Heterogeneous Dependence Between Green Finance and Cryptocurrency Markets: New Insights from Time-Frequency Analysis

Nguyen Mau Ba Dang[*]

Abstract: Green finance is becoming more and more important as a way to fund environmentally friendly initiatives and lower carbon emissions. Green bonds have emerged as a significant financing tool in this context, and it is critical to understand how they interact with other components of the finance ecosystem, such as cryptocurrency and carbon markets, particularly during recent crises such as the COVID-19 outbreak and the Ukraine invasion. This study aims to empirically investigate the lead-lag associations between major cryptocurrency markets and green finance measured in terms of green bonds. For empirical estimation, the wavelet analysis and spectral Granger-causality test are employed to analyze the daily data, covering the period from 2018 to 2023. The results show that the correlation between the returns of the green bond market and cryptocurrencies is not stable over time, which rises from the short- to long-run horizon. However, the co-movements between these assets tend to be different and, in some cases, strong, especially during recent crises. Furthermore, the Granger causality test demonstrates the existence of a bi-directional causality between the prices of the cryptocurrencies and green bonds. These findings have significance for portfolio managers, investors, and researchers interested in investing strategies and portfolio allocation, suggesting that green markets may be used as a hedge and diversification tool for cryptocurrencies in the future.

Keywords: green bonds; cryptocurrencies; wavelet analysis; causality.

JEL classification: G10; G11; G15.

---

[*] Faculty of Finance and Banking, University of Finance - Marketing, Ho Chi Minh City, Vietnam; e-mail: badang@ufm.edu.vn.

1. INTRODUCTION

Climate change has become one of the most severe concerns confronting the world in recent decades, necessitating a worldwide agenda for green and sustainable development in the future (Gozgor and Karakas, 2023; Thi Xuan and Thai Hung, 2024). The question of whether green bonds would be used as a method of hedging in the context of financial risk management has grown increasingly relevant as their popularity in the financial markets grows (Udeagha and Muchapondwa, 2023). Since the introduction of this new way of banking and investing, public interest in crypto currencies has grown significantly. Due to their success and ability to diversify, cryptocurrencies have drawn in investors from all around the world (Patel *et al.*, 2023). Since then, there has been a growing interest in investigating the influence these financial innovations have on the global environment in the direction of a climate-resilient economy (Ye *et al.*, 2023).

Institutional and individual investors can also diversify their portfolios with green bonds and cryptocurrencies (Yadav *et al.*, 2023a). The need for safe haven securities and the diversification of portfolios have long been important elements of investment strategy. Among the alternative investments are cryptocurrencies and green bonds (Hung, 2023; Ul Haq *et al.*, 2023; Ye *et al.*, 2023). Investors and portfolio managers utilize these investment alternatives for hedging to lower risk due to their safe haven features. This paper examines the lead-lag relationship between green bonds and the main cryptocurrency markets in light of the increased demand for environmentally conscious investments in financial markets and the need to allocate financial resources for green initiatives.

Our motivation is that participants in cryptocurrency and sustainable financial markets have a variety of investment horizons and goals, which necessitates not only differentiating between social and financial returns due to environmental effects but also using a wavelet analysis to draw conclusions in a time-frequency space. The scholarly research on hedging shows potential distinctions between traditional cryptocurrencies. Additionally, during the past five years, the hedging and diversification functions of Bitcoin and other cryptocurrencies have grown (Ren and Lucey, 2022; Ye *et al.*, 2023); nevertheless, the hedging and diversification functions of green bonds with sustainable cryptocurrencies are still underutilized (Ye *et al.*, 2023; Zhang and Umair, 2023). We examine the leading and lagging roles of all asset types to answer these concerns.

To the best of our knowledge, no prior articles have looked at the intercorrelation and co-movement between crypto markets and green bonds, despite the fact that many studies have looked at the relationship between green and conventional financial markets, such as the stock, energy, and precious metals markets (Arfaoui *et al.*, 2023; Huang *et al.*, 2023; Lee *et al.*, 2023). This study attempts to address a gap in the literature by analyzing the interplay between green markets and the key cryptocurrencies (Ethereum - ETH, Bitcoin cash - BCH, Ripple - XRP, Bitcoin - BIT, and Ethereum Operating System - EOS) in recent crises (COVID-19 outbreak and the Ukraine invasion).

Accordingly, this study explores the causal causality and lead-lag linkage between the green bond market and cryptocurrency indices using a time-frequency analysis. The primary goal of this study is to determine differences in the pattern of the green-crypto nexus over recent crises (the COVID-19 pandemic and the Russia-Ukraine war) and to give a clear picture of the complex, time-varying, and multiscale relationships of green bond markets and cryptocurrencies. Hence, the current work investigates the multiscale links between the green

bond index and the cryptocurrency markets. Our research provides straightforward insights into the financial implications of introducing green bonds, as well as the possible advantages they offer over other green financial vehicles. Therefore, we contribute to new strands of literature on green bond markets by investing in their relationship with key cryptocurrencies.

This article contributes to the related literature in several ways. Firstly, the present study expands understanding by examining the dynamic co-movements between cryptocurrencies and green financial instruments within the context of sustainable finance. Prior studies have concentrated on traditional cryptocurrencies, which is consistent with increased environmental and financial concerns in the presence of particular and ambiguous shocks – that is, the COVID-19 pandemic and the Ukraine invasion. Secondly, the co-movements of green bonds and cryptocurrencies are time-dependently analyzed in the study. Instead of passive investors, who are more concerned with the long-term success of their portfolios, active investors, like huge investment banks, are more focused on the short term. Investors from various groups, therefore, have various risk management. A simultaneous evaluation of the strength of co-movements across various frequencies and the size of this strength over time is possible thanks to the wavelet analysis. We therefore use wavelet techniques in this investigation, more specifically continuous wavelet transformation and wavelet coherence. The evaluation of the time-varying co-movement among the researched variables is made possible by the wavelet coherence and cross-wavelet plots. We also check the robustness of the results using spectral Granger causality test. Thirdly, this study improves our understanding of the interplay of sustainable investment markets by taking into account the specific dynamics and intercorrelations among these financial factors. It also helps to provide a more sophisticated understanding of portfolio diversification, risk management, and investment strategies in the context of sustainable finance.

The research is divided into five sections: Section 2 presents the related literature. Section 3 represents methodology and Section 4 the data. Section 5 shows the empirical results. Section 6 concludes the study.

2. LITERATURE REVIEW

Many studies have previously looked at the cryptocurrency markets from different perspectives, including their function as hedges (Gozgor and Karakas, 2023; Yadav et al., 2023a), safe havens (Ren and Lucey, 2022; Huang et al., 2023; Yadav et al., 2023b), particularly during the COVID-19 crisis (Sharif et al., 2023), and diversification from conventional financial markets (Abakah et al., 2023; Patel et al., 2023). Due to the significant energy use involved in most of the cryptocurrency mining and transactions, traditional energy assets have been frequently taken into account in the literature that currently exists on the relationship between cryptocurrencies and other assets. Although the green energy sector has grown significantly in recent years, little research has been done on the relationship between cryptocurrencies and the green energy markets (Sharif et al., 2023).

Despite the fact that the green market has seen a significant increase in recent years, there has been little literature on the relationship between green markets and cryptocurrencies. Siddique et al. (2023) examine the relationship between cryptocurrency, carbon, and green markets using TVP-VAR approach and provide evidence of strong intra-class connectedness clusters with little interconnectedness among the markets. Similar findings are made by Zhang and Umair (2023), who also find important dynamic spillover effects between carbon markets

and renewable energy stocks as well as between green bonds and renewable energy stocks. As per Gozgor and Karakas (2023), the returns on US Treasury bonds and the US dollar are inversely correlated with the returns on green bonds.

The impact of green bonds on cryptocurrency markets was heavily debated during the COVID-19 and Ukraine invasions. For example, Huang *et al.* (2023) use a TVP-VAR model to investigate the dynamic interlinkages between green markets and Bitcoin during the COVID-19 outbreak. The authors put forward the idea that green assets will continue to serve as an efficient hedge for Bitcoin regardless of the pandemic. Arfaoui *et al.* (2023) document that green bonds have the least integration with other financial markets, which points to their importance in helping investors diversify their portfolios. For the American, European, and Asian markets, Sharif *et al.* (2023) examine the intercorrelations and spillover effects between green economy indices, five clean cryptocurrencies, and five black cryptocurrencies. They show that, compared to dirty cryptocurrencies, the overall correlation between green economic indices and clean cryptocurrencies is higher. According to Ul Haq *et al.* (2023), there will be a moderate short-term (positive) and long-term (negative) co-movement between the markets for green bonds and sustainable cryptocurrency. Ye *et al.* (2023) look into the role of asymmetries in identifying the association between blockchain technology and green investment in the global environment. They show that assuming symmetric and weak coherence relationships between blockchain technology and green investment in the global environment leads to biased and misleading findings that do not reflect the real-world scenario.

While the available research has yet to identify obvious linkages between crypto markets, green investments, and sustainable equity, their nexus can be seen in a number of studies. Using Granger-causality in quantiles, Lee *et al.* (2023) investigate the heterogeneous causal linkages among cryptocurrencies, green bonds, and sustainable stocks and propose that the three investing tools interact under different market conditions. The findings indicate a high tail dependence between green bonds, sustainable stocks, and cryptocurrency. Patel *et al.* (2023) investigate the spillovers between Green-Dirty cryptocurrencies and socially responsible investments during the war in Ukraine and demonstrate that the magnitude of spillovers and relative roles of each cryptocurrency and socially responsible investments change during the war. Based on the rolling window wavelet correlation and QVAR models, Abakah *et al.* (2023) point out that the blockchain market has considerable adverse effects on the environment that could cause financial assets that support the ecosystem to experience shocks. Additionally, they discover a substantial association between the blockchain market and green financial assets during the Russia-Ukraine war and the COVID-19 epidemic, and a low correlation between the two before the emergence of the disease. Similarly, Yadav *et al.* (2023a) explore the nexus between the green bond, energy, crypto, and carbon markets. It was discovered that Bitcoin has the least connectivity compared to other asset classes, whereas the energy market has the best connectivity. The authors also came to the conclusion that there is more short-term diversity potential than medium- and long-term diversity among green bonds, energy stocks, bitcoin, and the carbon markets. Furthermore, Ye *et al.* (2023) examine the impact of asymmetries in influencing the relationship between blockchain and green investment and conclude that there is an asymmetric relationship between crypto currency and biofuel usage in the short and long run. Udeagha and Muchapondwa (2023) look at how economic development impacts green finance and financial technology for the BRICS countries and reach the same finding that environmental sustainability is enhanced by green finance. Yadav *et al.* (2023b) demonstrate the prevalence of long-run spillovers from green

bonds to renewable energy and the cryptocurrency market. The findings of Lorente *et al.* (2023) reveal that the green bond and clean energy markets are inversely related to the GPR at the extreme 10th and 90th quantiles.

Although a definite association between green bonds and cryptocurrencies has not yet been established in the literature, there are hints of such a relationship in a number of research. A substantial body of literature points to significant linkages between cryptocurrencies and other assets in terms of tail dependency (Siddique *et al.*, 2023), return and volatility spillover effects (Abakah *et al.*, 2023; Lorente *et al.*, 2023), and linear correlation (Lee *et al.*, 2023). Furthermore, although time-frequency connections are minimal, Urom (2023) and Ye *et al.* (2023) report that there exist symmetry and asymmetry in shocks between green bonds and financial asset classes, such as foreign currency markets, equities, commodities, and cryptocurrencies. From this, it can be speculated that a time-frequency impact exists between green bonds and cryptocurrencies, and we conduct our research using wavelet analysis and the spectral Granger causality test. Put differently, the body of knowledge regarding the connection between green bond markets and cryptocurrency markets is rapidly expanding. Prior research, however, says nothing about examining the time-frequency characteristics of this nexus. As a result, this article aims to close the gap in the existing literature.

3. METHODOLOGY

Cross wavelet transform (XWT), wavelet coherence (WTC) are utilized in this work to show how the domestic variance and covariance of two examined variables change in time-frequency space, as well as the lead-lag interactions between them. The majority of studies use traditional statistical approaches to investigate how green bonds connect to cryptocurrency assets (Husain *et al.*, 2023; Almeida *et al.*, 2024). Nevertheless, these methods presume that the distribution parameters remain the same throughout time, which may not represent the dynamic nature of these connections (Hung, 2022b; Ul Haq *et al.*, 2023). Participants in the financial market come in several forms, each with their own investment time horizons, such as short-term traders and long-term investors (Arif *et al.*, 2021). Using a wavelet method, our study addresses these issues (Almeida *et al.*, 2024). This approach preserves the temporal component while enabling the analysis of non-linear behavior at different frequencies and time scales. The wavelet approach has a number of benefits, such as its robustness to shocks, being applicable to non-stationary data, and being able to show the link between time series on a single graph in both the time and frequency domains (Almeida *et al.*, 2024). Additionally, it allows the investigation of Granger causality over a range of frequencies and time scales and captures the strength of co-movement (Almeida *et al.*, 2024). These advanced econometric techniques have been employed in various fields of knowledge, including in finance. As a result, we employ the wavelet analysis in accordance with previous research (Arif *et al.*, 2021; Hung, 2022a, 2022b; Husain *et al.*, 2023; Ul Haq *et al.*, 2023) and in the context of our study, given that the linkages between different markets may vary across time and frequency. This section provides a quick overview of wavelet techniques.

Continuous wavelet transform (XWT)

$W_x(s)$ denotes the XWT which allows us to estimate the joint behavior of time series for both frequency and time. The wavelet is given as:

$$W_x(s) = \int_{-\infty}^{\infty} x(t) \frac{1}{\sqrt{s}} \psi^* \left(\frac{t}{s} \right) \tag{1}$$

where * shows the complex conjugate and s is the scale parameter which determines whether the wavelet can detect higher or lower elements of the series $x(t)$, possible when the admissibility condition yields.

Wavelet coherence

WTC is efficient in estimating the localized interconnection between indicators in a time and frequency domains. The cross-wavelet of two series $x(t)$ and $y(t)$ can be written as:

$$W_n^{XY}(u, s) = W_n^X(s, \tau) W_n^{Y*}(s, \tau) \tag{2}$$

where the scale is s, u presents the position, and * demonstrates the complex conjugate. The WTC can be written as follows:

$$R_n^2(s, \tau) = \frac{|S\left(s^{-1} W_n^{XY}(s, \tau)\right)|^2}{S\left(s^{-1} |W_X(s, \tau)|^2\right) S\left(s^{-1} |W_Y(s, \tau)|^2\right)} \tag{3}$$

where S connotes smoothing process for both time and frequency simultaneously. $R_n^2(s, \tau)$ is in the range $0 \le R^2(s, \tau) \le 1$.

4. DATA

This study aims to explore the time and frequency relationship between green financial instruments and major cryptocurrency markets for daily data from August 1, 2018, to August 30, 2023. The S&P Green Bond Index was used as a proxy to represent green financial instruments (GF). The performance of international green bonds, which finance environmentally friendly projects, is measured by the S&P Green Bond Index (Husain *et al.*, 2023). For cryptocurrencies, we employed five cryptocurrencies, which were gathered from the website www.coindesk.com, are Ethereum (ETH), Bitcoin Cash (BCH), Ripple (XRP), Bitcoin (BIT), and Ethereum Operating System (EOS). Existing studies utilize these markets for green and cryptocurrencies' representations. For details, see: Arif *et al.* (2021), Husain *et al.* (2023), Hung (2023) and Siddique *et al.* (2023).

The daily data for the green bond index is collected from the S&P Global website (https://www.marketplace.spglobal.com/) while cryptocurrencies are extracted from the link www.coindesk.com. We convert index prices into logarithmic first differences as a proxy for returns.

The dynamic prices and returns are shown in Figure no. 1, which provides evidence of fluctuations and volatility clustering in the market under investigation during different timeframes. More importantly, the peaks of prices and volatility can be seen from January 2020 in all markets, suggesting that COVID-19 remarkably impacted the green bond and cryptocurrencies markets.
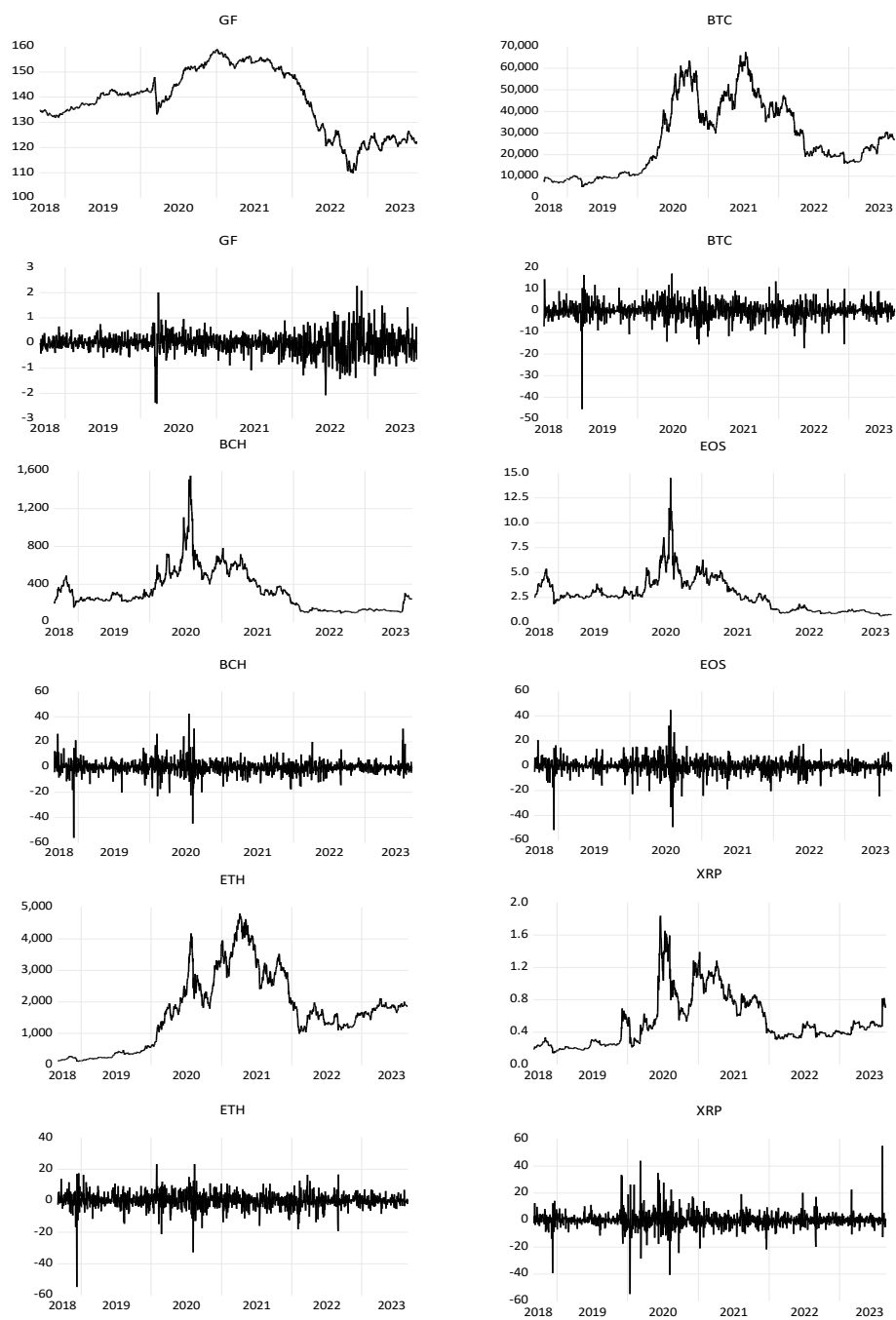
Figure no. 1 – Daily prices and returns of GF, BTC, BCH, EOS, ETH and XPR market indices

The descriptive statistics for the return series are represented in Table no. 1. The mean return for all selected cryptocurrencies is positive, while green finance has a negative value during the sample period. According to the standard deviation, BCH, ETH, EOS, and XRP are more volatile than the GF and Bitcoin markets. The coefficients of skewness and kurtosis indicate that all markets have a leptokurtic distribution. In this regard, the findings of the Jarque-Bera test uncover that the examined series do not have a normal distribution. In addition, the ADF unit root test suggests that GF and all cryptocurrency returns are stationary.

Table no. 1 – Descriptive statistics of sample return data

	GF	BTC	ETH	BCH	EOS	XRP
Mean	-0.007422	0.092798	0.204377	0.012944	0.096108	0.100785
Maximum	2.271737	17.19993	23.23139	42.39830	44.72424	54.95832
Minimum	-2.409932	-45.55871	-54.70192	-56.12829	-51.70109	-54.74531
Std. Dev	0.408307	3.733022	4.862004	5.571933	5.873120	6.074729
Skewness	-0.189252	-1.386594	-1.357431	-0.533642	-0.776129	0.425061
Kurtosis	7.794214	22.09335	18.62057	19.68429	16.70413	21.65015
Jarque-Bera	1254.681***	20194.38***	13636.96***	15163.12***	10319.03***	18908.89***
ADF	-29.89807***	-38.01121***	-38.90268***	-39.71634***	-41.5688***	-38.3468***

Notes: ADF is the computed statistics of the Augmented Dickey and Fuller unit root test. *** significant at 1%.
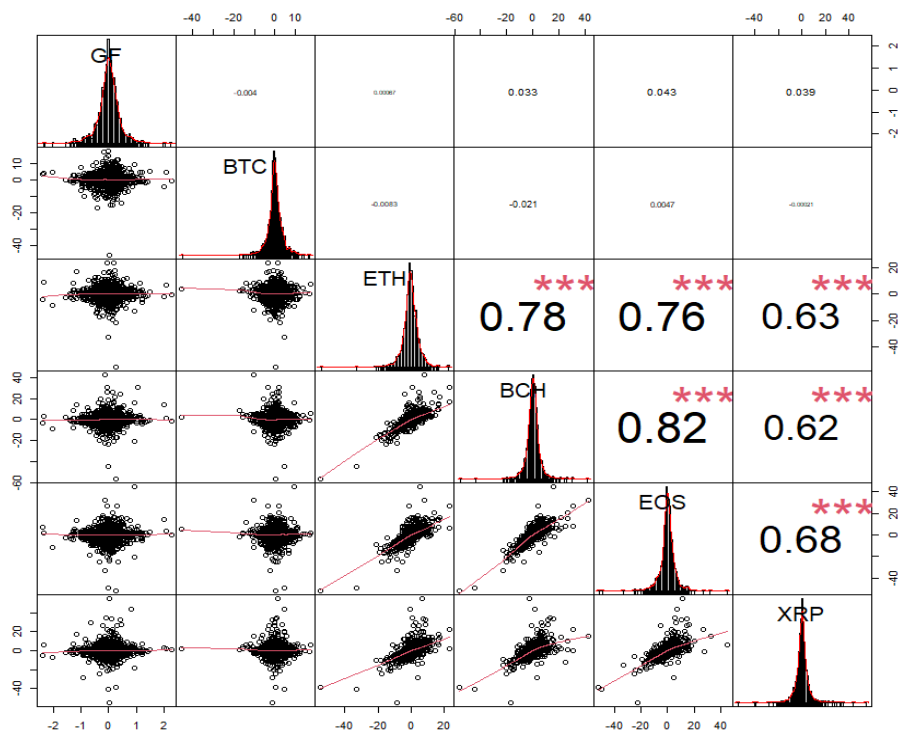

Figure no. 2 – Correlation plot of the examined variables

The unconditional correlations between GF and the cryptocurrency markets are reported in Figure no. 2. As shown in Figure no. 2, the linear correlations are significant and high between the cryptocurrency assets, revealing a strong association with others. Nevertheless, GF had no relationship with cryptocurrencies during the sample period. In general, we would demonstrate that no correlation might provide diversification benefits to portfolio holders in cryptocurrencies.

5. EMPIRICAL RESULTS

5.1 Wavelet Power Spectrum

Figure no. 3 illustrates the wavelet power spectrum of all-time series under consideration. The vertical axis shows frequency, while the horizontal axis denotes time. The color code goes from blue to red, with blue representing low power and red indicating high power. Figure no. 3 shows that these markets have various characteristics at different time frequencies. Specifically, during COVID-19, around 2020, power increased dramatically up to the medium run in the cryptocurrency markets, in particular, BTC and XPR indices. Among them, the first region is from 2019 to 2020, which is mainly affected by the first wave of the COVID-19 crisis. After an increase in power in the short run, there is a significant rise in power in the long run around 2020. This is true for green bond markets, revealing that major cryptocurrency markets are more volatile than GF. An increase in power around 2020 indicates an increase in variation because of the COVID-19 pandemic.

5.2 Wavelet coherence

Figure no. 4 shows the cross-wavelet transform (left side) and wavelet coherence (right side) between GF and the selected cryptocurrency markets. The color bar is depicted on the right side of each figure. Blue represents little power, while yellow, reddish yellow, and red represent high, higher, and maximum power, respectively. The power of the wavelet increases with the amount of color density.

Figure no. 4 depicts that with time covering our sample period on the horizontal axis and frequencies on the vertical axis. The areas with heavy shaded contours are significant at the 5% level. Warmer colors (red) indicate places with high significant dependence, whereas colder colors (blue) indicate regions where the two markets are significantly less dependent on one another. The lead-lag phase relationships between the GF and crypto markets are revealed by the phase arrows. Left arrows denote anti-phase, which indicates the opposite, while right arrows denote in-phase, which indicates the co-movement of two markets on a specific scale. The first market leads, as indicated by the right-down or left-up arrows, while the second market leads, as indicated by the right-up or left-down arrows.
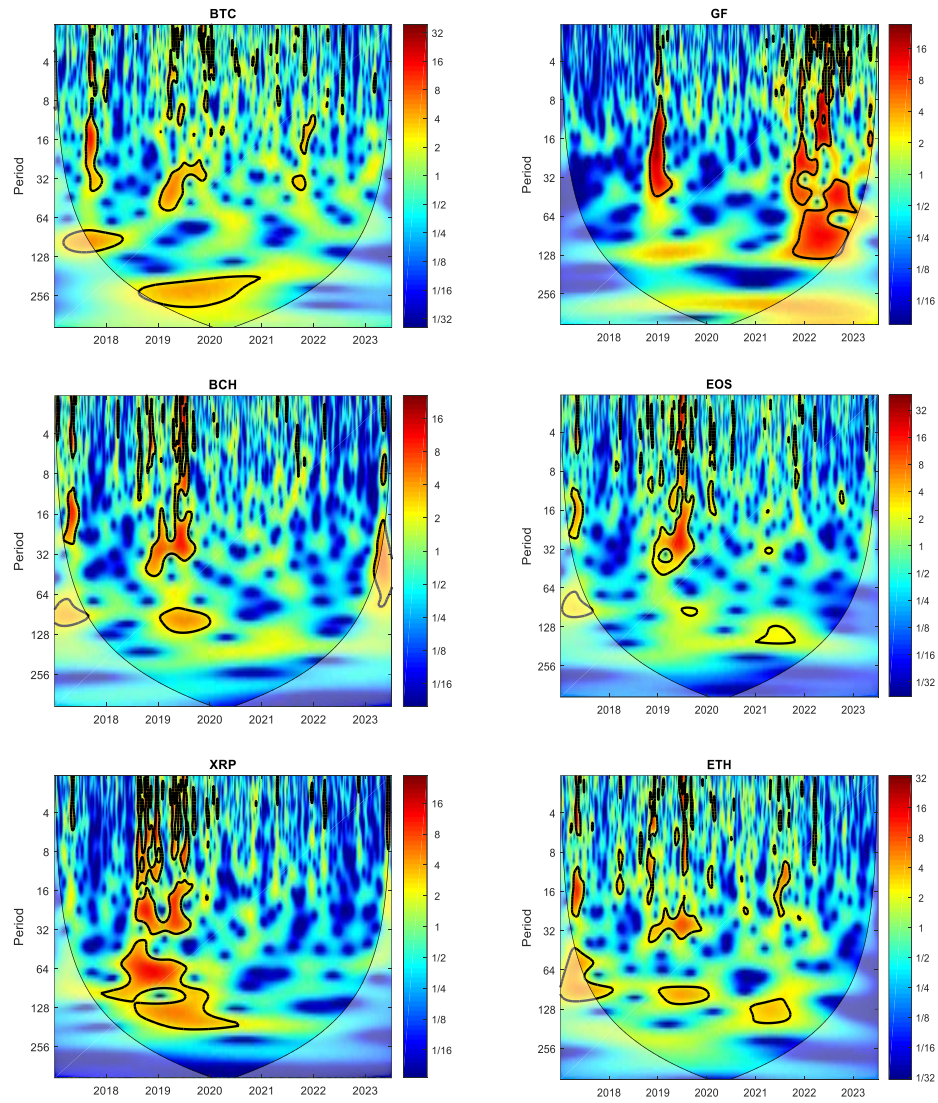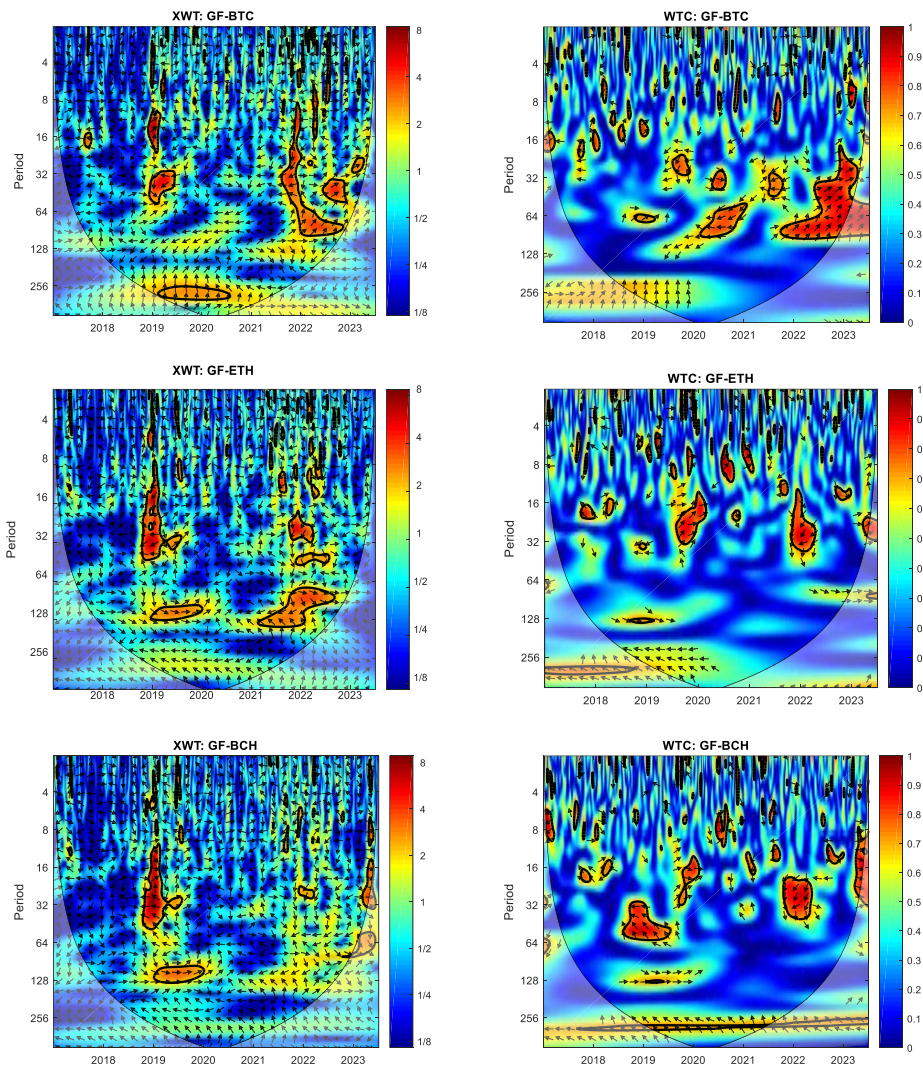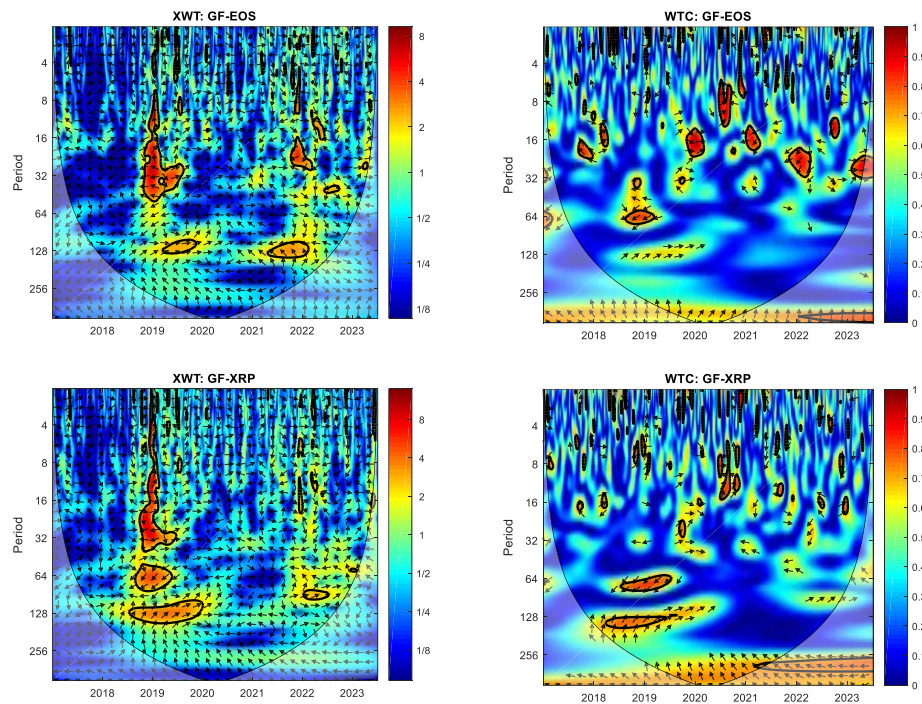
Figure no. 3 – Wavelet Power Spectrum for the employed variables

Cross wavelet transform   **Wavelet coherence**
Figure no. 4 – The wavelet coherence pairs of GF and cryptocurrencies

It is worth noting that the direction of the arrows at different scales and across time in Figure no. 4 (cross wavelet transform) differs between the pairs of GF and crypto market returns. Throughout 2019–2020, the green bond and cryptocurrency returns pair exhibits a zone of significant coherency and co-movement at the lower frequency band. XWT systematically explains the popular power of two indicators without normalizing to the single wavelet power spectrum. This can occasionally produce similar outcomes because the jump created in the cross-spectrum, which is a multiplication of the continuous wavelet transformation of two series, cannot be attributed to the nexus between two series if one of the spectra is local and the other one exhibits a very high jump. As a result, we employ wavelet coherence analysis to capture the significant lead-lag interplay between GF and cryptocurrencies in the time-frequency spaces. The findings of wavelet coherence are presented on the right-hand side of Figure no. 4.

In terms of cross-mean effects, we see various narrow and small zones with a high degree of coherence that are spread across the whole analysis period. Most important local dependencies have a propensity to be short-lived, existing within various short-run time scales. Furthermore, the arrows in such places have either a rightward or a leftward trajectory, showing the existence of positive or negative contagion effects between the GF and crypto markets.

The following plot reports the coherency between GF and Bitcoin. Strong coherencies between these variables, where the GF is driven, are mostly localized at the medium and low frequencies, suggesting that there is a long-term association between BTC and GF during the COVID-19 and Russia-Ukraine crises. The arrows pointing right indicate an in-phase nexus

between these variables, revealing a positive relationship during the recent crises in low frequency. However, this relationship is negative from 2018 to 2020 in the short and medium frequencies. These results corroborate the studies of Huang *et al.* (2023) and Arfaoui *et al.* (2023).

In the case of the GF-BCH pair, red zones are detected, suggesting the existence of a lead-lag nexus between green bond and BCH markets in the medium run. The direction of the arrows is left side down in the 8–16 cycle period in the periods 2018–2019 and 2021–2022, which reveals the negative relationship between the two series. Nevertheless, some in-phase cyclic effects are also visible in this association during 2019–2020 in the long run, a 2-4 cyclic period. Similarly, the wavelet coherence for GF-EOS represents the left side up in the 4–16 cycle period between 2019 and 2023. This indicates an anti-phase cyclic effect led by EOS. By contrast, the in-phase cyclic effect with arrows right side down will occur in 2019 and 2023 in the long run. Overall, it is clearly understood that BCH and EOS have leading effects on GF in the short and medium run during the sample period. BCH and EOS have solid green attributes; they are good hedges, and their prices are significantly impacted by the appreciation and depreciation of the green bond market (Ye *et al.*, 2023).

For the GF-ETH pair, we observe strong dependence during 2020–2023 for the frequency of 16–32 days, with arrows pointing to the lower left, which highlights they are anti-phase and ETH is leading. Conversely, significant areas between GF and ETH are also visible during 2019–2020 and 2023, where they are in phase and GF is leading. We note that there is both a negative and positive relationship between GF and ETH in the short, medium, and long run at different time periods. However, these movements are not very strong, in line with the literature (Lee *et al.*, 2023).

It is evident that the GF-XPR pair co-moves in a similar direction in the lower frequency scale, that is, 128–256-day cycles during 2019–2020 and 2021–2023. By contrast, the relationship changes in the opposite direction in the high and medium frequency scales, that is, 8- to 32-day cycles, over the sample period. Overall, we see weak coherence between XRP and GF during the period shown, which implies that XPR provides a chance for diversification. The findings are in agreement with those of Arfaoui *et al.* (2023) and Ye *et al.* (2023).

5.3 Robustness check

To validate our estimates, we propose the spectral Granger-causality test of Breitung and Candelon (2006). This approach works well for both stationary and non-stationary time series (Khalfaoui *et al.*, 2022). We chose the best lags for the various VAR models using the Akaike information criterion and the Schwarz Bayesian information criterion. As a result, the optimal lag is 4. In other words, this technique allows us to explore causality tests in the sense of Granger under the frequency domain to capture relationships between GF and cryptocurrency markets. At various frequencies (0-1, 1-2, and 2-3), the causal association between crypto and green bond markets uncovers long, medium, and short term, respectively. Our goals are to highlight the linkages between green bonds and cryptocurrency markets in time and frequency domains; wavelet analysis has yielded findings on these interactions in the short, medium, and long term. As a result, the spectral Granger causality test is used, which can also indicate bidirectional relationships between pairs of time series in different frequencies and time periods, so validating the results of wavelet analysis. The results of the test are depicted in Figure no. 5. The upper line (red) shows a level of significance of 5%, while the bottom line (blue) suggests a level of significance of 10%.
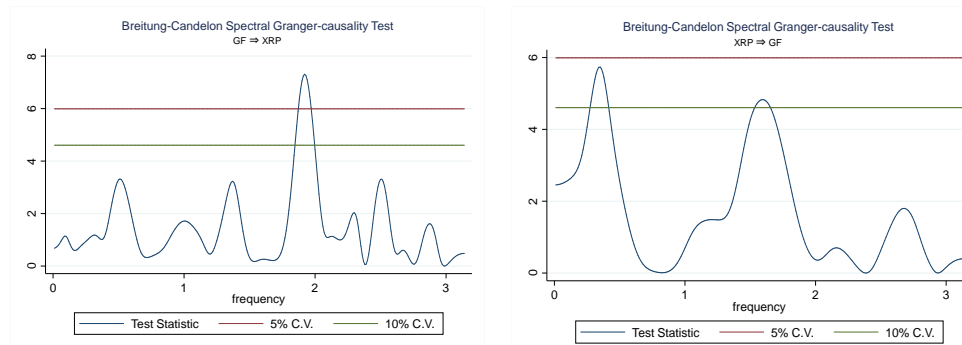
Figure no. 5 – Breitung-Candelon spectral Granger causality test between GF and cryptocurrency markets

As indicated in Figure no. 5, it is illustrated that the hypothesis that the crypto markets do not Granger-cause the green bond market can be rejected for high and medium frequencies at a 10% significance level. The outcomes demonstrate that there is a bidirectional causality between GF, BTC, BCH, XPR, and BCH in the short and medium run, except that the EOS does not cause a green bond market. In fact, it is in line with our wavelet analysis that there is a significant lead-lag relationship between GF and cryptocurrency markets in different time and frequency domains.

Overall, our findings indicate the presence of a causal association between variations in GF and changes in cryptocurrency prices using a wavelet technique, as do those of Yadav *et al.* (2023a) and Arfaoui *et al.* (2023), among others. The results of Ye *et al.* (2023), Yadav *et al.* (2023b) and Lee *et al.* (2023) are all in agreement with our findings that there is a bidirectional association between changes in the price of cryptocurrencies and green bond markets. Furthermore, our findings are consistent with existing articles that green markets offer hedging potential and effective diversification for cryptocurrency markets (Abakah *et al.*, 2023). In light of the existing literature (Lorente *et al.*, 2023; Udeagha and Muchapondwa, 2023), the importance of green assets as a hedge can be explained by two underlying factors, namely the process of green economic transformation and the dynamics of production costs. In the context of globally rising energy consumption and CO_2 emissions, environmental challenges have pushed the financing of cleaner energy while simultaneously advocating for a green transition of the energy-intensive development mode, including cryptocurrency trading and mining. Despite the existence of active cryptocurrency trading aimed at generating financial gains, green investors would choose to stick with safer investments, resulting in an insignificant or even opposite relationship between the dynamics of the two types of assets (Ren and Lucey, 2022).

Important policy consequences result from understanding the heterogeneous relationship between the markets for green bonds and cryptocurrencies. Our work demonstrates a lead-lag association between price movements in green bonds and cryptocurrencies. Under different market conditions, how green or sustainable investments behave has little impact on how cryptocurrencies behave. We also discover that significant cryptocurrency changes have a negative influence on green bonds. To enhance environmental sustainability through legislation, governments and businesses should take into account the asymmetric nexus between cryptocurrency markets and changes in green bonds. Additionally, governments and businesses can reduce the environmental impact of cryptocurrency use by supporting the

creation of green bonds through regulations that encourage the consumption of clean energy in cryptocurrency mining and trading activities. What is more, green bonds have an asymmetric influence on cryptocurrency values, which governments, corporations, and investors should be aware of in order to consistently incentivize the development of green bonds and ensure environmental sustainability.

6. CONCLUSION

Green investments opened a new space in the financial world as a result of the widespread concern over climate change. Many investors are keeping an eye out for green instruments as a source for supporting and promoting sustainability as the SDGs receive greater attention. Previous research revealed that traditional cryptocurrencies might benefit from using green assets as a hedge or safe haven. This empirical study sheds light on the dynamic dependence structure between green financial instruments and major cryptocurrency markets for daily data from August 1, 2018, to August 30, 2023. We use the wavelet analysis and Granger causality frameworks as they highlight the strength, causality direction, and lead-lag nexus between the selected market returns.

Our analysis illustrates that the correlation between the returns of the green bond market and key cryptocurrencies is not stable over time. The intensity of coherence is significant across the time-scale domain, and it rises from the short to the long run. The short-term relationship between GF and crypto markets is weaker than the medium- and long-term effects. However, the co-movements between these assets tend to be different and, in some cases, strong, especially during recent financial crises. Furthermore, the Granger causality test demonstrates the existence of a bi-directional causality between the prices of these cryptocurrencies and green bonds.

Our empirical results provide several key policy implications for different stakeholders, crypto traders, and researchers in terms of hedging strategies and sustainability policy, especially during the recent global crises such as the COVID-19 outbreak and the Ukraine invasion. Based on these outcomes, by considering the diversification benefits of introducing green bond markets, investors and portfolio managers could construct cross-asset hedging strategies. Understanding the relationship between green bonds and cryptocurrencies can help regulators limit the negative consequences of contagion, particularly during extreme risk events. Portfolio managers can reduce downside risk by incorporating responsible investing assets into their portfolios. Our findings would encourage scholars to look into the interconnections of important asset types, which are currently understudied.

ORCID

Nguyen Mau Ba Dang ⓘD https://orcid.org/0000-0001-8516-073X

References

Abakah, E. J. A., Wali Ullah, G. M., Adekoya, O. B., Osei Bonsu, C., & Abdullah, M. (2023). Blockchain market and eco-friendly financial assets: Dynamic price correlation, connectedness and spillovers with portfolio implications. *International Review of Economics & Finance, 87*, 218-243. http://dx.doi.org/10.1016/j.iref.2023.04.028

Almeida, J., Gaio, C., & Gonçalves, T. C. (2024). Crypto market relationships with bric countries' uncertainty–A wavelet-based approach. *Technological Forecasting and Social Change, 200*, 123078. http://dx.doi.org/10.1016/j.techfore.2023.123078

Arfaoui, N., Naeem, M. A., Boubaker, S., Mirza, N., & Karim, S. (2023). Interdependence of clean energy and green markets with cryptocurrencies. *Energy Economics, 120*, 106584. http://dx.doi.org/10.1016/j.eneco.2023.106584

Arif, M., Hasan, M., Alawi, S. M., & Naeem, M. A. (2021). COVID-19 and time-frequency connectedness between green and conventional financial markets. *Global Finance Journal, 49*, 100650. http://dx.doi.org/10.1016/j.gfj.2021.100650

Gozgor, K., & Karakas, M. (2023). How do global financial markets affect the green bond markets? Evidence from different estimation techniques. *Ekonomska Istrazivanja, 36*(2), 2177703. http://dx.doi.org/10.1080/1331677X.2023.2177703

Huang, Y., Duan, K., & Urquhart, A. (2023). Time-varying dependence between Bitcoin and green financial assets: A comparison between pre-and post-COVID-19 periods. *Journal of International Financial Markets, Institutions and Money, 82*, 101687. http://dx.doi.org/10.1016/j.intfin.2022.101687

Hung, N. T. (2022a). The COVID-19 effects on cryptocurrency markets: Robust evidence from time-frequency analysis. *Economics Bulletin, 42*(1), 109-123.

Hung, N. T. (2022b). Re-study on dynamic connectedness between macroeconomic indicators and the stock market in China. *Journal of Economic Forecasting, 25*(2), 104-124.

Hung, N. T. (2023). What effects will Covid-19 have on the G7 stock markets? New evidence from a cross-quantilogram approach. *Regional Statistics, 13*(2), 240-264. http://dx.doi.org/10.15196/RS130203

Husain, A., Yii, K. J., & Lee, C. C. (2023). Are green cryptocurrencies really green? New evidence from wavelet analysis. *Journal of Cleaner Production, 417*, 137985. http://dx.doi.org/10.1016/j.jclepro.2023.137985

Khalfaoui, R., Mefteh-Wali, S., Viviani, J. L., Ben Jabeur, S., Abedin, M. Z., & Lucey, B. M. (2022). How do climate risk and clean energy spillovers, and uncertainty affect US stock markets? *Technological Forecasting and Social Change, 185*, 122083. http://dx.doi.org/10.1016/j.techfore.2022.122083

Lee, C. C., Yu, C. H., & Zhang, J. (2023). Heterogeneous dependence among cryptocurrency, green bonds, and sustainable equity: New insights from Granger-causality in quantiles analysis. *International Review of Economics & Finance, 87*, 99-109. http://dx.doi.org/10.1016/j.iref.2023.04.027

Lorente, D. B., Mohammed, K. S., Cifuentes-Faura, J., & Shahzad, U. (2023). Dynamic connectedness among climate change index, green financial assets and renewable energy markets: Novel evidence from sustainable development perspective. *Renewable Energy, 204*, 94-105. http://dx.doi.org/10.1016/j.renene.2022.12.085

Patel, R., Kumar, S., Bouri, E., & Iqbal, N. (2023). Spillovers between green and dirty cryptocurrencies and socially responsible investments around the war in Ukraine. *International Review of Economics & Finance, 87*, 143-162. http://dx.doi.org/10.1016/j.iref.2023.04.013

Ren, B., & Lucey, B. (2022). A clean, green haven?—Examining the relationship between clean energy, clean and dirty cryptocurrencies. *Energy Economics, 109*, 105951. http://dx.doi.org/10.1016/j.eneco.2022.105951

Sharif, A., Brahim, M., Dogan, E., & Tzeremes, P. (2023). Analysis of the spillover effects between green economy, clean and dirty cryptocurrencies. *Energy Economics, 120*, 106594. http://dx.doi.org/10.1016/j.eneco.2023.106594

Siddique, M. A., Nobanee, H., Karim, S., & Naz, F. (2023). Do green financial markets offset the risk of cryptocurrencies and carbon markets? *International Review of Economics & Finance, 86*, 822-833. http://dx.doi.org/10.1016/j.iref.2023.04.005

Thi Xuan, H., & Thai Hung, N. (2024). Does green investment mitigate environmental degradation in Vietnam: the time-frequency effect of nonrenewable energy investment and globalization? *Management of Environmental Quality: An International Journal, ahead-of-print*(ahead-of-print). http://dx.doi.org/10.1108/MEQ-09-2023-0332

Udeagha, M. C., & Muchapondwa, E. (2023). Striving for the United Nations (UN) sustainable development goals (SDGs) in BRICS economies: The role of green finance, fintech, and natural resource rent. *Sustainable Development, 31*(5), 3657-3672. http://dx.doi.org/10.1002/sd.2618

Ul Haq, I. U., Maneengam, A., Chupradit, S., & Huo, C. (2023). Are green bonds and sustainable cryptocurrencies truly sustainable? Evidence from a wavelet coherence analysis. *Ekonomska Istrazivanja, 36*(1), 807-826. http://dx.doi.org/10.1080/1331677X.2022.2080739

Urom, C. (2023). Time–frequency dependence and connectedness between financial technology and green assets. *International Economics, 175*, 139-157. http://dx.doi.org/10.1016/j.inteco.2023.06.004

Yadav, M. P., Kumar, S., Mukherjee, D., & Rao, P. (2023a). Do green bonds offer a diversification opportunity during COVID-19?-an empirical evidence from energy, crypto, and carbon markets. *Environmental Science and Pollution Research, 30*(3), 7625-7639. http://dx.doi.org/10.1007/s11356-022-22492-0

Yadav, M. P., Pandey, A., Taghizadeh-Hesary, F., Arya, V., & Mishra, N. (2023b). Volatility spillover of green bond with renewable energy and crypto market. *Renewable Energy, 212*(928-939), 928-939. http://dx.doi.org/10.1016/j.renene.2023.05.056

Ye, W., Wong, W. K., Arnone, G., Nassani, A. A., Haffar, M., & Faiz, M. F. (2023). Crypto currency and green investment impact on global environment: A time series analysis. *International Review of Economics & Finance, 86*, 155-169. http://dx.doi.org/10.1016/j.iref.2023.01.030

Zhang, Y., & Umair, M. (2023). Examining the interconnectedness of green finance: An analysis of dynamic spillover effects among green bonds, renewable energy, and carbon markets. *Environmental Science and Pollution Research, 30*, 77605-77621. http://dx.doi.org/10.1007/s11356-023-27870-w