0.05961 | -0.23017 |
| Std. Dev | 0.012808 | 0.011125 | 0.01247 | 0.0085 | 0.02583 |
| Skewness | -0.83895 | -1.46468 | -1.27468 | -0.7136 | -1.04628 |
| Ex. kurtosis | 7.66 | 21.08 | 12.686 | 4.81 | 14.182 |
| ADF | -40.75* | -14.16* | -38.18* | -41.15* | -40.35* |

Note: * indicates that ADF results are statistically significant at 1% (p < 0.01)

# 5. Empirical results and discussion

Using quantile frequency connectedness approach, we assess long-term and short-term interdependencies between new-age Indian equity indices (Nifty India Digital, Nifty100 Enhanced ESG, and Nifty EV & New Age Automotive) and commodity indices (Gold and Energy) over the period April 2018 to December 2024. By capturing the directional spillovers of volatility, we offer a detailed perspective on the transmission of shocks across asset classes under varying market conditions.

Table 3 highlights the correlation matrix of the five indices, revealing moderate positive correlations between the Nifty indices. For instance, Nifty100 Enhanced ESG and Nifty EV exhibit the highest correlation (0.596), indicative of shared market dynamics among ESG and EV-focused investments. Conversely, correlations between commodity indices and equity indices are generally low or insignificant. The limited co-movement between commodities and equities suggests potential diversification benefits.

**Table 3: Correlation Matrix**

| Kendall Correlation | Nifty India Digital | Nifty100 Enhanced ESG | Nifty EV | Gold | Energy |
|---|---|---|---|---|---|
| **Nifty India Digital** | 1.000*** | 0.576*** | 0.486*** | 0.001 | 0.054*** |
| **Nifty100 Enhanced ESG** | 0.576*** | 1.000*** | 0.596*** | -0.008 | 0.042** |
| **Nifty EV** | 0.486*** | 0.596*** | 1.000*** | -0.01 | 0.056*** |
| **Gold** | 0.001 | -0.008 | -0.01 | 1.000*** | 0.070*** |
| **Energy** | 0.054*** | 0.042** | 0.056*** | 0.070*** | 1.000*** |

Note: ***, **, and * denote statistical significance at the 1%, 5%, and 10% respectively; values without symbols are not significant at 10%.

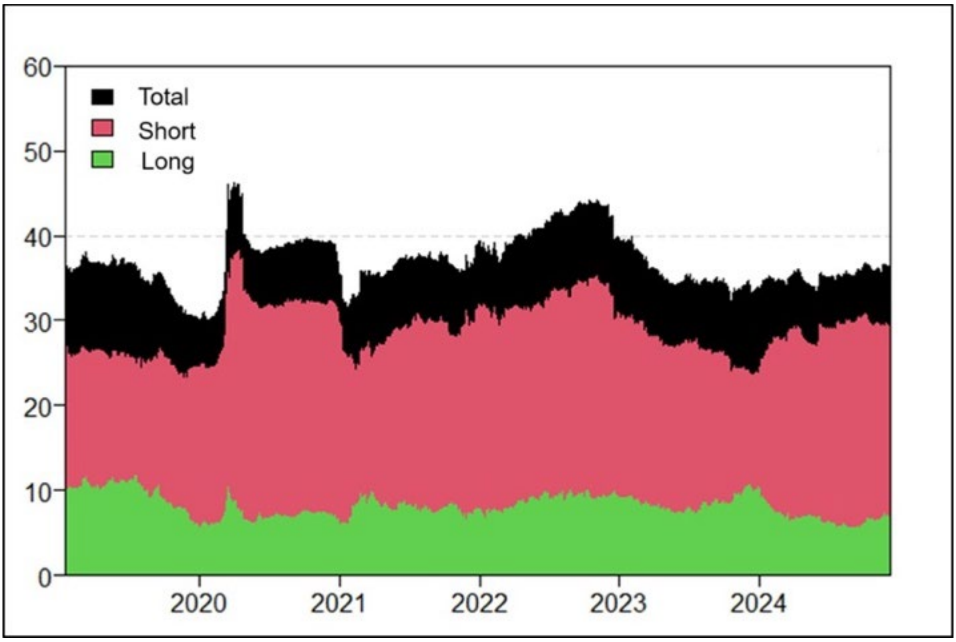


**Figure 3. Total Connectedness**

Figure 3 illustrates total connectedness among the five indices from 2018 to 2024, decomposed into short-term and long-term components. The results reveal that both total and short-term connectedness intensified markedly during periods of global distress, notably COVID-19 pandemic (2020–2021) and subsequent geopolitical crises in Russia-Ukraine and Israel-Hamas (2022–2023). These surges reflect rapid transmission of shocks across asset classes, especially those linked to technology and sustainability themes, underscoring their increased sensitivity to systemic uncertainty. In contrast, long-term connectedness remained relatively stable throughout the sample period, suggesting that volatility spillovers at lower frequencies are weaker and less persistent. This finding indicates that market shocks tend to dissipate over extended horizons, consistent with the theoretical expectation that long-run co-movements are driven more by structural factors than short-term sentiment or news effects.

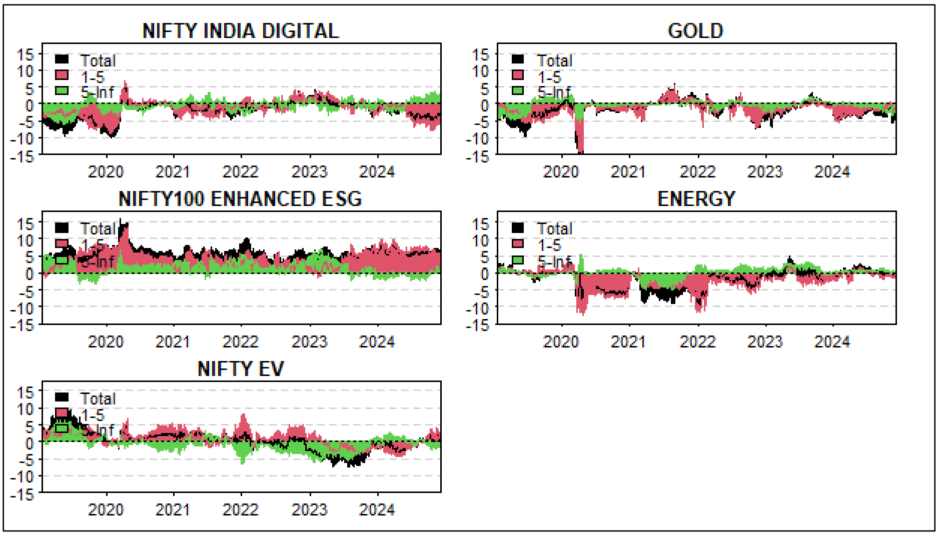


**Figure 4. Net Connectedness**

Figure 4 illustrates the net connectedness of each index over time. The results reveal that the Nifty100 Enhanced ESG index consistently acts as a net transmitter, with pronounced peaks during systemic stress periods, signalling heightened sensitivity to macro shocks, possibly due to its integration with global sustainability trends and investor sentiment, which amplify its influence during uncertain conditions. On the other hand, the Nifty EV index demonstrates a shifting role over time. In the short run, it operates as a volatility transmitter, likely driven by policy announcements, innovation cycles, or investor speculation. However, over the long term, it transitions into a net receiver, suggesting that electric vehicle investments may depend structurally on broader economic stability and long-term capital flows. We also observe that the Nifty India Digital index consistently behaves as a net receiver across time and frequencies. This suggests that while it is influenced by market-wide volatility, it does not contribute significantly to systemic risk transmission. Gold and Energy indices largely act as shock absorbers in the short term, reinforcing their traditional role as defensive assets. However, the Energy index shows a shift to net transmission in the long term, likely due to prolonged policy or commodity-driven price shifts. In contrast, Gold maintains a near-zero net position, affirming its reputation as a long-term safe haven.

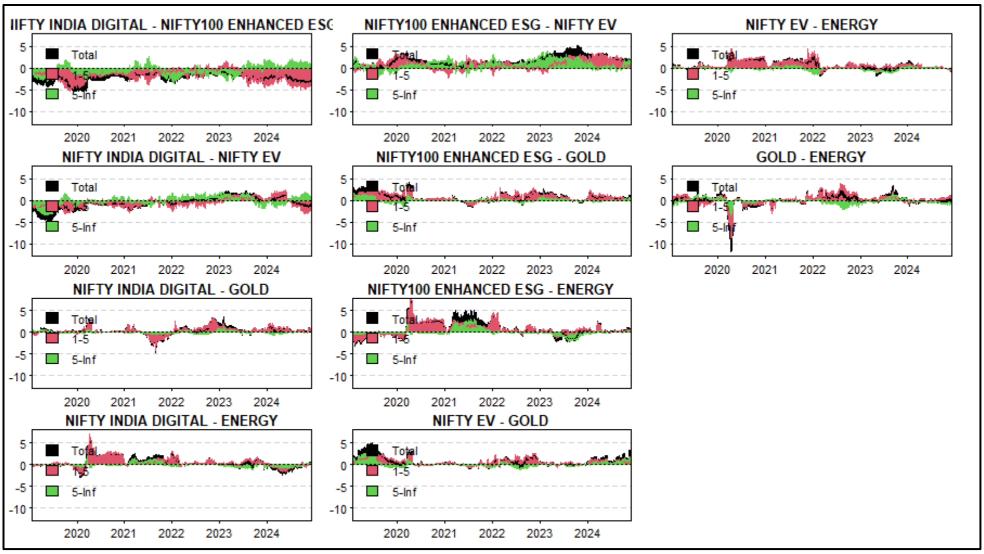

**Figure 5. Net-Pairwise Connectedness**

Figure 5 illustrates the connectedness between asset pairs and uncovers distinct bilateral dynamics not evident in system-wide connectedness measures. Notably, the Digital-ESG and ESG-EV pairs show strong short-term volatility transmissions during 2020-2021 and 2022-2023, reinforcing their tight coupling during high-sentiment or regulatory shocks. On the other hand, Gold-Digital, Energy-EV, and Gold-Energy pairs display subdued short-run interactions but increasing long-run co-movement post-2023, suggestive of emerging strategic or macroeconomic linkages. A particularly interesting observation is the persistent unidirectional volatility flow from Nifty100 Enhanced ESG to Digital and EV indices, underscoring the ESG index's centrality in transmitting broader market shocks. Furthermore, the Gold-Energy pair exhibits an inversion pattern, where Gold transitions from being a shock absorber to a mild transmitter during commodity-led inflation cycles post-2022. This dynamic has not been captured in earlier system-wide connectedness results, highlighting the granular value of pairwise decomposition. Finally, the visible decline in short-term pairwise connectedness across several equity-commodity pairs post-2023 indicates a reduction in reactive volatility and a possible movement toward more stable inter-asset relationships. The long-run connectedness lines show relatively greater persistence, particularly among ESG-commodity pairs, implying growing strategic integration between sustainability-linked financial segments

Table 4 reports the directional connectedness estimates across total, short-term, and long-term horizons. This breakdown helps explain how different indices transmit and receive volatility over varying time scales. In the total connectedness panel, the Nifty100 Enhanced ESG index emerges as the most dominant transmitter (TO = 63.84), with the highest Net value (+6), confirming its central role in spreading shocks. In contrast, Gold (Net = –2.03) and Energy (Net = –2.11) are the strongest receivers, acting as buffers within the system. The Nifty EV index shows a balanced profile (Net = +0.34), reflecting its dual role as both a transmitter and receiver. We observe that short-term connectedness contributes the most to overall volatility spillovers. Over 80% of each index's own connectedness lies within this horizon, underscoring the influence of high-frequency, event-driven volatility. During this period, Nifty100 Enhanced ESG continues to dominate transmission, while Nifty EV shows a slight positive Net (1.01), suggesting a temporary leadership role in short-run contagion, possibly due to policy shifts or investor sentiment. Over a relatively longer-term horizon, connectedness falls significantly. Most of the volatility is retained within each index (e.g., Gold: 12.5%, Energy: 12.41%), with very little exchanged across others. This reflects structural segmentation and lower contagion over time. Interestingly, while Gold remains a net receiver (Net = –0.28), Energy becomes a mild net transmitter (Net = +0.23), likely tied to persistent commodity trends or transition-related energy policies.

The insights show that ESG and EV indices are central to short-term market contagion, while commodities, especially Gold, provide relative stability. The findings highlight the benefit of frequency-sensitive risk monitoring and support portfolio strategies that differentiate between short- and long-horizon volatility dynamics.

**Table 4: Results from Quantile-Based Time-Frequency Analysis**

| **Total Connectedness** | | | | | | |
|---|---|---|---|---|---|---|
| | Nifty India Digital | Nifty100 Enhanced ESG | Nifty EV | Gold | Energy | FROM |
| Nifty India Digital | 46.2 | 29.25 | 22.62 | 0.64 | 1.28 | 53.8 |
| Nifty100 Enhanced ESG | 26.82 | 42.16 | 28.58 | 1 | 1.44 | 57.84 |
| Nifty EV | 21.91 | 30.45 | 45.11 | 1.23 | 1.29 | 54.89 |
| Gold | 1.07 | 1.83 | 2.05 | 91.94 | 3.11 | 8.06 |
| Energy | 1.79 | 2.31 | 1.98 | 3.16 | 90.76 | 9.24 |
| TO | 51.6 | 63.84 | 55.23 | 6.04 | 7.13 | 183.84 |
| Inc.Own | 97.8 | 106 | 100.34 | 97.97 | 97.89 | cTCI/TCI |
| Net | -2.2 | 6 | 0.34 | -2.03 | -2.11 | 45.96/36.77 |
| **Short-Term Connectedness** | | | | | | |
| | Nifty India Digital | Nifty100 Enhanced ESG | Nifty EV | Gold | Energy | FROM |
| Nifty India Digital | 38.79 | 24.55 | 18.79 | 0.53 | 1.06 | 44.93 |
| Nifty100 Enhanced ESG | 22.52 | 35.25 | 23.85 | 0.79 | 1.17 | 48.33 |
| Nifty EV | 18.11 | 25.02 | 37.26 | 0.99 | 0.97 | 45.09 |
| Gold | 0.94 | 1.6 | 1.7 | 79.44 | 2.59 | 6.83 |
| Energy | 1.6 | 1.99 | 1.77 | 2.78 | 78.35 | 8.14 |
| TO | 43.17 | 53.16 | 46.1 | 5.09 | 5.8 | 153.32 |
| Inc.Own | 81.96 | 88.42 | 83.36 | 84.53 | 84.15 | cTCI/TCI |
| Net | -1.76 | 4.84 | 1.01 | -1.74 | -2.34 | 38.33/30.66 |
| **Long-Term Connectedness** | | | | | | |
| | Nifty India Digital | Nifty100 Enhanced ESG | Nifty EV | Gold | Energy | FROM |
| Nifty India Digital | 7.41 | 4.7 | 3.83 | 0.11 | 0.23 | 8.87 |
| Nifty100 Enhanced ESG | 4.31 | 6.9 | 4.73 | 0.21 | 0.27 | 9.52 |
| Nifty EV | 3.81 | 5.42 | 7.86 | 0.25 | 0.32 | 9.8 |
| Gold | 0.13 | 0.23 | 0.35 | 12.5 | 0.52 | 1.23 |
| Energy | 0.19 | 0.32 | 0.21 | 0.38 | 12.41 | 1.1 |
| TO | 8.43 | 10.68 | 9.13 | 0.95 | 1.33 | 30.52 |
| Inc.Own | 15.84 | 17.58 | 16.98 | 13.45 | 13.75 | cTCI/TCI |
| Net | -0.44 | 1.16 | -0.67 | -0.28 | 0.23 | 7.63/6.10 |

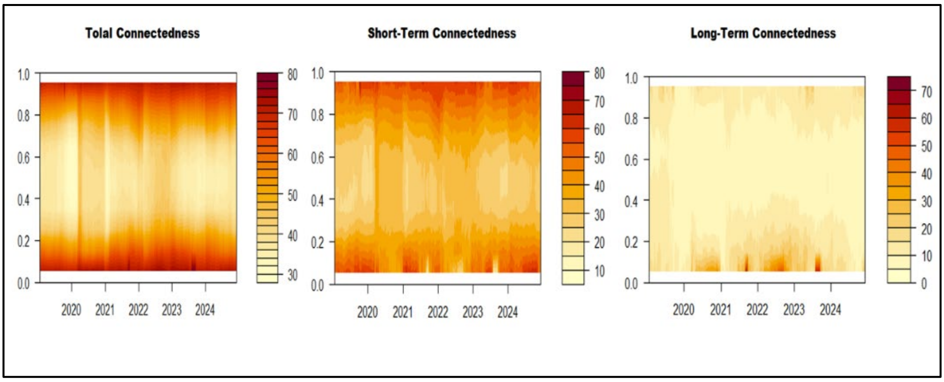


**Figure 6. Total Quantile Connectedness**

Figure 6 presents a 3D plot of TCI segmented into total, short-term, and long-term frequency domains across varying quantile levels (y-axis) and time (x-axis). These visualizations reveal how connectedness dynamics fluctuate not only over time but also across market states, from normal to extreme conditions. The Total Connectedness panel shows visibly higher connectedness across upper quantiles, especially during systemic events such as COVID-19 (2020–2021) and geopolitical conflicts (2022–2023). This indicates that extreme market conditions significantly elevate systemic volatility transmission. The Short-Term Connectedness panel exhibits strong clustering of higher values across most quantiles and time periods, reinforcing the earlier finding that short-horizon spillovers dominate the system. Peaks are most pronounced during stress episodes, highlighting the market's heightened sensitivity to sudden shocks. In contrast, the Long-Term Connectedness panel displays considerably lower values across all quantiles, with only sporadic mild intensification. This suggests that the persistence of volatility shocks is limited, and long-term co-movement among these indices remains weak, supporting the idea that structural or macroeconomic factors exert only a modest influence on sustained volatility spillovers in these markets. Overall, the figure reinforces the asymmetry of volatility transmission: it is more intense during crises, more reactive in the short run, and relatively subdued over the long horizon.

Figures 7, 8 and 9 present 3D plots of net connectedness across time and quantiles. These heatmaps use a red-to-blue colour scale, where warmer tones represent net transmission of volatility (i.e., the index is a source of shocks), and cooler tones signify net reception (i.e., the index absorbs shocks). The vertical axis captures quantiles, enabling a more nuanced understanding of behavior under varying market conditions, from calm (lower quantiles) to extreme stress (upper quantiles). Across all three figures, the Nifty100 Enhanced ESG index consistently emerges as net transmitter of shocks, especially in the upper quantiles, underscoring its vulnerability to and amplification of tail-risk events. This behaviour is particularly pronounced during systemic crises such as the COVID-19 outbreak (2020-2021) and geopolitical conflicts (2022-2023), reinforcing the ESG index's heightened sensitivity to macro shocks and investor sentiment. The Nifty EV index also displays episodes of strong net transmission, most visibly in short-term frequencies and especially under upper quantile conditions, indicative of speculative trading patterns and heightened investor responsiveness to policy or technology-related news. However, the EV index also transitions to a net receiver role at times, suggesting periods of relative passivity or dependency on broader market sentiment. The Nifty India Digital index exhibits the most frequent switching behaviour among all indices. While it generally absorbs shocks under low and median quantiles, it becomes a transmitter during high-volatility conditions, particularly in short-term windows. This pattern implies that Digital assets are reactive under normal markets but may amplify systemic risk during crises due to their tech-sector exposure and momentum-driven investor flows. In contrast, Gold and Energy indices predominantly act as net receivers, especially under lower and mid quantile conditions. Gold displays sustained blue tones across all panels, reinforcing its longstanding status as a safe haven that buffers volatility in periods of market volatility. Energy demonstrates slightly more variability, emerging as a mild transmitter in some high quantile, long-term regions, possibly due to persistent commodity price shocks, inflationary pressures, or policy-driven energy transitions.

Collectively, the time-quantile-frequency decomposition in these figures reveals that connectedness is not uniformly distributed across time, market stress levels, or investment horizons. Equity-linked sustainable indices (ESG, EV, Digital) dominate short-run transmission under high quantile conditions, while commodities continue to anchor portfolios through their shock-absorbing roles. These results support the case for incorporating both horizon and quantile-specific information in asset allocation and risk management strategies.

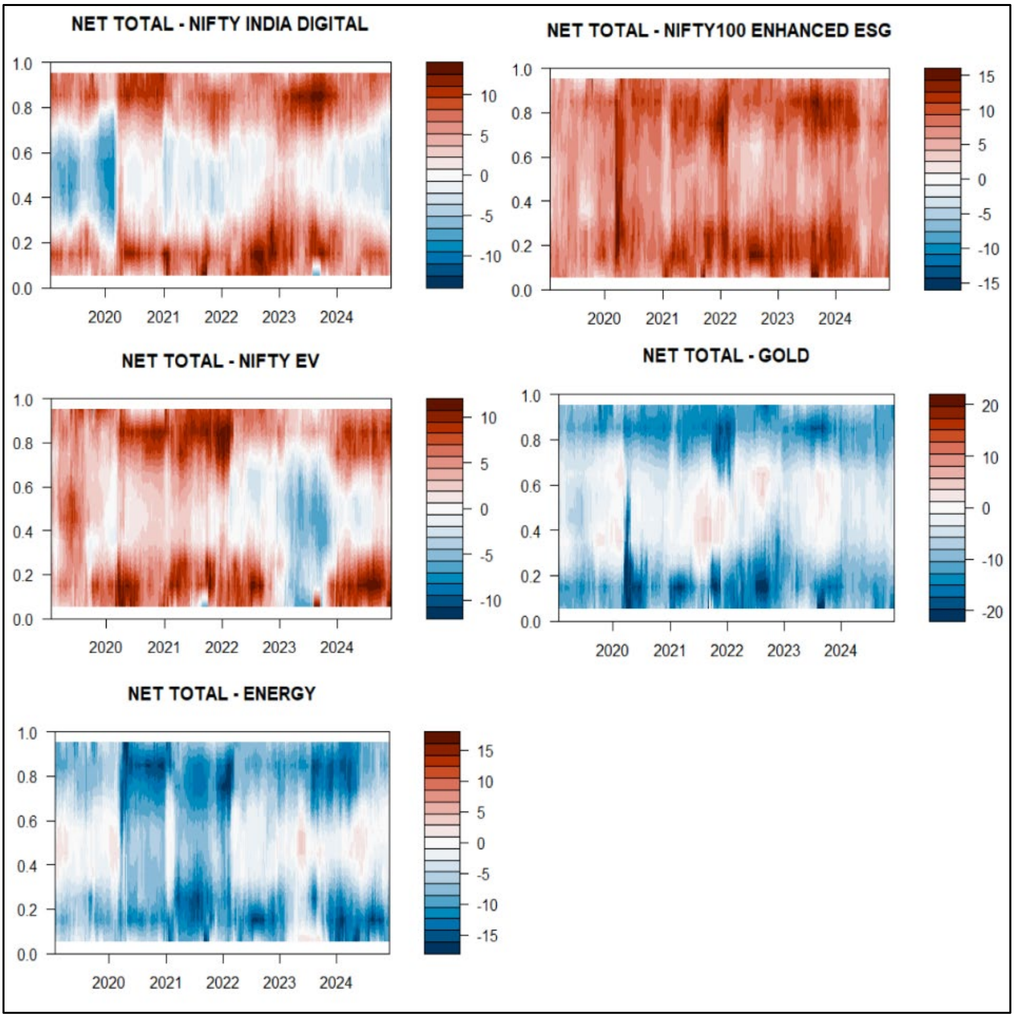


**Figure 7: Total Frequency-Quantile Directional Spillovers**

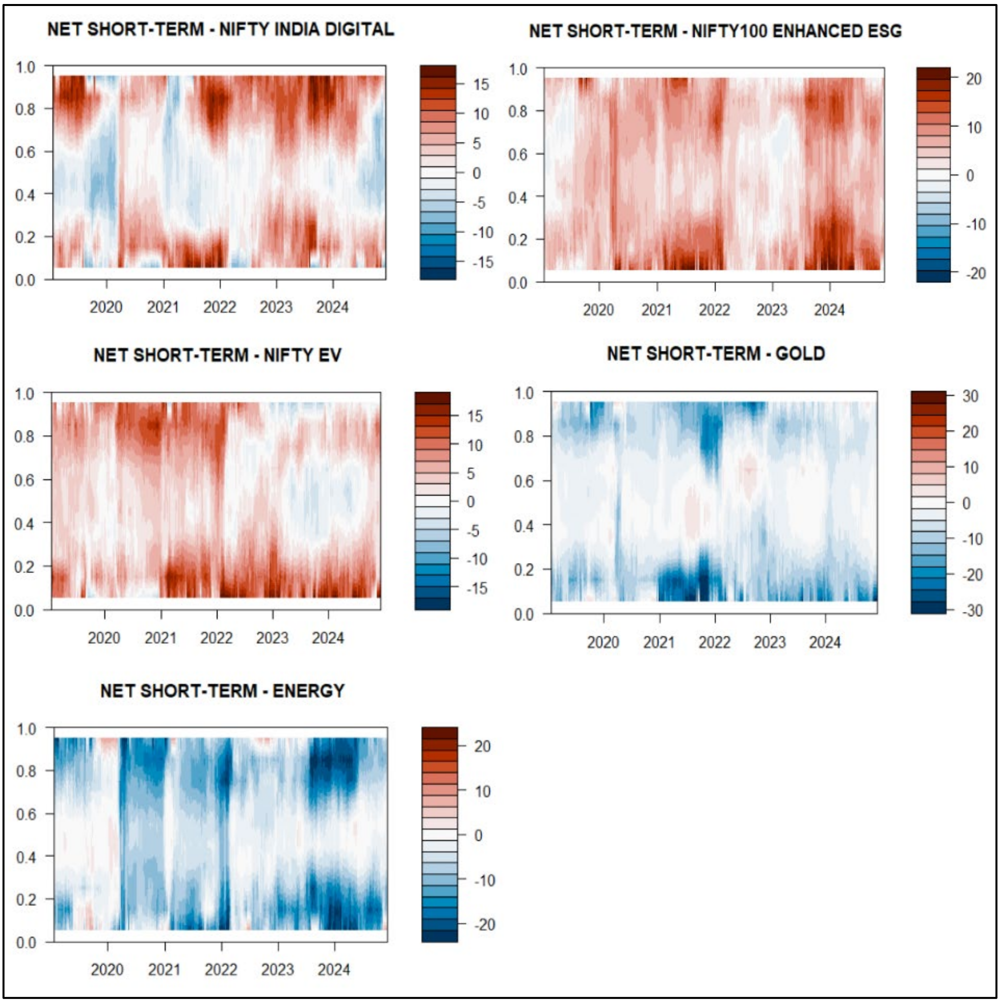


**Figure 8: Short-term Frequency-Quantile Directional Spillovers**

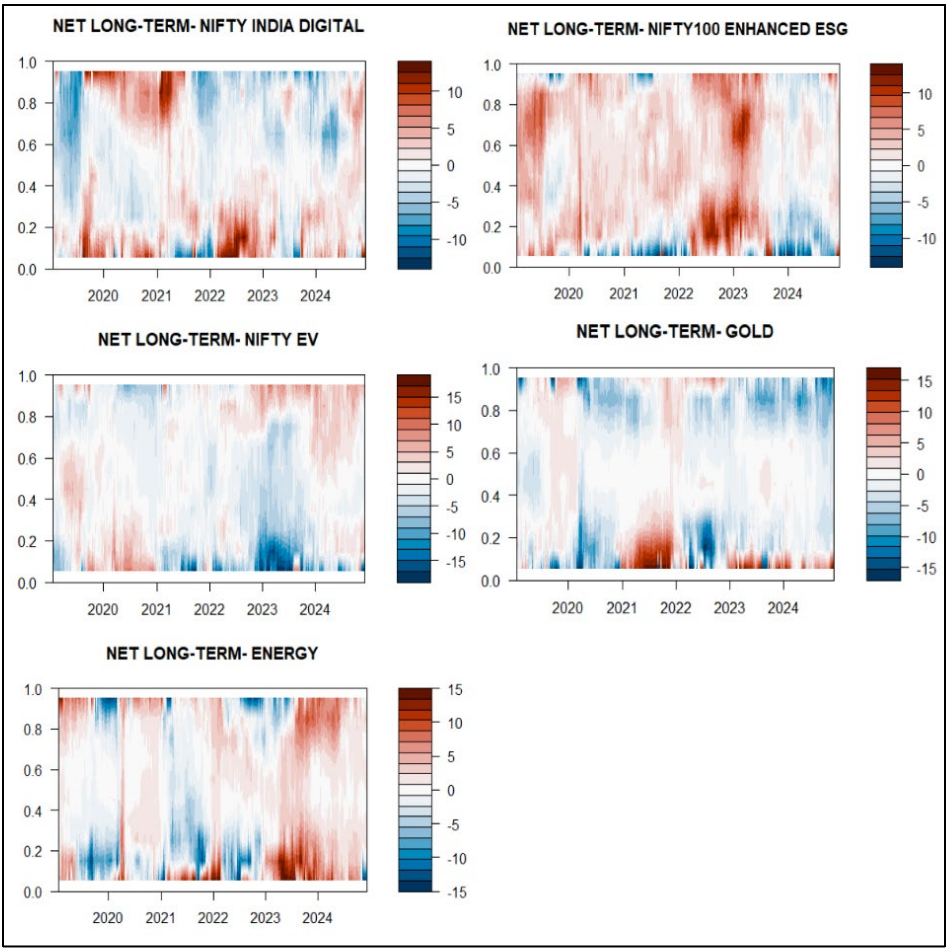


**Figure 9: Long-term Frequency-Quantile Directional Spillovers**

## Portfolio weight and cumulative returns

We present the recommended weight allocation for financial assets derived from three distinct portfolio optimization techniques. The Hedging Effectiveness (HE) measures effectiveness of portfolio allocations in mitigating risk, and the Sharpe Ratio (SR) offers a measure of the return earned per unit of risk, where greater ratios reflect more efficient performance under uncertainty. These metrics, alongside the recommended portfolio weights, offer a comprehensive understanding of each strategy's effectiveness in balancing risk and return.

Table 5 illustrates the weight allocations under the MVP technique, which minimizes overall portfolio variance. The optimal allocation assigns 4% to Digital, 34% to ESG, 6% to E-Vehicles, 52% to Gold, and 3% to Energy. Notably, the highest allocation is directed towards Gold, while the lowest allocations are to Digital and Energy indices. Based on the HE metrics, we observe that this configuration reduces asset-specific volatility by 76% for Digital, 68% for ESG, 75% for E-Vehicles, 46% for Gold, and 94% for Energy. Table 6 focuses on the MCP technique, which minimizes overall correlation among portfolio assets. The recommended allocations are 13% to Digital, 9% to ESG, 17% to E-Vehicles, 33% to Gold, and 28% to Energy. The reductions in asset-specific volatility are 49% for Digital, 32% for ESG, 46% for E-Vehicles, -16% for Gold, and 87% for Energy. The MCP approach continues to prioritize Gold as the largest weight due to its portfolio-stabilizing attributes, though allocations to Digital and Energy indices are notably higher compared to the MVP strategy. Table 7 presents the MCoP approach, which minimizes overall connectedness among assets, addressing systemic risks and contagion effects. This technique recommends allocating 18% to Digital, 5% to ESG, 16% to E-Vehicles, 31% to Gold, and 30% to Energy. The resultant reductions in volatility are 41% for Digital, 22% for ESG, 38% for E-Vehicles, -34% for Gold, and 86% for Energy. Compared to the MCP strategy, MCoP assigns greater weights to Digital and Energy, while Gold remains the dominant asset in terms of allocation.

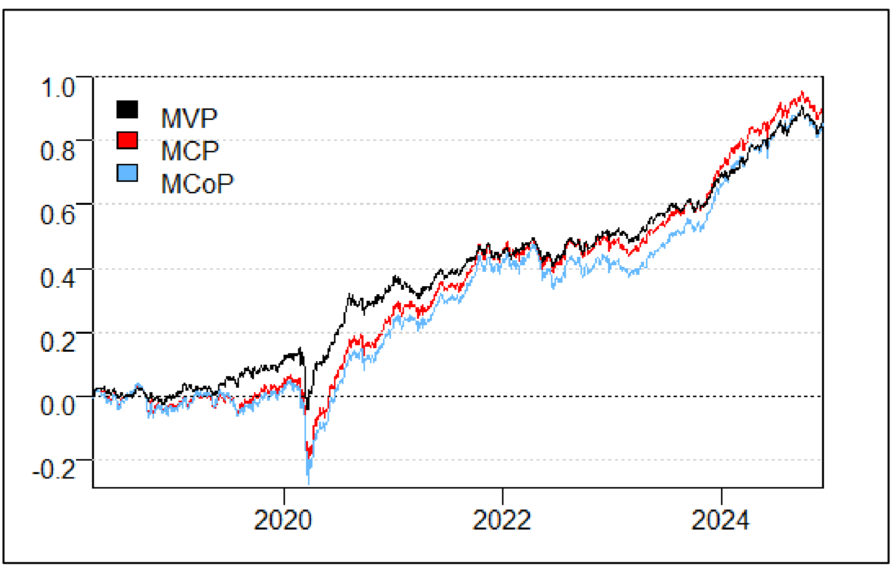


**Figure 10: Dynamic cumulative returns for distinct portfolio techniques**

**Table 5: Asset allocation based on MVP**

| | Mean | Standard Deviation | 5th Percentile | 95th Percentile | HE | SR |
|---|---|---|---|---|---|---|
| **Nifty India Digital** | 0.04 | 0.05 | 0 | 0.1 | 0.76 | 1.3 |
| **Nifty100 Enhanced ESG** | 0.34 | 0.13 | 0 | 0.6 | 0.68 | 1.3 |
| **Nifty EV** | 0.06 | 0.07 | 0 | 0.2 | 0.75 | 1.3 |
| **Gold** | 0.52 | 0.09 | 0.4 | 0.7 | 0.46 | 1.3 |
| **Energy** | 0.03 | 0.03 | 0 | 0.1 | 0.94 | 1.3 |

**Table 6: Asset allocation based on MCP**

| | Mean | Standard Deviation | 5th Percentile | 95th Percentile | HE | SR |
|---|---|---|---|---|---|---|
| **Nifty India Digital** | 0.13 | 0.05 | 0 | 0.2 | 0.49 | 0.5 |
| **Nifty100 Enhanced ESG** | 0.09 | 0.06 | 0 | 0.2 | 0.32 | 0.5 |
| **Nifty EV** | 0.17 | 0.06 | 0.1 | 0.3 | 0.46 | 0.5 |
| **Gold** | 0.33 | 0.02 | 0.3 | 0.4 | -0.2 | 0.5 |
| **Energy** | 0.28 | 0.03 | 0.2 | 0.3 | 0.87 | 0.5 |

**Table 7: Asset allocation based on MCoP**

| | Mean | Standard Deviation | 5th Percentile | 95th Percentile | HE | SR |
|---|---|---|---|---|---|---|
| **Nifty India Digital** | 0.18 | 0.03 | 0.1 | 0.2 | 0.41 | 0.4 |
| **Nifty100 Enhanced ESG** | 0.05 | 0.04 | 0 | 0.1 | 0.22 | 0.4 |
| **Nifty EV** | 0.16 | 0.04 | 0.1 | 0.2 | 0.38 | 0.4 |
| **Gold** | 0.31 | 0.03 | 0.3 | 0.3 | -0.3 | 0.4 |
| **Energy** | 0.3 | 0.02 | 0.3 | 0.3 | 0.86 | 0.4 |

Cumulative portfolio returns based on the three optimization methods are presented in Figure 10. The MVP portfolio consistently outperforms the others in terms of cumulative returns, highlighting its efficacy in balancing risk and return.

# 6. Conclusion

## 6.1 Synthesis of Empirical Contributions

This study provides a comprehensive investigation of volatility spillovers and systemic connectedness among five pivotal Indian indices (Nifty100 Enhanced ESG, Nifty EV & New Age Automotive, Nifty India Digital, Gold, and Energy) using a quantile-based time-frequency connectedness framework. This approach allows for a horizon-sensitive, quantile-specific decomposition of risk flows, critical in today's volatile and policy-influenced financial environment.

The findings reveal that short-run volatility spillovers dominate, with marked surges during crisis events such as the COVID-19 pandemic and geopolitical escalations in 2022–2023. These short-horizon spikes indicate that Indian sustainable and tech-linked assets are highly responsive to global macro and sentiment-driven shocks. In particular, the Nifty100 Enhanced ESG index consistently acts as a transmitter, reflecting its dual exposure to global ESG narratives and domestic policy cues. Its centrality also makes it a leading indicator of sustainability-driven market stress.

Meanwhile, the Nifty EV index exhibits time-variant transmission patterns, acting as a transmitter in the short term, potentially due to speculation and innovation cycles, but gradually transitioning to a net receiver over longer horizons, signalling structural reliance on policy continuity and long-term capital flows. In contrast, the Nifty Digital index functions largely as a volatility absorber, particularly in median and lower quantiles, offering a stabilizing effect in diversified portfolios amid digital sector uncertainty.

The commodity segment continues to fulfil its traditional roles, but with evolving subtleties. Gold is long considered a haven (Baur & Lucey, 2010), and it retains this function across all quantiles and frequencies, especially during systemic stress. Its decoupled behaviour affirms its value in hedging ESG and fintech-linked equity exposures. Energy, on the other hand, displays a temporal duality, absorbing shocks in the short run but progressively emerging as a transmitter in longer horizons. This evolution reflects structural shifts in global energy markets, inflation volatility, and the green transition.

Pairwise spillover analysis further reveals that Nifty100 Enhanced ESG is deeply embedded in the core transmission architecture, exerting significant influence over both EV and Digital indices. These bilateral dynamics highlight the structural interdependence of sustainability themes in Indian equity markets. Notably, post-2023, ESG's linkages with commodity indices deepen, suggesting that green finance flows and transition narratives are now increasingly embedded in real asset pricing and inflation hedges, particularly via green capital flows and climate finance.

From a portfolio optimization perspective, the comparative performance of strategies underscores practical implications. The MVP emphasizes stability through Gold-heavy allocations and delivers the highest cumulative returns with strong hedging performance. The MCP expands exposure to riskier assets but at a cost to Sharpe efficiency. Meanwhile, the MCoP strikes an optimal balance, minimizing systemic exposure while diversifying across ESG, Digital, and traditional assets. This validates the value of connectedness-aware portfolio design, especially in multi-asset, sustainability-aligned investment strategies.

Taken together, these insights carry practical implications for investors, regulators, and policymakers. For asset managers, calibrating exposures by frequency and quantile is essential, leveraging ESG as a systemic signal, Gold as a stabilizer, and Digital as a diversification anchor. For policymakers, tracking ESG-based indices can provide early warnings of latent systemic imbalances, while climate-aligned regulations may influence volatility channels across both financial and real asset classes.

Ultimately, the study contributes a multi-frequency, multi-dimensional perspective to understand the interlinkages across asset classes within India's evolving financial ecosystem. As India steers toward a sustainable and digitally integrated economy, this research offers a forward-looking lens for systemic risk monitoring, intelligent asset allocation, and policy design attuned to time-varying volatility structures. By extending and empirically enriching the frameworks of Chatziantoniou & Gabauer (2021), Marco et al. (2023), and Huang (2021), this work contributes to the evolving literature on volatility transmission, hedge effectiveness, and portfolio resilience in climate-conscious, tech-driven financial systems. Together, the findings of this paper offer valuable insights for investors and policymakers navigating the complexities of climate-aligned, tech-anchored markets, highlighting the importance of frequency-aware portfolio design and volatility-responsive policy formulation in India's evolving financial landscape

## 6.2 Limitations and Future Research Directions

This research fills a gap in literature as it jointly applies quantile and frequency-domain connectedness analysis to sustainability and innovation-linked Indian indices, which remains an underexplored area in systemic risk studies. However, some of the limitations are acknowledged as follows. First, the scope is limited to five Indian indices representing ESG, digital, EV, and commodity sectors. While these capture major structural themes, the selection is not exhaustive. Future research could expand the asset universe by including instruments like green debt or carbon credit indices. Second, the empirical framework is applied solely to the Indian market. Extending the analysis to cross-country or regional comparisons would enhance generalisability and offer comparative insights across developed and emerging markets. Finally, while the quantile time-frequency approach effectively captures non-linear and time-varying spillovers, it does not incorporate exogenous macroeconomic or behavioral drivers. Integrating such factors could provide a more causally robust understanding of volatility transmission.

Despite these limitations, this study contributes novel insights into how volatility transmission varies across states and investment horizons, offering implications for both academics and practitioners in climate-aligned, ESG-driven, and innovation-oriented investment landscapes.

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