European Financial Management

EUROPEAN FINANCIAL MANAGEMENT

ORIGINAL ARTICLE OPEN ACCESS

Transitioning to Sustainability: Dynamic Spillovers Between Sustainability Indices and Chinese Stock Market

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Received: 13 August 2024 | **Revised:** 9 April 2025 | **Accepted:** 14 April 2025

Funding: The authors received no specific funding for this work.

Keywords: Chinese stock market | macro risk factor | sustainability index | tail risk | wavelet quantile correlation

ABSTRACT

This paper investigates the dynamic transition of the Chinese stock market towards a just and sustainable future by examining the tail risk connectedness and frequency-quantile dependence between a series of sustainability indices and Chinese stock market sectors. Employing the novel TVP-VAR-CAViaR connectedness method and the wavelet quantile correlation (WQC) method, we capture the evolving relationship between sustainability factors and market performance. Considering the significant, far-reaching, and lasting effects of such uncertainties on the financial markets, our analysis provides essential guidance for investors and policymakers alike in navigating decisions and crafting regulations.

1 | Introduction

As the second largest globally, the Chinese stock market has expanded substantially in recent decades. It is also the most prominent emerging stock market (Ali et al. 2022). The sector includes multiple industries such as finance, manufacturing, and consumer goods, making it essential to the Chinese financial system. On the one hand, it provides a channel for corporate financing, supporting enterprise development (He et al. 2013); on the other hand, it offers significant investment opportunities for both Chinese and international investors through mechanisms such as the Shanghai and Shenzhen-Hong Kong equity Connect (Allen et al. 2005).

In recent years, the Chinese equity market has been making significant strides towards sustainability, aligning with the global imperative for a just transition. This shift is characterized by the integration of sustainability factors into investment decisions, the development of green financial products, and the implementation of policies supporting sustainable development (Liu et al. 2023). The transition is not merely about environmental considerations but also encompasses social equity and economic resilience, reflecting the multifaceted nature of a just transition (Y. Zhang and Xu 2023). As the market evolves, it faces the challenge of balancing economic growth with sustainability goals, necessitating innovative financial instruments and practices. This transformation of the Chinese equity market presents a unique case study in how emerging markets can navigate the complex landscape of sustainable finance while addressing socioeconomic vulnerabilities and fostering inclusive growth.

Since 2020, the global onslaught of COVID-19 has inflicted unprecedented damage on the world economy, which to this day has not fully recovered. Furthermore, on 24 February 2022, Russia initiated military action against Ukraine, causing severe tremors in the global financial markets. Currently, the global economic recovery continues to face immense challenges. From a Chinese perspective, against the backdrop of both internal economic downturn pressures and external geopolitical conflicts,

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economic growth has noticeably decelerated in recent years (Mertzanis and Tebourbi 2025). The leverage in the Chinese financial sector rapidly expanded, leading to a sustained accumulation of risks in related industries, thereby imposing substantial pressure that could potentially trigger significant financial risks and exacerbate the likelihood of financial risk exposure. Therefore, an examination of tail risks and risk spillovers becomes imperative (Karim et al. 2024; Mertzanis and Tebourbi 2025).

Furthermore, as a potent lever in addressing global climate change, sustainable development investments play a crucial role in mobilizing societal forces, embodying the principles of green development, and propelling sustainable development (Hariram et al. 2023; Hornuf and Yüksel 2024). Academic attention focuses on how to remove the constraints hindering the efficacy of sustainable development investments and better harness the guiding and amplifying effects of green investments (Cumming et al. 2024). This is especially pivotal in the context of intensifying macroeconomic pressures and escalating global uncertainties, making it even more crucial to enhance the quality and effectiveness of promoting sustainable development investments.

Amidst the swift advancements over the previous several decades, the Chinese economy has achieved remarkable feats. However, environmental problems and resource pressures have accompanied this growth. For example, extensive expansion and exploitation of fossil energy resources have led to increasingly prominent environmental pollution and resource scarcity issues (Usman et al. 2022). To promote sustainable economic development, the Chinese authorities have taken a succession of measures, such as issuing the "Outline of National Ecological Civilization Construction" and the "Beautiful China Construction Plan for the New Era", investing in sustainable development areas, especially in new energy vehicles, clean energy, green infrastructure, and ecological restoration (Chen et al. 2017). These policies and measures can enhance the sustainability performance of relevant Chinese companies through policy and finance, improving their value and sustainability capabilities, competitiveness, and positively affecting the Chinese equity market (Hansen et al. 2018). Especially in the financial field, sustainable investment is gradually emerging, and investors are increasingly focusing on integrating sustainability factors into their portfolios to achieve both economic benefits and green sustainable social responsibility (Alda 2021), especially when carbon neutrality is a global goal.

The sustainability index evaluates companies based on sustainability factors (Wang and Li 2023). The green finance index in China has witnessed a swift expansion in recent years, with the government providing support through the establishment of green finance standards and regulatory frameworks, as well as the introduction of financing products like green bonds and green loans to encourage green investment and innovation (Ren et al. 2020). This has led to new financial tools in the Chinese green finance market, including carbon emissions trading and renewable energy securitization. These provide more funding sources for the environmental industry and more green investment opportunities for investors (Jia 2023). Against this backdrop, more and more investors are focusing on the opportunities and challenges of sustainable investment, and the Chinese financial market is gradually integrating sustainability factors (Wang et al. 2022).

Beyond the aforementioned research motivations, this paper also aims to explore the intrinsic connection between the transition to sustainable development and financial market efficiency. As the Chinese market shifts towards sustainability, traditional financial theories must re-examine the relationship between market efficiency and sustainability indicators. The rise of sustainable investment may have altered risk perceptions and behavioural patterns amongst market participants, thereby influencing asset price formation mechanisms and risk spillover pathways. Particularly under conditions of information asymmetry, investors' ability to accurately assess corporate sustainability performance and its impact on financial outcomes has become a key factor affecting market efficiency (Z. Wang et al. 2022).

Chinese sustainability indices and stock market sectors are potentially linked. Specifically, since sustainability indices typically select companies that meet specific environmental, social, and governance standards as constituent stocks, these companies perform well in sustainable development (Sun and Chen 2022). Therefore, investors may be inclined to allocate funds to sustainability indices. Stock market sectors can be affected by the constituent stocks of the index (Consolandi et al. 2009). Furthermore, sustainability factors may affect a company's profitability and volatility, impacting its stock price and consequently affecting the equity market sectors (Moradi et al. 2021).

The Sustainability Index, as a critical metric for assessing the sustainability performance of corporations, has become a focal point of interest amongst global investors and policymakers. Nevertheless, the academic community currently exhibits a gap in dynamic correlation studies between the Chinese sustainability index and various segments of its stock market. This paper unfolds against the backdrop of the following research motivations: First, in recent years, the global surge in extreme events has inflicted significant shocks upon financial markets. Illustrated by the 2015 Chinese equity market turbulence and the COVID-19 crisis in 2020, the market's severe volatility underscored the destructive power of systemic risks. Studies on tail risk correlation offer pivotal insights into the characteristics of financial risks from the perspective of extreme events, bearing critical significance for bolstering contemporary risk management frameworks and ensuring financial stability. Specifically, investigating tail risk correlation enhances our understanding of cross-market risk transmission patterns and mechanisms. For investors, focusing solely on the correlation of asset returns is insufficient during asset allocation and risk management processes. Examining the correlation of tail risks facilitates effective identification, measurement, and control of risks (Kelly and Jiang 2014). For policymakers, the contagion and spillover effects of tail risks across markets serve as a crucial perspective for discerning the mechanisms behind systemic risk formation, offering significant implications for implementing macroprudential management and effective market regulation.

Second, the correlation between assets may exhibit heterogeneous characteristics as market states (e.g., bull or bear

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markets) and investment horizons (e.g., long, medium, or short-term) change. Market participants, such as speculators, value investors, and institutional investors, may expose themselves to potential risk vulnerabilities if they overlook this complex dependency structure (Baruník and Křehlík 2018). Hence, systematically depicting the heterogeneity in asset dependency relationships is vital for a comprehensive understanding and management of financial risks. It is also imperative to acknowledge that given the heterogeneity of effects that extreme shocks or anomalous events have on network connectivity, a reliance solely on the average characteristics of a sample period is insufficient. Therefore, the dynamic evolution of connectivity networks across different periods can more accurately delineate the rules of risk transmission within complex networks compared to relying solely on static average features.

Third, the profound interplay between macroeconomic fundamentals and asset prices exerts a significant influence on financial markets and the broader economic system (Asprem 1989). Clarifying the correlation patterns between the two holds substantial theoretical and practical significance for investors aiming to optimize their portfolios and regulators striving to mitigate risks effectively. Based on these motivations, this article proposes the following research hypotheses for verification: (1) What pattern characteristics does the tail risk correlation between Chinese sustainability index and stock market segments exhibit? Is this correlation influenced by extreme market events? (2) How does the complex dependency structure between the sustainability index and stock market segments differ under various market conditions (bull and bear markets) and investment horizons (long-, medium-, and short-term)? What were the differences in the tail risk spillover patterns of the connectedness network across different periods within the sample? (3) What are the macroeconomic determinants of the tail risk correlation between the sustainability index and stock market segments? How do these factors operate and what mechanisms are involved?

This study aims to enhance our understanding of the complex dynamic evolution and contagion mechanisms between sustainability assets and the tail risks of the Chinese stock market, especially during crisis periods and across different investment durations (frequencies). The methodology employed in this paper boasts the following prominent advantages: (1) This article is the first to check the tail risk spillover effects in sustainability indices and Chinese equity markets using the TVP-VAR-CAViaR connectedness method. On the one hand, the asymmetric slope CAViaR method's advantage lies in its non-distributive approach to directly modelling quantiles as they evolve over time (Engle and Manganelli 2004). Unlike methods that model and estimate the entire return distribution, CAViaR focuses on direct modelling of quantiles (Naeem and Arfaoui 2023), obviating the need for strict prior assumptions about the return distribution (e.g., the normal distribution assumption) like other methods (e.g., CoVAR and DCC-GARCH). Moreover, Monte Carlo simulations have confirmed that CAViaR outperforms most indirect VaR methods when returns exhibit fat-tailed characteristics (Abad et al. 2014). Importantly, CAViaR also reveals asymmetries and nonlinear trends present in the data (Li et al. 2022). On the other hand, the advantage of the TVP-VAR method lies in its robustness to outliers and the flexibility in selecting rolling windows (Zeng et al. 2023). Based on the discussion above, to gain deeper insights into the systemic tail risk transmission mechanisms between the sustainability index and the Chinese stock market, this introduces a novel approach that combines CAViaR techniques with the TVP-VAR-based connectedness method (Chatziantoniou et al. 2022; Lucey and Ren 2023). In summary, the innovative TVP-VAR-CAViaR connectedness method inherits the strengths of different techniques, creating a more capable and broadly applicable econometric framework, especially for financial return data characterized by non-normality, fat tails, and other complex features, providing more robust and reliable statistical inferences. (2) Moreover, this study incorporates the recently developed Wavelet Quantile Correlation (WQC) method (Kumar and Padakandla 2022), marking the first investigation into the complex interplay of quantiles and frequencies between the sustainability index and Chinese equity market applying WQC. The advantage of WQC is that it is a robust and enhanced quantile correlation procedure that, in addition to possessing the benefits of other traditional wavelet coherence methods, explores the dependencies of market portfolios across different time frequencies and quantiles (market conditions). In contrast, existing literature predominantly utilizes the QVAR frequency connectedness method to consider quantile-time frequency relatedness, which often only addresses specific quantile conditions and their complex interplay with frequency (e.g., Zeng et al. 2024). The substantial workload involved hampers a comprehensive overview covering as many quantiles (market conditions) and frequencies as possible. Finally, the study also undertakes supplementary analysis based on rolling window regression, revealing significant asymmetries and time-varying characteristics in the influence of macroeconomic factors like economic policy uncertainty on the tail risk connectedness network. This finding provides important clues for elucidating the internal mechanisms of TCI pattern evolution and highlights the necessity of dynamically monitoring key macroeconomic indicators in risk management practices. Overall, this study broadens our understanding of the risk contagion mechanisms between sustainability assets and the Chinese stock market, and the conclusions drawn have significant implications for optimizing investment portfolio strategies and improving systemic risk prevention systems.

Building on the foregoing discussion, the novel contributions of this study can be summarized as follows: (1) In the existing scholarly landscape, this study stands as a pioneering exploration of the correlation of tail risks between the sustainability index and the stock market in China within the context of carbon neutrality. It addresses a notable void in prior research. (2) By investigating the evolving relationship dynamics between the sustainability index and the stock market across different market conditions and investment periods, this study sheds light on their interplay, offering new perspectives. Simultaneously, on the temporal dimension, we also considered the potential heterogeneous impacts of different crisis periods (e.g., the 2015 Chinese stock market turbulence and the 2020 COVID-19 pandemic) on the connectedness network during the sample period. (3) It assesses how the interconnection of tail risks between the sustainability index and Chinese stock market is influenced by various macroeconomic uncertainties.

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Considering the significant far-reaching and lasting effects of such uncertainties on the financial markets, our analysis provides essential guidance for investors and policymakers alike in navigating decisions and crafting regulations.

Key findings revealed by the study include: (1) Tail risks exhibited significant volatility and an upward trend during crisis periods (e.g., the 2015 Chinese equity market turbulence and the COVID-19 crisis in 2020), with notable increases in the tail risks within the financial sector following the outbreak of the COVID-19 crisis. (2) Empirical analysis indicates that the overall tail connectedness between the Chinese stock market and the sustainability index reached its peak during 2015–2020 but showed a marked decline following the outbreak of COVID-19. (3) The CSI 300 index emerged as the largest contributor to tail risk spillover within the Chinese equity market, whereas the Carbon Efficiency Index played a predominant role in risk spillover within the sustainability indices. In contrast, the Energy sector and Nasdaq OMX green economic index were identified as the segments most severely impacted by shocks within the Chinese stock market and sustainability indices, respectively. (4) Net pairwise spillover analysis demonstrated that the Carbon Efficiency Index and the Sustainable Development Screened Index exerted a positive net spillover effect on the Chinese stock market throughout the sample period, while the Nasdaq OMX green economic index and the CSI Xiangmi Lake Green Finance Index displayed negative net spillover effects. Moreover, the net pairwise spillover network figure revealed that systemic risk reached its lowest level during 2015–2020. (5) WQC empirical results indicate a homogeneity in the wavelet quantile correlation patterns between the sustainability index and Chinese stock market, with cross-frequency correlations often observed at intermediate quantile levels as opposed to extreme quantile levels. Interestingly, long-term frequencies often exhibited a more significant impact than short-term frequencies. (6) Amongst the macroeconomic risk factors examined, the VIX index had the most pronounced effect on the TCI between the sustainability index and Chinese stock market. The insights gained from this study aid investors and policymakers in deepening their understanding of the influence of sustainable development factors on the Chinese equity market, providing practical guidance for portfolio management and volatility control, thereby fostering more sustainable investment decisions.

The structure of the subsequent sections of this document is outlined as follows. Section 2 provides a review of previous literature. The introduction of the data set and the explanation of the methodological approach are provided in Section 3. Section 4 details the empirical research conducted. Finally, the conclusion and discussion of the study's outcomes are shown in Section 5.

2 | Literature Review

This article examines the sustainability index of the Chinese equity market and the extreme correlations and risk spillovers across the Chinese equity market and seven sectors. In this section, we summarize two mainstream areas of literature relevant to our research: first, the correlation between the sustainability index and other assets; and second, the relationship between Chinese stock market sectors and their related assets.

Sustainability factors in finance have gradually gained attention in the academic community as global attention to sustainable development increases. Sustainability factors in the financial market have become a prominent research area. (Dios-Alija et al. 2024) studied sustainability in the equity market by comparing various statistical characteristics between traditional stock indices and recent sustainability markets. (Schaeffer et al. 2012) analyzed the impact of a selected group of oil firms participating in the DJSI World index on their market value. The results showed that only two companies' beta values decreased due to participation in DJSI. The volatility or correlation with oil prices did not change for all companies. Therefore, oil companies taking a proactive environmental stance, such as joining DJSI, still have no positive impact on their stock prices or at least no statistically proven positive impact.

As sustainable investment gains increasing attention, greenwashing has emerged as a significant risk factor affecting market efficiency. Delmas and Burbano (2011) define greenwashing as a corporate behaviour that exaggerates environmental friendliness or sustainability achievements, potentially leading investors to misjudge a company's true sustainability performance. Du (2015) found that greenwashing is more prevalent in market environments lacking effective regulation, thereby weakening the reliability of sustainability indices as indicators of sustainable development. In the context of the Chinese market, greenwashing risks may be more complex due to an evolving regulatory framework and considerable variation in the quality of corporate sustainability disclosures (X. Wang et al. 2025). This information asymmetry may distort the mechanisms of risk transmission between sustainable development assets and traditional markets, thereby influencing overall market risk spillover effects.

Previous studies have explored the relationship between sustainability indices and other assets. (W. Zhang et al. 2022) examined the dynamic relationships amongst sustainability stock indices. They found that carbon emission indices were volatility transmitters, while green bonds were volatility receivers. Generally, dynamic relationships are influenced by international politics, economics, and other events. According to Maraqa and Bein (2020), there are distinct dynamic interrelationships between sustainable development stocks, European importing countries' stock returns, and the oil index. Exporting countries and the oil market have a strong correlation with sustainable development stock indices.

Recent studies have also focused on the transition of equity markets towards sustainability, particularly in emerging markets like China. (Cao et al. 2019) investigated the peer effects of corporate social responsibility (CSR) in China, finding that a firm's CSR performance is positively associated with the CSR performance of its peers. This suggests a diffusion of sustainable practices across the Chinese corporate landscape, which could have significant implications for the equity market. Similarly, (Cheung et al. 2018) examined the relationship between national stakeholder orientation, corporate social responsibility,

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and bank loan costs in China. Their findings indicate that firms with better CSR performance enjoy lower loan costs, highlighting the financial benefits of sustainable practices in the Chinese market.

The Chinese stock market sector has also been studied extensively. Su and Liu (2021) examined the spillover structure of market shocks and the impact of economic policy uncertainty amongst China's top ten industries. They found that the consumer, industrial, and materials industries were essential to the economy during the sample period. (X. Wu et al. 2021) confirmed that Chinese and global economic policy uncertainties significantly negatively impact the long-term volatility of the Chinese stock market. (F. Wu et al. 2019) showed the connections between various industries in the Chinese equity market and studied volatility spillovers. Their empirical findings indicate that the industrial sector plays a core role in the Chinese equity market and should be considered the most critical sector in the system. The risk spillover structure exhibits time-varying characteristics.

Several studies have looked at the connection between the Chinese sustainability index and specific sectors of the stock market. Mensi et al. (2021) discovered return spillovers amongst oil and gold futures and the Chinese equity market. The findings indicated that the industrial and consumer durables sectors were the most significant senders of shocks. The primary materials sector was also a net spillover contributor, while crude oil futures and the remaining industries were net spillover receivers. Dai et al. (2022) conducted an analysis of volatility spillovers and dynamic connections amongst markets in China, including the automobile, technology, new energy, coal, and high-tech industries. Their results showed that all analyzed assets were highly interdependent, and volatility spillovers sharply increased during major crises. Stock markets in all analyzed countries were net systemic shock transmitters on average.

The transition of the Chinese equity market towards sustainability is a complex process that has attracted increasing scholarly attention. This transition is characterized by the integration of sustainability factors into investment decisions, the development of green financial products, and the implementation of policies supporting sustainable development. Liang and Renneboog (2017) conducted a comprehensive study on the foundations of corporate social responsibility, providing insights into how legal origins and political institutions shape CSR practices, which is particularly relevant for understanding the Chinese context. Hu et al. (2021) examined the impact of green credit policy on corporate environmental violations in China. Their findings suggest that the implementation of green credit policies has led to a significant reduction in environmental violations, particularly for firms with high pollution propensity. This demonstrates how policy interventions can drive the transition towards sustainability in the Chinese equity market. X. Chen and Lin (2021) investigated the relationship between corporate social responsibility, social trust, and corporate financial performance in China. They found that CSR positively affects both social trust and financial performance, with social trust partially mediating the relationship between CSR and financial performance. This study highlights the importance of sustainable practices in building trust and enhancing financial performance in the Chinese market context.

From the foregoing, previous studies have summarized the correlations and spillover links between the Green Finance Index and the Chinese equity market sector and other financial markets. They have drawn some interesting conclusions. However, to our knowledge, even though a quantitative connection exists between the Chinese sustainability index and stock market segments, there has been no in-depth research on it. Therefore, this study aims to explore this connectedness and investigate the impact of sustainability factors on the Chinese stock market. It also examines the mechanisms through which the sustainability index transmits volatilities amongst stock market sectors. In summary, this study aims to provide useful references and insights for a better understanding of sustainable development in the Chinese financial asset. It also promotes sustainable investment and enhances market participants' volatility management capabilities.

3 | Methodology and Data

3.1 | Tail Risk Connectedness

3.1.1 | Conditional Autoregressive Value-at-Risk (CAViaR)

To assess the risk of extreme market losses—known as tail risk—we use a method called the CAViaR model, specifically the asymmetric slope (AS) version introduced by (Engle and Manganelli 2004). This model was adapted by (Chatziantoniou et al. 2022) to better capture how financial risks behave under different market conditions.

Unlike traditional models, AS-CAViaR allows the impact of positive and negative market movements to differ. This helps us better understand how financial shocks influence risk.

The basic idea is that today's estimated risk (Value-at-Risk or VaR) depends on yesterday's risk estimate and whether the market moved up or down. This is modelled as:

$$f_{\alpha,t}(\beta) = \beta_0 + \beta_1 f_{\alpha,t-1}(\beta) + \beta_2 x^{+}_{t-1} + \beta_3 x^{-}_{t-1}, \quad (1)$$

where $f_{\alpha,t}$ is today's VaR at a given confidence level α. β_0 is a constant, and β_1 captures the influence of past VaRs. β_2 and β_3 measure the effects of positive and negative market movements, respectively. This allows the model to adjust risk estimates based on how the market behaved the day before.

3.1.2 | Time-Varying Parameter Vector Autoregressive (TVP-VAR) Connectedness

To understand how tail risks spread across markets, we use the TVP-VAR model developed by (Antonakakis et al. 2020). Unlike older models that use fixed windows of data, TVP-VAR updates continuously and automatically, which improves accuracy.

The model looks at how past values of market variables influence their current values, allowing us to track how relationships between markets evolve over time. The general form is:

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$$\begin{aligned} y_t &= \Phi_t z_{t-1} + \epsilon_t \qquad \epsilon_t \mid I_{t-1} \sim N(0, \Sigma_t), \\ \text{vec}(\Phi_t) &= \text{vec}(\Phi_{t-1}) + e_t \qquad e_t \mid I_{t-1} \sim N(0, E_t), \end{aligned} \tag{2}$$

where y_t is a vector of market variables, and z_{t-1} includes their past values. ϵ_t and e_t are error terms that reflect unexpected changes. The model parameters and variances (Φ_t, Σ_t) change over time, which allows the model to stay up to date.

To measure how risks move from one market to another, we use generalized forecast error variance decomposition (GFEVD). This tells us how much of the variation in one market's risk comes from another. The model is converted to a moving average (MA) form:

$$y_t = \sum_{i=1}^{p} \Phi_{i,t} y_{t-i} + \epsilon_t = \sum_{j=0}^{\infty} A_{j,t} \epsilon_{t-j}, \tag{3}$$

$$\phi_{i,j}(H) = \frac{\sigma_{j,j}^{-1} \sum_{h=0}^{H-1} e_{i}' A_h \Sigma e_j^2}{\sum_{h=0}^{H-1} e_{i}' A_h \Sigma A_h' e_i} \tilde{\phi}_{i,j}(H) = \frac{\phi_{i,j}(H)}{\sum_{j=1}^{N} \phi_{i,j}(H)}. \tag{4}$$

Using this, we calculate:

- Total connectedness (TC): Overall spillover of risk across all markets,
- Directional Connectedness (DC): Risk received from or sent to another market, and
- Net Connectedness (NET): Difference between risk transmitted and received.

The connectedness measures are computed as:

$$\text{TC}(H) = \frac{\sum_{i,j=1, i\neq j}^{N} \tilde{\phi}_{i,j}(H)}{N} \times 100, \tag{5}$$

$$\text{DC}_{i\leftarrow j}(H) = \frac{\sum_{j=1, j\neq i}^{N} \tilde{\phi}_{i,j}(H)}{N} \times 100, \tag{6}$$

$$\text{DC}_{i\rightarrow j}(H) = \frac{\sum_{j=1, j\neq i}^{N} \tilde{\phi}_{j,i}(H)}{N} \times 100, \tag{7}$$

$$\text{NET}_i(H) = \text{DC}_{i\rightarrow j}(H) - \text{DC}_{i\leftarrow j}(H). \tag{8}$$

Since the total connectedness can exceed 100%, we use an adjusted version:

$$\frac{\sum_{i,j=1, i\neq j}^{N} \tilde{\phi}_{i,j}(H)}{(N-1)} \times 100. \tag{9}$$

3.2 | Wavelet Quantile Correlation (WQC)

To analyze how two financial variables relate under different market conditions and timescales, we use the WQC method developed by (Kumar and Padakandla 2022). This extends the quantile correlation (QC) technique by combining it with wavelet analysis to examine relationships in more detail.

The method focuses on how variables relate at specific quantiles (e.g., during extreme events) and at different frequencies (short-term vs. long-term). Using wavelets, the data is broken down into components, and the correlation is assessed at each level.

WQC is calculated as:

$$\text{WQC}_\tau[d_j(X) d_j(Y)] = \frac{qcov_\tau(d_j[Y], d_j[X])}{\sqrt{\text{var}(\varphi_\tau(d_j[Y] - Q_{\tau, d_j[Y]})\text{var}(d_j[X])}}, \tag{10}$$

where X is the independent variable and Y is the dependent one. $d_j(X)$ and $d_j(Y)$ are wavelet components at level j. The function φ_τ adjusts the correlation for specific quantiles.

3.3 | Risk Driver Factors of the Tail Risk

To observe the potential risk from external factors influencing the overall tail risk connectedness structure over a period, we adopted the methodology outlined by (Lucey and Ren 2023). Our approach involved a dynamic calculation method utilizing a rolling window spanning 120 days to assess the impact of external drivers on tail risk connectedness. The model can be expressed as follows:

$$\begin{aligned} TC(H) = \beta_0 + \beta_1 VIX_t + \beta_2 OVX_t + \beta_3 EPU_t \\ + \beta_4 USDCNY_t + \beta_5 GPRD_t + \epsilon_i. \end{aligned} \tag{11}$$

In the mentioned equation, *VIX* represents the Chicago Board Options Exchange (CBOE) Volatility Index, *OVX* denotes the Crude Oil Volatility Index, *EPU* stands for the Economic Policy Uncertainty Index, *USDCNY* indicates the exchange rate between the USD and the CNY, and *GPRD* signifies the Geopolitical Risk Index. The raw data were sourced from Datastream and the Economic Policy Uncertainty Index website[1].

3.4 | Data

The data set used in this study comprises daily price data spanning multiple sustainability indices and ten sub-industries of the Chinese equity market, providing a comprehensive perspective in the market's shift towards sustainability. Specifically, we selected the following sustainability indices: CSI Xiangmi Lake Green Finance Index (CNI)[2], Nasdaq OMX Green Economy Index (OMX)[3], S&P China A-Share 300 Sustainable Development Screened Index (SUS), S&P China A-Share Carbon Efficiency Index (CARBON), and CSI 300 Index (CSI). This study employs four sustainable indices that, to a considerable extent, reflect market emphasis on sustainable development assets in the Chinese stock market. This approach accounts for the inherent limitations of relying on a single sustainable index. First, different sustainable indices adopt varying evaluation criteria and weighting schemes, which may result in inconsistent sustainability assessments for the same enterprise. Second, challenges related to data availability and quality persist in sustainability index construction processes. As a result, a single sustainable index may fail to comprehensively and accurately capture a firm's true sustainable development performance, thereby impacting the

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precision of market risk assessments. In summary, the selected indices are intended to capture different dimensions of sustainable development—from green finance to carbon efficiency—highlighting the multifaceted nature of the sustainability transition in the Chinese stock market.

Additionally, we included ten sub-industries of the Chinese stock market: Telecommunications (TELE), Utilities (UTI), Information Technology (INF), Financials (FIN), Healthcare (HC), Consumer Staples (CONS), Consumer Discretionary (CD), Industrials (IND), Energy (ENE), and Materials (MAT). This sub-industry classification system is widely recognized in Chinese equity market research. Price data for SUS and CARBON indices were obtained from the S&P Global Indices website, while CNI index data originated from the Wind database in China, and stock market data came from the DataStream database.

To comprehensively explore market evolution in recent years, the study selected the longest available sample period post-global financial crisis, from 1 March 2014, to 29 February 2024. This period encompassed significant events that shaped the sustainability journey of the Chinese market, including the equity market turbulence in 2015–2016, the US-China trade war, the COVID-19 crisis, and the Russia-Ukraine war in 2022. These events provided critical context for understanding the resilience and adaptability of sustainable investments amidst market shocks.

Daily return data for each variable were computed by taking the natural logarithmic difference of the closing price multiplied by 100. Figure 1 illustrates the time series trend of these converted returns, revealing substantial volatility across all variables during the sample period. Volatility was notably pronounced surrounding major events such as the Chinese equity market turbulence in mid-2015, the market circuit breaker incident in early 2016, and the COVID-19 outbreak in early 2020. These volatility patterns suggest significant impacts on both traditional and sustainability-focused market segments, highlighting the need to investigate the transmission pathways and effects of these events in the market's sustainability transition.

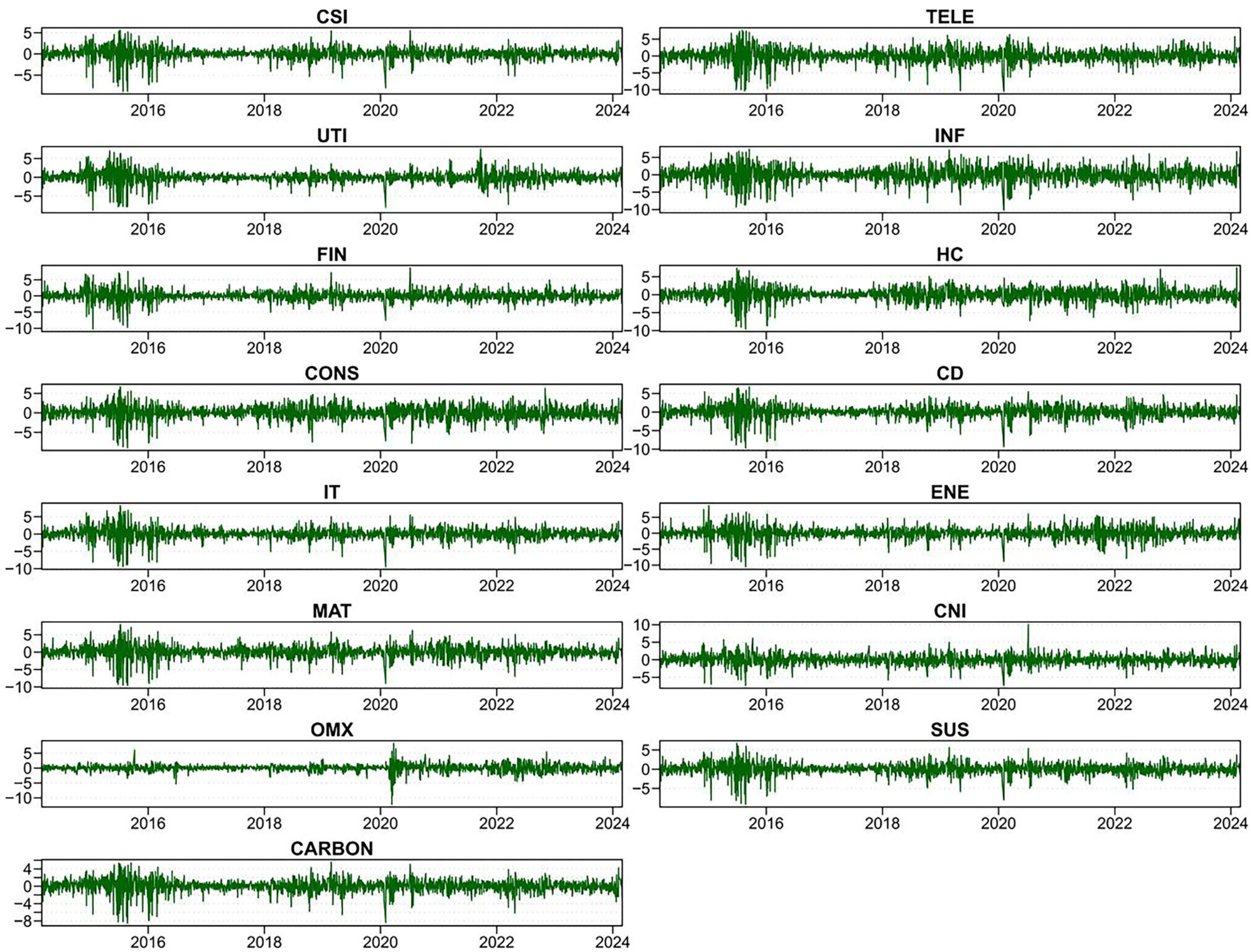

FIGURE 1 | Time-varying return plots of sustainability (CSI Xiangmi Lake Green Finance Index (CNI), Nasdaq OMX Green Economy Index (OMX), S&P China A-Share 300 Sustainable Development Screened Index (SUS), S&P China A-Share Carbon Efficiency Index (CARBON), and CSI 300 Index (CSI)) and stock market subindustry indices (Telecommunications (TELE), Utilities (UTI), Information Technology (INF), Financials (FIN), Health care (HC), Consumer Staples (CONS), Consumer Discretionary (CD), Industrials (IND), Energy (ENE), and Materials (MAT)). Calculated as natural logarithmic differences of closing price. [Color figure can be viewed at wileyonlinelibrary.com]

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TABLE 1 | Summary statistics.

Asset	Mean	Variance	Skewness	Kurtosis	JB	ERS
CSI	0.015	1.711	−1.093	7.739	6545.401***	−11.425***
TELE	0.024	3.773	−0.714	4.189	1982.632***	−6.677***
UTI	0.021	2.125	−0.647	6.760	4793.958***	−5.912***
INF	0.003	4.227	−0.397	2.148	530.556***	−8.850***
FIN	0.021	2.211	−0.148	6.175	3867.329***	−13.631***
HC	0.013	2.796	−0.497	3.541	1369.139***	−12.003***
CONS	0.044	2.683	−0.530	3.084	1076.557***	−6.767***
CD	0.01	2.534	−0.760	4.904	2668.067***	−7.391***
IT	0.016	2.6	−0.614	6.123	3946.905***	−9.718***
ENE	0.017	3.066	−0.547	4.468	2141.198***	−18.674***
MAT	0.018	3.036	−0.754	4.796	2557.980***	−11.070***
CNI	0.009	1.874	−0.114	3.985	1612.821***	−19.821***
OMX	0.031	1.314	−0.780	11.530	13701.041***	−8.656***
SUS	0.023	1.907	−0.790	5.941	3824.340***	−15.151***
CARBON	0.018	1.986	−1.001	5.861	3882.684***	−9.914***

Note: ERS: Elliott et al. (1996)'s unit root check.
***denotes significance at the 1% level.

By examining how sustainability indices and various market sectors respond to and recover from such shocks, this study aims to provide insights into the evolving relationship between sustainability considerations and market dynamics in China.

4 | Results Analysis

4.1 | Descriptive Statistics and Preliminary Tests

In Table 1, summary statistics for various assets are presented. The mean values indicate that CONS exhibited the highest mean amongst all sectors in the Chinese stock market, while OMX displayed a higher average compared to other sustainability indices and the Chinese stock market as a whole. Notably, with the exception of CNI, the sustainability indices generally exhibited higher mean levels compared to the Chinese equity market sectors over the sample period.

Regarding variance, the sustainability indices showed lower volatility compared to the Chinese equity market sectors. Additionally, the return distributions for both Chinese equity market sectors and sustainability indices were left-skewed, with kurtosis values exceeding 3. The Jarque-Bera test results further confirmed that the return distributions for all indices were not normally distributed. However, the results of the ERS test indicated that all series were stationary, suggesting that our transformed data is suitable for subsequent empirical analysis.

We applied the BDS test to detect nonlinear correlations in the return series (Broock et al. 1996). As shown in Table 2, the *P*-values for the return series of all variables were markedly small, well below 0.01. This indicates strong evidence to reject the null hypothesis that these time series are purely random processes. Instead, the results suggest that these time series may exhibit nonlinear dependencies or chaotic characteristics. Given these findings, it is appropriate to utilize statistical techniques that are robust to non-normal distributions in our empirical analysis.

TABLE 2 | BDS test.

Asset	Test statistics
CSI	8.886*
TELE	7.198*
UTI	13.236*
INF	4.862*
FIN	7.268*
HC	5.732*
CONS	4.985*
CD	8.456*
IT	10.273*
ENE	8.580*
MAT	7.798*
CNI	3.598*
OMX	11.801*
SUS	6.087*
CARBON	7.560*

*denotes significance at the 1% level.

4.2 | Static Correlation Analysis

According to the Kendall correlation coefficient heat map analysis in Figure 2, the indices CNI, OMX, SUS, and CARBON exhibit notably distinct correlation patterns with sectoral

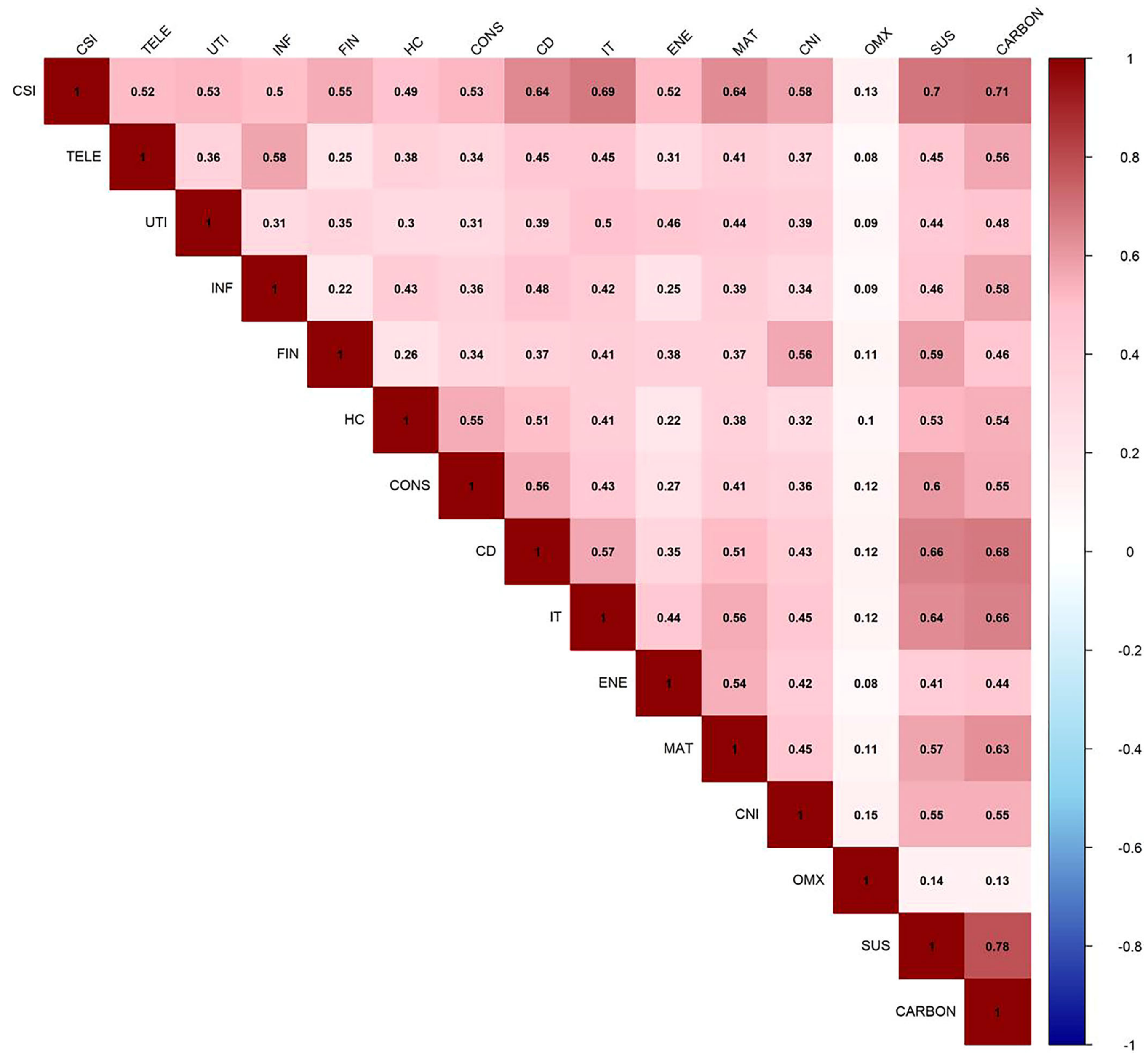

FIGURE 2 | Kendall correlation coefficient heat map analysis. [Color figure can be viewed at wileyonlinelibrary.com]

indices in the Chinese stock market. Specifically, CNI shows moderately strong correlations with most sectors, such as CSI (0.58), TELE (0.37), and IT (0.45), indicating its role as a broad-based index influencing various industries though not with particularly strong associations. Notably, the OMX index demonstrates relatively low correlations with most Chinese sector indices, with coefficients generally below 0.15, suggesting that it may be influenced by unique market factors. Similarly, the SUS index displays higher correlations with the IT (0.64) and CD (0.66) sectors, while its associations with other sectors, such as ENE (0.41), are more moderate. CARBON also shows selective correlations, with moderate associations with the FIN (0.46) and ENE (0.44) sectors, reflecting the varying sensitivity of different industries in China to sustainable development policies.

The diversity in correlation structure and the evident differences amongst asset correlations suggest that no highly similar assets exist within our analytical model, thereby mitigating the risk of information redundancy. This heterogeneous correlation pattern provides a solid foundation for subsequent connectedness analyses using the TVP-VAR-CAViaR method. It ensures that the research findings are not artificially inflated due to asset similarity, thereby enhancing the accuracy and reliability of systemic risk transmission and inter-market influence assessments. Consequently, this diversified correlation structure offers an ideal data basis for market connectivity research, enabling the identification of genuine risk spillover pathways rather than statistical artifacts.

4.3 | Tail Risk Connectedness

Table 3 offers empirical insights into market dynamics and the impact of significant events such as the Chinese stock market

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TABLE 3 | Average statistics of tail risk connectedness index in different subperiod.

	CSI	TELE	UTI	INF	FIN	HC	CONS	CD	IT	ENE	MAT	CNI	OMX	SUS	CARBON	FROM
CSI	16.79 (15.07, 18.51)	2.33 (3.12, 2.39)	4.99 (5.92, 3.00)	3.03 (4.80, 3.70)	5.07 (3.55, 3.72)	3.18 (4.88, 3.09)	5.20 (6.17, 4.62)	7.21 (7.90, 7.84)	8.79 (8.59, 8.47)	2.16 (1.21, 0.66)	7.10 (6.67, 6.82)	7.94 (7.37, 7.65)	0.10 (0.55, 0.31)	14.29 (12.13, 14.50)	11.81 (12.07, 14.70)	83.21 (84.93, 81.49)
TELE	5.52 (6.20, 5.64)	36.19 (31.30, 50.27)	5.21 (5.22, 3.31)	12.24 (13.15, 9.67)	1.76 (1.94, 2.35)	4.06 (5.22, 1.17)	2.75 (3.53, 1.57)	7.07 (6.98, 4.51)	5.86 (5.00, 6.36)	2.58 (3.00, 1.99)	5.32 (6.31, 3.96)	2.51 (2.98, 1.96)	0.38 (0.37, 0.51)	3.82 (4.30, 3.74)	4.72 (4.49, 2.99)	63.81 (68.70, 49.73)
UTI	8.95 (9.02, 6.37)	3.77 (3.99, 2.76)	30.55 (24.02, 51.47)	4.02 (5.73, 2.11)	4.67 (3.76, 3.55)	2.15 (4.61, 1.33)	3.75 (4.27, 2.05)	5.67 (7.33, 3.22)	10.04 (9.46, 5.71)	4.77 (3.25, 3.74)	6.89 (6.67, 5.04)	3.23 (4.25, 4.09)	0.26 (0.51, 0.44)	6.68 (6.99, 4.09)	4.60 (6.15, 4.03)	69.45 (75.98, 48.53)
INF	6.05 (7.49, 7.72)	10.60 (10.71, 8.60)	4.98 (6.02, 2.19)	31.30 (24.51, 42.92)	1.57 (2.05, 1.17)	6.57 (6.52, 2.87)	3.63 (4.71, 2.32)	8.54 (7.84, 5.44)	5.43 (5.57, 5.25)	1.73 (1.53, 0.97)	5.08 (5.72, 3.43)	2.60 (4.32, 1.79)	0.55 (0.31, 0.46)	4.23 (5.32, 7.15)	7.15 (7.37, 7.73)	68.70 (75.49, 57.08)
FIN	9.68 (7.82, 7.97)	1.40 (2.11, 1.87)	4.95 (5.54, 3.49)	1.55 (2.65, 1.27)	32.51 (35.90, 42.42)	1.02 (2.43, 0.88)	1.64 (3.58, 2.01)	4.26 (4.62, 4.58)	6.80 (6.53, 4.78)	10.17 (5.77, 4.72)	6.34 (5.10, 4.88)	7.05 (5.15, 12.07)	0.26 (0.37, 0.23)	10.22 (9.58, 6.57)	2.13 (2.84, 2.24)	67.49 (64.10, 57.58)
HC	6.78 (7.38, 7.14)	3.86 (4.12, 1.21)	2.43 (4.61, 1.32)	7.04 (6.43, 3.22)	1.10 (1.55, 0.76)	33.91 (25.71, 45.03)	7.92 (9.97, 9.54)	7.63 (9.44, 5.13)	4.28 (5.32, 3.01)	0.75 (0.98, 0.54)	4.06 (4.84, 2.20)	3.61 (4.12, 2.28)	0.27 (0.43, 0.34)	6.69 (7.76, 9.91)	9.68 (7.34, 8.37)	66.09 (74.29, 54.97)
CONS	8.94 (8.81, 8.49)	1.89 (2.52, 1.17)	3.38 (4.03, 1.57)	3.38 (4.36, 2.05)	1.69 (2.30, 1.69)	6.49 (9.24, 7.73)	28.53 (23.29, 35.80)	8.52 (9.36, 7.74)	4.60 (5.55, 3.37)	1.28 (0.84, 0.31)	6.22 (4.99, 3.18)	4.44 (5.25, 3.98)	0.66 (0.48, 0.64)	10.18 (9.84, 13.71)	9.78 (9.12, 8.54)	71.47 (76.71, 64.20)
CD	9.53 (9.67, 11.34)	4.20 (4.20, 2.71)	4.31 (5.88, 2.35)	5.70 (6.10, 3.51)	3.01 (2.58, 3.13)	4.67 (7.38, 3.02)	6.26 (7.78, 5.94)	20.94 (19.10, 27.52)	7.69 (6.84, 7.81)	2.02 (1.37, 0.52)	8.38 (6.13, 5.43)	4.53 (4.46, 4.08)	0.25 (0.31, 0.28)	9.37 (9.99, 13.27)	9.15 (8.20, 9.09)	79.06 (80.90, 72.48)
IT	11.38 (11.19, 12.40)	3.44 (3.18, 3.86)	7.49 (8.09, 3.97)	3.37 (4.46, 3.48)	4.65 (3.82, 3.23)	2.75 (4.45, 1.78)	3.45 (4.95, 2.55)	7.66 (7.20, 7.66)	22.04 (20.46, 28.59)	3.80 (2.52, 1.26)	8.69 (7.02, 8.43)	4.27 (5.08, 3.93)	0.15 (0.38, 0.20)	9.53 (9.37, 10.04)	7.34 (7.83, 8.61)	77.96 (79.54, 71.41)
ENE	5.16 (3.46, 1.89)	2.90 (4.34, 2.50)	6.60 (6.22, 5.34)	2.29 (2.38, 1.42)	12.38 (7.86, 7.03)	0.57 (2.18, 0.96)	1.30 (1.92, 0.71)	3.67 (3.31, 1.27)	6.87 (5.90, 2.99)	39.77 (46.39, 64.53)	11.22 (11.24, 6.26)	2.37 (1.11, 1.31)	0.47 (0.42, 0.89)	3.76 (2.61, 1.53)	0.68 (0.67, 1.38)	60.23 (53.61, 35.47)
MAT	9.65 (9.45, 11.29)	3.12 (4.40, 2.79)	5.43 (6.14, 3.92)	3.64 (5.02, 2.80)	4.70 (3.31, 3.73)	2.72 (4.40, 1.49)	4.81 (4.95, 2.83)	8.90 (7.03, 6.15)	9.08 (7.63, 9.56)	6.40 (5.91, 3.02)	22.56 (24.27, 32.59)	4.12 (4.36, 4.28)	0.21 (0.30, 0.20)	8.35 (6.61, 8.45)	6.32 (6.21, 6.87)	77.44 (75.73, 67.41)
CNI	12.97 (11.47, 12.72)	1.16 (2.41, 1.45)	2.71 (4.55, 3.07)	1.96 (4.55, 1.69)	5.91 (3.53, 9.36)	2.98 (4.23, 1.62)	4.28 (5.59, 3.44)	5.44 (5.69, 4.68)	5.29 (6.12, 4.68)	1.41 (0.65, 0.81)	4.68 (4.88, 4.40)	27.33 (23.86, 31.86)	0.91 (1.07, 0.57)	12.90 (10.16, 10.10)	10.07 (11.26, 9.55)	72.67 (76.14, 68.14)

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TABLE 3 | (Continued)

	CSI	TELE	UTI	INF	FIN	HC	CONS	CD	IT	ENE	MAT	CNI	OMX	SUS	CARBON	FROM
OMX	0.41 (1.74, 1.24)	0.87 (0.74, 0.88)	0.82 (1.27, 1.04)	0.56 (0.75, 1.09)	1.73 (0.69, 0.76)	0.76 (1.18, 0.55)	1.59 (1.50, 1.36)	0.77 (1.12, 0.88)	0.76 (1.14, 0.69)	1.13 (0.81, 0.72)	0.50 (0.62, 0.62)	0.75 (2.34, 1.48)	88.04 (82.30, 85.17)	0.48 (1.96, 1.38)	0.83 (1.83, 2.14)	11.96 (17.70, 14.83)
SUS	15.12 (13.27, 14.94)	1.65 (2.40, 1.70)	3.88 (5.05, 2.11)	2.27 (3.71, 3.58)	5.82 (4.68, 3.22)	3.39 (5.43, 4.45)	6.31 (7.28, 7.51)	7.68 (8.79, 9.39)	7.84 (7.87, 7.23)	1.74 (0.98, 0.53)	6.51 (5.20, 5.40)	8.29 (7.16, 6.36)	0.14 (0.54, 0.35)	17.72 (16.56, 19.10)	11.64 (11.09, 14.14)	82.28 (83.44, 80.90)
CARBON	14.16 (14.00, 17.00)	2.34 (2.70, 1.53)	3.14 (4.69, 2.20)	4.48 (5.62, 4.33)	1.53 (1.57, 1.31)	5.59 (5.62, 4.21)	6.71 (7.27, 5.31)	8.59 (7.79, 7.30)	6.98 (7.05, 6.94)	0.26 (0.25, 0.44)	5.66 (5.40, 5.00)	7.33 (8.35, 6.74)	0.22 (0.58, 0.58)	13.25 (11.79, 15.89)	19.76 (17.30, 21.21)	80.24 (82.70, 78.79)
TO	124.31 (120.98, 126.15)	43.53 (50.94, 35.43)	60.30 (73.22, 38.88)	55.54 (69.71, 43.93)	55.60 (43.19, 45.01)	46.90 (67.77, 35.15)	59.60 (73.48, 51.78)	91.59 (94.40, 75.80)	90.32 (88.57, 76.84)	40.20 (29.08, 20.23)	86.65 (80.80, 65.05)	63.05 (66.31, 62.02)	4.85 (6.63, 6.01)	113.75 (108.40, 120.33)	95.89 (96.48, 100.39)	1032.07 (1069.96, 903.00)
NET	41.10 (36.05, 44.66)	−20.28 (−17.76, −14.30)	−9.15 (−2.76, −9.65)	−13.17 (−5.78, −13.15)	−11.89 (−20.90, −12.56)	−19.19 (−6.52, −19.81)	−11.87 (−3.24, −12.42)	12.53 (13.50, 3.32)	12.35 (9.03, 5.43)	−20.03 (−24.53, −15.24)	9.21 (5.07, −2.36)	−9.62 (−9.83, −6.12)	−7.11 (−11.08, −8.82)	31.47 (24.96, 39.44)	15.65 (13.78, 21.60)	TCI = 68.80 (71.33, 60.20)
NPDC	14.00 (14.00, 14.00)	2.00 (3.00, 3.00)	6.00 (7.00, 4.00)	4.00 (5.00, 5.00)	6.00 (2.00, 4.00)	2.00 (6.00, 4.00)	6.00 (8.00, 7.00)	10.00 (11.00, 10.00)	11.00 (10.00, 11.00)	2.00 (1.00, 0.00)	9.00 (9.00, 9.00)	7.00 (4.00, 8.00)	1.00 (0.00, 1.00)	13.00 (13.00, 13.00)	12.00 (12.00, 12.00)	

Note: The values in parenthesis represent the connectedness framework before 19 June 2015 (the Chinese equity market turbulence), while the values on the left side inside the table represent the situation between 19 June 2015 and 22 January 2020, and the values on the right side inside the table represent the situation after 23 January 2020 (after the outbreak of COVID-19). TCI stands for overall connectedness index.

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turbulence and the COVID-19 crisis on the tail risk of selected sectors. It presents changes in connectedness between the Chinese stock market and sustainability indices across three distinct sub-sample periods:

1. Before the Chinese equity market turbulence on 19 June 2015 (sub-sample period 1).
2. Between 19 June 2015, and 22 January 2020 (sub-sample period 2).
3. After the COVID-19 outbreak on 23 January 2020 (sub-sample period 3).

This analysis facilitates a comparison of tail risk connectedness patterns amongst different indices across these sub-sample periods, providing a deeper understanding of how market events influence the relationships and interdependencies between the Chinese equity market and sustainability indices over time.

Table 3 reveals crucial insights into the Chinese equity market's transition towards sustainability. From the findings provided in Table 3, it could be seen that compared to the connectedness dynamics before the 2015 Chinese equity market turbulence and after the COVID-19 outbreak in early 2020, the Chinese stock market and sustainability indices exhibited a greater degree of spillover effects (TCI = 71.33%) in the 2015–2020 sample period. Surprisingly, the TCI between the Chinese stock market and sustainability indices decreased significantly after the COVID-19 outbreak. It was worth noting that according to the information in the 'NET' row (the net spillover received/sent by individual variables from the system) CSI, IT, CT, SUS, and CARBON were the main spreaders of net tail spillover effects to other variables in the system. Additionally, it was noteworthy that the tail connectedness of CSI, SUS, and CARBON on other markets in the system increased significantly after the COVID-19 outbreak. Specifically, CSI's contribution to the system's tail spillover led all other indices after the COVID-19 outbreak (44.66%), followed by CARBON (39.44%). This was partially in line with the findings of (W. Zhang et al. 2022), who found that carbon emission futures were the main spillover senders. The reason for such a situation might be that the sudden outbreak of COVID-19 caused unexpected disturbances to the financial market, but investors eventually turned to a more value-oriented investment pattern (Naeem et al. 2024).

Moreover, considering quality and liquidity, socially responsible sustainability products might be more attractive to investor groups in the context of carbon neutrality (Lucey and Ren 2023). Last but not least, we noticed that considering all sub-sample periods and compared to other Chinese stock market segments, CSI occupied the absolute dominant share of the net spillover contribution of Chinese equity market-related indices to the system, and this situation was more prominent in the post-COVID-19 era, possibly because people tended to invest in indices representing the overall Chinese stock market. This also reminded us that during any period of significant market stress, the overall index of the Chinese stock market was often not a safer and more diversified choice for sustainability asset investors during a crisis.

Next, we turned our attention to other markets within the system. From Table 3, it can be seen that ENE generally maintained a stable role as a net recipient of tail risk throughout the entire sample range. The driving factors behind this fact might be the cyclicality of the energy industry itself, economic structural reform, the impact of new energy, and market sentiment, which together led to its stable position as a net risk recipient in the stock market risk transmission network (Gong et al. 2023). Meanwhile, the role of the largest cross-market tail risk net recipient within the system exhibited heterogeneity during different extreme risk events, which seemed to indicate that market structure and internal connections were dynamically evolving. It was noteworthy that during the COVID-19, HC was the largest net recipient of systemic tail risk shocks. This might be due to the widespread influence of COVID-19 on the healthcare industry. This was consistent with the research of (Mensi et al. 2021), who confirmed the sensitivity of the healthcare industry to spillover effects from other Chinese stock market industries. The above findings deepened our currently limited understanding of risk shock transmission between sustainability indices and the Chinese financial system. Importantly, these insights complement and extend previous research on spillover effects in Chinese stock markets (e.g., Mensi et al. 2023), offering a nuanced view of how sustainability factors are reshaping market interconnections and risk profiles.

4.4 | Dynamics of Tail Risk Transmission

Figures 3 and 4 show the dynamic total connectedness and pairwise net spillover of the Chinese equity market and sustainability indices calculated under the 2.5%, 5%, and 10% levels based on AS-CAViaR. First, the dynamic findings in Figure 3 extended the understanding of the static connectedness results within the system in Table 3. First, according to Figure 3, we noted that the total connectedness index exhibited significant dynamic change characteristics, and its overall time-varying trend was almost unchanged at different AS-CAViaR levels. Additionally, it should be noted that, with the help of Figure 3, we were able to explain the situation we previously found where the average total tail connectedness index decreased in the post-COVID-19 period. We indeed observed that in the early stages of COVID-19, the tail risk transmission increased sharply and briefly, but the magnitude and speed of the decline in tail risk were greater than after 2015, which was after the Chinese stock market experienced the 2015 stock market turbulence and the early 2016 circuit breaker. This was reasonable and related to Chinese economic recovery and investor confidence growth after the initial COVID-19 lockdown was lifted, while benefiting from Chinese strict epidemic control policies, coupled with the relatively chaotic market situation faced by the external world under the influence of COVID-19 and its variants at the time. Unfortunately, this positive trend reversal was also reflected in Figure 3. Since 2022, the tail risk spillover effect had temporarily surged, halting the previous downward momentum, which was caused by the 2022 Russia-Ukraine war and Chinese strict zero-COVID policy implemented after 2022.

Figure 4 intuitively shows the differences in the average net pairwise directional tail risk transmission network between sustainability indices and Chinese stock market indices, which was also what needed to be focused on according to the theme of this paper. Interestingly, the SUS and CARBON indices

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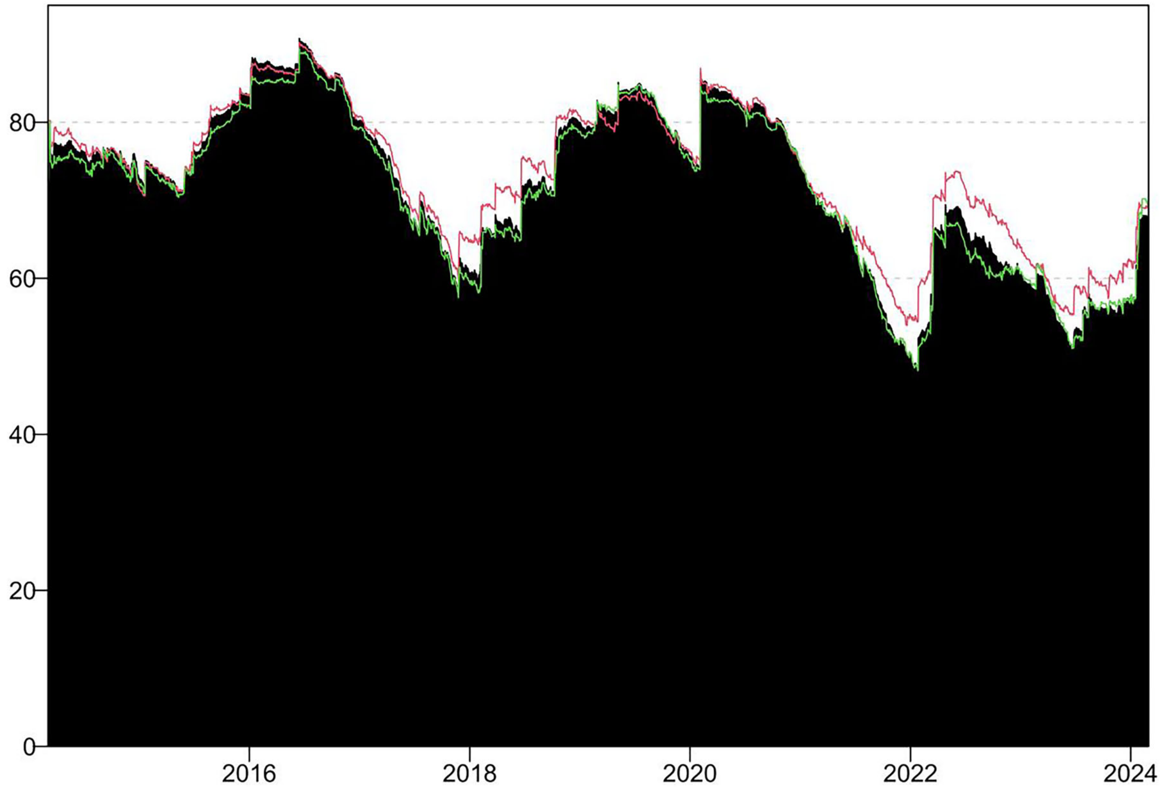

FIGURE 3 | Time-varying total tail risk connectedness index. The black area provides the spillover level of 5% based on AS-CAViaR; the red line provides the spillover rate of 10% based on AS-CAViaR; the green line provides the spillover effect at the 2.5% level based on AS-CAViaR. [Color figure can be viewed at wileyonlinelibrary.com]

generally played the role of net tail risk transmitters to almost all Chinese stock market sectors during the sample period. We speculated that the possible reason for this result was that the Chinese government increased investment in green, low-carbon, and circular economy, included the renewable energy field in the '14th Five-Year Plan', and implemented a series of government policies supporting sustainable development (Hepburn et al. 2021). However, when we turned our attention to CNI and OMX, we found that although these two indices occasionally exhibited sporadic and intermittent positive spillovers to Chinese stock market sectors, their weakness in influencing the Chinese stock market was undeniable, as evidenced by the fact that the spillover direction sometimes even reversed. Overall, although CNI was a risk sender for some Chinese stock market sectors, it could not serve as a sustained and dominant risk sender for the Chinese stock market. Furthermore, current evidence also confirmed that OMX had become a persistent net risk recipient in the system, as Figure 4 provided evidence of positive pairwise net spillovers from most Chinese stock market industries to OMX during the study sample range. On average, we noticed in Figure 4 that the overall Chinese stock market index (CSI) transmitted risk to sustainability indices more significantly than the Chinese equity market segments, especially as evidenced by the significant overall upward trend towards the end of the sample range. This was consistent with our previously provided static connectedness results, which might be due to the dominant position of the Chinese equity market in systemic spillovers. It should be emphasized that since the outbreak of the COVID-19 crisis, the tail risk transmitted by the Chinese stock market to sustainability indices had surged and exacerbated the volatility of the green finance market (Ma and Cheok 2023).

4.5 | Tail Risk Network Structure and Regime Shifts

It could be clearly seen from Figure 5 that the risk spillover network structure underwent significant transitions in different sub-sample periods, especially after the outbreak of the 2015 Chinese stock market turbulence and the 2020 COVID-19 crisis, the internal network framework of the selected indices within the system underwent significant reconfiguration. This indicated that extreme risk events might affect the complex interactions of tail risks of different markets throughout the system by changing the topological structure of the risk transmission network. Carefully examining Figure 5a,b, first, we noted that before the COVID-19 outbreak, CSI, CARBON, SUS, MAT, IT, and CT were uninterrupted net tail risk senders in the system. It was noteworthy that CSI consistently maintained its role as a net risk sender in the system across all sub-sample periods, as we previously discovered in the static connectedness results in Figure 3. Second, the cross-market tail risk spillover structure underwent a mutation after the COVID-19 outbreak. Specifically, MAT transformed from a net tail risk spillover sender in the previous period to a major recipient of net risk spillover effects in the post-COVID-19 period. This was not surprising, as this situation might be attributed to the structural transformation of the Chinese economy after the COVID-19 outbreak, as the sudden outbreak of COVID-19 plunged Chinese real estate

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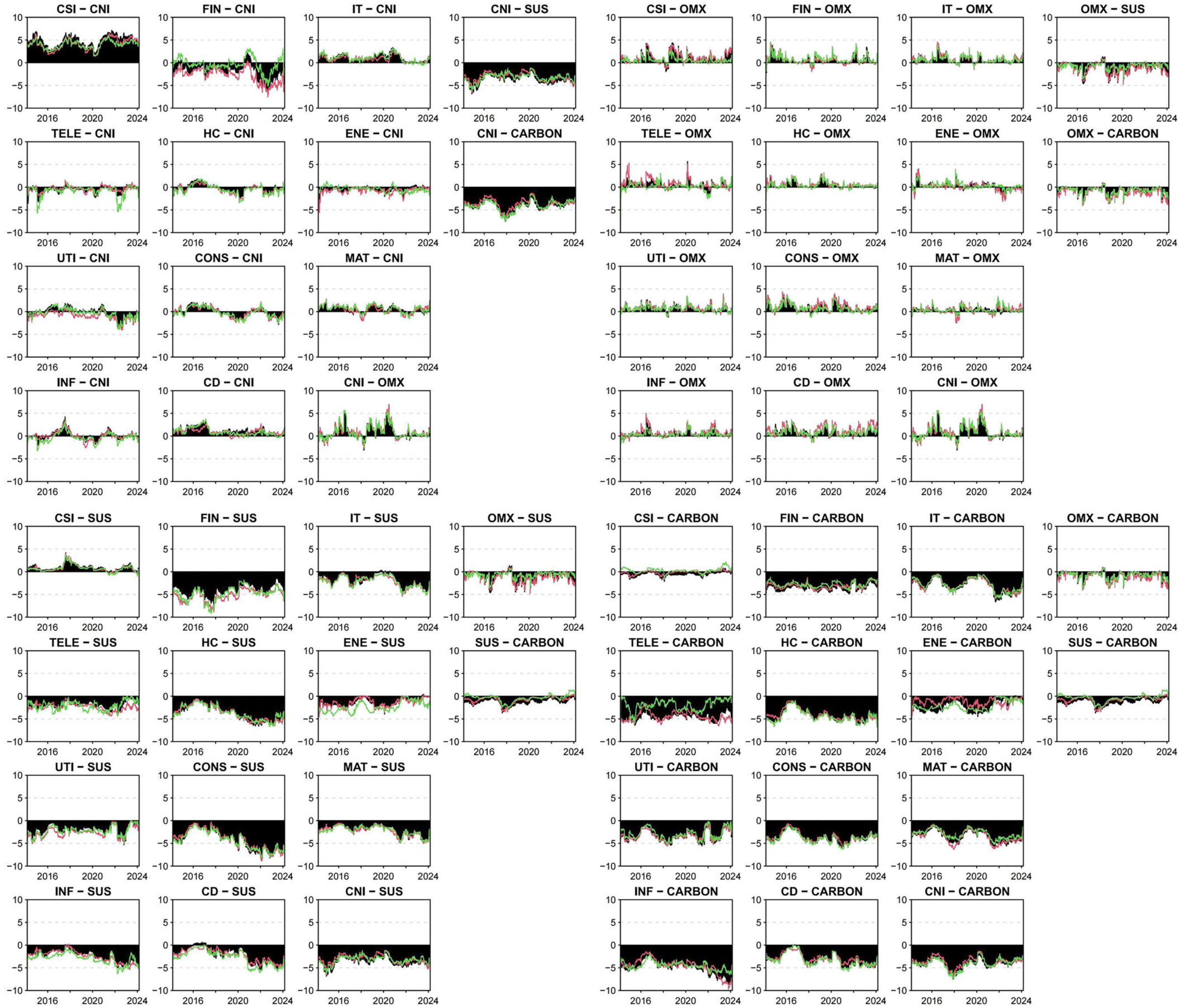

FIGURE 4 | Pair-wise net total connectedness between sustainability indices and the Chinese equity market. The black area represents the spillover level of 5% based on AS-CAViaR; the red line represents the spillover rate of 10% based on AS-CAViaR; the green line represents the spillover effect at the 2.5% level based on AS-CAViaR. [Color figure can be viewed at wileyonlinelibrary.com]

market into a winter and subsequently reduced related supply chain demands (W. Zhang et al. 2022). Surprisingly, unlike CARBON and SUS, OMX, and CNI seemed to continuously act as net tail risk recipients rather than senders in the network. Last but not least, comparing the thickness of the lines in (a), (b), and (c) in Figure 5 (the greater the interaction, the thicker the line), we found that although SUS, CARBON, and CSI continuously sent pairwise tail risk spillovers to other indices across all sub-samples, the intensity of network spillovers decreased in the sub-sample period after the 2015 Chinese stock market turbulence and before COVID-19, while the net tail risk linkages between sustainability indices and Chinese stock market sectors became active again after the COVID-19 outbreak. This might imply that after the 2015 Chinese stock market turbulence, the stability of the Chinese financial system improved, and its ability to resist risk contagion increased. However, the subsequent unprecedented major shock events (such as COVID-19) unfortunately magnified the vulnerability of the financial system again and increased the connectedness of tail risk. The above study on the network tail risk spillover mechanism helped us better understand how financial risks evolved in complex networks during different sub-sample periods and how to improve system stability by adjusting the network structure. At the same time, it also provided investors and regulators with a new perspective to understand and grasp the changing patterns of market microstructure under the impact of different risk events.

4.6 | Frequency-Quantile Dependence Analysis

Subsequently, we unveiled the specific characteristics of the frequency and quantile linkage structure between the sustainability index and the Chinese equity market, derived through the implementation of a novel wavelet quantile procedure. Accordingly, Figure 6 and Appendices A-C display the quantile

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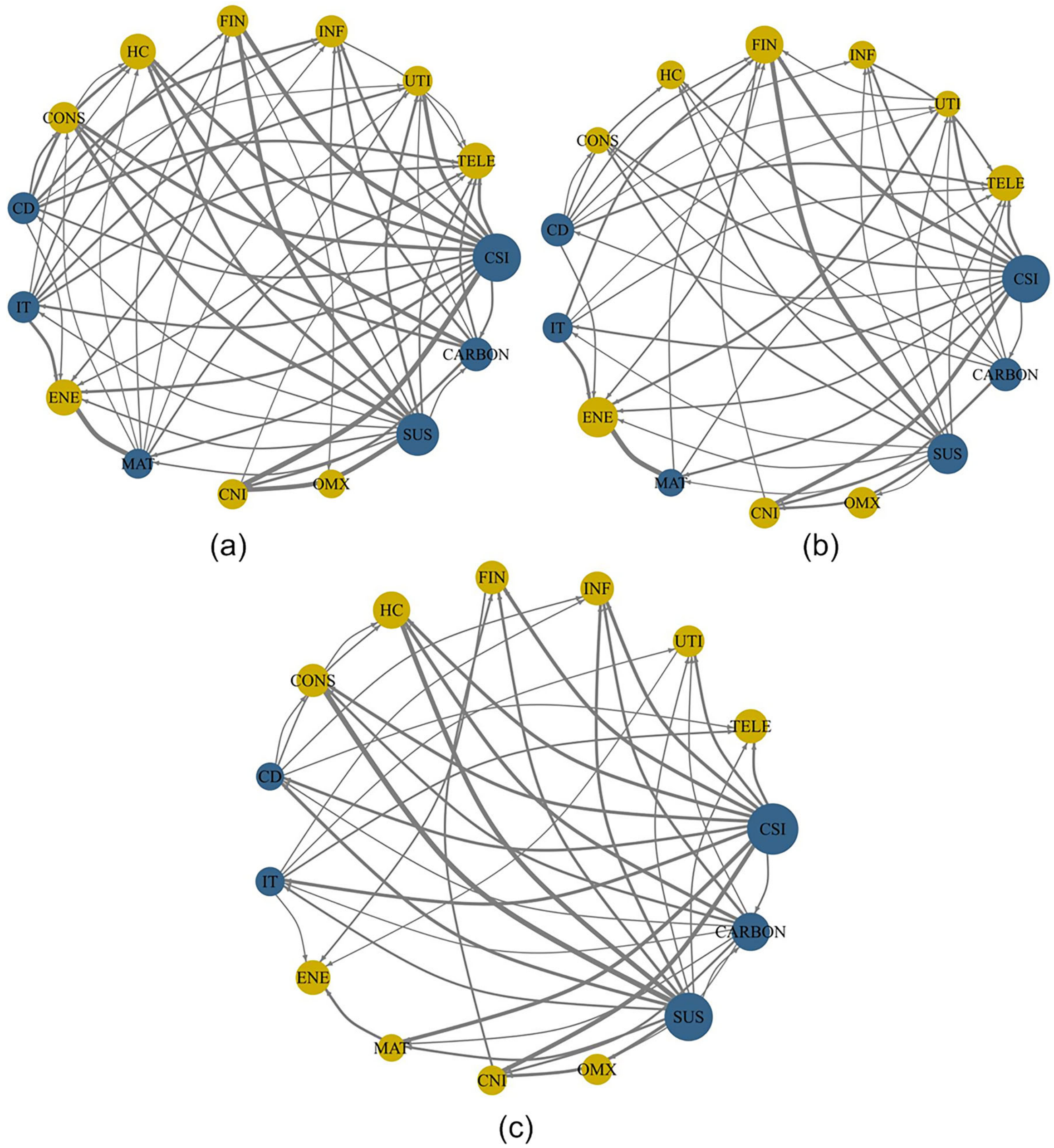

FIGURE 5 | Visualization of the net pair-wise directional tail risk network between sustainability indices and the Chinese stock market. Blue represents risk emitters; yellow represents risk recipients; node size represents the magnitude of the TO connectedness; arrows represent the direction of spillovers; line thickness represents the strength of the interaction. (a) represents the network connectedness situation before 2015-06-19 (the Chinese stock market turbulence), (b) represents the network connectedness situation between 2015-06-19 and 2020-01-23, and (c) represents the network connectedness situation after 2020-01-23 (after the outbreak of COVID-19). [Color figure can be viewed at wileyonlinelibrary.com]

wavelet correlations between SUS, OMX, CNI, and CARBON. The relevant information on frequency distribution was divided into eight-time scales spanning 2–512 days, which were further segmented into short-term (2–16 days), medium-term (16–64 days), and long-term (64 days and above) frequency intervals. It is imperative to highlight that, as indicated by the colour bar on the right side of each figure, deep black squares symbolize a notably weak quantile correlation, suggesting the need for bolstered efforts towards achieving sustainability objectives. In contrast, rich yellow areas denote a strong correlation, underscoring the significant influence of the sustainability index on the nuanced segments of the equity market.

Figure 6a–k presents the nonlinear dynamic connections between SUS and the Chinese equity market across different frequencies and quantiles. This complex pattern of quantile-frequency dependence reflects the interactive characteristics of these two markets across various time scales and market conditions. Initially, we observed significant quantile heterogeneity in the connection between SUS and the Chinese stock market. Specifically, compared to extreme quantiles, the most pronounced positive dependence (densest yellow) was observed at intermediate quantiles (normal market conditions). This suggests that during stable market operations, the linkage between listed companies' sustainability performance and their stock

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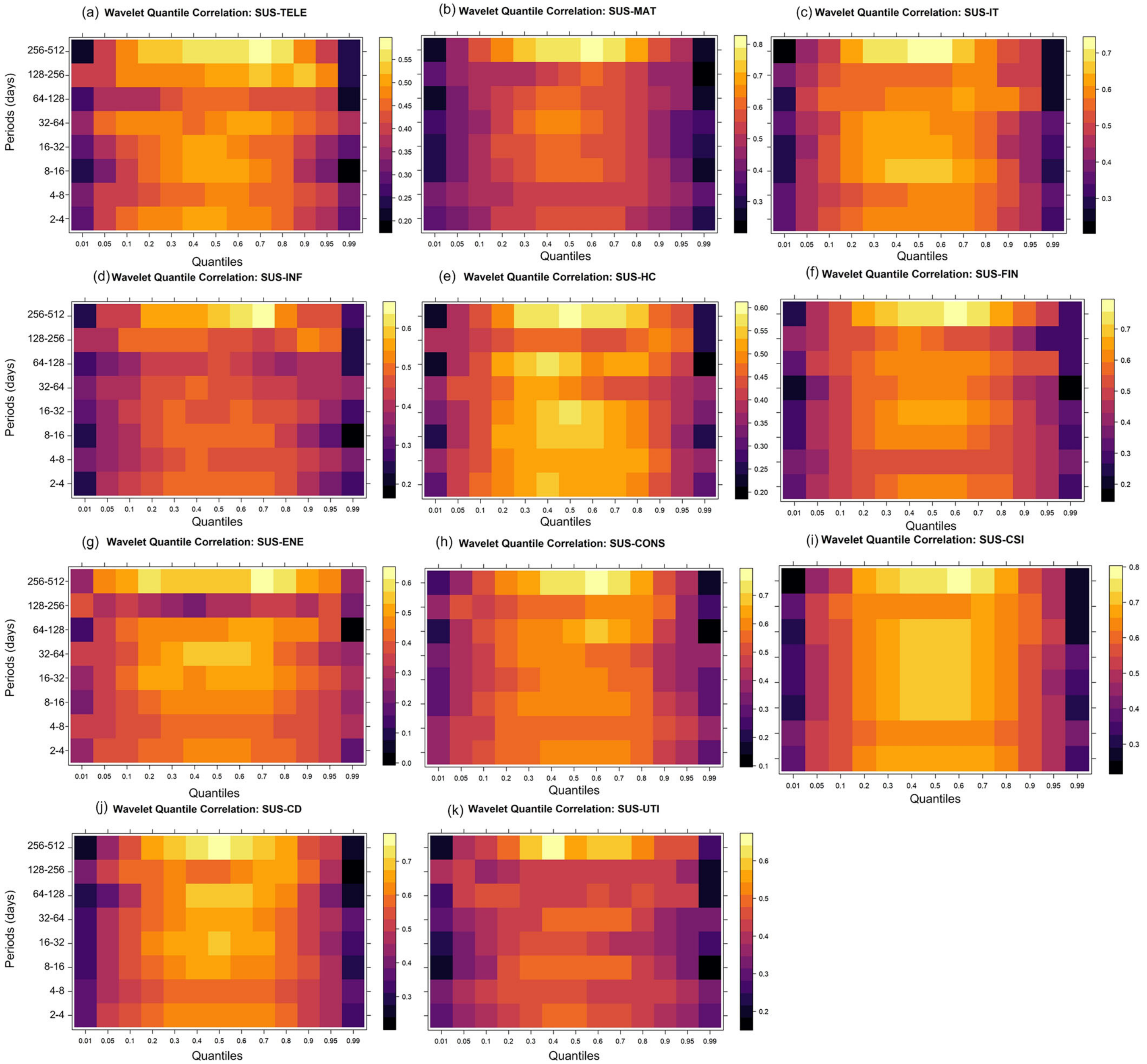

FIGURE 6 | Nonlinear dynamic connections between SUS and the Chinese equity market across different frequencies and quantiles. [Color figure can be viewed at wileyonlinelibrary.com]

prices is tighter, reflecting the gradual recognition of sustainable development as an integral factor in value investing. Conversely, evidence suggests that the correlation between SUS and the equity market is lower under extreme quantiles (tail risk conditions). This may be due to drastic changes in investor risk preferences in extreme market environments, where market-averse sentiments predominate, overshadowing traditional valuation logics with short-term disturbances (Bekaert et al. 2022). Hence, during market stress periods, the influence of sustainable development factors on asset pricing diminishes. Moreover, it is crucial to emphasize the varying quantile correlations between SUS and the Chinese stock market across different frequencies. At lower frequencies (long-term), a clear positive dependence exists between SUS and the Chinese stock market. This seems to imply that, in the long run, the rising prominence of sustainability concepts indeed correlates positively with the Chinese stock market's performance. Notably, SUS-HC of Figure 6e was observed to have a stronger correlation in both the quantile and frequency domains compared to SUS with other Chinese stock market indices.

Appendix A reveals the subtle dynamic correlations between OMX and the Chinese stock market's sectors across different frequency-quantile levels. This is significant as it reflects the transmission mechanisms and the extent of influence of international sustainability indices on the Chinese equity market. Overall, the correlation between OMX and the Chinese stock market was not positive across most frequencies and quantiles, indicating potential disparities in the development stages and paths of sustainability investment between China and international markets. The international green economy wave has yet to impact the Chinese stock market comprehensively and

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deeply, with Chinese sustainable development transformation being more driven by endogenous factors. However, under intermediate quantiles (stable market conditions), OMX showed a weak but gradually strengthening positive correlation with the Chinese equity market. This implies that, at stable market levels, the international capital market's pursuit of sustainability concepts might, through investor expectations and industry cooperation channels, exert a certain exemplary effect and favourable stimulus on related industries in China (Lin and Hong 2022). It is necessary to stress that this positive correlation is mainly confined to intermediate quantiles and high-frequency (over 64 days) intervals. At extreme quantiles (tail risk) and mid-low frequency intervals (medium to short term), OMX's impact on the Chinese stock market was observed to be relatively limited. Furthermore, we noted the closest connection between OMX-INF within the Chinese stock market's segmented sectors. This could be related to global supply chain cooperation. OMX's green economy index constituents include information technology companies (e.g., CISCO), which may have upstream and downstream cooperation with Chinese information technology enterprises. In summary, the development momentum of the green economy, represented by the United States, may provide a positive stimulus to related sectors in the Chinese stock market under stable market states, especially the information technology industry, though such influence is limited and easily submerged by extreme risk events and medium to short-term disturbances.

Appendix B explores the correlation between the CNI index and various segments of the Chinese stock market across different frequencies and quantile levels, revealing some intriguing heterogeneity characteristics and investment implications. First, as an index devised by Chinese domestic companies, the CNI's impact on the Chinese equity market was observed to be inconsistent across different time scales and market conditions. Such heterogeneity might reflect the differential performance of sustainability assets and traditional stock market sectors in China across various economic cycle stages, along with the dynamic changes in market sentiment and policy orientation. Second, the study identified a significant long-term linkage between the CNI and the Chinese equity market at the median quantile level, particularly within the energy sector (CNI-ENE). This was anticipated, given the substitutability of renewable for traditional energy sources, suggesting that the Chinese stock market's energy sector would be more influenced by the Chinese green finance index. This also indicates that, in the long term, the correlation between the CNI and the overall trend of the Chinese equity market is relatively stable, and this correlation becomes more evident when the market is in a stable state. This could also benefit from the Chinese government's long-term policy support for green finance. Based on these findings, it is crucial for investors in the Chinese equity market to pay attention to and grasp the long-term spillover effects of the CNI on the Chinese equity market. On the one hand, as a barometer of green finance development, the CNI could exert a structural impact on traditional industries, guiding capital flows and industrial transformation. On the other hand, the long-term positive correlation between the CNI and the stock market implies that incorporating it into investment portfolios can help diversify risks and enhance long-term returns. Especially when the market is in a neutral state, the CNI could become an effective investment choice. It is noteworthy, however, that while there is a tight linkage between the CNI and the equity market at the long-term median level, this correlation may weaken or vary in the short term or under extreme market conditions. Therefore, investors still need to closely monitor market trends and dynamically adjust strategies. Furthermore, the development of green finance is impacted by multiple factors, including policies, technology, and international cooperation, requiring a broad perspective for cautious investment opportunity assessment.

From the analysis of Appendix C, the CARBON index's correlation with the Chinese stock market exhibited some unique characteristics, offering significant insights into the interaction between carbon-related assets and the Chinese equity market. First, like other sustainability indices, the wavelet quantile linkage between CARBON and the Chinese equity market was observed to be strong, a fact verified by the prevalent light colours. This might reflect Chinese policy orientation and market expectations in addressing climate change and promoting a low-carbon economic transition. Given Chinese position as the leading carbon dioxide emitter globally, the government has escalated its initiatives aimed at reducing emissions and conserving energy, and green development in recent years. These measures may have heightened investors' attention to carbon-related assets, strengthening the connection between the CARBON index and the Chinese equity market, consistent with previous research (X. Chen and Lin 2021). Furthermore, we noticed that the correlation between CARBON and the Chinese equity market also exhibited significant asymmetry across different quantile levels. Evidence suggests that under extreme market conditions (such as bear or bull markets), the impact of CARBON on the Chinese equity market differs from that under normal market states (median quantiles). This asymmetry could stem from dynamic changes in investor sentiment, risk preferences, and policy expectations. For example, during market downturns, investors might focus more on the defensive attributes and long-term value of carbon assets, whereas during prosperous market periods, the growth potential and policy benefits of carbon assets might be amplified. Some existing literature has also drawn similar conclusions (Brannstrom et al. 2022). Moreover, although CARBON exhibits differences in quantile correlation with the Chinese equity market compared to other sustainability indices, they also share some commonalities. It is important to emphasize that the cross-quantile frequency correlation between CARBON-ENE was the strongest amongst the combinations of CARBON and all Chinese stock market sectors. This observation for CARBON was consistent with that for CNI. Based on the nature of these two markets, it could be reasonably inferred that this was related to the demand for alternative energy under carbon neutrality. Meanwhile, Appendix C shows that CARBON has a positive cross-frequency correlation with the Chinese stock market at intermediate quantiles. This suggests that within the normal market volatility range, the trends of CARBON and the stock market are generally consistent. This positive correlation could benefit from the widespread adoption of sustainability investment principles and investors' increasing emphasis on sustainable development and social responsibility. More interestingly, this positive correlation tends to be more significant at long-term frequencies than at short-term ones. This might imply that CARBON's impact on the Chinese equity market is more reflective of long-term structural changes and value

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reassessment, rather than short-term fluctuations and sentiment-driven movements. From an investor's perspective, this hints at the importance of value investing and seeking strategic allocation opportunities in CARBON assets, rather than focusing solely on short-term trading and market timing.

In summary, the WQC analysis offers a rich tapestry of insights into the complex dynamics between sustainability indices and the Chinese stock market, providing a valuable framework for investors seeking to leverage sustainable investing principles in one of the world's largest and most dynamic markets. As the landscape of global finance continues to evolve with a growing focus on sustainability, these insights will be instrumental in shaping the future of investment strategies.

Figure 7 shows the impact of several important external risk drivers (VIX, OVX, EPU, USDCNY, GPRD) on the tail risk connectedness of the Chinese equity market and sustainability indices. By observing the time-varying trend characteristics of the influence of these macroeconomic factors on the tail risk connectedness of the selected indices, we summarized the following insightful views:

1. The impact of various risk drivers on the selected markets exhibited significant asymmetry and time-varying characteristics. Specifically, their impact on tail risk connectedness differed significantly in different sub-sample periods, especially during crisis periods (such as the COVID-19 crisis and the Russia-Ukraine conflict), reflecting the sensitivity of the tail risk of the Chinese stock market and sustainability indices to extreme crisis events.
2. The GPRD index showed that the impact on the tail risk of the Chinese equity market and sustainability indices surged significantly when geopolitical tensions escalated (such as the outbreak of the Russia-Ukraine war in 2022). However, overall, the significance of GPRD's impact on total tail connectedness was not as strong as other factors.
3. The VIX index, as an important indicator of the expected volatility of US stocks, had the largest correlation with the risk contagion between sustainability indices and the Chinese stock market among all macroeconomic factors. We noticed that when panic sentiment (e.g., the COVID-19 outbreak in 2020) rose, the VIX increased, and systemic risk contagion from external sources intensified.
4. The expected volatility of oil prices (OVX) was positively correlated with risk spillovers in non-crisis periods, but this relationship reversed during periods of sharp oil price fluctuations (such as in early 2022). This might be because sharp fluctuations in the energy market triggered risk aversion sentiment, and various stock sectors were generally under pressure.

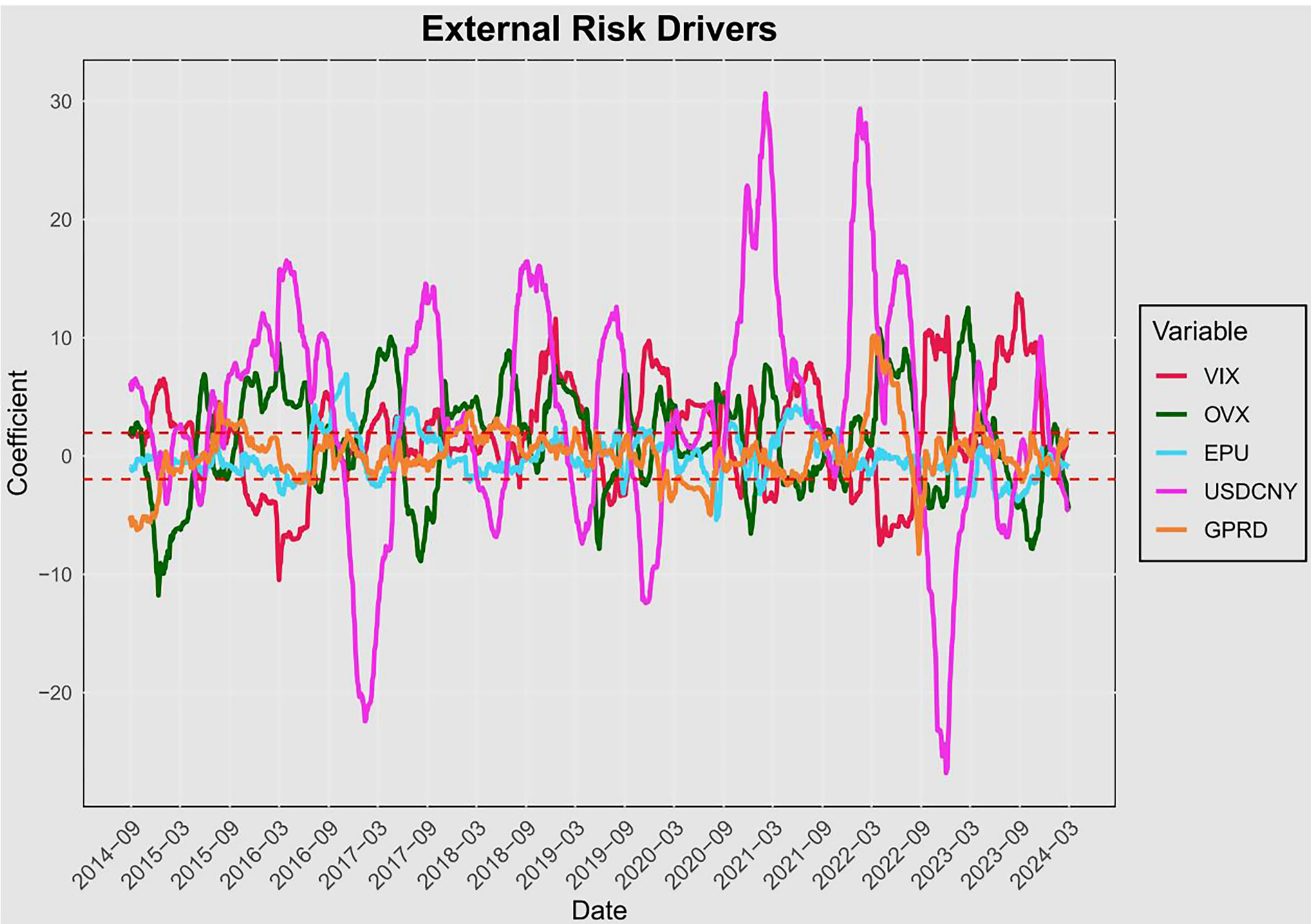

FIGURE 7 | Rolling t-statistics based on rolling window. The horizontal red lines represent the 5% critical values of ± 1.96 (Lucey and Ren 2023). [Color figure can be viewed at wileyonlinelibrary.com]

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5. The impact of the EPU index and USDCNY on total tail connectedness was relatively weak and mainly concentrated for a period after major events such as COVID-19. The mechanism behind this phenomenon might be that economic policy uncertainty could exacerbate risk spillovers, while the depreciation of the RMB might attract more foreign capital inflows and alleviate market panic. Overall, the influence of external macroeconomic factors on the total tail connectedness of the Chinese stock market and sustainability indices had complex heterogeneous dynamic characteristics, amongst which the linkage of VIX to the tail risk connectedness between sustainability indices and the Chinese stock market was the most significant. We believed this stemmed from the fact that as an important indicator of the expected volatility of the US stock market, the VIX tended to rise rapidly when market uncertainty increased. This negative sentiment could quickly spread to global financial markets, triggering a decline in risk appetite and corresponding asset price adjustments. In contrast, some other macroeconomic indicators reflected more the impact on the real economy, and the process might be relatively slow and indirect.

Next, we conducted a sensitivity analysis to test the robustness of the TVP-VAR-CAViAR results, as shown in Appendixes D and E. This deployment was to check whether the patterns of interconnectedness and impact between the Chinese stock market and sustainability indices were consistent with the main results after changing key parameters in the model. We could observe that the dynamic total tail risk connectedness, illustrated in Appendix D and E using the AS-CAViaR model with tail risk set at 2.5% and 10% VaR, was highly consistent with the tail risk dynamic and static characteristics shown in the results of Appendix F. Therefore, the findings of the robustness test indicated that the total tail risk spillover effects did not change significantly after changing the key parameters in our model, confirming the robustness of our TVP-VAR-CAViAR results.

4.7 | Structural Break Test on TCI Time Series

To further ensure the robustness of our main results, we conducted structural break tests on the TCI time series data. In our analysis, we focused on two key breakpoints: 19 June 2015 (associated with the 2015 Chinese stock market crash) and 23 January 2020 (the early outbreak of COVID-19, marked by the Wuhan lockdown). To examine whether these major risk events induced structural changes in the time series, we employed the Chow test methodology.

This method is based on the following statistical hypothesis testing framework:

- Null hypothesis (H_0): The structural parameters of the time series remain stable before and after the specified breakpoints, indicating no structural change.
- Alternative hypothesis (H_1): The structural parameters of the time series differ significantly before and after the breakpoints, indicating the presence of structural changes.

The theoretical basis of the Chow test lies in comparing the differences in the residual sum of squares (RSS) between the full sample and two segmented subsamples. The test statistic follows an F-distribution and is computed as:

$$F = \frac{(\mathrm{RSS}_c - (\mathrm{RSS}_1 + \mathrm{RSS}_2))/k}{(\mathrm{RSS}_1 + \mathrm{RSS}_2)/(n - 2k)}, \tag{12}$$

where RSS_c is the residual sum of squares for the complete sample; RSS_1 and RSS_2 are the residual sums of squares for the subsamples before and after the breakpoint, respectively; k is the number of parameters in the regression model; and n is the total sample size.

Statistical inference is drawn according to conventional significance thresholds. When the p-value is less than 0.05, we reject the null hypothesis, indicating that significant structural changes occurred in the TCI time series. Conversely, if the p-value is greater than or equal to 0.05, we fail to reject the null hypothesis, suggesting insufficient evidence for a structural break.

Figure 8 demonstrates that the TCI experienced significant structural changes during two critical periods of market stress, as confirmed by the Chow test results.

Figure 8a reveals a structural break associated with the 2015 Chinese stock market crash. The Chow statistic of 20.9899 and the extremely low p-value (4.858e-06) indicate that this event significantly altered the risk transmission mechanisms between markets. The TCI displayed markedly different dynamics before and after this point, rising sharply from mid-2015 to a peak of approximately 90, followed by a steep decline before 2018. This trend reflects the risk spillover effects triggered by the crisis and their subsequent evolution.

Figure 8b confirms the structural break triggered by the COVID-19 outbreak and the lockdown in Wuhan on 23 January 2020. The extraordinarily high Chow statistic of 921.4718 and p-value of virtually zero ($0e + 00$) suggest that this public health crisis delivered an even more severe shock to the market risk network. The TCI exhibited a sustained downward trend following the outbreak, reaching a low of approximately 48 by 2022, and later rebounding slightly but remaining at relatively low levels.

The identification of these two structural breaks provides critical temporal reference points for the tail risk connectedness analysis using the TVP-VAR-CAViaR method. These insights enable a more precise assessment of the evolution of risk transmission between sustainable investment indices and traditional industry sectors in China under extreme market conditions.

5 | Conclusions and Remarks

This study investigated tail risk spillover effects and quantile-frequency dependencies amongst sustainability indices, the CSI 300 Index, and various industry sub-indices within the Chinese equity market to assess the strength and direction of market connectedness. Our research aimed to address significant gaps in existing literature concerning sustainability indices in the Chinese equity market, offering critical insights into the market's transition towards sustainability. Additionally, we examined how different market crises impacted tail risk spillover effects and evaluated the

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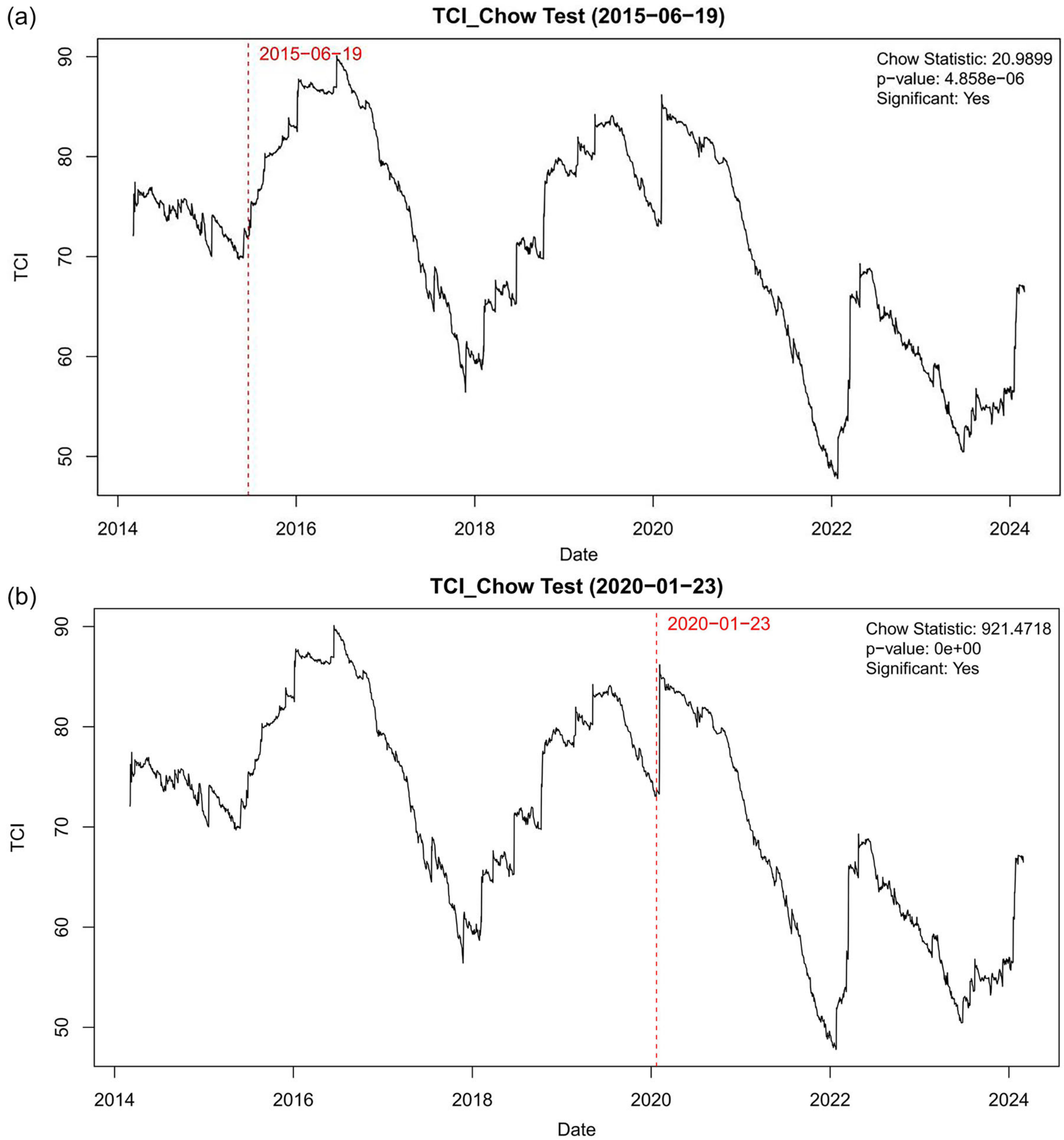

FIGURE 8 | Structural breaks in TCI between sustainability indices and Chinese stock market sectors. Notes: (a) Chow Test on 19 June 2015—The test identifies a significant structural break (Chow Statistic: 20.9899, *p* value: 4.858e-06) coinciding with the 2015 Chinese stock market turbulence. (b) Chow Test on 23 January 2020—The test confirms an extremely significant structural break (Chow Statistic: 921.4718, *p*-value: 0e + 00) corresponding to the early COVID-19 outbreak in China. These structural breaks mark critical turning points where risk transmission mechanisms were fundamentally altered due to major market events. [Color figure can be viewed at wileyonlinelibrary.com]

varying influence of macroeconomic factors on tail risk between sustainability indices and the broader Chinese stock market.

This study not only reveals the tail risk spillover characteristics between the Chinese stock market and ESG indices but also deepens our understanding of how the transition to sustainable development reshapes market risk structures. The empirical results show that different sustainability indices play distinct roles in risk transmission, reflecting the market's differentiated evaluation of various dimensions of sustainable development. Furthermore, the study highlights the influence of quantification levels and frequency characteristics on the correlation between sustainability indices and the stock market, reinforcing the heterogeneous value of ESG information across different market conditions and investment cycles. This heterogeneity suggests that the transition towards sustainable development is not only a critical factor in asset allocation decisions but also a key lens through which to understand market risk dynamics.

Initially, we employed the novel TVP-VAR-CAViaR connectedness method to explore tail risk connectedness between sustainability indices and the Chinese stock market. Our findings revealed several key insights: First, the trajectory of total tail risk connectedness illustrated dynamic changes in both the Chinese equity market and sustainability indices throughout the sample period, particularly during extreme events. Notably,

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the period from 2015 to 2020, encompassing the Chinese equity market turbulence and the COVID-19 crisis, showed heightened spillover effects between these markets. Analysis of net risk spillover structures identified CSI, IT, CT, SUS, and CARBON as major contributors to tail risk transmission within the system. Following the COVID-19 outbreak, CSI and CARBON significantly amplified their contributions to the system's tail risk spillovers, indicating increased market sensitivity to external shocks. Conversely, ENE consistently acted as a net recipient of tail risk throughout the sample period. Amongst sustainability indices, SUS and CARBON played predominant roles in transmitting tail risk across various sectors of the Chinese equity market, whereas OMX and CNI generally acted as net recipients rather than senders of tail risk.

Subsequently, our WQC results revealed nonlinear quantile- and frequency-dependent dynamic correlations between sustainable indices and the Chinese equity market. The empirical findings indicate the following: (1) Under normal market conditions, sustainable indices exhibit the strongest connection with the stock market, while this connection weakens under extreme market conditions. (2) Correlations at long-term frequencies (64 days and above) are generally stronger than those at short-term frequencies, suggesting that ESG factors hold greater relevance for long-term investors. (3) The energy sector shows the closest association with sustainable indices—particularly CARBON and CNI—highlighting the central role of the energy transition in China's sustainable development process. Furthermore, after controlling for external macroeconomic risk factors, our study identified the VIX index as having the most significant linkage effect on tail risk connectedness between sustainability indices and the Chinese equity market. This underscores the role of global market uncertainty in influencing risk transmission between sustainable investments and traditional equity markets in China.

Our findings provide critical insights into the on-going sustainability transition within the Chinese equity market. Increasing connectedness between sustainability indices and traditional sectors, particularly post-significant events like the COVID-19 outbreak, indicates growing integration of sustainability considerations into market dynamics. The prominence of the CARBON index in risk transmission underscores Chinese commitment to carbon neutrality goals, reflecting evolving market priorities towards environmental sustainability.

To further support the Chinese equity market's transition to sustainability, we propose the following policy recommendations:

1. Given that different sustainable indices play varied roles in risk transmission, regulatory authorities should consider establishing differentiated regulatory requirements for various types of sustainable assets. For instance, CARBON and SUS indices, which act as primary risk transmitters, may warrant more stringent information disclosure requirements, while risk receivers such as OMX and CNI might benefit from enhanced liquidity support mechanisms.
2. Regulatory authorities and market institutions could develop investor education materials based on the findings of this study to help market participants better understand the risk characteristics of sustainability investments.
3. Efforts should be made to incorporate sustainability criteria into major market indices, thereby gradually shifting market attention towards more sustainable companies.
4. Implement tax incentives or preferential policies for investments in companies or funds that meet specific sustainability criteria, encouraging greater capital flow into sustainable sectors.
5. Foster collaboration between financial institutions, industry leaders, and sustainability experts to develop innovative financial solutions that align investment returns with long-term sustainability goals.

More importantly, financial regulatory authorities can utilize our tail risk spillover network analysis to establish an early warning system. For instance, they can monitor the risk transmission intensity between the CSI 300 index and the CARBON index, which we identified as the primary channel for risk propagation. Special attention should also be given to risk exposures in the energy sector of the Chinese stock market, as this sector acts as a major risk receiver within the network. In addition, enhanced oversight of the financial sector is essential during major market crises, as our findings indicate a significant increase in tail risk for this sector during the COVID-19 period.

To operationalize this approach, regulatory authorities could develop a 'risk spillover dashboard' that monitors real-time risk connectivity between market sectors. When specific thresholds are triggered—such as the overall tail risk connectivity index surpassing a defined value—targeted regulatory measures could be implemented. These may include increased liquidity support for vulnerable industries or adjustments to macroprudential policy instruments.

For investors, strategic considerations include incorporating sustainability factors into long-term asset allocation and risk management strategies to mitigate investment risks and optimize portfolio returns under varying market conditions. Additionally, improving sustainability information disclosure and promoting a sustainable financial ecosystem are crucial for sustainable investment decisions. Finally, recognizing the substantial impact of external macroeconomic factors, especially the VIX, on tail risk connectedness underscores the importance of comprehensive risk assessment and early warning models in market risk management. Specifically, based on our research findings, investors may consider using the SUS and CARBON indices as risk warning tools, as they typically act as risk transmitters. During periods of market stability—corresponding to medium quantiles—increasing ESG asset allocations may be beneficial, given their stronger long-term correlations with traditional markets. Conversely, reducing exposure to the energy sector during times of extreme market volatility may help mitigate risk, as this sector tends to function as a primary risk receiver.

Last but not least, with regard to improving the quality of sustainable indices, this study offers the following recommendations based on empirical findings. First, the construction of Chinese sustainability indices should strike a balance between standardization and localization. Our finding that the OMX index has a weaker risk connection with the Chinese market highlights the limitations of relying solely on international

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standards. Second, sub-indices targeting specific ESG dimensions—environmental, social, and governance—should be developed to provide more refined and targeted risk management tools. Third, regulatory authorities should enhance the standardization and enforceability of ESG information disclosure, while also improving the reliability of data verification mechanisms to reduce greenwashing behaviour. Fourth, sustainability indices should adopt more flexible adjustment mechanisms to promptly reflect changes in corporate sustainability performance, particularly in response to extreme market events. Finally, given the observed relationship between traditional risk indicators, such as the VIX and ESG-related risk spillovers, future efforts could incorporate conventional risk factors into the ESG assessment framework to create more comprehensive and integrated sustainable risk indices. These enhancements would considerably improve the reliability of sustainability indices and offer more robust analytical tools for examining China's transition towards a sustainable financial market.

Future research avenues may explore broader sustainability indices, examine higher moments of spillover effects (e.g., skewness, kurtosis), and examine sector-specific sustainability transitions within the Chinese equity market. Comparative analyses with other emerging markets could also provide a global perspective on sustainability transitions in equity markets.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The authors have nothing to report.

Endnotes

[1] https://www.policyuncertainty.com/.

[2] The CSI Xiangmi Lake Green Finance Index was a key index in the Chinese capital market, aiming to comprehensively reflect the overall performance of listed companies in the green finance field. This index mainly included listed companies that had outstanding performance and extensive influence in areas such as green finance, environmental protection, clean energy, and sustainable development. As a weathervane of Chinese green finance development, the CNI Index provided an important benchmark for measuring and tracking market trends in related industries. This index was obtained from the Wind database in China (www.wind.cn).

[3] The Nasdaq OMX Green Economy Index was a global sustainability index that covered international firms with outstanding performance in sustainability aspects, especially US companies. This paper introduced the OMX Index as an important variable representing the performance of international sustainability assets to examine its spillover effects on the Chinese stock market. Incorporating the OMX Index into the research perspective helped to examine the development of Chinese green finance from a global perspective, reveal the impact mechanism of international sustainability investment trends on Chinese capital market, and provide a reference for grasping the trend of Chinese economic green transformation.

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Appendix A

See Figure A1.

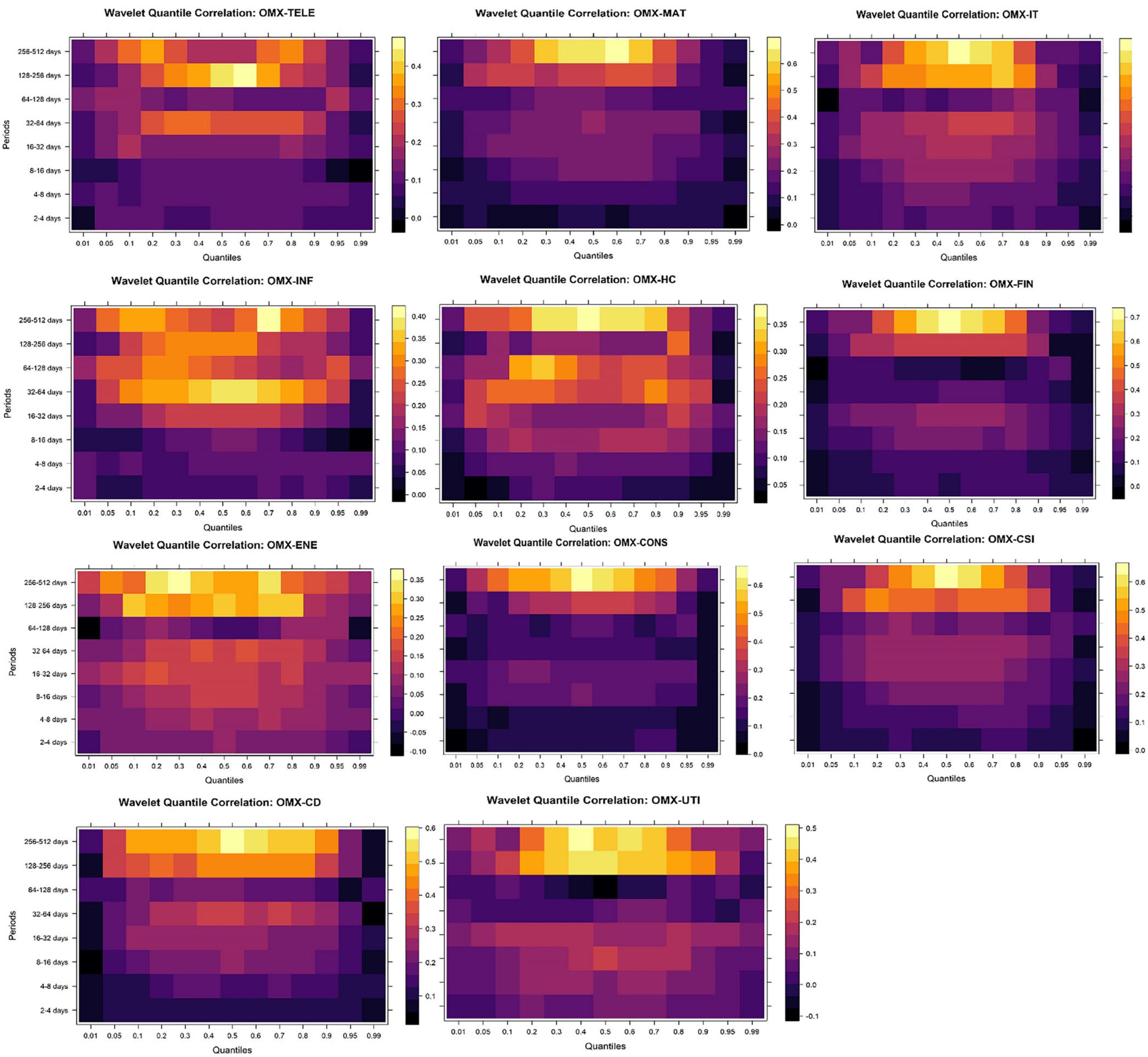

FIGURE A1 | Nonlinear dynamic connections between OMX and the Chinese equity market across different frequencies and quantiles. [Color figure can be viewed at wileyonlinelibrary.com]

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Appendix B

See Figure B1.

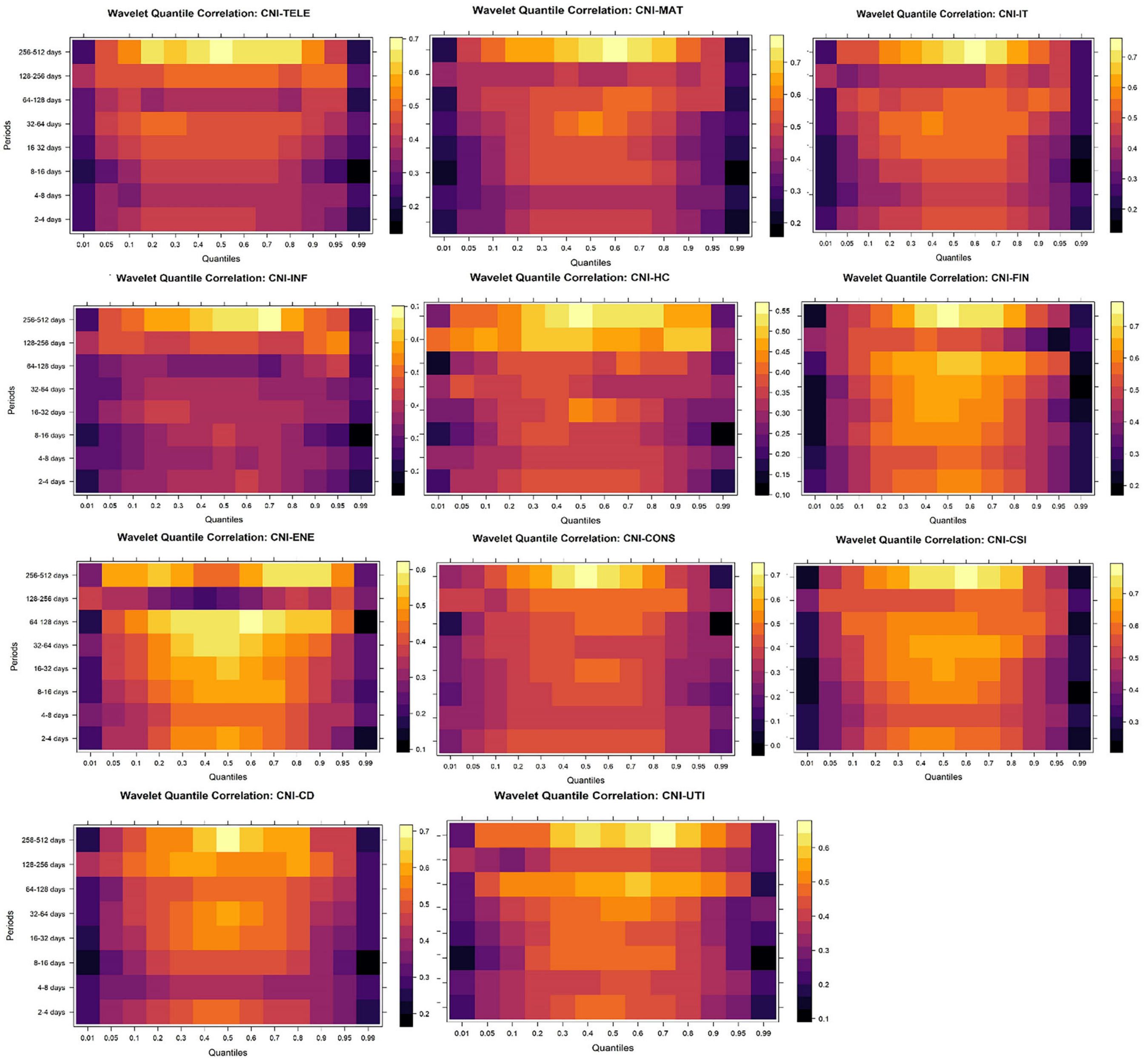

FIGURE B1 | Nonlinear dynamic connections between CNI and the Chinese equity market across different frequencies and quantiles. [Color figure can be viewed at wileyonlinelibrary.com]

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Appendix C

See Figure C1.

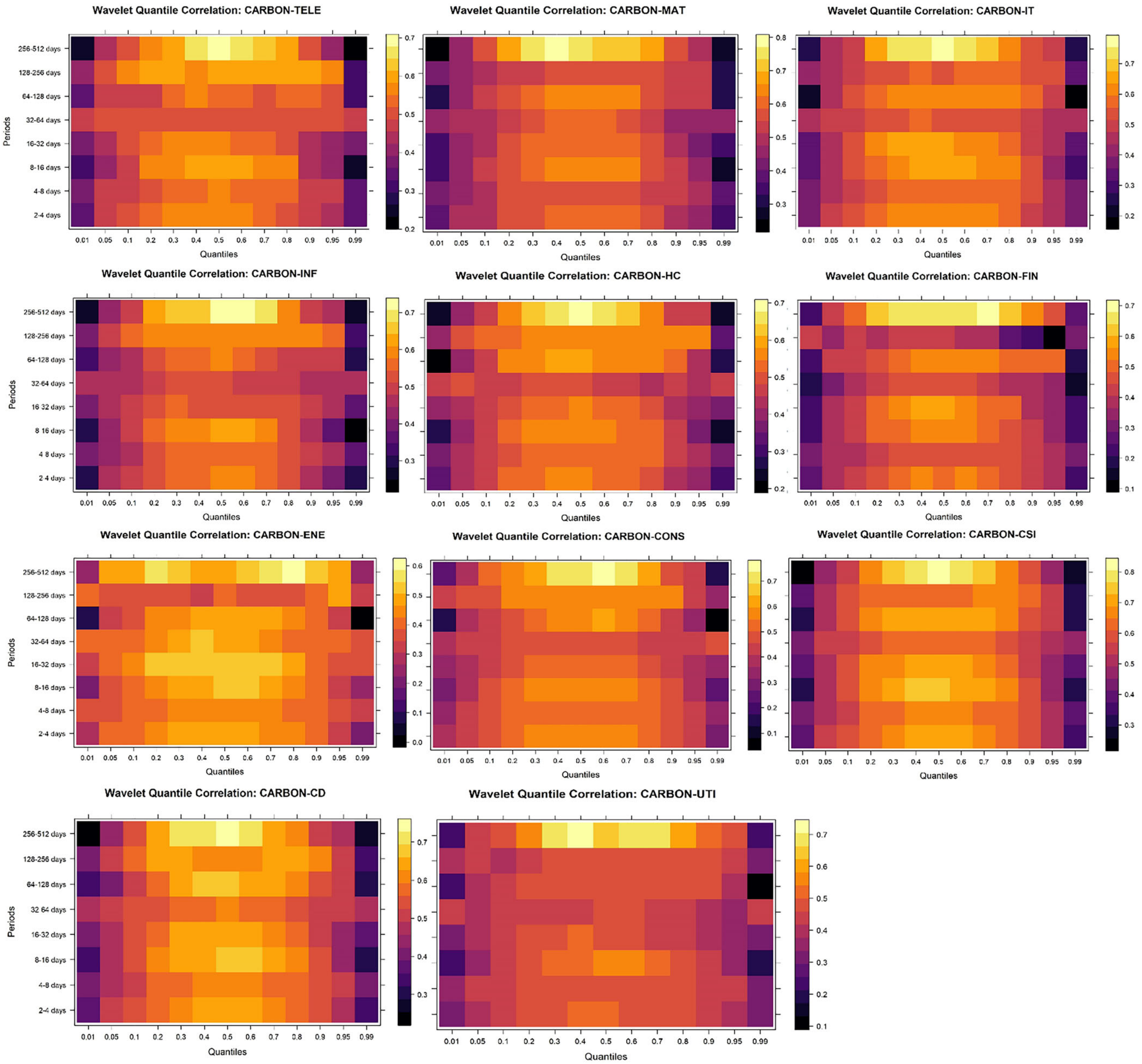

FIGURE C1 | Nonlinear dynamic connections between CARBON and the Chinese equity market across different frequencies and quantiles. [Color figure can be viewed at wileyonlinelibrary.com]

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Appendix D

See Figure D1.

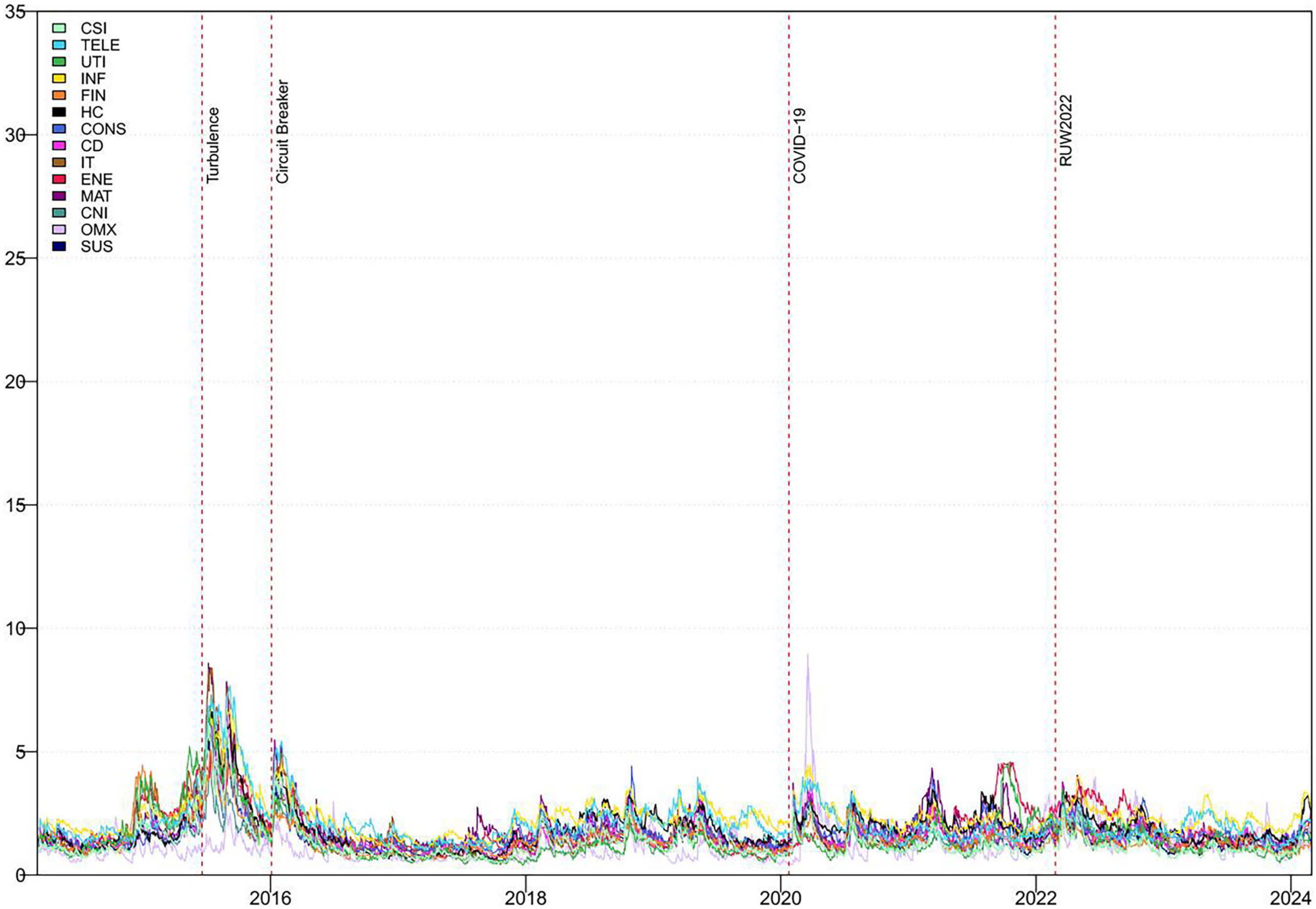

FIGURE D1 | Tail risk calculated as 10% VaR applying the AS-CAViaR model. [Color figure can be viewed at wileyonlinelibrary.com]

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Appendix E

See Figure E1.

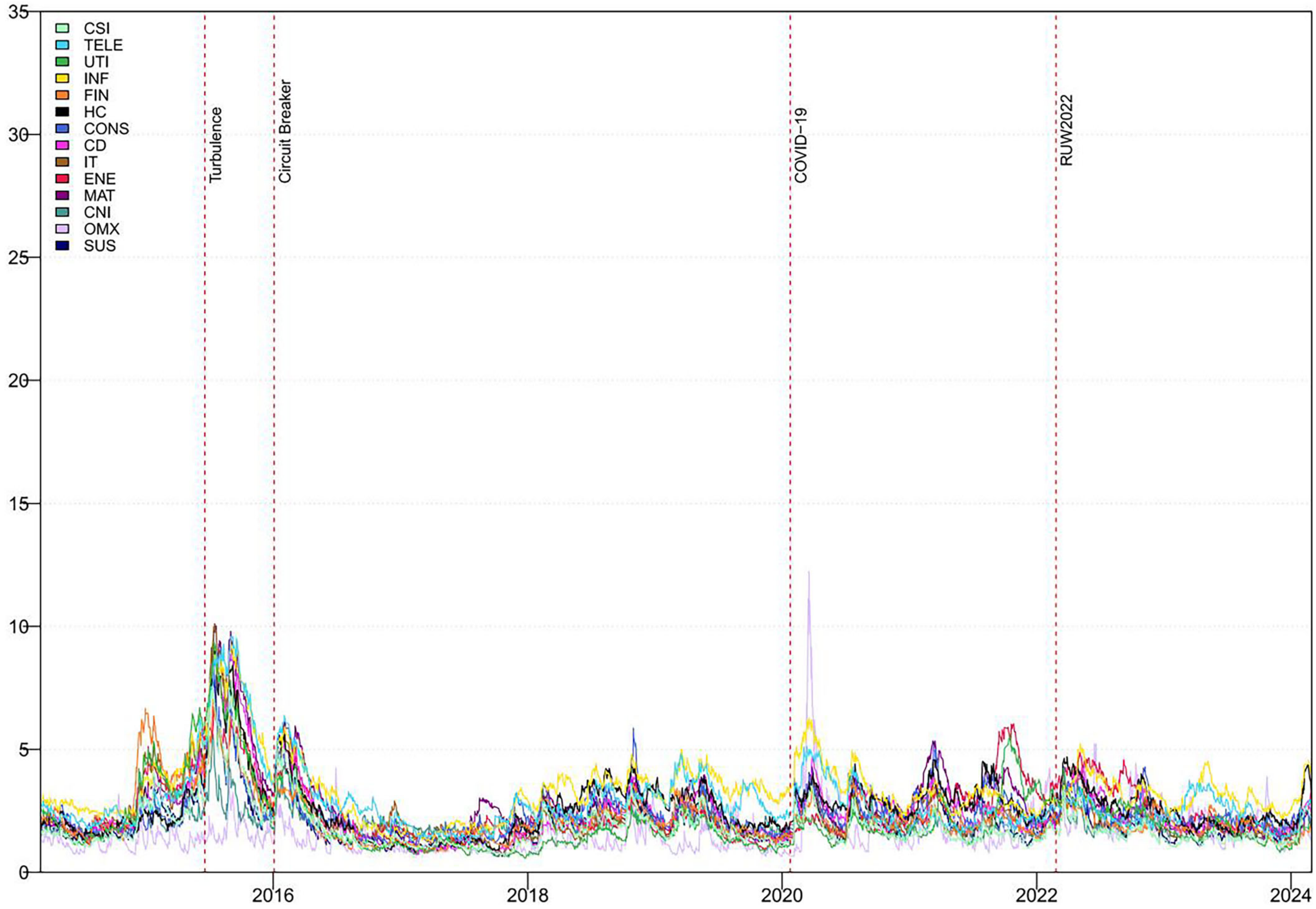

FIGURE E1 | Tail risk calculated as 2.5% VaR applying the AS-CAViaR model. [Color figure can be viewed at wileyonlinelibrary.com]

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Appendix F

See Figure F1.

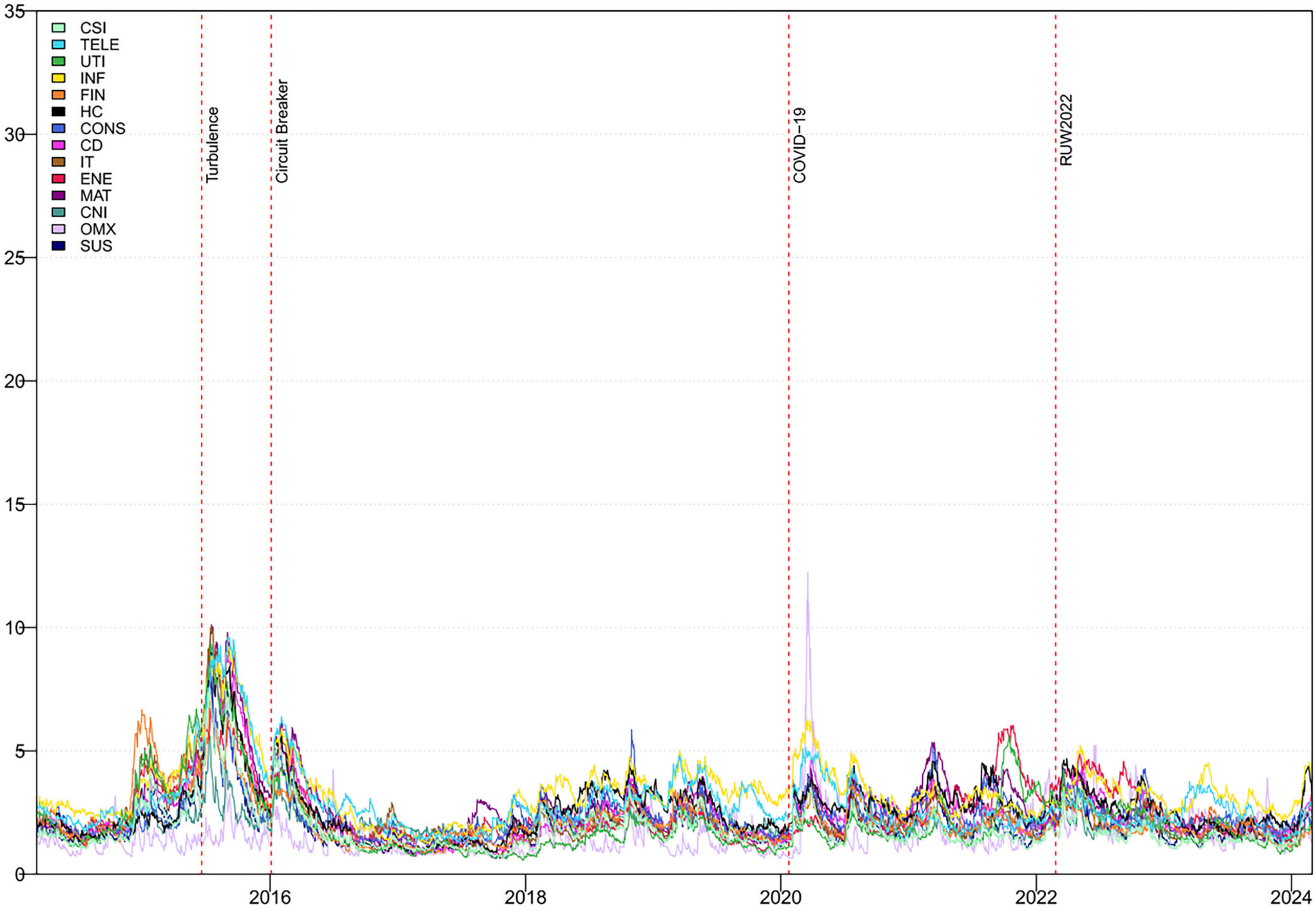

FIGURE F1 | Tail risk calculated as 5% VaR applying the AS-CAViaR model. [Color figure can be viewed at wileyonlinelibrary.com]

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