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Quantile Dependence and Portfolio Diversification between Green Bonds and International Financial Markets: Evidence from Quantile-on-Quantile Regression

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ABSTRACT

In this study, the green bond market is investigated with respect to its connectedness with certain international financial markets, employing the Quantile-on-Quantile Regression (QQR) technique that is used to measure this connectedness. Green bonds have emerged as a significant financial tool for financing low-carbon growth and building environmentally responsible investment portfolios, especially in the context of the increasing climate risk and the rising requirement for sustainable financing. But their diversification, hedging or safe-haven properties will depend on their interactions with other financial markets in various market conditions. Daily log-return data for the S&P Green Bond Index and some global markets, namely the S&P 500, S&P GSCI Commodity Index, S&P Global Clean Energy Index, Bitcoin, and the Shanghai index are analyzed. The QQR method allows the analysis to reflect the nonlinear and asymmetric relationships throughout the bearish, normal and bullish quantiles. The results show that green bond connectedness is market specific and condition dependent. The connectedness of green bonds with Bitcoin is weak and unstable, indicating a potential for diversification, while the connectedness is strong and positive with clean energy market, which indicates their similar sustainable finance attributes. The correlation of the S&P 500 and Shanghai market grows stronger in bull markets, while the connectedness of the commodity market is mixed. Overall, the results show that green bonds are not completely immune from international financial market fluctuations and the advantages of green bond portfolios depend on the state of the market. The study helps advance the body of work on sustainable finance and provides empirical insights using quantiles to understand the connectedness of green bonds, which can be applied by investors, portfolio managers, and policymakers to advance climate-resilient and sustainable financial systems.This study goes beyond the previous research, which has mainly examined linear relationship, and explores the interaction between green bonds and international financial markets in terms of time-varying and quantile-dependency, offering new insights in green portfolio construction, hedging effectiveness, and sustainable asset allocation.

Introduction

The economic and financial dynamics of the world have changed because of the climate change. This is a systemic financial concern with significant consequences for investing, asset valuations, portfolio diversification, financial stability, and sustainable development which has been seen primarily as an environmental and ethical concern (Campiglio et al., 2023). Green bonds have become a key tool for sustainable finance as governments, investors and financial institutions shift towards climate-friendly investment approaches. These bonds are dedicated to funding projects that are environmentally friendly, such as renewable energy, clean transportation, pollution control, energy efficiency, and climate adaptation (Reboredo, 2018). Their rapid expansion is a sign of a larger shift in the worldwide financial markets, with investors increasingly looking to assets that have both monetary and ecological results.

Although green bonds have become more prominent, one question is still not answered: how do green bonds relate to other international financial markets in various market conditions? This question is particularly relevant as the usefulness of green bonds as a diversification, hedging or safe haven instrument depends on the extent to which they are connected with other assets (Chai et al., 2025; Nguyen et al., 2021, 2021; Reboredo & Ugolini, 2020). Green bonds that are highly correlated with conventional equity markets, commodities, clean energy stocks or digital assets in times of market stress might not have enough risk reduction properties. But green bonds can also be of great value for investors with different risk preferences and investment strategies if their relationship shifts over the bear, normal and bull market phases (Arif et al., 2021; Naeem et al., 2021; Tiwari et al., 2025).

Previous research indicates a linkage between green bonds and traditional bonds, equities, commodities, energy markets and other sustainable financial assets. But this does not always form a stable, linear, and symmetric relationship. It has been observed that, financial markets act differently during the period of depression, normal state and boom (Chai et al., 2025; Mensi et al., 2023). For example, the ‘stock market' of a green bond may be different when the market is bear than during bull markets. Likewise, the influence of extreme price shifts on international financial markets on green bonds could differ from normal price fluctuations. Thus, dependence between green bonds and global financial markets might be underestimated by using only a mean-based model or by conducting a simple correlation analysis.

Therefore, this study aims to investigate the nonlinear and asymmetric connectedness between green bonds and some international financial markets. While the conventional studies are based on the average relationship between variables, this study uses the Quantile-on-Quantile Regression methodology to investigate the influence of various quantiles of international financial markets on various quantiles of green bond returns (Shah et al., 2026; Umar et al., 2022). This approach is especially helpful as this analysis can capture the dependence of assets during different market conditions, including lower quantiles for bearish or crisis periods, middle quantiles for normal market periods and upper quantiles for bullish or expansionary periods.

What is missing from the literature is that many previous studies on green bond connectedness have been based on linear model, static correlation analysis or average based spillover analysis. While all of these methods have their merits, they have the disadvantage of not capturing the heterogeneous behavior of financial markets throughout the return distribution. In fact, investors are more interested in the performance of their assets in periods of market extremes than in periods of average markets. A relationship that is on average weak may be strong during a market downdraft and a relationship that is of apparently positive strength may be of negative strength in a stress period. Thus, a quantile based framework is needed to see whether green bonds can actually act as a diversification/hedging tool in various market regimes (Arif et al., 2021; Naeem et al., 2021; Pham & Nguyen, 2021).

The Quantile-on-Quantile methodology provides a more flexible, extensive framework for this purpose. It brings together the best of both worlds, the quantile regression approach and the nonparametric approach, this study enables us to look into the effect of quantiles of one financial market on the quantiles of the other. The methodological approach allows for the identification of whether green bonds react differently with respect to the low, medium and high return conditions in international financial markets within the scope of this study (Sim & Zhou, 2015a). This is particularly crucial as green bonds can react differently under the stress of the market in time of financial stress, energy market volatility, stock market instability, or increasing investor appetite for sustainable assets.

The objectives of this study are threefold. Firstly, to examine the asymmetric and nonlinear connectedness between green bonds and the selected international financial markets. Second, it aims to investigate whether it is possible to observe a shift in the green bond market's relationship to other financial markets in both bearish, normal and bullish market conditions. Third, the study examines the green bond's role in diversification, hedging, and safe-haven benefits to investors depending on the different market

states, classified using quantiles. These targets are relevant as investors, policymakers and financial institutions are more and more asking for evidence of the role green bonds can play in sustainable portfolio construction.

This study has a number of contributions. On the one hand, it adds to the literature on sustainable finance with the application of Quantile-on-Quantile to the market for green bonds. Second, it offers a better understanding of green bond connectedness than an average-based analysis alone and instead concentrates on the complete distribution of market behavior. Third, it provides concrete takeaways for portfolio managers and institutional investors that could help them better appreciate and appreciate how green bonds perform in good and bad markets. Lastly, the study informs policy makers and regulators by demonstrating how sustainable financial instruments interrelate with the wider financial markets and if they can help make climate-resilient investment systems stronger.

The study is of particular significance in the face of the ongoing volatility of global financial markets. Asset allocation is now more complicated than ever, as climate risk, energy transition uncertainty, inflationary pressure, geopolitical tensions and financial market volatility have complicated the process (Arif et al., 2022; Mensi et al., 2023). In this uncertain environment, green bonds are not only anticipated to be used for financing sustainable development, but also to deliver financial resilience. But, it is an empirical question that needs to be verified. Consistent with this, if green bonds continue to be negatively associated with risky financial assets in market downturns, then they could be a diversification or safe haven asset. Investors need to seriously rethink their engagement in sustainable portfolios if their connectedness does grow during crises (Ben Ameur et al., 2024).

Hence, this paper contends that the linkages between green bonds and international financial markets cannot be viewed as linear, homogeneous and constant. It should rather be viewed as a dynamic, asymmetric relationship which evolves over the course of market return distribution. This paper uses the Quantile-on-Quantile methodology to examine the relationship between green bonds and the global financial markets under various market conditions. The results will be shared with the literature on sustainable finance, climate-risk investment, green portfolio management and the general contribution of green bonds to sustainable economic development.

Literature Review

Past studies of green bonds and international financial markets indicate that the number of connections between green bonds and conventional and/or alternative asset classes is increasing, but their nature and magnitude are dependent on the market and time/market conditions. Green bonds are also strongly linked to the traditional fixed-income markets, namely corporate bonds and treasury bonds, while in a lesser degree with stock and energy markets, as pointed out by (Reboredo, 2018). This means that green bonds provide diversification options to those investors who are invested in equity and commodity markets, but are not allowed to be separated from the traditional bond markets (Ben Ameur et al., 2024; Vihervuori, 2023).

This debate was advanced by follow-on research to explore the connectedness of green bonds to other asset classes. Its identified differences in the relationships between green bonds across the investment horizons investigated, based on wavelet coherence and connectedness techniques (Reboredo & Ugolini, 2020). Their results reveal that green bonds are not entirely autonomous from the global financial markets, but that this connectedness is different at short-run and long-run frequencies (Arif et al., 2022; Rehan et al., 2024; Tsipas et al., 2024). Similarly, a study using time-frequency analysis indicates that links between green bonds grow stronger in times of crisis, particularly in uncertainty, or liquidity stress and/or systemic shocks in the financial markets.

Green bonds and equity markets now have a new spotlight on them. Studies of equity markets worldwide and at the regional level in general indicate that during normal times green bonds are weakly or moderately connected to stocks, whereas during financial stress, they are more connected to stocks. This is particularly the case with the S&P 500, DAX and Shanghai Composite markets, which are the major developed and emerging equity markets (Mensi et al., 2023; Naeem et al., 2021; Shah et al., 2026). Equity shocks could have spillover effects and reduce the diversification benefits of green bonds in a bear market. Green bonds, however, may come in handy as portfolio stabilizers in calm markets.

The relatedness of green bonds and commodity markets is another theme in the literature. Inflation, uncertainty in the energy market and global economic cycles all have a bearing on commodities, and this interaction between commodities and green bonds is important to manage portfolios. So far, green bonds and commodities do not appear to be necessarily symmetrically and conditionally (Nguyen et al., 2021; Yadav et al., 2024). While green bonds can diversify from commodity risk during normal times, during times of inflation or crisis, commodity shocks could lead to greater financial market synchronization, which could reduce the hedging benefits.

The relationship between green bonds and clean energy markets has also been studied recently. Clean energy stocks and green bond are part of sustainable finance and climate policy and low-carbon investment. Accordingly, it is believed that their correlation will be more than that of green bonds and what are purely conventional assets. Green bonds and green equity markets are identified to possess frequency-dependency and quantile-dependency connectedness (Chai et al., 2025; Pham & Nguyen, 2021). This means that the relationship between them varies at short, medium and long time horizons and in normal and extreme markets.

A second stream of literature concentrates on the markets of green bonds and cryptocurrencies, in particular Bitcoin. Bitcoin is a digital asset that is very volatile and speculative, and green bonds are fixed-income, relative stable and oriented towards sustainability. As a whole, there is a low average connectedness between green bonds and cryptocurrencies, suggesting diversification opportunities (Kamal & Bouri, 2025a). However, in a very challenging market, the volatility of cryptocurrencies may affect the overall financial sentiment, so it is important to see whether there is different impact of Bitcoin on the returns of green bonds in lower, middle and upper quantiles.

The methodology of green bond connectedness has been tested in different ways in past studies. Initial evidence of co-movement is provided by traditional correlation and spillover models, which may not be able to capture nonlinear and asymmetric behavior. Diebold-Yilmaz spillover and TVP-VAR models provide a handy tool to help capture transmission of volatilities and returns over time (Kamal & Bouri, 2025b; Naeem et al., 2021; Yildirim & Mejri, 2026; Zhao & Park, 2024). Wavelets can capture short and long run connectedness and are also able to capture the time-frequency dependence. Copula and quantile regression methods are also widely used as they capture the extreme behavior of the market as well as tail dependency.

However, there are some drawbacks of the existing literature. First is that many of the studies use an average based model and this can mask the dependence structure in bear and bull markets. Second, while many studies have examined one or two markets, e.g. green bonds and stocks, or green bonds and clean energy, few have examined a variety of international markets in the same study. Third, the amount of joint studies is small, including equity markets (developed and emerging), commodities, clean energy, and cryptocurrency markets. Finally, many previous research note that the number of green bonds is relatively low to conclude whether green bonds still provide diversification or hedging properties across different quantiles of market returns.

This study aims to fill the gap by using the Quantile-on-Quantile Regression methodology to investigate the asymmetric dependence structure between the S&P Green Bond Index and the selected international financial markets: The S&P 500, DAX, Shanghai Composite Index, S&P GSCI Commodity Index, Bitcoin, and S&P Global Clean Energy Index. Whereas the traditional approaches are limited to investigating the influence on one situation of the green bond market from one situation of the respective explanatory market, QQR allows the analysis of the green bond market's influence from various market situations. Therefore, this paper makes a contribution to literature by examining the nature of the green bond asset in terms of diversification, hedging or risk-transmission, during the bear, the normal and the bull market conditions (Sim & Zhou, 2015b).

Reviewed literature generally shows that green bonds play a crucial role in sustainable finance, but the link between green bonds and international markets is complex and non-linear, and depends on the market conditions. This paper provides more specific empirical support to the importance of implementing green bonds for optimal portfolio rebalancing to facilitate greener and more sustainable investment strategies using log-return data and a quantile based approach.

Methodology

The objective of this paper is to analyze the asymmetric relationship between the S&P Green Bond Index and the financial markets of the selected countries using Quantile-on-Quantile Regression (QQR) approach (Sim & Zhou, 2015a). The main objective of this methodology is to find out how green bonds react in different market conditions in global equity, commodity, crypto and clean energy markets. Data collection and variables.

Data Collection and Variables

The study uses daily closing price data for the indices of S&P Green Bond Index and some of the international financial market indices. The S&P Green Bond Index is taken as the dependent variable as it represents the global green bond market and captures the performance of bonds issued for environmentally sustainable projects. These explanatory variables are the S&P 500 Index, the Shanghai Composite Index, the S&P GSCI Commodity Index, the S&P Global Clean Energy Index and the Bitcoin Index.

These markets are chosen as they are key parts of the worldwide financial system. The S&P 500 is the U.S. equity market, the Shanghai Composite is the Chinese equity market, the S&P GSCI is the global commodity market, Bitcoin is the cryptocurrency

market and the S&P Global Clean Energy Index is the clean energy investment market. Data has been obtained from trusted international financial databases and websites, such as S&P Global, Bloomberg, Yahoo Finance and Investing.com.

Data Preparation and Conversion into Analysis Form

The closing prices are daily collected and cleaned and prepared for the application of the econometric model. First, indices are all sorted by date, to make sure they are time aligned correctly between markets. Second, some observations are dropped to maintain a common set of observations for all variables due to holidays, weekends, and/or market closure differences. Thirdly, all numbers are then checked against one another, and they are all formatted the same way.

Financial price series are typically nonstationary, so the price data are converted to continuously compounded log returns. The log return is given by:

$$R_t = \ln\left(\frac{P_t}{P_{t-1}}\right) \times 100$$

Where (Rt) is the return on day (t), (Pt) is the current day's closing price and (Pt-1) is the previous day's closing price. Log returns are appropriate as it reduces the non-stationarity, captures percentage changes in prices, and makes the data more suitable for financial time-series analysis.

Application of Quantile-on-Quantile Regression

The price series is transformed into a series of log returns and the Quantile-on-Quantile Regression methodology is used. For these reasons, QQR should be used to reflect such nonlinear and asymmetric relationships between green bonds and international financial markets (depending on the market conditions). Ordinary least squares or traditional quantile regression can only report the effect of a certain quantile of the explanatory market on the whole market for green bonds, but the QQR can report the effect of a certain quantile of the explanatory market on a certain quantile of the green bond market.

The dependent variable in this study is the return of S&P Green Bond Index and the explanatory variables are the international financial market one by one. The general form of the QQR model is:

$$\beta^{\theta}(X_t) \approx \beta_0(\theta,\tau) + \beta_1(\theta,\tau)(X_t - X^{\tau})$$

where:

- θ represents the quantile of green bond returns;
- τ represents the quantile of the explanatory market;
- $\beta_0(\theta,\tau)$ captures the intercept effect between the quantiles;
- $\beta_1(\theta,\tau)$ captures the slope dependence between the τ-quantile of the explanatory market and the θ-quantile of green bond returns.

The analysis is performed on lower, middle and upper quantiles. The bearish or stressed market conditions are indicated by the lower quantiles, the normal market conditions by the middle quantiles, and the bullish or expansionary market conditions by the upper quantiles. This allows the study to determine the behavior of green bonds during market downturns, market stability and market booms.

Interpretation of QQR Results

The sign and strength of the estimated QQR coefficients is interpreted. Positive coefficient indicates that green bonds and the financial market selected will walk hand-in-hand. Negative coefficient is a sign of the inverse relationship between the two variables and that there may be some potential for hedging. A weak coefficient indicates more diversification benefits and a strong positive coefficient in the extreme quantiles indicates less diversification ability in stress periods, more market integration.

The results are displayed in quantile heat maps and 3D surface plots. The picture representations denote the intensity, directionality, and asymmetry of the connections of green bonds to each chosen international financial market. Overall, this methodology enables

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Results and Discussion

The Quantile-on-Quantile Regression results are shown between S&P Green Bond Index with selected international financial markets. With the QQR approach, the study investigates the impact of various quantiles of each financial market on various quantiles of green bond returns. Low quantiles signal bearish or stressed market situations; medium quantiles signal normal market situations while high quantiles signal bullish market situations. Results indicate that the relationship of green bonds with international financial markets is not uniform. The connectedness, on the contrary, asymmetric, nonlinear, and market-dependent.

Green Bonds and Bitcoin

Overall and at the quantile level, the QQR results suggest that the link between green bonds and bitcoin is weak and fragile. The values of the coefficients are generally near zero, spanning about -0.004 to 0.004. This demonstrates the lack of substantial influence of Bitcoin on the returns of green bonds (Mnif et al., 2025). At lower Green Bond quantiles Bitcoin exhibits a weak but positive influence at higher market quantiles, indicating that Bitcoin movements slightly affect the returns of green bonds in some bull market conditions of cryptocurrencies. However, when Bitcoin is in the highest quantile, the connection becomes somewhat negative in the middle and the upper quantiles of green bonds.

From this overall, it can be concluded that there is no significant relationship between Green bonds and Bitcoin. This low correlation suggests that green bonds could offer diversification opportunities to cryptocurrency risks. But the mixed signals are evidence that Bitcoin is not a stable green bond hedge.

Green Bonds and S&P 500

The outcomes of the S&P 500 are very much asymmetric. The positive effect of the S&P 500 index is in the lower quantiles of the U.S. equity market, and the negative effect of the S&P 500 index is in the higher quantiles of the S&P 500 market. This suggests that with less optimistic market dynamics in the green bond market, bull markets in the U.S. equity market may not necessarily lead to green bond performance (Nguyen et al., 2021; Reboredo et al., 2020).

The results in the upper green bond quantile are much more positive, and the coefficient increases from 0.001 to 0.028 from lower to upper quantiles of the S&P 500. This suggests that when market conditions are bull, green bonds are more positively correlated with U.S. equities. Thus, while green bonds can provide diversification at normal times, their unique nature of being equity market independent can be problematic in strong market upswings.

Picture-1 QQR Heat maps & 3D Surface Plot

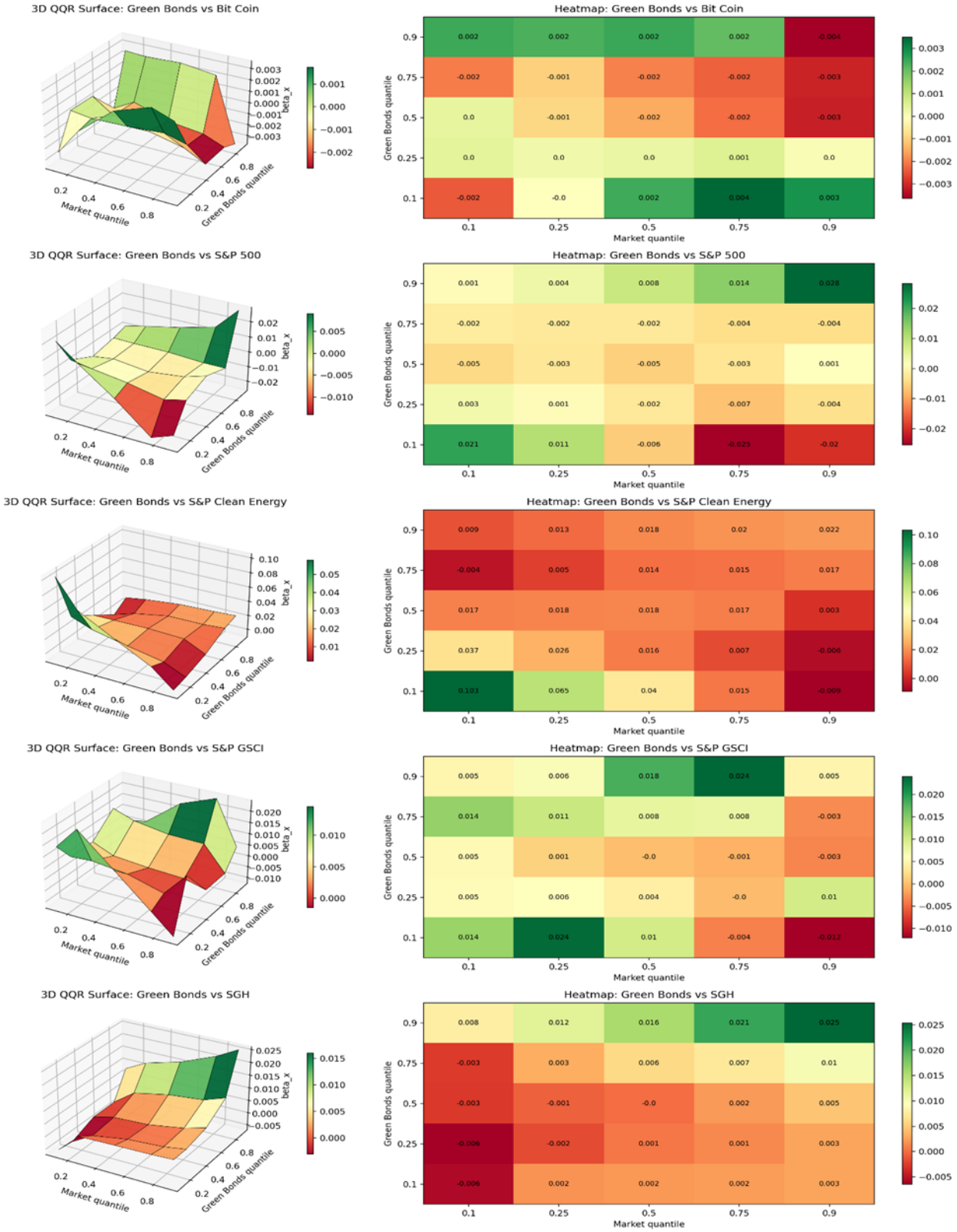

Table 1: Quantile-Based QQR Results

Market Pair	Lower Quantiles / Bearish Conditions	Middle Quantiles / Normal Conditions	Upper Quantiles / Bullish Conditions	Overall Interpretation
Green Bonds-Bitcoin	Very weak and mixed relationship; coefficients remain close to zero, with small negative and positive values.	Mostly weak negative or neutral association.	Weak positive at some upper quantiles, but negative at extreme Bitcoin quantile.	Bitcoin has limited influence on green bonds, suggesting possible diversification benefits, although it is not a stable hedge.
Green Bonds-S&P 500	Positive at lower S&P 500 quantiles but turns negative when the U.S. equity market moves upward.	Mostly weak negative association.	Strong positive relationship, especially at upper green bond and upper S&P 500 quantiles.	Green bonds and U.S. equities become more connected during bullish conditions, reducing diversification benefits in strong equity markets.
Green Bonds-S&P Clean Energy	Strong positive lower-tail connectedness, especially when both markets are under stress.	Stable positive relationship across normal market conditions.	Positive connectedness remains visible in upper quantiles.	Clean energy shows the strongest link with green bonds, reflecting their shared sustainable finance nature, but diversification benefits may be limited.
Green Bonds-S&P GSCI	Positive at lower and middle commodity quantiles but negative at extreme commodity quantiles.	Very weak and mostly neutral relationship.	Mostly positive connectedness, especially at middle-to-upper commodity quantiles.	Commodity connectedness is mixed and condition-dependent, offering partial diversification benefits.
Green Bonds-SGH / Shanghai Market	Negative or weak relationship during lower market conditions.	Relationship gradually improves from weak negative to weak positive.	Stronger positive connectedness at upper green bond and upper SGH quantiles.	Green bonds and the Shanghai market become more positively connected during bullish conditions, while diversification is stronger during weak market states.

Green Bonds and S&P Clean Energy

Green bonds are most closely related to the S&P Clean Energy Index. The coefficients are mostly positive for the majority of quantiles, with the greatest effect at the lowest green bond quantile at 0.103. It suggests that connectedness of lower tail is strong between the green bonds and clean energy markets. That is, when the green bonds are under stress, the dynamics of the clean energy market become critical.

The positive correlation is to be expected, as green bonds are part of the larger sustainable finance universe. The robust lower-tail linkage, however, indicates that green bonds will not necessarily be a “safe haven” for investors during a period of stress in the clean energy sector (Lu & Chen, 2023; Wu et al., 2025). Thus, while green bonds and clean energy assets can contribute to sustainable investment goals, they are not necessarily well-diversified assets during market downturns.

Green Bonds and S&P GSCI Commodity Index

Green bonds' relation to the S&P GSCI Commodity Index is mixed and quantile dependent. For the lower green bond quantiles, commodity market effects are positive at the lower and middle commodity quantiles and negative at the higher commodity quantiles. This indicates that the very high commodity market rises could exert pressure on the returns of green bonds, for instance, via inflation, energy-price uncertainty, or investor risk preferences (Jiang et al., 2022; Nguyen et al., 2021; Yadav et al., 2024).

The relationships are predominantly positive at upper green bond quantiles, particularly around the middle and upper commodity quantiles. It shows that commodity market movements can help performance of green bonds under favorable green bond market conditions. But the overall relationship still isn't as strong as the green bond–clean energy relationship. Hence, commodities offer some diversification opportunities but not in all market conditions.

Green Bonds and SGH Market

The positive correlation with green bonds gradually increases with market quantiles. The coefficients are negative for the lower and middle green bond quantiles at lower quantiles of SGH, suggesting that poor market conditions of the SGH market may negatively impact green bond returns. But for higher quantiles of SGH the relationship turns positive and will be steeper.

The maximum positive coefficient is found at the upper green bond quantile and upper SGH quantile with a value of 0.025. This indicates that green bonds and the SGH market are closer when the market is bullish.

The findings indicate that green bonds might provide some diversification benefits during weak SGH conditions, and that the SGH market might have a more positive impact on green bonds during expansionary times.

Overall Discussion

The overall results suggest that the relationship between green bonds and international financial markets is non-linear, asymmetric and market dependent. The relationship varies between bearish quantiles, normal and bullish quantiles. The S&P Clean Energy Index is the most connected among all markets and green bonds, suggesting high integration in sustainable finance markets. The strength of the positive connectedness is mostly observed in bull markets for the S&P 500 and SGH markets and very slight and unstable positive connectedness for Bitcoin. In the case of commodity shocks, the S&P GSCI Commodity Index has mixed results, implying that commodity shocks have varying effects on green bonds across market states.

These findings lend credence to the use of Quantile-on-Quantile Regression as average-based models would not pick these quantile-specific effects. Green bonds could offer an investment diversification benefit over Bitcoin and, to an extent, commodities (Jiang et al., 2022; Joshi et al., 2024; Tsipas et al., 2024; Umar et al., 2022). But they're not as diversified with clean energy markets and are constrained in bull markets in equities. While green bonds are important from a sustainable portfolio point of view, investors should not presume that they are always unaffected by global financial market shocks. The degree of their role as a hedge or diversification asset is highly market and quantile dependent.

Contributions of the Study

Theoretical Contributions

This study adds to the literature on sustainable finance by broadening the knowledge of the connectedness of green bonds with international financial markets. This paper differs from previous studies which are based on average measures of dependence, by using the Quantile-on-Quantile Regression methodology to capture nonlinear and asymmetric dependence in different market conditions.

This study offers more insights into the reaction of green bonds in the bear, normal and bull phases of the global financial market. The study also contributes to the theory of portfolios, in that it offers evidence that the diversification function of green bonds is not necessarily tenable in all market conditions. These findings indicate that green bonds may behave in a different manner when the equity, commodity, clean energy, cryptocurrency and emerging-market securities experience a change in performance.

Consequently, this study contributes to the theoretical discussion on the need to consider green bonds as a separate sustainable asset class or as part of the financial system. Furthermore, the paper is a contribution to the climate-finance literature, since the paper links green bonds to conventional and alternative markets: namely, the S&P 500, the S&P GSCI, the S&P Clean Energy Index,

Bitcoin and Shanghai market. It can thus help in the understanding of the potential of green bonds for financial resilience and sustainable investments in different market scenarios.

Practical Contributions

Therefore, this study can be implied to the investors, portfolio managers, risk managers and institutional fund managers. The results indicate some degree of heterogeneity in the link between green bonds and all financial markets. These are market type and market condition dependent to diversify and hedge their value.

The results indicate that for portfolio managers, green bonds could provide a diversification benefit to highly volatile markets like Bitcoin (and to a lesser extent, commodity markets). The more closely aligned green bonds and clean energy markets, however, suggest that the co-location may not necessarily be a good risk reduction mix, particularly in stressed or extreme market environments.

The study also provides investors with a guide to creating sustainable portfolios. The QQR results are designed to empower investors to make a more informed decision during bearish, normal and bull markets. This is particularly important for long-term investors, pension funds, and even ESG funds and other climate-conscious institutions aiming to balance financial and environmental returns.

Policy Contributions

This study's findings are very significant for policy makers, regulators and financial authorities. As green bonds are being deployed more and more to fund climate-friendly projects, awareness of the interactions between green bonds and international financial markets is crucial for the evolution of stable and effective sustainable finance systems.

Results indicate that green bonds are not entirely immune to financial disturbances in the world. So regulators need to think about financial instruments relating to climate in a larger context of financial stability. Some quantiles are highly connected to clean energy and equity markets, indicating that, under certain conditions, the green financial assets can also transmit and/or absorb shocks from the markets.

The study is also a sign of the need to better regulate, standardize and transparently the green bond market. Policymakers need to improve green bond disclosure requirements, minimize greenwashing risks and promote credible certification systems. These measures can contribute to enhancing investor confidence and paving the way for sustainable finance.

Finally, the study highlights the importance of green bonds in the green development policy. The government can help mobilize private capital for renewables, clean infrastructure, adapting to climate change, and low carbon economic growth through encouraging green bond issuance and market efficiency.

Limitations and Future Research Directions

Limitations of the Study

Despite the importance of this study in providing evidence on the linkages between green bonds and the selected international financial markets, it has some limitations. First, only a few markets are analyzed, including: The S&P 500, S&P GSCI, S&P Clean Energy Index, Bitcoin and Shanghai market. Thus, the results might not adequately reflect the characteristics of all financial markets worldwide.

Second, the authors use daily log-returns, which show only short-term changes within the market, and may not reflect long-term structural relationships. The results may differ for different data frequencies such as weekly, monthly data.

Thirdly, the authors apply the Quantile-on-Quantile Regression methodology that is useful to identify asymmetric and nonlinear relationships, but this methodology is not developed to explain the observed connectedness. Other factors that may impact the link between green bonds and other markets include monetary policy, inflation, geopolitical risk, climate-policy uncertainty and investor sentiment.

Fourth, the study mainly concentrates on return connectedness. It fails to comprehensively investigate volatilities spillovers, risk transmission and causal relationship between the markets considered. Thus the results should be interpreted as quantile relationships of dependence, but not necessarily causal relationships.

Future Research Directions

Further studies can be carried out to expand this research and include other international financial markets such as the European green bonds market, the emerging-market bond market, the carbon market, the oil prices market, the gold market, the Islamic indices market and the regional stock markets. This would help give a bigger picture of how green bonds fit in to the global portfolio diversification.

A possible extension of this research would also be to compare the findings of the Quantile-on-Quantile Regression with other complicated approaches such as TVP-VAR connectedness, wavelet coherence, copula models, VAR and Markov switching models in quantiles. This sort of comparison would help to confirm the results.

A useful rule of thumb is to think about the impact of the major crises affecting the world, such as the COVID-19 pandemic, the Russia-Ukraine conflict, and global inflationary pressures and climate policy news. This will help identify if green bonds act differently in times of global uncertainty.

Further research may also investigate the volatility connectedness and downside risk spillovers between green bonds and other financial assets. That's good news for risk managers and institutional investors that are more concerned about the losses in the event of extreme market conditions.

Finally, macroeconomic and climate policy uncertainty, interest rates, or energy prices have potential for future research to examine their importance, as well as inflation and ESG sentiment. These factors may be other contributing factors to the differences in green bond connectedness under market conditions.

References

1. 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.

2. Arif, M., Naeem, M. A., Farid, S., Nepal, R., & Jamasb, T. (2022). Diversifier or more? Hedge and safe haven properties of green bonds during COVID-19. *Energy Policy*, *168*, 113102.

3. Ben Ameur, H., Ftiti, Z., Louhichi, W., & Yousfi, M. (2024). Do green investments improve portfolio diversification? Evidence from mean conditional value-at-risk optimization. *International Review of Financial Analysis*, *94*, 103255. https://doi.org/10.1016/j.irfa.2024.103255

4. Campiglio, E., Daumas, L., Monnin, P., & Von Jagow, A. (2023). Climate-related risks in financial assets. *Journal of Economic Surveys*, *37*(3), 950–992. https://doi.org/10.1111/joes.12525

5. Chai, S., Chu, W., Zhang, Z., Li, Z., & Abedin, M. Z. (2025). Dynamic nonlinear connectedness between the green bonds, clean energy, and stock price: The impact of the COVID-19 pandemic. *Annals of Operations Research*, *345*(2–3), 1137–1164. https://doi.org/10.1007/s10479-021-04452-y

6. Jiang, Y., Wang, J., Ao, Z., & Wang, Y. (2022). The relationship between green bonds and conventional financial markets: Evidence from quantile-on-quantile and quantile coherence approaches. *Economic Modelling*, *116*, 106038.

7. Joshi, D., Paul, S., Singh, P., Mane, N. S., & Yadav, M. (2024). Sustainable Finance: The Role of Green Bonds in Driving ESG Investments. *Library of Progress-Library Science, Information Technology & Computer*, *44*(3). https://search.ebscohost.com/login.aspx?direct=true&profile=ehost&scope=site&authtype=crawler&jrnl=09701052&AN=180918270&h=R51fDrqVUvksjz%2F4egJthNZhJURktbC1W15aMcAIUhdM5EGWH%2BGFvsllpY44q%2BrHTotgPzDEsoGULQRiuK%2FctQ%3D%3D&crl=c

8. Kamal, E., & Bouri, E. (2025a). Green bond, stock, cryptocurrency, and commodity markets: A multiscale analysis and portfolio implications. *Financial Innovation*, *11*(1), 100. https://doi.org/10.1186/s40854-024-00749-6

9. Kamal, E., & Bouri, E. (2025b). Green bond, stock, cryptocurrency, and commodity markets: A multiscale analysis and portfolio implications. *Financial Innovation*, *11*(1), 100. https://doi.org/10.1186/s40854-024-00749-6

10. Lu, K.-C., & Chen, K.-S. (2023). Uncovering information linkages between bitcoin, sustainable finance and the impact of COVID-19: Fractal and entropy analysis. *Fractal and Fractional*, *7*(6), 424.

11. Mensi, W., Vo, X. V., Ko, H.-U., & Kang, S. H. (2023). Frequency spillovers between green bonds, global factors and stock market before and during COVID-19 crisis. *Economic Analysis and Policy*, *77*, 558–580.

12. Mnif, E., Naifar, N., & Jarboui, A. (2025). The role of bitcoin, sustainable investments, and financial stability in the transition to a green economy. *Quality & Quantity*, *60*(1), 1391–1415. https://doi.org/10.1007/s11135-025-02294-5

13. Naeem, M. A., Nguyen, T. T. H., Nepal, R., Ngo, Q.-T., & Taghizadeh–Hesary, F. (2021). Asymmetric relationship between green bonds and commodities: Evidence from extreme quantile approach. *Finance Research Letters*, *43*, 101983.

14. Nguyen, T. T. H., Naeem, M. A., Balli, F., Balli, H. O., & Vo, X. V. (2021). Time-frequency comovement among green bonds, stocks, commodities, clean energy, and conventional bonds. *Finance Research Letters*, *40*, 101739.

15. Pham, L., & Nguyen, C. P. (2021). Asymmetric tail dependence between green bonds and other asset classes. *Global Finance Journal*, *50*, 100669. https://doi.org/10.1016/j.gfj.2021.100669

16. Reboredo, J. C. (2018). Green bond and financial markets: Co-movement, diversification and price spillover effects. *Energy Economics*, *74*, 38–50.

17. Reboredo, J. C., & Ugolini, A. (2020). Price connectedness between green bond and financial markets. *Economic Modelling*, *88*, 25–38.

18. Reboredo, J. C., Ugolini, A., & Aiube, F. A. L. (2020). Network connectedness of green bonds and asset classes. *Energy Economics*, *86*, 104629. https://doi.org/10.1016/j.eneco.2019.104629

19. Rehan, A., Mohti, W., & Ferreira, P. (2024). Quantile Connectedness Amongst Green Assets Amid COVID-19 and Russia–Ukraine Tussle. *Economies*, *12*(11), 307. https://doi.org/10.3390/economies12110307

20. Shah, S. A., Nawaz, A., Yuan, D., & Su, C. W. (2026). Green bond performance under ESG uncertainty: Nonlinear Time–Frequency quantile analysis. *Economic Modelling*, 107631.

21. Sim, N., & Zhou, H. (2015a). Oil prices, US stock return, and the dependence between their quantiles. *Journal of Banking & Finance*, *55*, 1–8.

22. Sim, N., & Zhou, H. (2015b). Oil prices, US stock return, and the dependence between their quantiles. *Journal of Banking & Finance*, *55*, 1–8.

23. Tiwari, A. K., Kumar, S., & Abakah, E. J. A. (2025). Correlation and price spillover effects among green assets. *Annals of Operations Research*, *347*(1), 419–444. https://doi.org/10.1007/s10479-024-06154-7

24. Tsipas, F., Elrashidy, Z., & Sandretto, D. (2024). Green bonds efficiency and renewable energy: Insights from the Covid-19 pandemic. *Journal of Environmental Management*, *371*, 123090.

25. Umar, Z., Bossman, A., Choi, S.-Y., & Teplova, T. (2022). Does geopolitical risk matter for global asset returns? Evidence from quantile-on-quantile regression. *Finance Research Letters*, *48*, 102991.

26. Vihervuori, N. (2023). *Correlation between green bonds and financial markets: The impact of using green bonds in the stock-bond portfolio.* https://osuva.uwasa.fi/items/6c3aacf8-b35d-4fb4-9d8f-bdef06abc197

27. Wu, R., Yan, J., & Işık, C. (2025). The dynamics between clean energy, green bonds, grain commodities, and cryptocurrencies: Evidence from correlation and portfolio hedging. *Economic Change and Restructuring*, *58*(4), 60. https://doi.org/10.1007/s10644-025-09902-2

28. Yadav, M. P., Ashok, S., Taghizadeh-Hesary, F., Dhingra, D., Mishra, N., & Malhotra, N. (2024). Uncovering time and frequency co-movement among green bonds, energy commodities and stock market. *Studies in Economics and Finance*, *41*(3), 638–659. https://doi.org/10.1108/SEF-03-2023-0126

29. Yildirim, R., & Mejri, S. (2026). Dynamic interactions between green cryptocurrencies and ESG indices: A Multivariate Quantile-on-Quantile Regression approach. *Journal of Sustainable Finance & Investment*, 1–35. https://doi.org/10.1080/20430795.2026.2617647

30. Zhao, M., & Park, H. (2024). Quantile time-frequency spillovers among green bonds, cryptocurrencies, and conventional financial markets. *International Review of Financial Analysis*, *93*, 103198. https://doi.org/10.1016/j.irfa.2024.103198