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Spillover Dynamics of Sustainability Uncertainty: A Time-Varying Parameter Vector Autoregression Extended Joint Connectedness Analysis of BRIC Economies and the United States

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Abstract: Environmental, Social, and Governance (ESG) factors are increasingly shaping policies, investments, and risk assessments. The paper examines the cross-country spillovers and dynamic interlinkages of sustainability uncertainty between the BRIC economies (Brazil, Russia, India, and China) and the United States (U.S.) using the newly developed ESG-based Sustainability Uncertainty Index (ESGUI). To achieve this, we apply the Time-Varying Parameter Vector Autoregression (TVP-VAR) Extended Joint Connectedness Approach to a dataset spanning from November 2002 to September 2024.Our analysis reveals a moderate level of total connectedness (TCI) over the full sample period, indicating moderate cross-country spillovers. India emerges as the dominant transmitter of sustainability uncertainty, while Russia is the primary recipient of shocks. However, during the COVID and post-COVID period, the TCI increases significantly, reflecting heightened interconnectedness. Notably, India transitions from a major transmitter to a net receiver, while Brazil and Russia take on stronger roles in transmitting shocks. This study contributes novel insights into the time-varying and asymmetric nature of sustainability uncertainty transmission between the BRIC economies and the U.S. The results offer valuable implications for financial regulators, policymakers, and investors, highlighting the need for adaptive risk mitigation strategies and coordinated policy responses to manage systemic sustainability-related risks.

Keywords: ESG-Related Uncertainty Index; TVP-VAR; Extended Connectedness Analysis; BRIC Economies; Policy Uncertainty Spillovers; ESG Risk; Sustainability.

JEL classification: C32; F64; G15; Q56.

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1. INTRODUCTION

Environmental, Social, and Governance (ESG) factors have become central to the formulation of public policy, corporate strategy, and investment decision-making (Ellili, 2024). As global economies become increasingly interdependent (Kayani *et al.*, 2024), the transmission of sustainability-related shocks across countries (economies) has emerged as a critical concern for financial stability and policy coordination. Recent global disruptions ranging from the COVID-19 pandemic to ongoing geopolitical conflicts in Ukraine, Palestine, and the Middle East, coupled with intensifying climate risks have exposed the systemic, uncertain, and interconnected nature of sustainability challenges. These developments underscore the urgency of building adaptive economic systems that integrate ESG considerations to bolster resilience (Segovia-Vargas and Camacho-Miñano, 2024).

Ongan *et al.* (2025) introduced the ESG-based sustainability uncertainty index (ESGUI), a novel measure that quantifies sustainability-related risk dynamics across 25 developed and emerging economies. By leveraging textual analysis, the ESGUI captures the evolving landscape of ESG risks and regulatory developments, making it a valuable tool for policymakers, investors, and researchers. While the literature on economic policy uncertainty (EPU) and its cross-country spillovers is well-developed (Antonakakis *et al.*, 2018; Guo *et al.*, 2022; Guo *et al.*, 2025), empirical investigation into the interconnectedness of sustainability uncertainty invites attention. This study addresses this research gap by examining the interconnectedness and spillover dynamics of sustainability uncertainty (ESGUI) among the BRIC economies (Brazil, Russia, India, and China) and the United States (U.S.), the world's largest economy and a key player in ESG initiatives. Given their economic scale, resource endowments, and geopolitical significance, these economies play a crucial role in global financial markets, trade flows, and ESG policymaking (Balcilar *et al.*, 2018). Each of these economies presents distinct sustainability risks. Brazil faces sustainability concerns related to deforestation, political uncertainty in environmental governance, and resource overexploitation. Russia's sustainability risks stem from its fossil fuel dependency, exposure to climate change, and geopolitical instability. India confronts severe sustainability challenges, including extreme climate conditions, clean energy transition, and high pollution levels. China, despite being a global leader in renewable energy investments, remains heavily reliant on coal and faces significant environmental costs from industrialization and resource extraction. Meanwhile, the U.S. leads in clean energy innovation but grapples with policy inconsistencies, ongoing fossil fuel dependence, and increasing climate-related disasters. Sustainability uncertainty in these economies can generate spillover effects through trade linkages, capital markets, and policy coordination mechanisms (Huang and Li, 2024).

This study employs the Time-Varying Parameter Vector Autoregression (TVP-VAR) Extended Joint Connectedness Approach (Balcilar *et al.*, 2021) to quantify ESG uncertainty interdependencies among the BRIC economies and the U.S. using data from November 2002 to September 2024. Unlike static models, the TVP-VAR framework allows for time-varying coefficients, enabling the identification of evolving patterns in sustainability uncertainty spillovers over time. Leveraging the newly developed ESGUI, the paper provides a novel perspective by quantifying cross-country uncertainty spillovers from ESG dimensions. Focussing on the BRIC economies and the U.S. representing major emerging markets and a global financial leader, the paper underlines the importance of monitoring and managing sustainability risks in countries that have significant influence on the global economy and environmental outcomes. By identifying the primary transmitters and receivers of sustainability uncertainty, the study offers actionable insights for investors, policymakers, and regulators seeking to mitigate systemic ESG risks. The findings also have broader implications for multilateral institutions such as the IMF, World Bank, and United Nations, which can leverage these insights to foster coordinated international efforts, promote global financial stability, and support the design of cooperative sustainability policies across nations.

The remainder of this paper is structured as follows: Section 2 reviews the relevant literature. Section 3 presents the data and methodology. Section 4 discusses the empirical findings. Section 5 provides concluding remarks.

2. LITERATURE REVIEW

The extensive research on EPU spillovers provides valuable methodologies, such as vector autoregressions, spillover indices, and network analysis, that can be adapted and extended to explore the complex phenomenon of sustainability uncertainty spillovers, where ESG-related risks act as sources and channels of uncertainty. This foundation is invaluable for advancing research into sustainability uncertainty spillovers, which similarly require accounting for complex interdependencies and evolving transmission channels in an increasingly interconnected global economy.

Sum (2013) uncovered a persistent and bidirectional long-term relationship between U.S. and European economic policy uncertainty (EPU), illustrating that uncertainty shocks can flow in both directions across these major economies. Colombo (2013) corroborated this interdependence, demonstrating through a Structural Vector Autoregression (SVAR) framework that the Euro area is particularly vulnerable to changes in U.S. economic policy, underscoring the region's sensitivity to external policy signals. Extending this perspective, Klößner and Sekkel (2014) explored policy uncertainty spillovers among six advanced economies, finding that more than one-quarter of domestic EPU can be traced to international sources, a share that escalated to around 50% amid financial crises, when global interconnectedness intensifies. Balli *et al.* (2017) introduced further nuance by highlighting that the transmission of policy uncertainty is significantly mediated by the strength of economic linkages, such as trade openness and institutional quality, which shape both the intensity and pathways of spillovers. In the context of emerging markets, Bhattarai *et al.* (2020) documented that policy uncertainty exerts substantial impacts on key financial indicators including stock prices, exchange rates, and capital inflows demonstrating that these effects are not confined to advanced economies. Methodologically, Antonakakis *et al.* (2018) utilized a time-varying approach to chart the evolving dynamics of uncertainty spillovers, notably identifying the European Union as a primary source of uncertainty shocks affecting the U.S. , a reversal of commonly held assumptions of U.S. dominance. Adding further depth, Gabauer and Gupta (2018) focused on U.S.-Japan dynamics and emphasized the central role of monetary policy uncertainty in facilitating cross-border risk transmission. These studies highlight the multifaceted, evolving, and increasingly global nature of policy uncertainty spillovers, while also pointing toward the importance of economic structure, institutional frameworks, and temporal dynamics in shaping these relationships.

Several studies have also delved into the regional contours of policy uncertainty spillovers, broadening the evidence base beyond advanced economies. For instance, Çekin *et al.* (2020) identified strong interdependencies in policy uncertainty among major Latin American economies including Brazil, Chile, Colombia, and Mexico with these linkages being particularly pronounced in the years leading up to the Global Financial Crisis. Complementing this regional focus, Trung (2019) employed a Global VAR (GVAR) model to demonstrate that U.S. policy uncertainty has far-reaching disruptive effects on international trade and financial markets, reinforcing the centrality of the U.S. in global uncertainty transmission. Bai *et al.* (2019) further highlighted that the intensity of uncertainty spillovers escalates notably during episodes of financial turmoil, contributing to heightened market instability. In the Asia-Pacific context, Tang *et al.* (2021) and Osei *et al.* (2021) documented robust channels of uncertainty transmission among key regional players including China, India, Japan, and Korea suggesting that regional economic integration increases susceptibility to cross-border shocks. Adding another perspective, Abakah *et al.* (2021) showed that the transmission of policy uncertainty is often driven by country-specific factors rather than broad global trends, underscoring the significance of local context and highlighting the need for targeted, rather than universal, policy responses. These studies demonstrate that policy uncertainty spillovers exhibit considerable heterogeneity across regions, vary significantly in intensity and timing, and are shaped by both local dynamics and the broader global environment.

The COVID-19 pandemic further intensified the dynamics of uncertainty spillovers, as documented in several recent studies. Zhou *et al.* (2022) employed the spillover index approach to demonstrate that pandemic-related restrictions sharply increased cross-border uncertainty transmission, underscoring how global crises can amplify systemic risks. Ouyang *et al.* (2022) provided evidence that surges in U.S. monetary policy uncertainty during the pandemic significantly elevated systemic financial risks in China, highlighting the heightened vulnerability of emerging markets to external shocks in turbulent periods. Expanding on these findings, Guo *et al.* (2022) investigated cross-category spillovers between U.S. and Chinese policy uncertainties and uncovered that these transmission effects are distinctly time-dependent, suggesting that the direction and strength of spillovers fluctuate with evolving crisis conditions. Complementing these perspectives, Huang and Li (2024) used spatial econometric techniques to pinpoint trade, investment, and fiscal policy as the primary channels of uncertainty transmission, with financial investment particularly pronounced as a conduit during the pandemic. These studies illustrate that the COVID-19 shock not only intensified uncertainty spillovers across borders and policy domains but also reshaped the mechanisms and timing of transmission, emphasizing the need for robust, adaptive policy coordination in the face of global disruptions.

Recent studies employing advanced network analysis techniques have deepened the understanding of policy uncertainty (EPU) spillover dynamics, particularly among major economies and emerging markets. Cho *et al.* (2023) identify the U.S. and Europe as principal transmitters of EPU, with China notably emerging as a key player in transmitting policy uncertainty in the post-2020 period. This suggests a shifting geopolitical economic landscape where China plays an increasingly influential role in uncertainty propagation. Alkan *et al.* (2023) analyse contagion effects across 21 economies, confirming that the U.S., U.K., France, and Germany are primary sources of policy uncertainty spillovers. Their findings also highlight the high vulnerability of Greece and the U.K., illustrating that exposure to these shocks can differ significantly among countries. Guo *et al.* (2025) focus on spillovers between the U.S. and BRIC countries, reaffirming the strong and persistent influence of U.S. policy uncertainty on emerging market economies across various time horizons. This aligns with broader themes of U.S. monetary and fiscal policy acting as key global uncertainty drivers. Sikhwal (2024) quantifies the macroeconomic consequences of U.S. policy uncertainty on 39 emerging markets, documenting significant adverse effects on inflation rates and GDP growth, which underscores the real economy impacts beyond financial markets. Using monthly data from 2003 to 2023 and the Diebold and Yılmaz (2012) spillover index framework, Kayani *et al.* (2024) investigate the BRIC economies, finding China experiences the highest directional spillovers, making it the dominant uncertainty transmitter within the group. Brazil appears the least affected, reflecting heterogeneity within emerging markets. Adjei *et al.* (2025) extend the analysis to six emerging markets, identifying Korea as a central transmitter of EPU spillovers. They also detect strong short-term links between policy uncertainty, GDP fluctuations, and stock prices, highlighting the tight coupling between economic fundamentals and uncertainty in these economies.

These findings emphasize the importance of dynamic, regionally nuanced policy frameworks, enhanced surveillance of uncertainty transmission channels, and coordination among both advanced and emerging economies to buffer against systemic risks intensified by global policy uncertainty. These studies collectively confirm that EPU propagates through trade, financial markets, and institutional channels, shaping global economic stability. Sustainability uncertainty (ESGUI), driven by ESG factors, is similarly capable of generating cross-border ripple effects, influencing investments, market stability, and long-term growth. However, our understanding of sustainability uncertainty spillovers remains limited. Building on recent advances in understanding the multifaceted and evolving nature of policy uncertainty spillovers, as well as the intensified transmission effects observed during the COVID-19 pandemic, this paper investigates the cross-country spillovers and dynamic interlinkages of sustainability uncertainty among the BRIC economies and the U.S. This study offers novel insights into the evolving transmission mechanisms of ESG-related risks (ESGUI) between major emerging markets and the U.S., informing adaptive risk mitigation strategies and coordinated policy responses to effectively manage systemic sustainability-related risks in an increasingly interconnected and volatile global economy.

3. DATA AND MODEL

3.1. Data

This study employs the Sustainability Uncertainty Index (ESGUI) developed by Ongan *et al.* (2025), sourced from https://www.policyuncertainty.com/sustainability_index.html . The ESGUI dataset provides monthly data from November 2002 to September 2024 for 25 countries, including the BRIC economies and the U.S., capturing fluctuations in environmental, social, and governance (ESG) uncertainty over a 22-year period. By reflecting the impact of major global economic, political, and environmental events, the ESGUI offers a comprehensive measure of sustainability-related risk dynamics across economies.

The full sample period for this study spans from November 2002 to September 2024. To assess the impact of the COVID-19 pandemic and its aftermath, we define the COVID and post-COVID period as beginning in February 2020 and extending through September 2024, based on data availability.

Table no. 1 presents a summary of the ESGUI statistics across the selected economies, based on the first log-differenced series. The table is divided into two parts: Part A, which reports the statistics for the full sample period (November 2002–September 2024), and Part B, which focuses on the COVID and post-COVID period (February 2020–September 2024).

Table no. 1 – Summary Statistics

	Brazil	China	India	Russia	United States
Part A : Full Sample					
Mean	-0.001	0.004	-0.001	-0.005	-0.004
Variance	0.104	0.132	0.096	0.124	0.104
Skewness	-0.312**	-0.705***	-0.554***	0.267*	-0.044
Ex.Kurtosis	2.244***	10.158***	4.443***	3.336***	1.096***
JB	59.433***	1152.644***	229.786***	125.095***	13.244***
ERS	-4.062***	-5.706***	-2.550**	-1.295	-3.615***
Q(10)	82.623***	74.539***	78.154***	164.938***	29.388***
Q^2(10)	131.294***	50.827***	72.768***	145.518***	34.616***
Part B: COVID and Post COVID Sample					
Mean	0.001	0.005	0.007	-0.005	-0.012
Variance	0.015	0.005	0.009	0.011	0.044
Skewness	-0.892***	-0.452	-0.257	-0.286	0.097
Ex.Kurtosis	2.608***	-0.523	0.878	-0.121	1.820**
JB	23.291***	2.548	2.418	0.799	7.818**
ERS	-2.780***	-1.405	-4.974***	-0.549	-3.906***
Q(10)	15.976***	4.133	3.224	6.882	3.6
Q^2(10)	3.559	4.554	2.35	4.053	1.638

Note: ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

The mean ESGUI values near zero across the full sample suggest that sustainability uncertainty fluctuates around a neutral baseline, with no persistent trend for most countries. China's slightly positive mean value indicates a modest upward bias in uncertainty, likely due to evolving environmental policies and regulatory scrutiny. In contrast, Russia and all other economies show slightly negative means values, reflecting relatively lower or more stable uncertainty. China also exhibits the highest variance, indicating greater fluctuations, followed by Russia, the U.S., and Brazil, while India shows the lowest variability. Negative skewness in Brazil, China, and India implies more extreme negative shocks, whereas Russia shows slight positive skewness and the U.S. has an approximately symmetric distribution. All countries have significantly positive excess kurtosis, signalling fat tails and frequent large swings, with China's extreme kurtosis indicating a highly volatile environment. The Jarque-Bera test (Jarque and Bera, 1980) strongly rejects the assumption of normality for all countries at the 1% significance level, indicating notable deviations in both skewness and kurtosis. The Elliott-Rothenberg-Stock (ERS) stationarity test (Elliott *et al.*, 1996) indicates that the series is stationary for Brazil, China, India, and the U.S., but not for Russia. The weighted portmanteau tests (Fisher and Gallagher, 2012) reveal significant autocorrelation and volatility clustering in returns and squared returns [Q(10), Q2(10)] across all countries, reflecting common serial dependence and conditional heteroskedasticity in economic time series.

During the COVID and post-COVID period, notable shifts in sustainability uncertainty dynamics are observed with China, India and Brazil experiencing mild increases in uncertainty averages, while the U.S. and Russia show negative average uncertainty but with the U.S. exhibiting more volatile swings (high variance). This suggests the pandemic altered uncertainty dynamics, intensifying volatility especially in the U.S. The extreme negative skewness and fat tails seen in the full sample soften during the COVID and post-COVID sample except in Brazil and U.S. (pronounced tail risk). Stationarity properties remain largely stable. Serial dependence and volatility clustering weaken considerably during the COVID and post-COVID sample. These diagnostics justify the choice of flexible and dynamic frameworks such as TVP-VAR models that can adapt to evolving relationships, non-normal errors, and evolving statistical properties in the data.

The Figure no. 1 provides key insights into the evolution of sustainability uncertainty (ESGUI) across the BRIC economies and the U.S. during the full sample period.

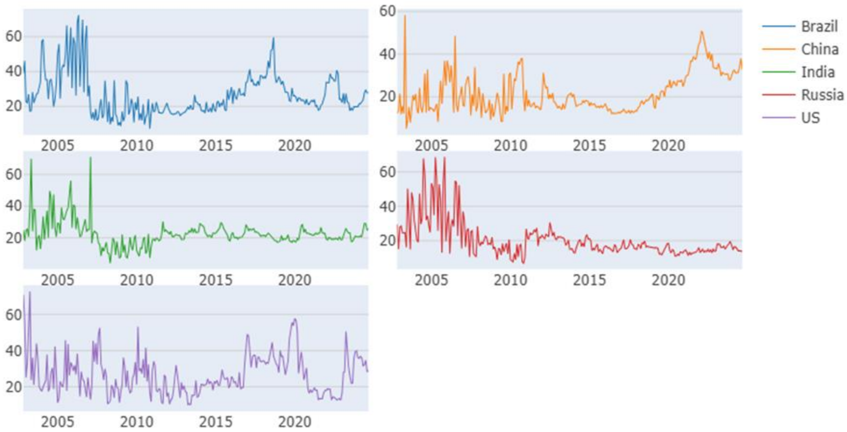

Figure no. 1 – Evolution of Sustainability Uncertainty (Full Sample)

3.2. Methodology

We analyse ESGUI spillover dynamics using the Extended Joint Connectedness measure within a TVP-VAR framework, following the methodology of Balcilar *et al.* (2021). This method builds on the connectedness framework introduced by Diebold and Yılmaz (2012), which is extensively applied in financial and macroeconomic spillover analysis.

In this study, we use a model with a lag order of one, determined by the Bayesian Information Criterion (BIC), as outlined below:

$$\mathrm{y_t} = \mathrm{M_t y_{t-1}} + \epsilon_t, \epsilon_t \sim N(0, \Sigma_t) \tag{1}$$

$$vec(M_t) = vec(M_{t-1}) + u_{t,} u_t \sim N(0, R_t) \tag{2}$$

In this model, y_t, y_{t-1} and ϵ_t are $Z \times 1$ dimensional vectors, while M_t and Σ_t are $Z \times Z$ dimensional matrices. The vectorized form of M_t, denoted as vec(M_t) along with u_t, are $Z^2 \times 1$ dimensional vectors, whereas R_t is a $Z^2 \times Z^2$ dimensional matrix. This framework allows all parameters, including M_t, and the relationships between successive series to change over time. Additionally, it assumes that the variance-covariance matrices Σ_t and R_t also evolve dynamically over time.

The TVP-VMA (Vector Moving Average) model is obtained as the moving average representation (Wold representation) of a TVP-VAR model and is defined as follows:

$$y_t = \sum_{h=0}^{\infty} N_{h,t} \epsilon_{t-1}$$

where $N_0 = I_Z$ and ϵ_t denotes a symmetric white noise shock that the $Z \times Z$ time-varying covariance matrix $E(\epsilon_t \epsilon_t') = \Sigma_t$ varies with time. The TVP-VMA representation is a natural extension of the TVP-VAR model that improves our ability to analyse dynamic spillovers. By transforming the autoregressive system into a moving average representation, the model provides a clearer interpretation of how shocks propagate across variables over time, facilitates the computation of connectedness measures, and enhances its applicability for spillover analysis.

$$g\,ST_{ij,t} = \frac{\varphi_{ij,t}^{gen}(L)}{\sum_{j=1}^{L} \varphi_{ij,t}^{gen}(L)} \tag{3}$$

Here, e represents a Z×1 zero selection vector with a value of one at its ith position. Additionally, $\varphi_{ij,t}^{gen}(L)$ denotes the proportional decrease in the prediction error variance of variable i when accounting for future shocks from variable j. The $\sum_{j=1}^{Z} \varphi_{ij,t}^{gen}(L) \neq 1$ is adjusted to ensure a total value of 1, resulting in the final value of $gST_{ij,t}$ and given as follows:

$$X_{i\leftarrow\bullet,t}^{gen,from} = \sum_{j=1, i\neq j}^{Z} g\ ST_{ij,t} \tag{4}$$

$$X_{i\rightarrow\bullet,t}^{gen,to} = \sum_{j=1, i\neq j}^{Z} g\ ST_{ij,t} \tag{5}$$

The net total directional connectedness is expressed as: $X_{i,t}^{gen,net} = X_{i\rightarrow\bullet,t}^{gen,to} - X_{i\leftarrow\bullet,t}^{gen,from}$. If $X_{i,t}^{gen,net} < 0$ ($X_{i,t}^{gen,net} > 0$), variable i acts as a net receiver (transmitter) of shocks.

The Total Connectedness Index (TCI) measures the overall level of interdependence within a network of variables. A higher TCI value signifies stronger spillovers, indicating greater transmission of shocks across the system. It is expressed as follows:

$$g\,ST_t = \frac{1}{Z}\sum_{i=1}^{Z} X_{i\leftarrow\bullet,t}^{gen,from} = \frac{1}{Z}\sum_{i=1}^{Z} X_{i\rightarrow\bullet,t}^{gen,to}, \tag{6}$$

where a higher value indicates a greater degree of network spillovers.

Finally, the net pairwise directional spillovers are expressed as: $X_{i,t}^{gen,net} = gST_{ij,t}^{gen,to} - gST_{ij,t}^{gen,from}$. If $X_{ij,t}^{gen,net} > 0$, this indicates that series i exerts a greater influence on series j.

Building on the methodologies of Lastrapes and Wiesen (2021) and Balcilar *et al.* (2021), and drawing insights from Ha and Nham (2022) and Kayani *et al.* (2024), this study employs the extended joint connectedness technique with additional scaling adjustments to improve accuracy and comparability. These enhancements refine spillover estimates across different time periods and economic conditions, ensuring greater precision and consistency. The method is represented as follows:

$$X_{i,t}^{jnt,net} = X_{i\to\bullet,t}^{jnt,to} - X_{i\leftarrow\bullet,t}^{jnt,from} \quad (7)$$

$$X_{ij,t}^{jnt,net} = gST_{ji,t} - gST_{ij,t} \quad (8)$$

This analysis will help identify which economies act as shock transmitters and which are more vulnerable to receiving shocks over time.

4. DISCUSSION OF RESULTS

4.1. Averaged joint connectedness

Table no. 2 displays the averaged joint connectedness estimates for BRIC and the U.S., illustrating the interconnectedness of these economies. The rows represent each economy's contribution to the forecast error variance of others, while the columns indicate the proportion of a given economy's forecast variance that is influenced by all other economies. This provides insight into the extent of cross-country spillovers and interdependencies.

Table no. 2 – Averaged Joint Connectedness Estimates

Part A: Full Sample						
	Brazil	**China**	**India**	**Russia**	**United States**	**FROM**
Brazil	84.95	1.2	7.69	4.74	1.42	15.05
China	2.36	74.38	10.1	1.3	11.86	25.62
India	10.16	8.92	76.12	1.1	3.69	23.88
Russia	5.54	5.58	6.4	78.55	3.93	21.45
US	2.94	2.31	6.09	3.07	85.58	14.42
TO	21	18.01	30.28	10.22	20.9	TCI
NET	5.95	-7.61	6.41	-11.23	6.48	20.08
Part B: COVID and Post COVID Sample						
	Brazil	**China**	**India**	**Russia**	**United States**	**FROM**
Brazil	73.55	16.53	0.86	7.9	1.15	26.45
China	21.8	54.45	2.09	14.83	6.83	45.55
India	8.4	5.77	68.44	10.12	7.26	31.56
Russia	9.25	3.68	8.85	74.39	3.83	25.61
US	9.01	13.8	1.62	6.33	69.23	30.77
TO	48.47	39.79	13.42	39.18	19.08	TCI
NET	22.02	-5.77	-18.13	13.57	-11.69	31.99

Note: This analysis quantifies sustainability uncertainty spillovers received (FROM), transmitted (TO), and net transmitted (NET) across the Full Sample and COVID and Post-COVID Sample. Spillovers are estimated using a one-lag specification and a 10-month-ahead generalized forecast error variance decomposition (GFEVD). Diagonal elements indicate an economy's own shock-induced uncertainty, while off-diagonal elements capture cross-economy uncertainty spillovers.

In Part A of Table no. 2, which presents the results for the full sample analysis, the TCI of 20.08% suggests that, on average, 20.08% of the forecast error variance within the system is attributable to cross-economy spillovers, while the remaining 79.92% remains idiosyncratic. It suggests that while sustainability risks are still largely rooted in domestic dynamics, international influences play a non-negligible role, especially in globally integrated economies. India emerges as the most significant transmitter of sustainability uncertainty, with a TO value of 30.28, underscoring its pivotal role in propagating shocks across the system. This reflects India's growing prominence in global sustainability discussions stemming from regulatory shifts, energy transition, or environmental challenges and can significantly influence other countries, especially economies with close trade and investment ties. In contrast, Russia is the most prominent net receiver, with a NET value of -11.23, indicating that its sustainability uncertainties are primarily influenced by external factors. This could be attributed to its dependence on global fossil fuel demand and exposure to geopolitical shifts. Similarly, China registers a negative NET value of -7.61, reinforcing its role as a net recipient rather than a key source of spillovers. This suggests that despite its domestic environmental reforms, China remains highly exposed to global ESG policy shifts due to its integration in international supply chains and reliance on external markets for resource security. Conversely, the U.S. (NET = 6.48) and Brazil (NET = 5.95) act as moderate transmitters, albeit to a lesser extent than India, reflecting their roles in shaping sustainability uncertainty. The U.S.'s role may stem from its influence over global ESG regulations, corporate governance norms, and clean tech investment trends, while Brazil's role could be linked to deforestation, agribusiness policy shifts, and environmental governance debates that have global consequences. The FROM values further illustrate the susceptibility of each economy to external uncertainty spillovers. China (25.62), India (23.88), and Russia (21.45) exhibit the highest exposure, highlighting their vulnerability to sustainability-related shocks from other economies. In contrast, the U.S. (14.42) and Brazil (15.05) display lower FROM values, indicating that their sustainability uncertainties are more domestically driven. While the full sample analysis indicates moderate interconnectedness, systemic shocks such as the COVID-19 pandemic and geopolitical conflicts can significantly amplify spillover intensity. Further investigation into the crisis periods is crucial to understanding evolving spillover dynamics (Antonakakis *et al.*, 2020).

Part B of Table no. 2 presents a stark contrast to the full sample period, reflecting heightened interdependence and intensified spillover effects during the COVID and post-COVID period. The TCI has surged from 20.08% to 31.99%, signalling a sharp rise in interconnectedness among the BRIC economies and the U.S. This indicates that sustainability uncertainty has become more globally interconnected, with a larger share of forecast error variance explained by cross-country spillovers. During this period, the U.S. (NET= -11.69), India (NET= -18.13), and China (NET= -5.77) transition into net receivers of sustainability uncertainty, signifying that their risks are increasingly shaped by external factors. This marks a significant shift from the full sample period, where India was the dominant transmitter reflecting its heightened vulnerability to global ESG shocks in the aftermath of COVID-19 and energy market disruptions. This transformation may be due to India's reliance on imported energy, and climate-related vulnerabilities that are exacerbated during systemic stress. For the U.S., this could be linked to domestic policy uncertainty amid shifting federal climate commitments and global supply chain disruptions. For China, increasing ESG scrutiny and exposure to external demand shocks could explain its greater sensitivity to external uncertainty. Conversely, Brazil (NET= 22.02) and Russia (NET= 13.57) emerge as the primary transmitters, reflecting their growing role in propagating sustainability-related shocks across the system. Brazil's expanded environmental degradation and global attention to Amazon deforestation, coupled with Russia's energy-export-centered economy and geopolitical aggression, have created significant outward spillover effects. The reversal of transmitter-receiver roles highlights the asymmetric and dynamic nature of sustainability uncertainty spillovers, underscoring how systemic shocks such as COVID-19 and geopolitical conflicts reshape spillover dynamics. The FROM values further reinforce this shift, with China (45.55), India (31.56), and Russia (25.61) facing the highest exposure to external spillovers. The "FROM" values reveal that China, India, and Russia became highly exposed to external shocks, suggesting these countries were heavily influenced by evolving ESG narratives, capital flows, and international regulatory developments during the crisis. Meanwhile, the U.S. and Brazil despite their transmitter status also experience non-negligible inflows of uncertainty, confirming the bi-directional nature of ESG spillovers. These results illustrate that systemic shocks can reconfigure the global sustainability risk network, turning transmitters into receivers and vice versa. This underscores the need for flexible, adaptive risk governance structures that are sensitive to global developments and capable of responding to rapidly evolving sustainability risks.

Further analysis of the COVID and post-COVID period is essential to understanding the evolving dynamics of spillovers. To this end, we extend our investigation by examining several dynamic measures, including the Dynamic Total Connectedness Index, Net Pairwise Directional Connectedness, Net Total Directional Connectedness, and constructing Network Diagrams illustrating interconnectedness specifically for the COVID and post-COVID period.

4.2. Dynamic total connectedness

Figure no. 2 illustrates the dynamic total connectedness (TCI) of the BRIC economies and the U.S. during the COVID and post-COVID period, providing insight into the time-varying nature of sustainability uncertainty spillovers among these economies.

In early 2020, TCI was relatively low, recorded at 19.57 in February, reflecting modest spillover effects. However, as the COVID-19 pandemic intensified globally, the interconnectedness of sustainability-related uncertainty escalated sharply. The TCI rose to 21.02 in March, surged to 36.55 in April, and peaked at an extraordinary 69.21 in August 2020 indicative of severe cross-country sustainability uncertainty spillovers. This peak corresponds with the height of the pandemic-induced economic and supply chain disruptions, highlighting how systemic global crises amplify interlinkages among national sustainability risks. Following this peak, a gradual normalization is observed. By early 2021, TCI declined and stabilized between 35 and 45, suggesting that although elevated uncertainty persisted, the extreme volatility of the initial pandemic phase had subsided. This stabilization phase signifies adaptive economic responses, effective public health measures, and supportive fiscal and monetary policies that helped economies shift toward a post-pandemic balance. During the mid-to-late 2021 period, the TCI remained within the 30–35 range, indicating moderate and sustained interconnectedness. Throughout 2022, TCI values hovered around 30–32, maintaining a relatively stable but interconnected regime. Notably, the TCI temporarily spiked to 34.65 in November 2022 potentially a reflection of market responses to escalating geopolitical tensions, particularly the Russia-Ukraine conflict and its implications for global energy markets and supply chains. However, by December 2022, TCI dropped again to 29.02, suggesting that policy makers had gradually incorporated such shocks into their risk expectations. From 2023 onwards, a consistent decline in TCI is observed. By May 2023, the TCI had fallen to 22.38 and remained around that level for most of the year. This downward trend persisted into 2024, with values decreasing to 19.51 in August and further to 18.43 in September, returning to pre-pandemic levels. Taken together, the sharp rise and gradual fall in TCI illustrate the dynamic, shock-sensitive nature of sustainability uncertainty. The results reinforce the importance of agile policy responses and the need for global coordination during systemic crises while emphasizing the return to localized sustainability dynamics in more stable periods.

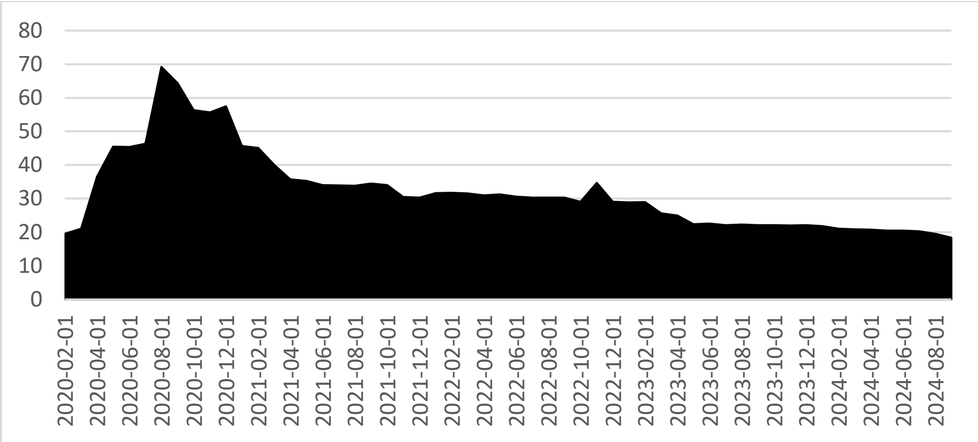

Figure no. 2 – Dynamic Total Connectedness (COVID and Post-COVID Sample)

4.3. Net pairwise directional connectedness

Figure no. 3 illustrates the Net Pairwise Directional Connectedness (NPDC) of sustainability uncertainty of the BRIC economies and the U.S. during the COVID and post-COVID period. It offers a quantitative assessment of spillover effects, identifying whether a country primarily acts as a net transmitter or net receiver of sustainability uncertainty in relation to other economies.

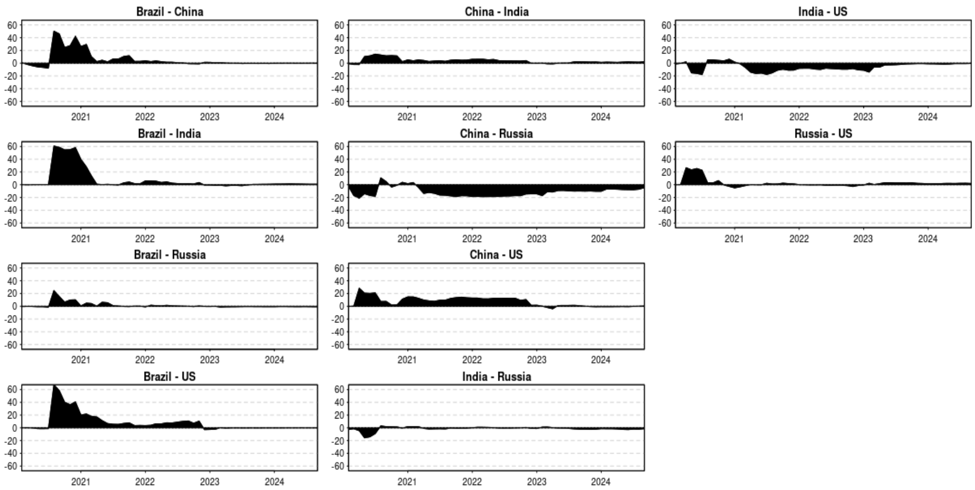

Figure no. 3 – Net Pairwise Directional Connectedness (COVID and Post-COVID Sample)

4.3.1. Brazil's trends

The NPDC values for Brazil-China, Brazil-India, Brazil-Russia, and Brazil-US were relatively low or negative, indicating that Brazil primarily absorbed uncertainty spillovers from these economies. The most significant decline occurred in June and July 2020, with Brazil-China and Brazil-US NPDC values dropping to -6.58 and -1.24, respectively. This period coincided with the initial economic disruptions caused by the COVID-19 pandemic, making Brazil highly vulnerable to external uncertainties.

A dramatic shift was observed in August 2020, when NPDC values surged across all country pairs. Brazil-China reached 50.27, Brazil-India 60.67, Brazil-Russia 24.69, and Brazil-US 67.42. This sharp increase suggests that Brazil transitioned from being a net receiver to a net transmitter of sustainability uncertainty. However, after peaking in late 2020, NPDC values declined and stabilized by mid-2021.

While Brazil maintained a net positive NPDC with India and the US indicating a sustained influence over these economies, its NPDC with Russia fluctuated around zero. The stabilization reflects economic adjustments, policy interventions, and a relative return to pre-pandemic interactions. Throughout 2023, Brazil's NPDC values remained negative or close to zero with China, Russia, and the US, indicating reduced transmission of sustainability uncertainty. Brazil-India NPDC remained slightly positive but at lower levels compared to previous years, ranging between -1.73 and 1.22.

By 2024, Brazil-India NPDC saw a slight resurgence, maintaining positive levels above 1.0. However, Brazil's NPDC with Russia remained negative, suggesting continued absorption of uncertainty from Russia rather than transmitting it. The Brazil-US NPDC fluctuated close to zero, indicating a balanced uncertainty transmission dynamic.

4.3.2. China's trends

In early 2020, China-India NPDC values were negative, suggesting that sustainability uncertainty flowed more from India to China. However, a significant shift occurred in May 2020, when NPDC turned positive and peaked at 14.16 in July, indicating that China became a net transmitter of sustainability uncertainty to India. After some fluctuations, NPDC values stabilized between 3 and 6 from 2021 to mid-2023. Since early 2024, NPDC has remained moderately positive, signifying that China continues to transmit sustainability uncertainty to India, albeit at a lower magnitude than in 2020.

The NPDC values for China-Russia were consistently negative throughout the period, indicating that Russia was the primary transmitter of sustainability uncertainty to China. The largest negative values appeared between April 2020 (-21.08) and March 2023 (-18.79), reflecting Russia's strong influence on China's sustainability uncertainty. However, a decreasing trend in negative NPDC was observed in 2024, with values rising from -10.24 in January to -4.58 in September.

For China-US, NPDC values fluctuated between positive and negative, suggesting bidirectional uncertainty spillovers. In April 2020, NPDC peaked at 28.34, indicating that China was the dominant transmitter of sustainability uncertainty to the US. This trend persisted through May-July 2020. From mid-2021 onward, NPDC remained mostly positive, with values peaking around 14-15 before gradually declining. By 2023-2024, NPDC values turned negative or hovered near zero, suggesting that the US was slightly influencing China's sustainability uncertainty rather than the reverse.

4.3.3. India's trends

India-Russia NPDC values remained predominantly negative, indicating that India was a net receiver of sustainability uncertainty from Russia. The lowest NPDC value was recorded in May 2020 (-15.71), coinciding with global trade and energy market disruptions caused by COVID-19. Brief positive NPDC values appeared in August-October 2020 and early 2022, suggesting temporary periods when India transmitted sustainability uncertainty to Russia. By 2023-2024, NPDC values continued to be negative, fluctuating between -2.68 and -1.30, reflecting persistent but reduced dependence on Russian uncertainty.

Similarly, India-US NPDC values were largely negative, signifying that India received sustainability uncertainty from the U.S. The most significant negative values were recorded in mid-2020 (-16.05 in June) and again in April-May 2021 (-14.09 and -16.21), likely linked to COVID-19's second-wave disruptions and policy uncertainties. From mid-2022 onwards, NPDC stabilized between -10 and -8, indicating sustained but reduced spillovers. However, the trend improved in 2023-2024, with values gradually rising toward zero, suggesting a diminishing dependence on U.S. sustainability uncertainty. Post-2021, NPDC values fluctuated between -2.76 and +3.20, reflecting a time-varying transmission dynamic.

4.3.4. Russia-US trends

The Russia- U.S. NPDC was predominantly positive, indicating that Russia was a net transmitter of sustainability uncertainty to the U.S. A significant spike was observed in April 2020 (26.63), May 2020 (23.25), and June 2020 (25.36), reflecting extreme uncertainty caused by the COVID-19 pandemic and oil market volatility. By 2023-2024, NPDC values hovered around 2, suggesting that Russia continued to exert moderate influence on sustainability uncertainty in the U.S.

4.4. Net total directional connectedness

Figure no. 4 illustrates the Net Total Directional Connectedness (NTDC) of the BRIC economies and the U.S. It provides a comprehensive view of each country's role in transmitting or receiving sustainability uncertainty spillovers. February to May 2020 shows substantial fluctuations, likely due to the COVID-19 pandemic's disruptions. Russia exhibited very high positive NTDC in May 2020, while India had negative values, indicating that Russia was a major transmitter and India a receiver of uncertainty during this period. The U.S., China, and Brazil also showed significant fluctuations, reinforcing the idea of global interconnectedness in sustainability uncertainty. Brazil exhibited a sharp spike in NTDC in August 2020 (203.07) and remained highly positive in the following months. This suggests Brazil transitioned from a net receiver to a dominant transmitter of sustainability-related uncertainty. The increase could be linked to environmental policies, deforestation concerns in the Amazon, and global discussions on climate policy. China's NTDC remains mostly negative throughout the dataset, implying that it consistently absorbs more sustainability uncertainty from the global network than it transmits. This pattern may be attributed to China's economic structure, large industrial emissions, and its role in global supply chains. From mid-2021 onwards, NTDC values stabilize for most countries. While India and China continue to be net receivers of uncertainty, Russia and Brazil maintain their roles as net transmitters. The U.S. exhibits fluctuations between positive and negative NTDC values, suggesting a more dynamic role within the network. Since 2023, the magnitude of these values has noticeably diminished compared to earlier periods. Brazil, which was earlier a major transmitter of uncertainty, shows NTDC values close to zero in the later part of the sample period, suggesting its influence has declined. In contrast, China and India continue to act as net absorbers of uncertainty.

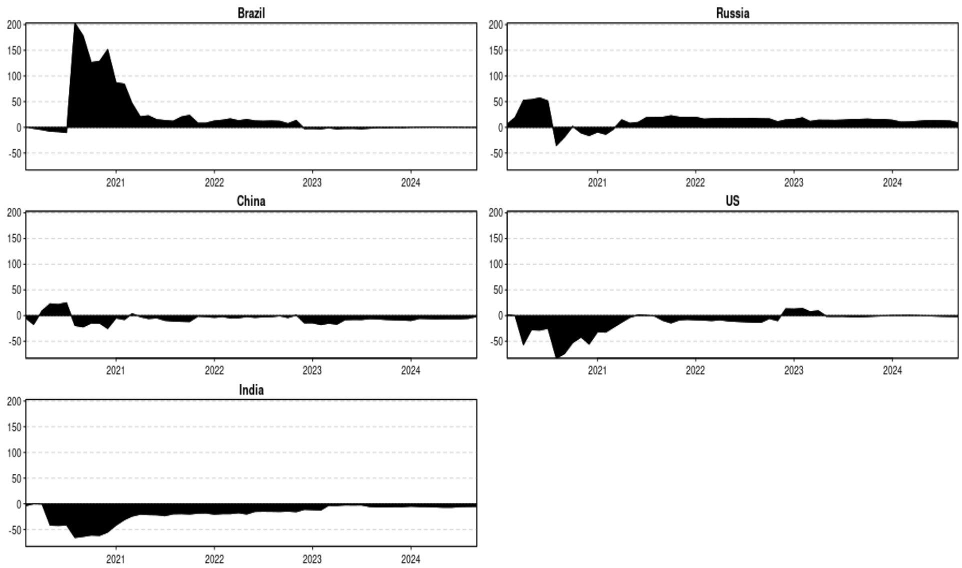

Figure no. 4 – Net Total Directional Connectedness (COVID and Post-COVID Sample)

4.5. Network diagram

The network diagram as shown in Figure no. 5 illustrates the spillover dynamics of sustainability uncertainty among BRIC economies (Brazil, Russia, India, China) and the U.S. during the COVID and post-COVID period. In this visualization, each node represents a country, while the directed edges (arrows) capture the direction and magnitude of spillover effects indicating the flow of sustainability-related uncertainty from source (transmitter) countries to destination (receiver) countries. The thickness of each edge corresponds to the strength of the spillover, with thicker lines signifying more substantial transmission. Node colours are used to distinguish roles within the network: blue nodes represent net transmitters of sustainability shocks, whereas yellow nodes indicate net recipients. The relative size of each node reflects its systemic importance, with larger nodes signifying higher levels of transmission or reception of uncertainty. This network structure allows for a clear visualization of the interdependencies and asymmetries in the propagation of sustainability risks, offering insight into which countries act as dominant influencers or vulnerable receivers within the global sustainability uncertainty framework.

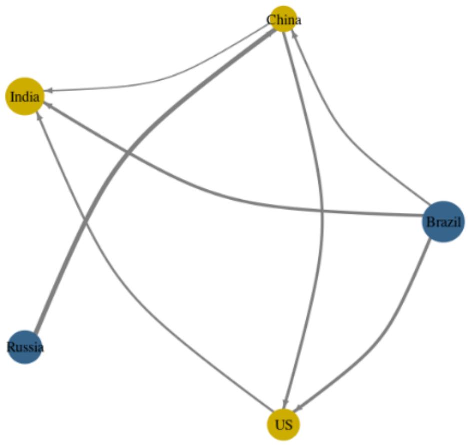

Figure no. 5 – Network Diagram (COVID and Post-COVID Sample)

5. CONCLUSION

This study applies a TVP-VAR extended joint connectedness framework to examine sustainability uncertainty spillovers among BRIC economies and the U.S. The TCI of 20.08 in the full sample period suggests moderate cross-country spillovers, with India emerging as the dominant transmitter and Russia as the primary receiver. However, during the COVID and post-COVID period, the TCI surged to 31.99, highlighting an increase in interconnectedness. Notably, India transitioned from being a major transmitter to a net receiver of sustainability uncertainty, while Brazil and Russia took on more prominent roles in transmitting shocks. This reversal underscores the asymmetric and dynamic nature of sustainability uncertainty transmission, influenced by external shocks such as the pandemic and geopolitical conflicts. India's transition from a major transmitter to a net receiver of sustainability uncertainty reflects broader global structural shifts shaped by contemporary economic, geopolitical, and environmental dynamics. The COVID-19 pandemic severely disrupted global supply chains and economic stability, heightening India's exposure to external shocks. Simultaneously, geopolitical conflicts in Ukraine, and the Middle East have disrupted energy markets, driving up commodity prices and exacerbating inflationary risks for net energy importers like India. In contrast, Brazil and Russia's increasing roles as transmitters align with their expanding influence in global energy and commodity markets, where supply disruptions directly impact inflation, trade balances, and investment flows across economies. These dynamics underscore the interconnected nature of sustainability uncertainty and the need for enhanced macroprudential regulation, diversification of energy sources, and strengthened regional supply chains to reduce exposure to global sustainability shocks. The time-varying analysis of TCI trends reveals that sustainability uncertainty exhibited extreme volatility during early 2020, peaking at 69.21 in August. Subsequent stabilization in 2021–2022 indicates adaptive policy responses and economic recovery efforts, with a gradual decline in interdependence observed in 2023–2024. The decreasing trend suggests the emergence of more country specific and segmented policy dynamics, potentially driven by localized policy frameworks, diversification of energy sources and supply chains, and reduced systemic contagion. The NPDC analysis further elucidates the shifting transmission dynamics. Brazil, initially a net receiver, became a major transmitter of sustainability uncertainty in mid-2020 before stabilizing in 2023–2024. China and Russia exhibited persistent roles as net receivers, while the U.S. and India transitioned between transmitter and receiver roles. The findings highlight how systemic crises, such as COVID-19, can rapidly alter spillover structures and necessitate flexible risk management strategies. The findings from this study provide crucial insights into the contagion effects of sustainability uncertainty across BRIC economies and the U.S., emphasizing the dynamic and asymmetric nature of uncertainty spillovers.

The evidence underscores the need for coordinated policy responses to mitigate uncertainty spillovers (Tawiah *et al.*, 2021). The surge in interconnectedness of sustainability risks observed during the COVID and post-COVID period amplifies the potential for sustainability-related shocks stemming from environmental degradation, climate change, pandemics, and geopolitical instability to propagate swiftly and asymmetrically across national borders. Such dynamics reinforce the inadequacy of fragmented, nationally confined policy responses and underscore the necessity for coordinated, multilateral action among both developed and emerging economies, especially major actors such as the BRIC nations and the U.S. Our analysis highlights how geopolitical conflicts and supply chain disruptions with their reverberating effects on commodity prices and economic expectations can fundamentally alter spillover directions, as vividly exemplified by India's shift from being a principal transmitter to a net receiver of sustainability uncertainty during the COVID and post-COVID period. This underscores the need for policy frameworks that explicitly integrate geopolitical risk considerations alongside environmental imperatives. In light of the time-varying, nonlinear characteristics of sustainability uncertainty spillovers identified in this study, policymakers are called to move beyond static or reactive governance models. To strengthen both national and global resilience, it's crucial to build real-time risk monitoring systems and stress-test sustainability strategies against potential crisis scenarios. Just as important are greater transparency, better cross-border data-sharing, and flexible institutions that can respond quickly to emerging risks. Given that countries vary in how exposed they are and the roles they play in the system, a dual approach is needed, one that combines country-specific and regionally adapted risk management plans, while keeping national actions aligned with broader international sustainability goals. Alignment with pivotal global initiatives, such as the Paris Agreement and the United Nations Sustainable Development Goals (SDGs), will foster coherence and reinforcement between local and global sustainability ambitions. Only through collective measures can the risks of sustainability uncertainty be effectively mitigated, shielding economies from systemic shocks and steering the world toward a more stable and sustainable developmental trajectory.

This study focuses exclusively on the BRIC economies and the U.S., which, while significant, does not capture the full spectrum of global sustainability uncertainty spillovers. Future research could extend the analysis to additional major economies based on the available dataset (Ongan *et al.*, 2025), providing a more comprehensive understanding of global sustainability risk transmission. Sectoral-level analysis would provide deeper insights into industry-specific vulnerabilities and the differential impact of sustainability risks, enabling more targeted policy interventions (Olalere and Mukuddem-Petersen, 2024). Although this study acknowledges the role of geopolitical events particularly Russia's invasion of Ukraine in shaping sustainability uncertainty spillovers, a more systematic analysis of geopolitical risks, trade tensions, and institutional governance structures could provide deeper insights into the mechanisms driving sustainability risk transmission (Balli *et al.*, 2017; Yang *et al.*, 2022; Urom and Ndubuisi, 2023).

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