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Extreme risk dependence between green bonds and financial markets

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Abstract

The current study investigates the extreme risk dependence between green bonds and financial markets by employing the dual approaches of time-varying optimal copula and extreme risk spillover analysis of dynamic conditional Value-at-Risk. We report significant symmetric (asymmetric) tail-dependent copulas in the upper (lower) tails characterizing independent regimes. Green bonds offer sufficient diversification, safe-haven, and

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hedging opportunities during stable and distressing times to financial markets. The extreme risk spillovers revealed that COVID-19 transformed the spillovers between green bonds and financial markets except Bitcoin. We proposed insightful implications for policymakers, governments, investors, and portfolio managers to relish the findings for their investment avenues.

KEYWORDS
CoVaR, COVID-19, financial markets, green bonds, TVOC

JEL CLASSIFICATION
C18, G11, G18

1 | INTRODUCTION

The past renowned crisis, such as Global Financial Crisis (GFC), Eurozone Sovereign Debt Crisis (ESDC), and the recent COVID-19 pandemic, catalyzed academicians and research scholars to examine the dependence and risk spillovers between the financial markets to stipulate policy implications further and grab the investors' attention to overcome the surmounted challenged appeared out of uncertain circumstances (Cesa-Bianchi et al., 2020). Investors' growing concern toward risk-adjusted portfolios during economically fragile periods has converged them to multiple investment opportunities in versatile financial markets which offer considerable diversification potential, safe-haven features during crisis periods, and strong hedge properties during stable economic conditions (Cochrane, 2022; Karim et al., 2023a, 2023b). Since financial markets represent different markets with varied risk-capacities, examining the dependence between financial markets is reflective of various useful avenues for policymakers, governments, and investors to formulate policies and design their portfolios optimistically.

Tail dependence and identifying the extreme relationship between financial markets are crucial components for portfolio allocation, design, and strategies. In the case of green bonds, the upsurge in the regulatory convergence (Arif, Hasan, et al., 2021; Flammer, 2020; Naeem, Adekoya, & Oliyide, 2021; Naeem, Farid, et al., 2021), investors' environmental orientation (Naeem & Karim, 2021), and seeking the most suitable investment potentials have increased the integration among the financial markets (Daubanes et al., 2021). In terms of regulation of green bonds, Saravade et al. (2023) imply that green bond policies implemented by Chinese financial market regulators are used to be effective in increasing the overall green bond issuance in China. Subsequently, the increasing worldwide focus on green and clean investments is motivated by environmental concerns and aspirations to step ahead in restructuring the current economy into a climate-resilient economy (Bolton & Kacperczyk, 2021; Naeem, Gul, et al., 2023; Naeem, Iqbal, et al., 2022c; Naeem, Nguyen, et al., 2021; Naeem, Peng, et al., 2020; Umar et al., 2022). The prevailing sustainable investment initiatives have fostered the attention of policymakers, regulators, governments, and worldwide investors to shift from the existing dirty energies to renewable and sustainable energy sources. In this stream, green finance offers sufficient opportunity to switch conventional investments into green investments. The proceeds of green investments are exclusively attributed to environment-friendly, clean energy, and renewable projects backed by these investments (Atif et al., 2021; Krueger et al., 2020).

First introduced by the European Investment Bank in 2007, green bonds provide an innovative solution to financial market participants to channel their financial resources toward sustainable programs and overcome the ongoing environmental challenges. Evidence suggests that green investments are an effective means of financing to overcome the cost of climate-oriented projects (Andersen et al., 2020) and achieve a low-carbon economy (Appiah et al., 2022; Leitao et al., 2021). Environmental and climate-friendly investments outperform traditional assets as green assets result in more green innovations (Karim & Naeem, 2022; Nguyen et al., 2020). Following this, multiple stock exchanges worldwide have introduced specialized green investments and assets that service the green concerns of both investors and issuers.

Given these contextual underpinnings, the increasing activities in green finance have raised the attention of recent scholars to investigate the underlying nature of green bonds while uncovering the potential benefits of these investments given the uncertain economic circumstances. For example, recent studies (Kanamura, 2020; Karpf & Mandel, 2017) reported a positive yield differential of green assets, whereas Flammer (2021) and Larcker and Watts (2020) documented an essentially zero-premium on green investments. Conversely, the other strand of literature (Billah et al., 2022; Naeem & Karim, 2021; Tang & Zhang, 2020; Wang et al., 2020) witnessed that both investors and issuers can benefit from green bond issuance. Scholars' pronounced interest and greater attention in understanding the nature and features of green bonds compared with other financial markets reflects growth and awareness among academicians and practitioners are given the importance of this new green strand of investment. However, the literature offers limited research regarding tail dependence between green bonds and financial markets. Correspondingly, the world has undergone serious shifts and unprecedented crises during the last two decades, which strongly affected the tail dependence between green bonds and financial markets. One of the severe shocks the world is still suffering from is the recent global pandemic of COVID-19, where financial markets experienced endangered susceptibility to the unexpected shocks propelled out of this world health emergency (Farid et al., 2022; Pham et al., 2022; Tiwari et al., 2022). These shocks have driven tail dependence and extreme risk spillovers between green bonds and financial markets, where multiple tail dependence regimes underline the dependence arrangements (Mensi et al., 2022; Naeem, Conlon, & Cotter, 2022; Naeem & Karim, 2021).

One of the main reasons that COVID-19 has transformed the spillovers among financial markets is the high degree of globalization and interconnectedness among different countries' economies (Alawi et al., 2022; Iqbal et al., 2022; Naeem, Karim, & Tiwari, 2022; Naeem, Karim, Uddin, et al., 2022). The pandemic has affected not only public health but also the economies of countries worldwide. The globalized nature of financial markets has made it easy for economic shocks to spread quickly from one market to another, leading to increased volatility and uncertainty (Billah et al., 2022; Karim, Naeem, Hu, et al., 2022c; Karim, Naeem, Mirza, et al., 2022d). In addition, COVID-19 has caused disruptions to global supply chains, leading to reduced trade volumes and a slowdown in economic activity (Bown, 2022; Siddique et al., 2022, 2023). This has affected various sectors, including manufacturing, transportation, and retail. As a result, the stock prices of companies in these sectors have been negatively affected, leading to spillover effects on the broader financial markets. Subsequently, governments and central banks have responded to the economic impacts of COVID-19 by implementing unprecedented monetary and fiscal policies (Yousaf et al., 2023). For example, central banks have lowered interest rates and provided liquidity to financial markets, while governments have implemented stimulus packages to support businesses and households. Finally, COVID-19 has also led to changes in investor behavior, with many investors adopting a more risk-averse approach (Arfaoui et al., 2023), leading to increased demand for safe-haven assets such as gold that ultimately leads to spillover effects on other asset classes such as equities and corporate bonds (Farid et al., 2023).

Traditionally, prior studies employed various connectedness methodologies to examine the relationship between green bonds and financial markets. For instance, Nguyen et al. (2020) and Reboredo et al. (2020) employed wavelet coherence analysis, Reboredo et al. (2019) utilized VAR models, Pham (2021) and Arif et al. (2021) used the cross-quantilogram technique, and Bouri et al. (2021) and Broadstock and Cheng (2019) applied GARCH model. While all these studies captured various aspects of green bonds, the sophistication of time-varying optimal copula (TVOC) under multiple regimes and economic and financial circumstances has not been explored by the earlier studies. In this vein, policymakers and investors are keen to understand the linkages between green bonds and financial markets at assorted copulas under various adverse conditions.

In light of the above arguments, the contribution of the current study is manifold. First, we employed the TVOC approach modelled by Liu et al. (2017) to examine the tail dependence between green bonds and financial markets, which characterize several stressful periods and symbolize discrete copulas for the period encapsulating January 2, 2012 to September 30, 2021. We contend that financial markets are exposed to various financial and economic risks, while tail dependence offers novel intuitions to the policymakers, financial market participants, and investors while weighing their portfolios amidst global crises. Second, we utilized a blend of financial markets, such as clean energy, stocks, commodities, US dollar, bonds, and Bitcoin, representing six different financial markets. Third, we measured the extreme risk spillovers between green bonds and financial markets using the Value-at-Risk (VaR) and conditional dynamic Value-at-Risk (CoVaR) arguing that spillovers at tails provide unique insights to investors under extreme circumstances. Fourth, we add to the existing literature by devising beneficial investment potentials and useful policy implications for governments and macro-prudential authorities.

Correspondingly, in terms of contribution of the study, we differ from the study of Pham and Nguyen (2021) on several aspects. First, the aforementioned study applied cross-quantilogram on the data set to identify asymmetric relationship of green bonds and other asset classes. We applied TVOC approach on the data set along with unique risk measure of VaR and CoVaR. Secondly, the data span of current study covers the time period from January 2, 2012 to September 30, 2021 whereas the data set of the aforementioned study covers October 2014 to February 2021. Finally, the current study also differs in terms of market selection and assessing their extreme risk dependence as compared to Pham and Nguyen (2021).

We document significant tail-dependencies between green bonds and financial markets where most of the markets exhibited numerous tail-dependent copulas corresponding to their respective symmetric and asymmetric tail-dependent relationships. Along with these, time-varying properties underscore various economic and financial trends which echoed European Sovereign Debt Crisis, Shale oil crisis, Brexit referendum, US interest rate hike, and COVID-19 pandemic. Pairwise analysis of financial markets with green bonds reveals that green bonds act as diversifiers for clean energy and stocks, while significant safe-haven features are emphasized for US dollar and Bitcoin markets. Concurrently, green bonds also provide strong hedge and safe-haven features to conventional bonds and commodities during normal and economically tumultuous periods, respectively. To validate our results further, the log-likelihood values also embodied justification for using the TVOC approach. Extreme risk spillover analysis substantiated spillovers during COVID-19, except Bitcoin, where extreme risk spillovers were formed during 2015, confirming a $5 million loss by Bitstamp.

Given these results, we proposed plentiful implications for policymakers, green investors, regulation authorities, macro-prudential bodies, portfolio managers, and financial market participants. Policymakers can encourage the markets to expand the growth of the green bonds due to their trifold benefits, such as diversification, risk-absorbance, and satisfying the eco-friendly motives of investors. Hence, policymakers can restructure and reformulate their existing policies to shelter investors from uncertain economic conditions. Investors and portfolio managers can include green bonds while synthesizing their portfolios to relish their risk mitigation attribute. When market circumstances are unfavorable, the perseverance of green bonds can shelter the investments of green and financial markets from extreme economic periods.

The rest of the paper unfolds as follows: Section 2 illustrates empirical strategy along with Data and Preliminary Statistics; Section 3 gives empirical results and discussion. Section 4 concludes the study with policy implications.

2 | EMPIRICAL STRATEGY, DATA AND PRELIMINARY ANALYSIS

2.1 | Data and descriptive statistics

This study endeavors to investigate tail dependence between green bonds and financial markets, where S&P Green Bond Index (SPGB) represents green bonds and financial markets included in the study are S&P Clean Energy Index (SPCL), which indicates clean energy market, MSCI Global Index (MSCI) is representative of world stock market, S&P GSCI Commodity Index (GSCI) which denotes commodity market, US Dollar Index (UDSX) is indicative of currency market, PIMCO Investment Grade Bond Index (BOND) symbolizes fixed-income bond market, and Bitcoin (BTCN) which denotes cryptocurrency market. The data have been extracted from Datastream for the period encompassing January 2, 2012 to September 30, 2021 and the price series is converted into first-log differenced returns to obtain empirical results.

Table 1 presents summary statistics and correlation of green bonds with other financial markets where BTCN reveals the highest average returns among all financial markets. SPCL and MSCI yield moderate and parallel average returns, whereas USDX and BOND generate minimum average returns. However, SPGB and GSCI yield negative average returns for the sample period. While considering the return series variability, BTCN marks the highest variability in the returns, whereas SPCL and GSCI show comparable variability in the return series. Conversely, MSCI, UDSX, BOND, and SPGB manifest parallel variability in the return series. Almost all return series, except UDSX, indicate negative skewness values, while the return series is leptokurtic, as evident from the kurtosis values. Multiple tests, for instance, the Jarque-Bera test of normality, exhibit that series are not normally distributed.

Further evidence of all return series reveals no serial correlation and conditional heteroskedasticity. Meanwhile, the correlation between green bonds and financial markets is mainly positive except for UDSX, which is negatively correlated with SPGB. Moreover, the highest (lowest) positive correlation is documented between SPGB and BOND (BTCN).

TABLE 1 This table presents descriptive statistics and correlation with green bond.

This table reports Jarque–Bera (J-B) normality statistics; ARCH tests the presence of heteroskedasticity in the return series; Q(20) is the Ljung-Box statistics of autocorrelation of t returns up to 20 lags, respectively. ***Statistical significance at the 1% level.

Market	Symbol	Mean	Max	Min	SD	SK	KT	JB	ARCH	Q(20)	Correlation with SPGB
S&P Clean Energy Index	SPCL	0.036	11.035	−12.498	1.378	−0.663	10.363	11,592.707	741.480	143.586	0.217
MSCI Global Index	MSCI	0.034	8.061	−9.997	0.847	−1.409	22.899	56,525.941	893.207	208.258	0.248
S&P GSCI Commodity Index	GSCI	−0.023	7.617	−12.522	1.273	−0.852	10.615	12,276.313	325.465	36.153	0.135
US Dollar Index	UDSX	0.006	2.032	−2.399	0.405	0.002	1.987	420.034	175.762	30.957	−0.682
PIMCO Investment Grade Bond Index	BOND	0.005	6.818	−5.083	0.389	−0.440	75.497	605,248.472	838.271	156.391	0.321
Bitcoin	BTCN	0.364	48.478	−66.395	5.379	−1.011	19.498	40,803.963	388.883	61.440	0.029
S&P Green Bond Index	SPGB	−0.002	2.007	−2.438	0.327	−0.380	5.788	3620.731	254.724	25.080	1

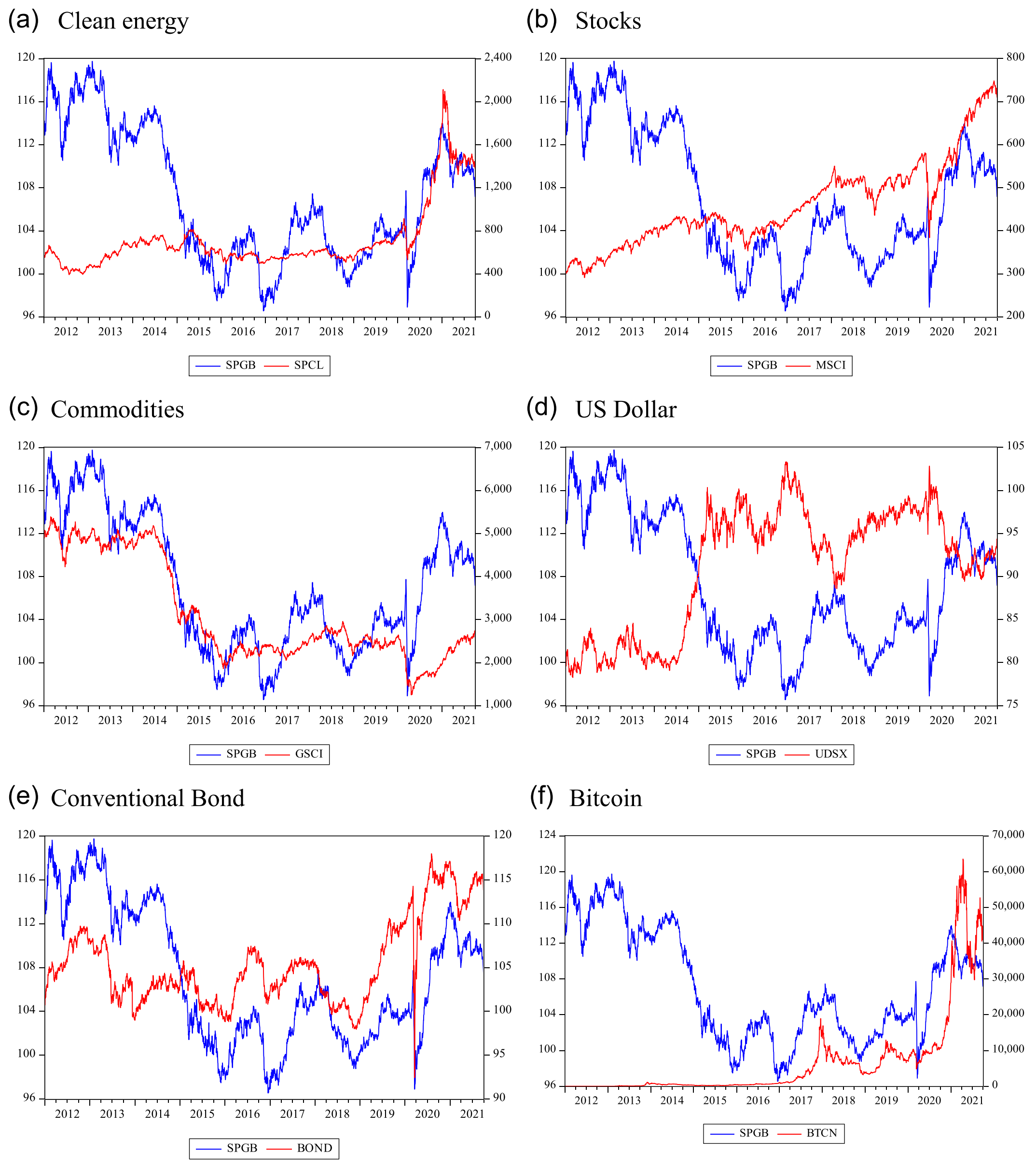

FIGURE 1 This figure presents time trend of green bonds and financial markets.

Figure 1 presents the time trend of green bonds and financial markets where SPCL, MSCI, UDSX and BTCN revealed highly volatile patterns whereas GSCI and BOND signpost parallel time-varying trend with SPGB.

2.2 | TVOC approach

Assuming that markets undergo several price changes and their interactions depend on external shocks and asymmetric information, the dependence structure among markets is dynamic. Thus, using a single copula to explain various markets' dynamics simultaneously restricts the dependence structure, and TVOC provides precise information across multiple financial markets. The dependence structure is generally split into positive and negative dependence, where external shocks make this structure nonlinear and complex. For this purpose, Kendall's τ measures the dependence direction and intensity. The two tail dependence structures of Joe (1997) and Caillault and Guégan (2005) for the upper and lower tail are employed. Additional functions of lower–upper tail and upper–lower tail explain the extreme dependencies across various financial markets in the presence of external shocks.

For two random constructs X and Y along with their respective distribution functions F_X and F_Y for $\alpha = 0.05$,

$$\tau^{UU}(\alpha) = \Pr(X > F_{X^{-1}}(1-\alpha)|Y > F_{Y^{-1}}(1-\alpha)), \tag{1}$$

$$\tau^{LL}(\alpha) = \Pr(X < F_{X^{-1}}(\alpha)|Y < F_{Y^{-1}}(\alpha)), \tag{2}$$

$$\tau^{LU}(\alpha) = \Pr(X < F_{X^{-1}}(\alpha)|Y > F_{Y^{-1}}(1-\alpha)), \tag{3}$$

$$\tau^{UL}(\alpha) = \Pr(X > F_{X^{-1}}(1-\alpha)|Y < F_{Y^{-1}}(\alpha)). \tag{4}$$

Here $\tau^{UU}(\alpha)$ denotes upper–upper (upper) tail-dependence, $\tau^{LL}(\alpha)$ is indicative of lower–lower (lower) tail-dependence, $\tau^{LU}(\alpha)$ depicts lower–upper tail dependence, and $\tau^{UL}(\alpha)$ shows upper–lower tail-dependence. The additive lower–upper ($\tau^{LU}(\alpha)$) and upper–lower ($\tau^{UL}(\alpha)$) characterize complete dependence structures across markets specifying extreme comovements. Therefore, $\tau^{LU}(\alpha)$ and $\tau^{UL}(\alpha)$ are more precise in terms of extreme dependence as compared to $\tau^{UU}(\alpha)$ and $\tau^{LL}(\alpha)$. Meanwhile, the asymmetric negative extreme dependence is expanded through Clayton and Gumbel copulas in the next subsection.

A copula is a multivariate probability distribution with uniform marginal distributions on the intervals 0 and 1. In other words, if random constructs U and V are said to be uniform following 0 and 1 interval, respectively, then the copula function is denoted as joint distribution of vectors U and V in terms of $(U, V) \sim C$. Following Sklar (1959), the bivariate random vector for X and Y constructs are obtained through joint distribution F as below:

$$F_{(x,y)} = C(F_X(x), F_Y(y)). \tag{5}$$

Here marginal distributions are denoted by F_X and F_Y and C denotes copula function describing the dependence structure between X and Y. We assume that all functions can be varied; therefore, bivariate joint density is given as:

$$f(x, y) = c(u, v).\, f_X(x).\, f_Y(y). \tag{6}$$

In Equation (6), $u = F_X(x)$ and $v = F_Y(y)$ along with the density function of copula $c(u, v) = \frac{\partial^2 C(u,v)}{\partial u \partial v}$.

The most renowned copulas are Normal, t where both copulas define symmetric and positive/negative dependence. In return, Gumbel, rotated Gumbel, Clayton, and rotated Clayton are representative of asymmetric positive dependence. It is important to note that a normal copula carries no tail dependence, whereas Student t copula possesses symmetric tail dependence. Meanwhile, Clayton and rotated Gumbel copulas symbolized lower tail dependence, and Gumbel and rotated Clayton signify upper tail dependence. The upper and lower tail dependence are manifested as:

$$\lambda_U(v) = \lim_{v \to 1} P[X > F^{-1}(v) | Y > F^{-1}(v)] = \lim_{v \to 1} \frac{1 - 2v + C(v, v)}{1 - v} \quad , \tag{7}$$

$$\lambda_L(v) = \lim_{v \to 0} P[X < F^{-1}(v) | Y < F^{-1}(v)] = \lim_{v \to 0} \frac{C(v, v)}{v}. \tag{8}$$

Here $0 \leq \lambda_U \leq 1$, $0 \leq \lambda_L \leq 1$.

For capturing extreme dependencies in counter directions, it is compulsory to construct fresh copulas by the rotation of 90 and 270°. In this way, updated upper and lower tail dependencies of freshly created half-rotated copulas are written as:

$$\lambda'_U(v) = \lim_{v \to 1} P[X < F^{-1}(1 - v) | Y > F^{-1}(v)] = \lim_{v \to 1} \frac{1 - 2v + C_{\frac{R90}{270}}(v, v)}{1 - v}, \tag{9}$$

$$\lambda'_L(v) = \lim_{v \to 0} P[X > F^{-1}(1 - v) | Y < F^{-1}(v)] = \lim_{v \to 0} \frac{C_{\frac{R90}{270}}(v, v)}{v}. \tag{10}$$

Here condition applies $0 \leq \lambda'_U \leq 1$ and $0 \leq \lambda'_L \leq 1$.

Given that Equations (7) and (8) present positive tail dependence in the third and first quadrants, Equations (9) and (10) reflect negative tail dependence in the fourth and second quadrants.[1]

TVOC joins all combinations of copulas as provided in Table 2 and signposts potential dependencies in the tails in terms of switching from positive to negative dependence. Thus, there are two steps to model TVOC approach (1) optimal copula (OC) and (2) time-varying modeling based on Liu et al. (2017).

2.3 | Modeling OC

As mentioned in the previous subsection, various types of copulas describe positive and negative tail dependencies. Nevertheless, it is very difficult for them to fit the dependence types concurrently. Thus, the first step involves testing the direction of dependence between X and Y where corresponding copulas are selected based on their direction. For this purpose, the distribution-free test is applied proposed by Liu et al. (2017) to identify the underlying relationships. For variables X and Y having n length, it is measured whether Kendell's τ is positive provided that it measures the average market dependence and whether it is negative, where both null hypotheses set tau to be zero, that is, $\tau = 0$.

Results are interpreted following the conditions:

[1]Refer to Karim, Khan, et al. (2022) for copula specifications employed in the TVOC framework.

TABLE 2 This table presents Kendall's τ over the whole sample period and proportions for the five categories of copulas.

This table reports that Kendall denotes Kendall's τ over the whole sample period. Lower–Upper denotes the proportion of the total number of best-fitting copulas for the Lower–Upper copulas (R2 Clayton and R1 Gumbel). Upper–Upper, Lower–Lower and Upper–Lower are similar. Symmetric denotes the proportion of symmetric dependence copulas (Normal and *t*). ***Rejection of null hypothesis of test T_1 at 1%.

	Kendall	Lower–Upper R2 C, R1 G (%)	Upper–Upper R C, G (%)	Lower–Lower C, R G (%)	Upper–Lower R1 C, R2 G (%)	Symmetric *N*, *t* (%)
SPGB-SPCL	0.123	0.040	15.980	14.360	14.710	54.900
SPGB-MSCI	0.155	0.000	8.190	5.210	11.560	75.040
SPGB-GSCI	0.086	0.610	13.880	31.960	1.750	51.800
SPGB-UDSX	−0.499	3.420	0.000	0.000	6.480	90.110
SPGB-BOND	0.201	0.000	2.150	42.290	1.880	53.680
SPGB-BTCN	0.014	9.110	14.450	12.830	12.610	51.010

(i) OC fitting samples are selected from the set of copulas encompassing [normal, Student *t*, Clayton, rotated Clayton, Gumbel, and rotated Gumbel] if the value of Kendall's τ is positively significant.
(ii) OC fitting samples are selected from the set of copulas carrying [normal, Student *t*, Clayton-90-degree, rotated Clayton-270 degree, Gumbel-90 degree, and rotated Gumbel-270 degree] if the value of Kendall's τ is negatively significant.
(iii) OC fitting samples are selected from all set of copulas as mentioned in (i) and (ii) then the value of Kendall's τ is insignificant.

By employing this process of fitting OC samples, we can compare the log-likelihood values for each copula. Meanwhile, the changes in the market dependencies are tracked by repeating the two steps for each subsample as given below:

Step 1: We fit the subsample at time t where t is considered as the last point within the subsample, and then we compute the marginal distributions for constructs F_X and F_Y independently. Thus, we attain the uniform (0, 1) series for u and v at each window;

Step 2: We calculate Kendall's τ for subsample at time t and perform the distribution-free tests as explained earlier. Given varying results in each copula, we select the OC from multiple sets of OC functions.

2.4 | Modeling time-varying (TV) process

Based on Liu et al. (2017), a fixed window of 260 days and a rolling ahead process for each day is used following the subsample characteristics mentioned above. When OC modeling is combined with TV modeling process, the obtained copula reveals distinct dependence structures as obtained from TV process. In other words, as Patton (2006) and Creal et al. (2008) explained, the resultant copula only possesses the dynamic features which solely reflect positive or negative dependencies. In our study, the TV process is parallel to a regime-switching method, where one of the major benefits is that we do not have to compute a large number of parameters with the increase in the regimes. Apart from Student *t* copula, the remaining copulas carry one respective parameter.

2.5 | Tail-risk in the spillovers

This subsection estimates the extreme risk spillovers from green bonds to financial markets by employing the technique of Adrian and Brunnermeier (2016). VaR is the value-at-risk and CoVAR is the conditional value-at-risk, which explains financial markets' conditional value-at-risk on green bonds. In other words, the VaR of green bonds in the q_1*-quadrant* is the conditional distribution (R_{GB}) of CoVaR of financial markets conditional distribution (R_{FM}) at q_2*-quadrant* as follows:

$$\Pr\left(R_{FM,t} \leq CoVaR^{FM|GB}_{q_2,t} \middle| R_{GB,t} \leq VaR_{GB,q_1,t}\right) = q_2. \tag{11}$$

Here we can say that $VaR_{GB,q_1,t}$ represents VaR of green bonds and *Pr* can be further explained as:

$$\frac{\Pr\left(R_{FM,t} \leq CoVaR_{q_2,t}^{FM|GB}, R_{GB,t} \leq VaR_{GB,q_1,t}\right)}{\Pr(R_{GB,t} \leq VaR_{GB,q_1,t})} = q_2. \tag{12}$$

Given that $P_r \leq VaR_{GB,\ \ q1,t} = q_1$, we can re-write the Equation (12) as:

$$\Pr\left(R_{FM,t} \leq CoVaR_{q_2,t}^{FM|GB}, R_{GB,t} \leq VaR_{GB,q_1,t}\right) = q_1 q_2. \tag{13}$$

Following this, Equation (13) can be rewritten for calculating copulas as:

$$F_{R_{FM,t},R_{GB,t}}\left(CoVaR_{q_2,t}^{FM|GB}, VaR_{GB,q_1,t}\right) = q_1 q_2. \tag{14}$$

If we invert the marginal distribution function $R_{FM}\,CoVaR_{q2,t}^{FM|GB} = F_{FM,t}^{-1}(u)$, then the above equation is written as:

$$C(u, v) = q_1 q_2. \tag{15}$$

Here, the copula function is represented as C(.,.) where $u = F_{R_{FM,t}}\left(CoVaR_{q2,t}^{\frac{FM}{GB}}\right)$ and $v = F_{R_{GB,t}}(VaR_{GB,q1,t})$. $F_{R_{FM,t}}$ and $F_{R_{GB,t}}$ are marginal distribution functions of $R_{FM,t}$ and $R_{GB,t}$ in an orderly manner. Afterward, for computing the value of u, all values of $C(u, v) = q_1 q_2$ and v $(v = q_1)$ are given; hence it becomes quite easy to calculate its value.

Since multiple copulas are used to capture the dynamic dependence, given the specific characteristics of each copula, u are obtained. Thus, considering the marginal modeling, $F_{R_{FM,t}}$ is achieved.

3 | EMPIRICAL RESULTS

3.1 | TVOC estimates

Empirical results in Table 2 and Figures 2–7 illustrate that the dependence structure between green bonds and financial markets are asymmetric and positive except for SPGB-UDSX, where dependence structure is mainly symmetric and negative with substantial tail-dependence. We also report that TVOC demonstrates higher values compared with each copula of green bonds and financial markets. Further, Table 2 displays that *t* copula contains the largest proportion of the best-fitting copulas, which determines that dependence between green bonds and financial markets is symmetric and tail-dependent, necessitating the TVOC technique. Meanwhile, given the varied periods, most of the copulas show rotated Clayton and rotated Gumbel arrangements which suggest that positive tail-dependence is evident in some of the pairs. In contrast, some pairs denote half-rotated Clayton and half-rotated Gumbel, providing evidence of negative asymmetric dependencies. Our findings are well-aligned with Liu et al. (2017), Naeem and Karim (2021), Karim, Naeem, Mirza, et al. (2022), Karim et al., (2023a, 2023b, 2023c) for demonstrating similar dependence structures among various types of markets.

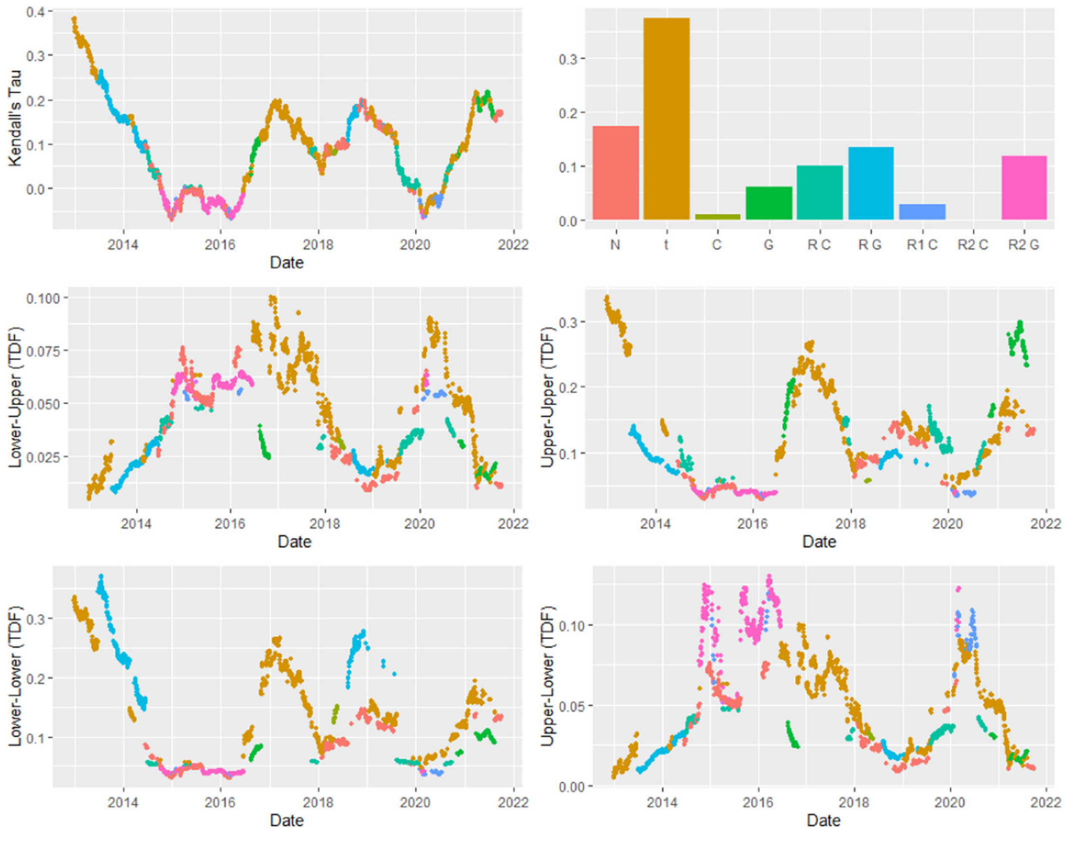

FIGURE 2 This figure presents TVOC estimates for green bonds and clean energy. Panel (a) presents Kendal's tau derived from the tail dependence parameters; Panel (b) presents the proportion of the total number of best-fitting copulas for every copula, where the horizontal axis represents the types of copula model under consideration (N: normal; t: Student *t*; C: Clayton; G: Gumbel; RC: 180° rotated Clayton; RG: 180° rotated Gumbel; R1C: 90° rotated Clayton; R1G: 90° rotated Gumbel; R2C: 270° rotated Clayton; R2G: 270° rotated Gumbel); Panels (c–f) are the time-varying tail dependence parameters. TDF, tail-dependence function; TVOC, time-varying optimal copula.

Further, detailed evidence of each pair of green bonds and financial markets suggests that each pair's time-varying OC vary. For instance, Figure 2 displays the TVOC estimates between green bonds and clean energy market where best-fitting copulas are mainly related to Student *t* (symmetric and tail-dependent) and Normal (symmetric and no tail-dependence) copulas. However, rotated Gumbel (asymmetric, positive dependence) and half-rotated Gumbel (asymmetric, negative dependence) copulas also reflect the dependence between green bonds and clean energy. Figure 2a represents time-varying attributes of TVOC where initially dependence between green bonds and clean energy market is symmetric and tail-dependent reflecting European Sovereign Debt Crisis (2010–2012). Soon after ESDC, the dependence shifted towards blue copula (rotated Gumbel), revealing positive dependence in the lower tails. A declining trend in the comovement between green bonds and the clean energy market until 2015 is observed where pink copula (half-rotated Gumbel) is dominant, highlighting asymmetric negative dependence of upper–lower tails during the start of Shale oil crisis (2015–2016). Nevertheless, the dependence turned out to be symmetric again during 2018,

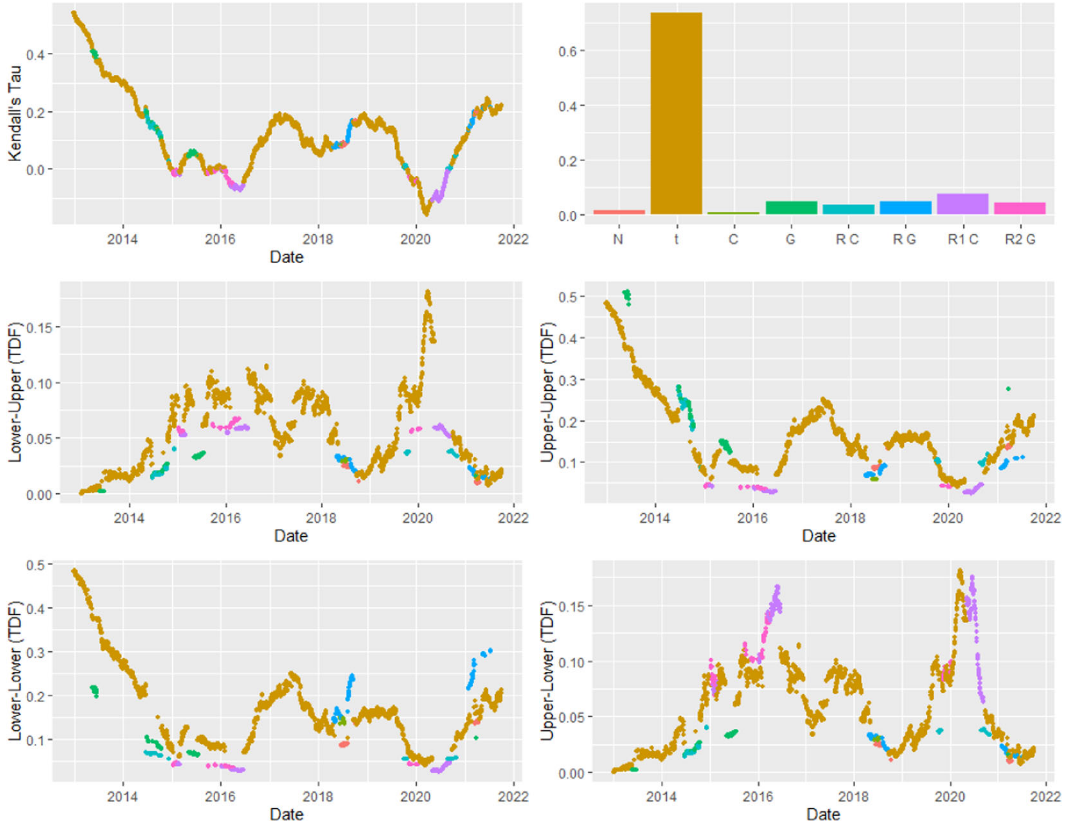

FIGURE 3 This figure presents TVOC estimates for green bonds and stocks. See notes in Figure 2. TVOC, time-varying optimal copula.

which reflects US interest rate hike and sudden increase in the interest rates surmounted the tail-dependence of financial markets (Kang et al., 2021; Naeem, Iqbal et al., 2022c; Naeem, Karim et al., 2022d). Concurrently, during the onset of COVID-19, the dependence structure shifted to sea green copula (rotated Clayton), symbolizing asymmetric positive dependence in upper tails. However, after COVID-19, markets started to stabilize and returned to their original operating positions. The dominant dependence is embodied by Student *t* copula. Figure 2c–f also illustrates time-varying OC in the lower–upper, upper–upper, lower–lower, and upper–lower dependence structures, stressing the existence of substantial asymmetric tail-dependence in both upper–upper classes and lower tails between green bonds and clean energy. Given the dependence structure between green bonds and clean energy, our findings corroborate Elsayed et al. (2020), who demonstrated the strong diversification potential of green bonds for several markets. Overall, it is revealed that considerable tail dependence between green bonds and clean energy exists given the sample period, and dependence structures are strengthened and predominantly tail-dependent following a stress period.

Figure 3 demonstrates the estimates between green bonds and stocks where dominant copulas are related to Student *t* copula, which carries symmetric and tail-dependent features. Meanwhile, the rest of the copulas show negligible dependence between green bonds and stocks. Lower dependence between green bonds and stocks echoes the findings of Arif et al. (2021), who documented diversification avenues of green bonds for stocks as the connectedness

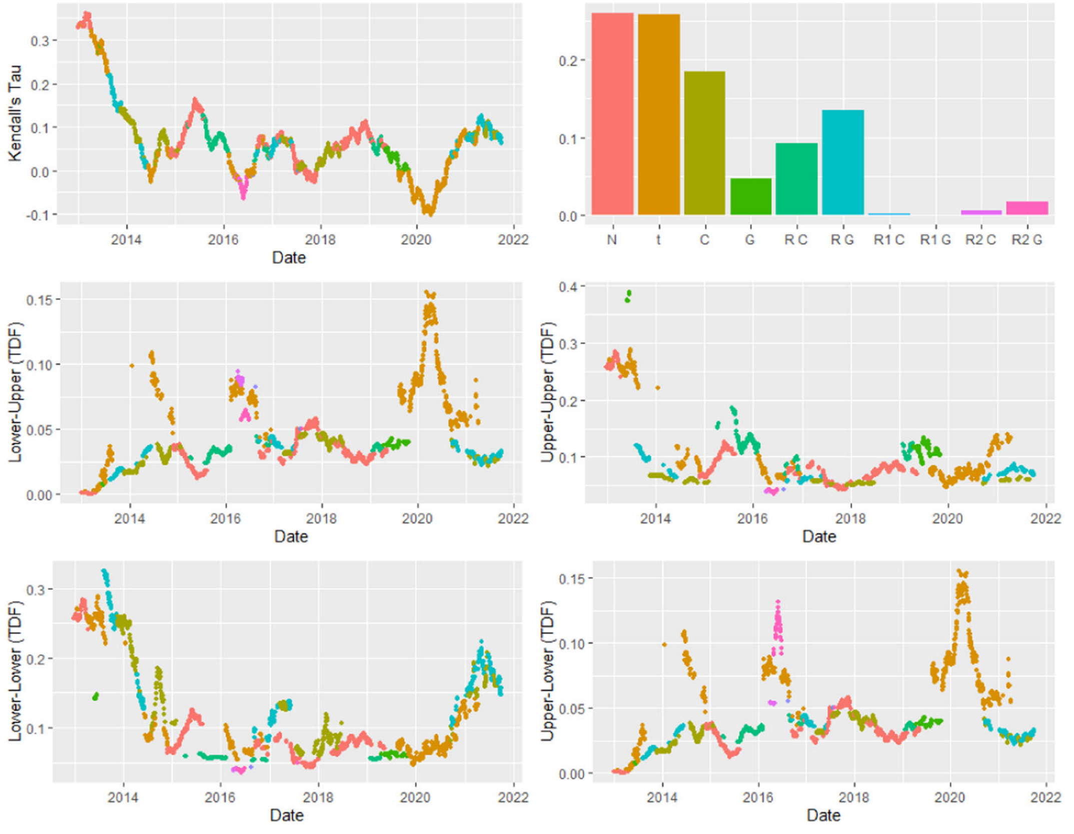

FIGURE 4 This figure presents TVOC estimates for green bonds and commodities. See notes in Figure 2. TVOC, time-varying optimal copula.

between green bonds and stocks is lower. In this way, green bonds can shelter the investments from adverse shocks and distressing periods by rescuing the investments from uncertainty and substantial losses. Figure 3a represents time-varying attributes of TVOC where the majority of the dependence structures following significant distressing events of European Sovereign Debt Crisis (Blundell-Wignall, 2012), Shale oil crisis, US interest rate hike (Kang et al., 2021), and COVID-19 pandemic signify Student *t* copula. Correspondingly, Figure 3c–f depicts that TVOC in the lower–upper, upper–upper, lower–lower, and upper–lower dependence structures where Student *t* copulas are dominant in the tails between green bonds and stocks. In summary, Figure 3 indicates that dependence between green bonds and stocks is symmetric with varying tail dependencies. Meanwhile, stress events reiterated the symmetric arrangements of copulas given time-varying attributes.

Figure 4 presents the TVOC measures for green bonds and commodities where histograms show best-fitting copulas are related to Normal, Student *t*, Clayton, rotated-Gumbel, rotated-Clayton, and Gumbel in an orderly manner. Since most of the dependence structures are dominated by Normal and Student *t*, intuitively, dependence between green bonds and commodities is symmetric with no tail dependence (Normal) and symmetric with tail-dependence (Student *t*) copulas. Clayton (parrot-green fragment) and rotated-Gumbel (blue fragment) copulas symbolize positive dependence in lower–lower tails, which suggests that green bonds and commodities show direct dependence mainly in their lower tails.

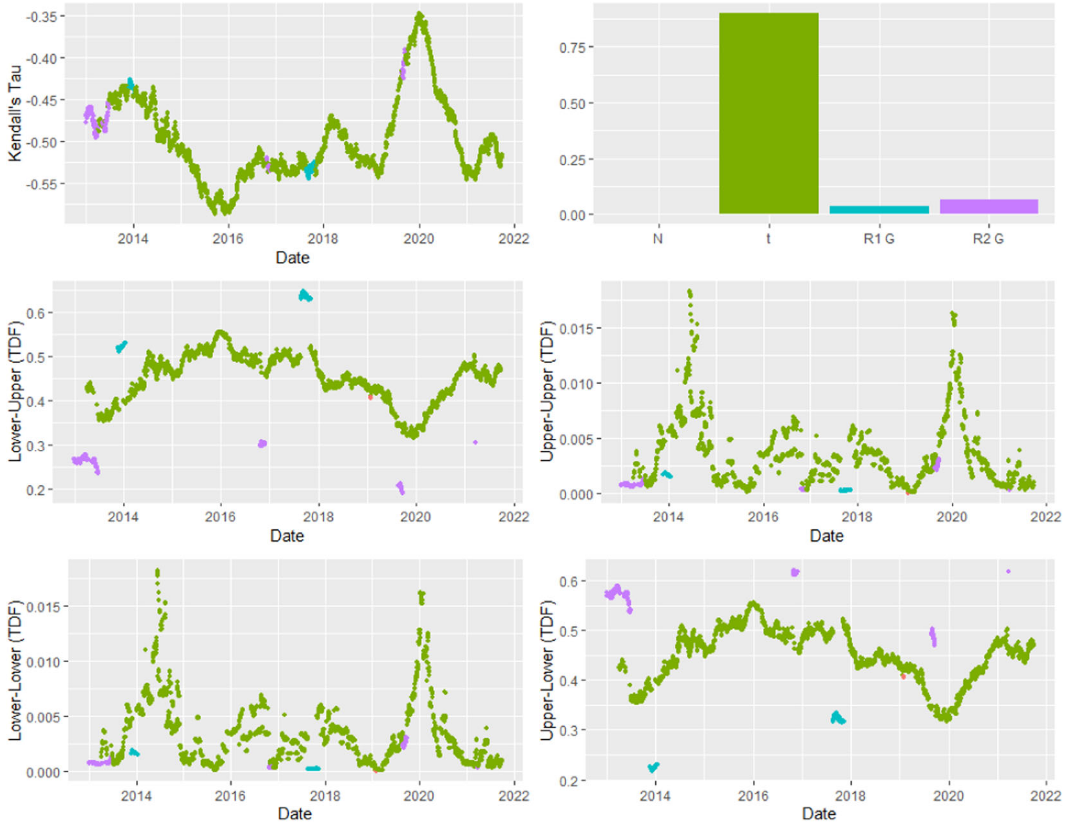

FIGURE 5 This figure presents TVOC estimates for green bonds and US dollar. See notes in Figure 2. TVOC, time-varying optimal copula.

Concurrently, rotated-Clayton (light-green fragment) and Gumbel (dark-green) copula arrays reveal positive dependence between green bonds and commodities in the upper–upper tails. Hence, direct dependence between green bonds and commodities in their upper and lower tails intuitively explains that green bonds are directly associated with commodities by reflecting their positive dependence implying positive comovements between green bonds and commodities due to the strong positioning of commodities in the financial markets and their inherent integration.

The aggregate dependence associations are reflected in Figure 4a, where time-varying characteristics between green bonds and commodities show varying dominance of copulas given multiple events of economic ups and downs. There is an increasing dependence during ESDC with symmetric arrangements of copula reflecting peach-colored fragment initially. As the dependence declines gradually, the comovement varies given the positive dependence in both upper–upper and lower-lower tails. During the Shale oil revolution and US interest rate hike, dependence re-echoes dominance of Normal copula contending prevalent direct dependence between green bonds and commodities during the oil crisis. However, the dependence structure during COVID-19 switched to Student *t* copula in the downward direction, which sufficiently explains the gigantic havoc and adversity created by the pandemic (Avramov et al., 2022), which substantially shifted the positive dependence into a negative relationship between green bonds and commodities. The negative dependence during the

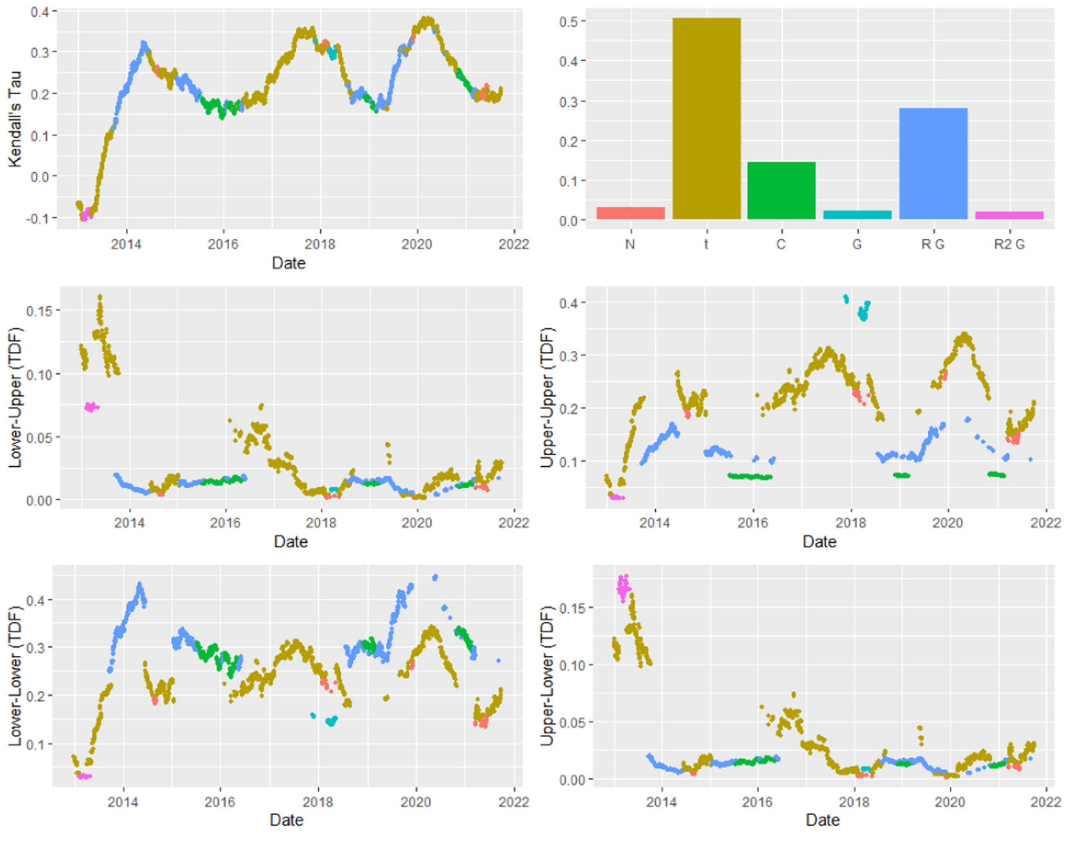

FIGURE 6 This figure presents TVOC estimates for green bonds and conventional bonds. See notes in Figure 2. TVOC, time-varying optimal copula.

COVID-19 pandemic reflects strong safe-haven features of green bonds for commodities in line with Arif et al. (2021), who demonstrated strong safe-haven characteristics of green bonds, particularly during the epidemic of COVID-19. Figure 4c–f manifests the dependence structures between green bonds and commodities in the lower–upper, upper–upper, lower–lower, and upper–lower tails where remarkable changes in the comovements suggest positive tail-dependence between commodities and green bonds.

Figure 5 demonstrates the TVOC estimates between green bonds and US dollar index, where interesting findings are obtained with discrete dominance of Student *t* copula for the whole sample period, which explicitly explains the symmetric arrangements with considerable negative tail-dependence. Meanwhile, minor fragments of rotated (R1G) and half-rotated Gumbels (R2G) copulas are reported, symbolizing negative dependencies in the upper–lower tails. The predominant negative dependence between green bonds and US dollar indicates that both financial markets counter-move for the given sample period. Meanwhile, the intuitive explanation of these negative time-varying results for the whole sample period point toward hedge and safe-haven attributes of green bonds for US dollars during normal and distressing periods, respectively. These findings imply the correlations between US dollar and green bonds are negative, necessitating the strong safe-haven feature of green bonds against US dollar given

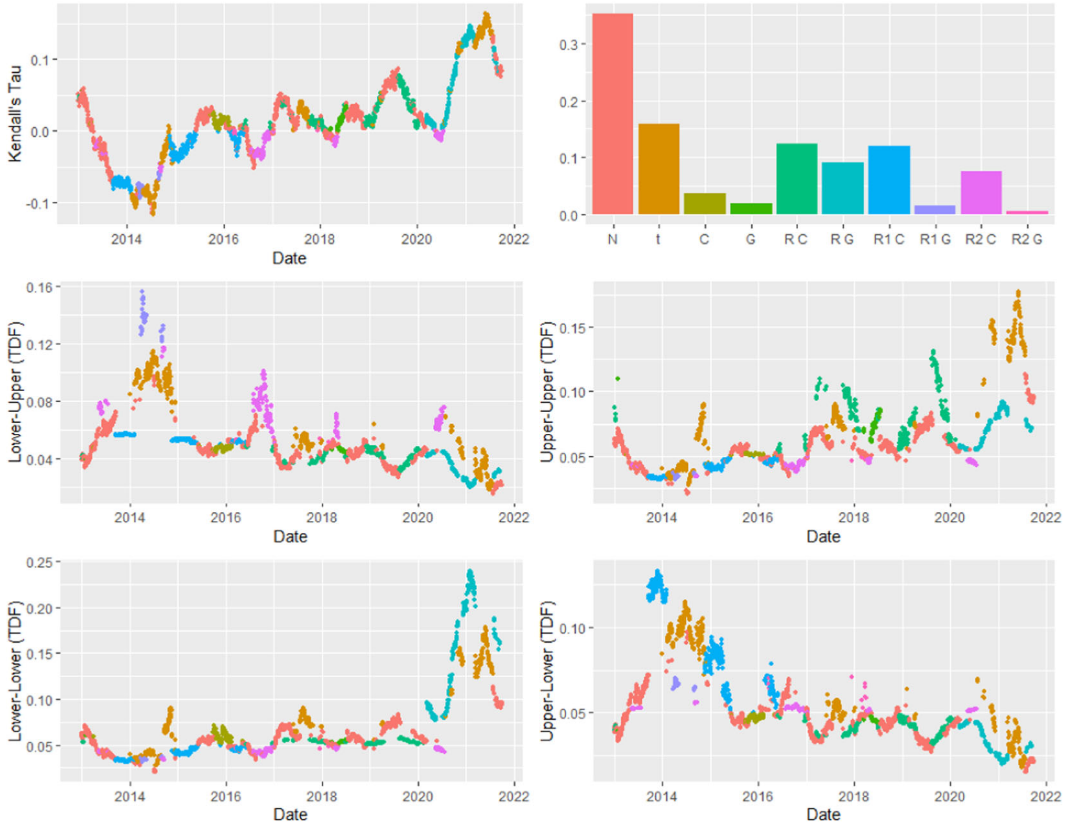

FIGURE 7 This figure presents TVOC estimates for green bonds and Bitcoin. See notes in Figure 2. TVOC, time-varying optimal copula.

the tumultuous economic strains (Karim, Khan, Mirza, et al., 2022a; Karim, Lucey, Naeem, et al., 2022b).

Moreover, strong safe-haven characteristics of green bonds for US dollar also indicate that investors can consider green investment potentials as prospective beneficial investment streams that ultimately shield the investments from harsh economic circumstances. The cumulative time-varying features in Figure 5a narrate parallel findings where initially negative tail-dependence is evident during ESDC while the rest of the plot echoes dominance of Student *t* copula for each distressed episode with inclined dependence. Figure 5c–f illustrates leading dependence in the upper–lower and lower-upper tails, whereas small scattered dependence fragments are evident in the upper and lower tails. The negative tail-dependence between green bonds and US dollar reverberate underlying uncertainty in the US dollar as well as strong safe-haven properties of green bonds for US dollar. In addition, the potential of safe-haven attributes can also be reported, which intuitively justifies the inclusion of green bonds in mainstream investment portfolios to avoid exponential losses due to economic and financial uncertainties.

Figure 6 exhibits TVOC estimates between green bonds and conventional bonds where best-fitting copulas correspond to Student *t*, rotated-Gumbel, and Clayton, whereas the little contribution of Normal, Gumbel, and half-rotated Gumbel is also reported. The dependence structure between green bonds and conventional bonds is symmetric and mainly tail-dependent, referring to Student *t* copula, while rotated-Gumbel and Clayton show asymmetric positive dependence in the lower–lower tails. The positive dependence between green bonds and conventional bonds refers to the arguments of Reboredo et al. (2020), who narrated green bonds are subsets of conventional bonds and share comparable features of fixed-income securities. In this way, conventional bonds and green bonds comove for the whole sample period. The aggregate dependence in Figure 6a demonstrates time-varying features between green and conventional bonds where initially declining dependence coincides with the ESDC and symmetric tail-dependent characteristics are dominant. An incline in the graph is observed with asymmetric positive dependence in the lower tails, given the aftermaths of ESDC. However, decreasing dependence is evident with varying copulas during Shale oil crisis, Brexit referendum, and US interest rate hike.

Moreover, negative dependence during ESDC shadows on the safe-haven features of green bonds for conventional bonds and consistent positive dependence afterward reflects the hedge capacity of green bonds. Thus, green bonds tend to act as safe-haven during ESDC and hedge during stable periods with continuous positive dependence. Similar findings are reflected in Figure 6c–f where, at different tails, the dependence structure is predominantly symmetric and tail-dependent, with few traces of asymmetric positive dependence in the lower tails of both markets.

Figure 7 represents tail-dependence between green bonds and Bitcoin where best-fitted copulas are Normal, Student *t*, rotated and half-rotated Clayton (90-degree), rotated-Gumbel, half-rotated Clayton (270-degree), and Clayton. The copula arrangements reveal that the dependence structure between green bonds and Bitcoin is symmetric with no tail-dependence. Meanwhile, Student *t* copula pattern suggests symmetric and tail-dependence structures. The RC and RG arrays are indicative of positive dependence in the upper-upper and lower-lower tails, respectively, which ascertains that dependence between green bonds and Bitcoin is positive in the upper and lower tails. Correspondingly, R1C and R2C manifest negative dependence between the two financial markets in the upper–lower and lower-upper tails following the sample period, which sufficiently justifies the strong safe-haven characteristics of green bonds for Bitcoin (Liu & Tsyvinski, 2021; Naeem & Karim, 2021). Our findings narrate that the dependence arrangement between green bonds and Bitcoin is mostly tail-dependent irrespective of positive (negative) and upper (lower) tails. The cumulative dependence in Figure 7a shows that initially, during ESDC, dependence corresponds to Normal copula and is positive without significant tail-dependence when markets were undergoing distressed episodes following the European Sovereign Debt Crisis. One plausible explanation for symmetric dependence between green bonds and Bitcoin is the lowest concentration of investors and governments toward green initiatives during this period; therefore, there is negligible positive tail-dependence. Right after ESDC, the dependence shifts toward negative dependence, reflecting recovery of the financial markets with dominant Student *t* copula, which symbolizes hedging properties of green bonds for Bitcoin. During the Shale oil crisis, the dependence switched between Normal and Clayton copulas, which sufficiently describe the shift in dependence from symmetric to the asymmetric arrangement, particularly in the lower tails signifying the stress period characterized the dependence in the lower tails.

Further, prominent ups and downs are observed during the eras of Brexit, the cryptocurrency bubble burst (Corbet et al., 2018; Karim, Appiah et al., 2022e; Lucey et al., 2021), US interest rate hike, and COVID-19, where sizable comovements are illustrated between green bonds and Bitcoin. The dependence structure remained positive for most of the crisis periods except after ESDC, which substantiates the hedging features of green bonds against Bitcoin. Overall, it is manifested that tail-dependence between green bonds and Bitcoin features the

TABLE 3 This table presents the log-likelihood values for TVOC, time-varying copula and nondynamic copula models.

	TVOC	TV-Normal	TV-t	Normal	*t*
SPGB-SPCL	70.548	59.505	67.606	39.177	49.860
SPGB-MSCI	124.670	106.264	123.079	68.890	99.543
SPGB-GSCI	48.581	38.958	43.681	21.963	26.179
SPGB-UDSX	861.156	818.153	859.792	828.908	864.843
SPGB-BOND	206.189	178.323	198.813	126.804	152.223
SPGB-BTCN	12.760	10.297	8.751	1.279	−0.079

external shocks and intensity of stress events determine the appropriate copulas for dependence along with safe-haven and hedge characteristics of green bonds for Bitcoin (Liu & Tsyvinski, 2021). Figure 7c–f also explains subsequent dependence in the respective tails where substantial tail-dependence is reported in the upper–lower and lower-upper tails, conquering our findings in Figure 7b.

As additional evidence, Table 3 explains the log-likelihood of TVOC with time-varying copula and nondynamic copula models, which exhibits that the employed methodology supersedes all financial markets pairs compared to other benchmark techniques. Moreover, the table's values also prove that the TVOC approach can best determine the dynamic dependence features between green bonds and financial markets.

3.2 | VaR and CoVaR estimates

For further validating our findings of TVOC approach, we examined the risk spillovers of green bonds and financial markets by quantifying the VaR and CoVaR measures of risk. Figure 8 presents the upside and downside values of VaRs and CoVaRs between each pair of green bonds and financial markets. In general, parallel risk spillovers are examined by each risk pair where the sizable influence of external shocks, particularly COVID-19, is imprinted except for the SPGB-BTCN pair, which revealed surmounted risk spillovers during the 2015 wallet hack of Bitstamp increased the risk spillovers between green bonds and Bitcoin.[2] While quantifying the risk spillovers, we report parallel trends for SPGB-SPCL, SPGB-MSCI, SPGB-GSCI, and SPGB-BOND pairs, while SPGB-BTCN pairs revealed high-risk spillovers during 2015 and moderate risk during the COVID-19 pandemic. Noticeably, risk spillovers for SPGB-UDSX pair displayed scattered upside and downward VaRs and CoVaRs, which reiterate our findings in Figure 5 where tail dependence between green bonds and US dollar manifested abnormal dependence with a predominance of Student *t* copula echoing uncertainty in the US dollar index following uncertain economic conditions (Avramov et al., 2022; Cesa-Bianchi et al., 2020; Karim et al., 2023b; Naeem, Iqbal, et al., 2022c; Naeem, Karim, et al., 2023). In this way, extreme risk spillovers analysis highlights that uncertainty of the external economic circumstances shaped the dependence of green bonds and financial markets with significant spillovers during COVID-19 in particular.

[2]See https://www.coindesk.com/markets/2015/12/31/14-headlines-that-rocked-bitcoin-and-the-blockchain-in-2015/

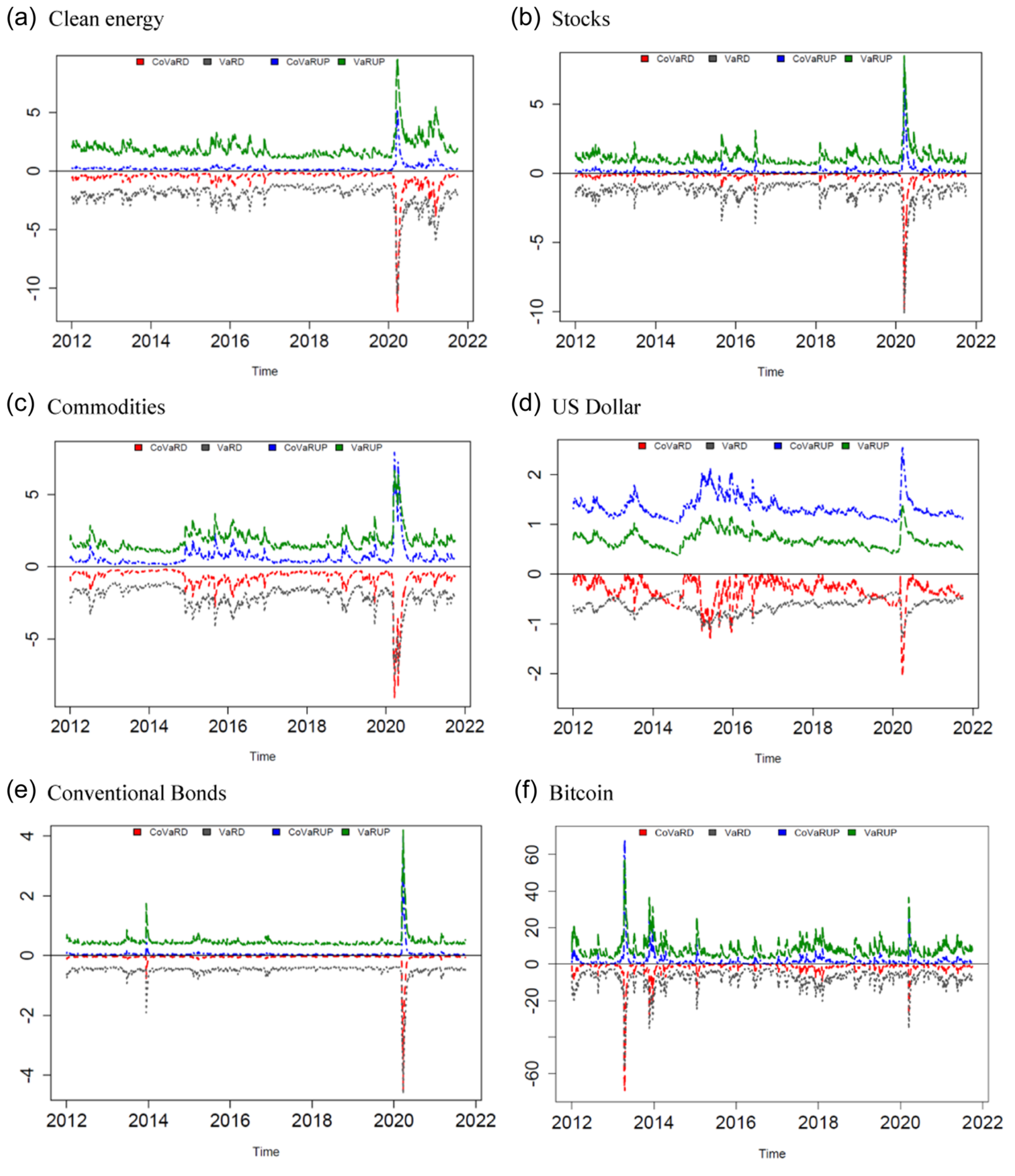

FIGURE 8 This figure presents spillovers from green bonds to financial markets. These figures show conditional value-at-risk (*CoVaR*) of the green bond.

4 | CONCLUSION

We examined the tail-dependence between green bonds and financial markets using the data of six financial markets, such as clean energy market, stock market, commodities, US dollar, conventional bonds, and Bitcoin, by employing the novel technique of TVOC proposed by Liu et al. (2017) for the period spanning January 2012 to September 2021. In addition, we quantified the risk spillovers between green bonds and financial markets by employing the VaR and

CoVaR estimates. Our findings highlight significant tail-dependencies between green bonds and financial markets, where most of the markets exhibited numerous tail-dependent copulas corresponding to their respective symmetric and asymmetric tail-dependent relationships. Along with these, time-varying properties characterize various economic and financial trends, which echoed European Sovereign Debt Crisis, Shale oil crisis, Brexit referendum, US interest rate hike, and COVID-19 pandemic. An independent analysis of financial markets reveals that green bonds act as diversifiers for clean energy and stocks, whereas significant safe-haven features are illuminated for US dollar and Bitcoin markets. Concurrently, green bonds also provide strong hedge and safe-haven features to conventional bonds and commodities during normal and distressing periods in an orderly manner. For further validation, the log-likelihood values also symbolized justification of the use of TVOC approach. Risk spillover analysis substantiated the COVID-19 pandemic except for Bitcoin, where it manifested enhanced risk spillovers during 2015, corroborating Bitstamp loss. We devise useful implications for policymakers, governments, macro-prudential authorities, investors, financial market participants, and portfolio managers by reporting these results.

Policymakers can relish these findings by including green bonds in the mainstream investments and assessing the tail dependence and diversification, safe-haven, and hedging avenues given the uncertainty of the economic and financial circumstances. As tail-dependence between green bonds and diverse financial markets depict varying patterns, the study can be utilized as a benchmark by the governments for determining the effectiveness of green bonds and their dependence structures with other financial markets in terms of their diversifiers safe-haven and hedgers roles. Investors can also cherish the study's findings by cautiously evaluating the available investment opportunities that service their profit-seeking and socially responsible motives. Concurrently, financial market participants and institutional investors can employ various risk measures to observe the costs and benefits of each investment pair keenly. In addition, investors can utilize the study's findings to evaluate the diversification potential, offer safe-haven or hedging avenues, and select the investments with minimum losses under uneven economic circumstances. Investors and portfolio managers can design their mainstream portfolios with less risky investments and include green bonds as diversifiers to mitigate risk by adopting useful strategies under haphazard economic episodes. As reported by the earlier empirical studies, green bonds act as diversifiers due to their high risk-absorbance during economically fragile periods. Thus, these findings provide support to the prior literature and insightful ramifications for the practitioners to reap the benefits of the study.

As a future research agenda, further studies can assess the hedge and safe-haven features of green bonds and other financial markets or stock markets such as global stocks, and so forth. Moreover, future research studies can employ other tail dependence methodologies, for instance, quantile connectedness to comprehensively assess whether the selected financial markets perform better than the other under extreme settings.

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DATA AVAILABILITY STATEMENT

All data are publically available and described in full in the paper. The data that support the findings of this study are available from the corresponding author upon reasonable request.

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