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Impact of sustainability uncertainty on the volatility dynamics of digital asset class

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ABSTRACT

The association between cryptocurrency and sustainability is a complex and growing topic. Given that such linkage requires a continuous investigation, this empirical research, unlike the existing literature, explores if the volatility dynamics of digital assets are driven by the changes in sustainability uncertainty. In doing so, we use a recently developed ESG-based sustainability uncertainty index (ESGUI) and examine its effect on the volatility dynamics of Bitcoin and Ethereum ETFs. Employing the mixed data sampling (MIDAS) approach shows that ESGUI exerts a negative effect on the realized volatility of cryptocurrency markets. One possible explanation for this linkage is that as sustainability-related uncertainty rises, investors tend to adopt sustainability practices and initiatives. This shift towards sustainable practices can result in more consistent and foreseeable long-term economic conditions, thereby reducing the volatility of financial markets including the digital asset class. Our analysis offers key implications to cryptocurrency investors.

1. Introduction

The association between cryptocurrency and its energy consumption has been a topic of rising concern in recent years. Sarkodie et al (2022), for instance, argue that while cryptocurrencies offer potential benefits such as financial inclusion and decentralized transactions, they also elevate concerns related to energy consumption, environmental impact, and electronic waste. In particular, the energy-intensive nature of cryptocurrency mining, primarily due to the proof-of-work consensus mechanism, has raised questions about its environmental impact.¹ A number of empirical studies (De Vries, 2018, 2020, 2021; Delgado-Mohatar et al., 2019; Das and Dutta, 2020; Chitkasame et al., 2022; Maiti, 2022; Qin et al., 2023; Adewuyi et al., 2024) claim that the high energy consumption associated with cryptocurrency mining contributes to carbon emissions and exacerbates climate change. These authors also document that Bitcoin mining alone consumes a significant amount of electricity, comparable to the energy usage of entire countries.

However, it is also worth noting that the cryptocurrency industry is exploring more energy-efficient alternatives, such as proof-of-stake consensus mechanisms, which require significantly less energy compared to proof-of-work. Additionally, some mining operations are shifting towards renewable energy sources to reduce their carbon

footprint. More specifically, blockchain technology underlying cryptocurrencies can be leveraged for various sustainable initiatives. For example, blockchain can enhance supply chain transparency, traceability of goods, and facilitate carbon offset trading.

In sum, the intersection of cryptocurrency and sustainability is a complex and evolving topic, which requires a continuous assessment. In this research, unlike the above-mentioned studies, we examine if the volatility dynamics of digital assets (e.g., Bitcoin and Ethereum) are sensitive to the changes in sustainability uncertainty. To the best of our knowledge, this is the initial attempt to investigate such linkages, which is important to understand if the sustainability uncertainty has directional predictability for the risk linked to digital assets.

Our study extends the prior works in several aspects. Firstly, we utilize a new text-based indicator to proxy sustainability uncertainties. This ESG-based index (ESGUI), developed by Ongan et al., (2025), can be considered as a leading measure of sustainability uncertainty as it is constructed using selected ESG-related keywords from the Economist Intelligence Unit (EIU) monthly country reports. A number of recent studies (Gaies et al., 2025; Özkan et al., 2025) also recommend the application of this index to proxy the uncertainties concerning sustainability. Secondly, given that a more precise understanding of the relationship between sustainability uncertainty shocks and cryptocurrency volatility necessitates treating good and bad volatilities separately, this

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¹ The annual estimates of Bitcoin's energy consumption range from 91 to 150 terawatt-hours, primarily due to its complex Proof of Work mining process.

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study decomposes the daily volatility of different crypto assets into good and bad volatilities to examine whether these two components react differently to sustainability uncertainty shocks. This strand of analysis is important as based on our findings, risk managers might need to improve their volatility prediction approaches by considering the information content of ESGUI.

What follows provides an elaboration on why this research topic relevant and timely. First, sustainability-related uncertainty—arising from environmental, social, or governance (ESG) factors—can shape how investors view cryptocurrency as an asset. Heightened uncertainty may lead to increased risk aversion, causing investors to withdraw or reduce their shares in the cryptocurrency markets, which can amplify price volatility. Secondly, governments and regulators may respond to sustainability concerns by implementing new regulations or standards for cryptocurrencies. Such policy shifts can lead to abrupt changes in market conditions, contributing to volatility as participants adjust to the evolving landscape. Thirdly, public sentiment toward cryptocurrencies is closely tied to sustainability debates: positive developments including greener mining practices may fuel optimism, while negative news such as restrictions on environmentally harmful activities can trigger pessimistic reactions and short-term volatility. Fourthly, the relationship between sustainability uncertainty and volatility can drive innovation within the cryptocurrency sector. Developers may focus on creating more energy-efficient solutions or sustainable protocols, potentially reducing volatility in the long run as the market becomes more resilient to external shocks. Finally, regions reliant on Bitcoin mining for economic activity may face challenges if sustainability concerns lead to regulatory clampdowns or shifts in public sentiment. This can create economic instability and volatility within local markets tied to cryptocurrency operations. To sum up, the relationship between sustainability uncertainty and Bitcoin volatility has broad implications across the financial ecosystem, influencing investment behavior, market dynamics, regulation, and the overall perception of cryptocurrencies. Stakeholders need to navigate these complexities carefully to foster a more stable and sustainable crypto environment.

Methodologically, we employ the mixed data sampling (MIDAS) regression to study the impact of ESGUI on the volatility levels of digital assets. The MIDAS approach is appropriate for our investigation, since it can deal with the data frequency disparity between the daily cryptocurrency price series and the monthly uncertainty indicator.

Our findings reveal that ESGUI exerts a negative impact on the realized variance (volatility) of these digital assets implying that with the increase in sustainability uncertainty, the volatility of digital assets tends to decrease. This result may be explained by the fact that when sustainability-related uncertainty increases, sustainability practices and initiatives are implemented, which can lead to more stable and predictable long-term economic conditions, thereby lowering the volatility of these digital assets. Overall, our analysis suggests that investors may consider the information content of ESGUI to precisely predict the risk linked cryptocurrency investments.

The rest of this article proceeds as follows: [Section 2](#) includes a brief review of the relevant literature. [Section 2](#) outlines the datasets used in our empirical part. The methods are explained in [Section 4](#). Empirical findings are discussed in [Section 5](#), while [Section 7](#) summarizes the paper.

2. Literature review

2.1. Cryptocurrency and its energy consumption

This section briefly reviews previous studies focusing on the relationship between cryptocurrency and its energy consumption. We begin with the study by [De Vries \(2020\)](#), which estimates that as of September 30, 2019, the Bitcoin network consumed 87.1 TWh of electricity each year, which is comparable to the annual energy consumption of Belgium. In addition, [De Vries \(2021\)](#) documents that with the growing

price of Bitcoin, the negative externalities linked to its mining such as energy consumption and electronic waste generation tend to increase as well. To deal with these glitches, the author proposes a simple economic model to evaluate the ecological effect of mining process for a given Bitcoin price. [Maiti \(2022\)](#) employ a threshold regression (TR) model to estimate the impact of Bitcoin's energy consumption on its price levels. The study shows that such effect is regime-specific as the TR regression detects six regimes for the Bitcoin price changes. Applying the time-varying parameter vector autoregressive (TVP-VAR) approach, [Yuan et al. \(2022\)](#) emphasize that energy consumption is significantly associated with risk in the Bitcoin market, serving a crucial role in the mechanism of tail risk transmission. [Qin et al. \(2023\)](#) also adopt the TVP-VAR model to report that the price of Bitcoin mostly has a positive effect on carbon emissions and energy consumption, suggesting that a higher Bitcoin price could lead to increased energy demand for mining. The study further reveals that this mining process also results in carbon dioxide emissions. [Liu et al. \(2023\)](#) describe Mining Domestic Production (MDP) as a method for assessing the overall output of the Bitcoin mining industry and conclude that the carbon emissions from Bitcoin mining are not consistently the highest when compared to other industries. More recently, [Adewuyi et al. \(2024\)](#) show that two important variables related to Bitcoin mining – energy consumption and carbon footprint – experience certain bubble episodes which occur as a consequence of financial turmoil and geopolitical shocks.

2.2. Dynamics of cryptocurrency markets under uncertainties

A number of empirical studies investigate how uncertainties caused by geopolitical events, financial stress, climate change and pandemic influence the dynamics of cryptocurrency markets. Some recent contributions include [Aras et al. \(2025\)](#), [Almeida et al. \(2025\)](#), [Patra and Singh \(2025\)](#), [Ding et al. \(2025\)](#), [Şerban \(2025\)](#), [Sheikh and Suleman \(2025\)](#), [Yi et al. \(2025\)](#), [Chen et al. \(2024\)](#), [Dong et al. \(2024\)](#), [Gill-de-Albornoz et al. \(2024\)](#), [Jana and Sahu \(2025\)](#), [Kayani et al. \(2024\)](#), [Fasanya et al. \(2023\)](#), [Nouir and Hamida \(2023\)](#), [Taera et al. \(2023\)](#), [Jana and Sahu \(2023a,b\)](#), [Al-Shboul et al. \(2022\)](#) and among others. [Aras et al. \(2025\)](#), for instance, study the effect of investor attention indices such as the Google Trends Cryptocurrency Attention (GTCA) index, and key uncertainty indices including global economic policy uncertainty (GEPUI) and geopolitical risk (GPR) on Bitcoin volatility. Employing the GARCH-MIDAS model, the authors show that the information on GTCA is a better predictor compared to GEPUI and GPR. An interesting study by [Almeida et al. \(2025\)](#) reveals that the dynamics between sustainability-based and AI-related crypto assets depend on the market conditions. In particular, these assets display high correlations with the increase in market uncertainty. [Patra and Singh \(2025\)](#) find that financial stress index (FSI) and the US Equity Market Uncertainty (EMU) also play a pivotal role explaining the variations in cryptocurrency markets. In particular, the study finds that the impact of these uncertainty measures is asymmetric in the long run, but symmetric in the short run. Using a genetic programming (GP), [Ding et al. \(2025\)](#) examine the impact of climate policy uncertainties (CPU) on cryptocurrency volatility and find that such effect, depending on the crypto assets, tends to vary across time scales. [Şerban \(2025\)](#) proposes a novel multi-objective optimization approach for sustainable portfolio rebalancing under uncertainty. This model is applied to a set of crypto assets including Bitcoin, Ethereum, Solana, and Binance Coin and the simulation results confirm its adaptability to varying market conditions and investor sentiment, consistently generating stable and diversified allocations. Moreover, [Yi et al. \(2025\)](#) investigate the causal association between the US trade policy uncertainty (TPU) and cryptocurrency returns applying the quantile Granger causality test. The findings suggest that fluctuations in cryptocurrency prices consistently lead to changes in trade policy uncertainty across various quantiles, indicating that cryptocurrencies could act as early indicators of shifts in economic policy sentiment. While exploring the effect of EPU on Bitcoin volatility,

Gill-de-Albornoz et al. (2024) document that although the country level does not have any impact on Bitcoin volatility, the global EPU does. Moreover, Jana and Sahu (2025) document that the linkage between Indian stock market and digital currency shows a strong positive correlation during financial turmoil caused by the COVID-19 pandemic and the Russian invasion of Ukraine. The study also reveals that although cryptocurrencies can act as a means of diversification or hedging in the Indian equity market when the market remains stable, they do not function as effective diversifiers or safe havens during periods of financial distress. Applying the TVP-VAR model, Kayani et al. (2024) study the quantile connectedness among digital assets, traditional assets, and renewable energy prices during extreme economic crisis. The results reveal that the association between these assets is sensitive to three waves of COVID-19, the Russia-Ukraine conflict, and the recent Israel-Gaza dispute. In addition, Chen et al. (2024) examine how political uncertainty, proxied by GPR, influences Bitcoin market volatility. The study documents that the impact of GPR is strong during the turmoil periods. The findings also indicate that Bitcoin can hedge political uncertainty. Nour and Hamida (2023) also report similar findings. In particular, they show that Bitcoin can act as hedge for the US EPU and GPR. Applying the GARCH methodology, Taera et al. (2023) provide evidence that cryptocurrency markets become more volatility due to the uncertainties caused by COVID-19 pandemic and the Russo-Ukrainian War. Jana and Sahu (2023a) employ the DCC-GARCH model to investigate the possibilities of cryptocurrencies as hedges and diversifiers in the Indian stock market before and during financial crisis due to the COVID-19 pandemic and the Russo-Ukrainian War. The study finds that while Bitcoin, Ethereum, Binance Coin and Ripple emerge as the most effective diversifiers for the equity market amid the periods of turmoil, Tether acts as a safe haven. Another important study by Jana and Sahu (2023b) reports that cryptocurrencies such as Bitcoin, Ethereum, Binance Coin, and Dogecoin act as a hedge when the stock markets behave normally, but not amid the crisis periods. The authors further find that Tether serves as a diversifier regardless of the market conditions.

The primary objective of this paper is to build on existing research by examining how cryptocurrency market volatility reacts to growing sustainability-related uncertainty. As eco-friendly investors increasingly prioritize sustainability in their portfolios, perceptions of cryptocurrencies as a non-sustainable asset may discourage them, leading to diminished demand and increased volatility. Conversely, progress toward more sustainable mining practices could help stabilize or even strengthen prices. Moreover, heightened uncertainty can amplify risk aversion, leading investors to withdraw or reduce their positions in cryptocurrencies, which may further intensify price fluctuations. Understanding this relationship is therefore essential for market participants given that it enables them to adjust their strategies, risk tolerance, and asset allocations in favor of cryptocurrencies that align with sustainable principles.

3. Data

We consider two digital assets in our analysis: Grayscale Bitcoin Trust ETF (GBTC) and Grayscale Ethereum Trust ETF (ETHE). These ETFs are passively invested in Bitcoin and Ethereum, respectively. For example, the investment objective of GBTC is to reflect the value of Bitcoin held by the Trust, less expenses and other liabilities. We collect these data from the Bloomberg terminal.

Notably, while cryptocurrency ETFs have some limitations (e.g., limited trading hours, indirect exposure), they have quickly become popular, particularly among conventional investors. These ETFs provide access to digital assets without the challenges associated with trading, managing, or storing the actual assets. For example, cryptocurrency ETFs can be traded through standard brokerage accounts, which means investors do not have to familiarize themselves with crypto exchanges, wallets, or private keys. Besides, ETFs are regulated by organizations

such as the Securities and Exchange Commission (SEC), which enhances investor protection. Additionally, the fund issuer takes care of security and custody, relieving investors of these responsibilities.

The use of cryptocurrency ETFs in this study is motivated by the following facts: A crypto ETF trades on a stock exchange instead of a crypto exchange, which can lead to more stable pricing. Babalos et al. (2025), for instance, also argue that this feature allows investors and portfolio managers to more easily get exposure on the spot market without taking additional steps required to purchase actual digital assets from cryptocurrency exchanges, which are often subject to cyberattacks, thefts, or flash crash, thereby raising the volatility of digital assets. Moreover, unlike the cryptocurrency price indexes, crypto ETFs are subject to regulatory scrutiny, which can boost the confidence among investors given that this regulatory framework can help stabilize prices by ensuring fair practices and reducing the potential for manipulation. Furthermore, ETFs can provide greater liquidity because they are traded on traditional exchanges during normal trading hours. This can result in more orderly buying and selling, reducing sharp price movements that can occur in the relatively less liquid spot markets for Bitcoin.

Proceeding further, the information on ESGUI is sourced from the website of economic policy uncertainty. Note that the ESGUI is determined on a country-by-country basis by averaging the ESG sub-index and uncertainty sub-index values for each month. Additionally, Ongan et al. (2025) calculate a global ESGUI in two ways: Global-equal-weighted and Global-GDP-weighted means of the ESGUI indices from individual countries. All values are scaled (normalized) to ensure that the highest value is 100 and the lowest value is 0. We use the global indexes in our analysis. Note that this new uncertainty measure can serve as either an independent or dependent variable in empirical research that explores the concepts of sustainability and uncertainty, individually or in combination, thereby enriching the existing literature. An increase in this index will signify greater challenges and risks to sustainability initiatives in various countries. Additionally, ESGUI can assist businesses and policymakers in understanding how shifting uncertainties impact ESG performance, enabling them to adjust their sustainability and investment strategies accordingly (Ongan et al., 2025).²

Our sample period runs from December 17, 2021 to March 31, 2025. This period is based on the availability of cryptocurrency ETFs. Figure 1 depicts the ETFs, which demonstrates an upward trend, though a drop is observed after the Russian invasion of Ukraine in 2022. We also plot the ESGUI values shown in Figure 2. This graph indicates that ESGUI has increased substantially in recent years.

4. MIDAS regression model

From a methodological standpoint, we employ the MIDAS framework introduced by Ghysels et al. (2004) to assess how sustainability uncertainty influences volatility within the digital asset market. This approach offers several advantages. First, the MIDAS model accommodates variables sampled at different frequencies within a single regression. Second, it adopts a distributed-lag structure, allowing the dependent variable in a given period to be explained by multiple lags of a higher-frequency independent variable (Qiu, 2020). Third, MIDAS mitigates the over-parameterization problems commonly encountered in standard regression models that require aggregating high-frequency data. Fourthly, MIDAS can complement existing econometric frameworks by providing a means to incorporate additional high-frequency predictors into predictive models, enhancing their explanatory power.

² The ESGUI is valuable for analyzing how the rising prominence of ESG factors in today's business and investment landscape relates to economic uncertainties. Effectively identifying environmental, social, and governance risks is essential for both investors and policymakers. All of these aspects make this index a vital resource for comprehending the sustainability-related risks that companies and markets encounter.

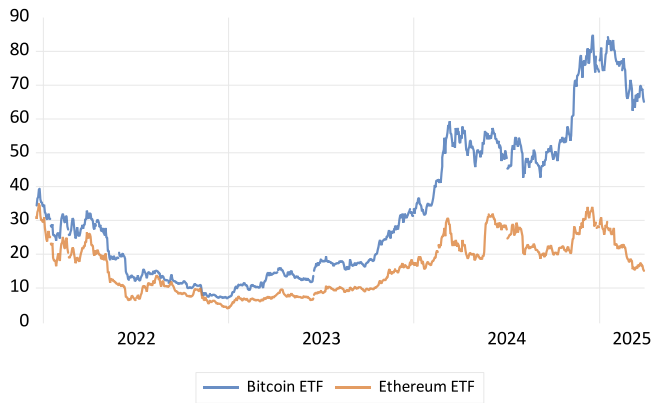


Fig. 1. Bitcoin and Ethereum ETF over the sample period. Notes: This figure exhibits the time series of two cryptocurrency exchange-traded funds (ETFs): GBTC and ETHE. The sample period runs from December 17, 2021 to March 31, 2025. Here, X-axis indicates the timeline, while Y-axis indicates the ETF values.

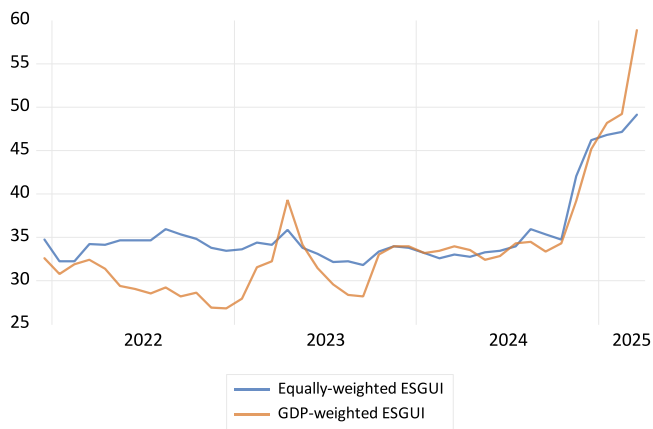


Fig. 2. ESG-based sustainability uncertainty index over the sample period. Notes: This figure exhibits the time series of ESG uncertainty index (ESGUI). The sample period runs from December 17, 2021 to March 31, 2025. Here, X-axis indicates the timeline, while Y-axis indicates the equally- and GDP-weighted ESGUI.

Finally, traditional methods may require aggregating high-frequency data to match the frequency of low-frequency data, which can lead to a loss of information. MIDAS regression avoids this problem by directly using high-frequency data without aggregation, making the estimation process more efficient. Therefore, the MIDAS process appears to be suitable for our empirical analysis given that it can manage the data frequency mismatch between the monthly sustainability uncertainty index and the daily volatility data for the cryptocurrency markets.³

This model is expressed as follows:

$$RV_{t+1} = \alpha + \beta W\left(\frac{1}{L^m}; \theta\right) \Delta ESGUI_t^{(m)} + \varepsilon_t \quad (1)$$

where, RV_t indicates the realized volatility of cryptocurrency ETF, $\Delta ESGUI_t$ denotes the first order difference of the ESG-based uncertainty index with m being the number of data points for the uncertainty

measure and $W\left(\frac{1}{L^m}; \theta\right) = \sum_{k=0}^K \omega(k; \theta) L^{k/m}$; $\omega(k; \theta)$ represents a parameterized weight function, $L^{k/m}$ refers to the lag operator and $k = 0, 1, 2, \dots, K$ is the lag-order for the explanatory variable.

Now following Andreou et al. (2013), Equation (1) is extended as follows:

$$RV_{t+1} = \alpha + \delta RV_t + \beta W\left(\frac{1}{L^m}; \theta\right) \Delta ESGUI_t^{(m)} + \varepsilon_t \quad (2)$$

The above model is called the autoregressive distributed lag mixing data regression (ADL-MIDAS) model (Zhang and Wang, 2019; Gong et al., 2022).

Note that we employ the Parkinson (1980) measure to estimate the RV as follows:

$$RVP_t = \frac{1}{4 \ln 2} [\ln H_t - \ln L_t]^2 \quad (3)$$

where H_t and L_t appear to be the highest and lowest prices on a trading day t .

Next, we select the weight function. In order to avoid the complexity of parameters, the Beta function is selected as the weight function in this study. Thus, the probability density function of Beta distribution family is considered in our MIDAS model. Since a Beta distribution family can be formed with only two parameters, our analysis is free of the parameter proliferation issue prompted by mixing data (Ghysels et al., 2016). Now, the Beta function is given as:

$$\omega_i(\theta) = \omega_i(\theta_1, \theta_2) = \frac{f(z_i, \theta_1, \theta_2)}{\sum_{i=1}^{i^{\max}} f(z_i, \theta_1, \theta_2)} \quad (4)$$

In Equation 4, i ($i = 0, 1, 2, \dots, i^{\max}$) refers to the distribution lag order and i^{\max} denotes the maximum lag order of the weight function. Additionally, $z_i = i/i^{\max}$ and $f(z_i, \theta_1, \theta_2)$ is specified as:

$$f(z_i, \theta_1, \theta_2) = \frac{z_i^{\theta_1-1} (1-z_i)^{\theta_2-1} \Gamma(\theta_1 + \theta_2)}{\Gamma(\theta_1) \Gamma(\theta_2)} \quad (5)$$

$$\text{with } \Gamma(\theta) = \int_0^{\infty} e^{-z} z^{\theta-1} dz$$

5. Empirical results

5.1. Estimates of the MIDAS regressions

Table 1 reports the findings of the MIDAS model: Panel A shows the results for the Bitcoin ETF, while Panel B presents the findings for the Ethereum ETF. Our analysis documents several interesting findings. Firstly, the equally weighted ESGUI does not have any statistically significant impact on the RV of Bitcoin ETF, although the GDP-weighted index exerts a negative effect on the volatility of this digital asset. For the Ethereum ETF, however, we find this result to hold in reverse order. Secondly, for the Bitcoin ETF, the RV is not sensitive to its lagged value. For the Ethereum ETF, on the other hand, the volatility persistence is observed as the corresponding coefficient is found to be statistically significant. Thirdly, we find that the Beta distribution parameters (θ_1, θ_2) appear to be positive and significant, which justifies the use of Beta weight functions in our investigation.

Notably, the negative impact of ESGUI indicates that the realized volatility of cryptocurrency ETFs tends to decrease with an increment in the sustainability uncertainty index. This finding could be explained by the fact that when sustainability-related uncertainty increases, sustainability practices and initiatives are implemented, which can lead to more stable and predictable long-term economic conditions. This

³ Some recent studies which recommend the application of this MIDAS regression include Khoo (2021), Dong et al. (2025), Jiang et al. (2025) and Wang et al. (2025).

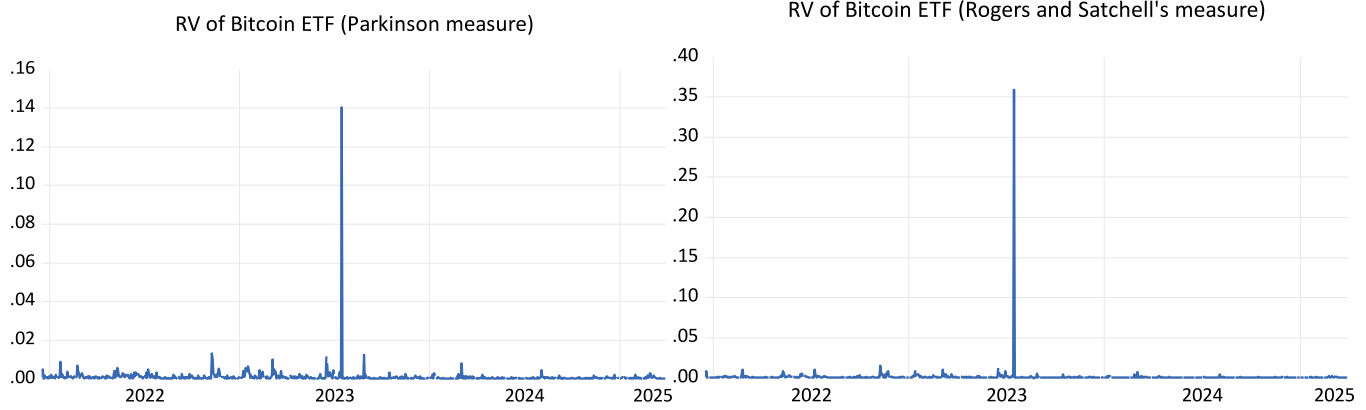


Fig. 3. Realized volatility of Bitcoin ETF over the sample period. Notes: This figure exhibits the realized volatility (RV) of Bitcoin exchange-traded funds (ETF). The sample period runs from December 17, 2021 to March 31, 2025. Here, X-axis indicates the timeline, while Y-axis indicates the RV measured by two different estimators.

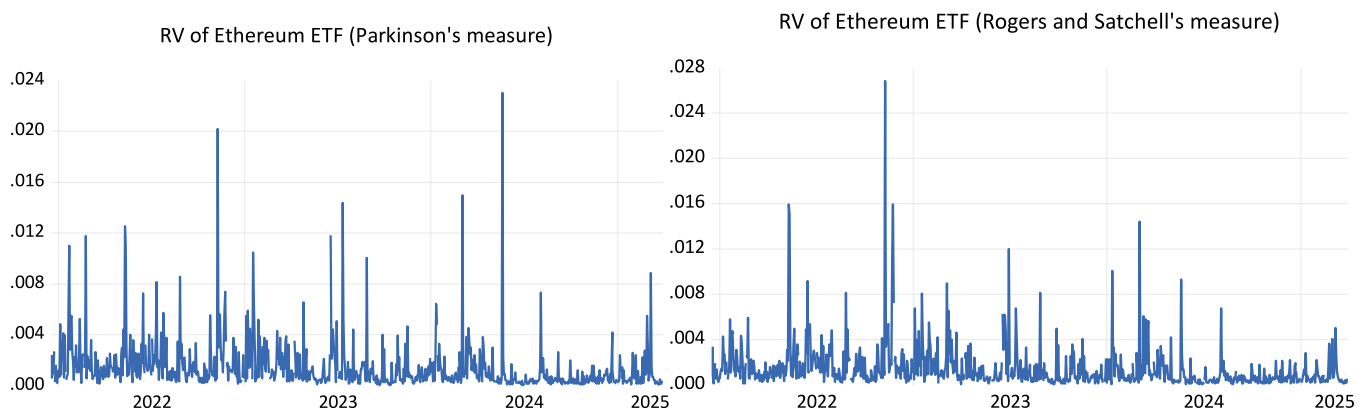


Fig. 4. Realized volatility of Ethereum ETF over the sample period. Notes: This figure exhibits the realized volatility (RV) of Ethereum exchange-traded funds (ETF). The sample period runs from December 17, 2021 to March 31, 2025. Here, X-axis indicates the timeline, while Y-axis indicates the RV measured by two different estimators.

Table 1
Results of MIDAS regressions for realized variance.

	Equally-weighted ESGUI		GDP-weighted ESGUI	
	Estimate	S.E.	Estimate	S.E.
Panel A: Bitcoin ETF				
α	0.0011***	0.0002	0.0012***	0.0002
δ	0.0093	0.0375	0.0049	0.0375
β	-0.0002	0.0002	-0.0002**	0.0001
θ_1	1.2323***	0.0346	1.2321***	0.0277
θ_2	19.9979***	0.0019	19.9979***	0.0009
Log-likelihood	2791.16		2792.68	
Panel B: Ethereum ETF				
α	0.0012***	0.0001	0.0011***	0.0002
δ	0.2039***	0.0370	0.2089***	0.0644
β	-0.0002**	0.0001	-0.0001	0.0001
θ_1	1.1838***	0.0855	1.1953***	0.2675
θ_2	19.9991***	0.0018	19.9998***	0.0085
Log-likelihood	3524.98		3523.72	

Notes: This Table reports the findings of our MIDAS analysis: Panel A shows the results for the Bitcoin ETF, while Panel B presents the findings for the Ethereum ETF. The parameter β measures the effect of ESG uncertainty index (ESGUI) on the realized volatility (RV) of cryptocurrency exchange exchange-traded funds (ETFs). θ_1 and θ_2 refer to the Beta distribution parameters. *** and ** imply statistical significance at 1 % and 5 % levels, respectively.

stability may reduce the overall market uncertainty, thereby lowering the volatility of cryptocurrency markets.

Additionally, rising sustainability uncertainty may initiate increased transparency, accountability, and ethical practices within companies and industries. This enhanced transparency can build trust among investors and stakeholders, leading to more confidence in the market and potentially reducing sudden price swings or extreme fluctuations in highly volatile markets including digital assets.

Next, we check the robustness of our findings by employing an alternative measure of realized volatility proposed by [Rogers and Satchell \(1991\)](#)⁴. This estimator is given as:

$$RVRS_t = \ln\left(\frac{H_t}{O_t}\right) \ln\left(\frac{H_t}{C_t}\right) + \ln\left(\frac{L_t}{O_t}\right) \ln\left(\frac{L_t}{C_t}\right) \tag{6}$$

with O_t and C_t indicating the opening and closing prices on a trading day t .

[Table 2](#), which shows the results of our robustness analysis, document similar output. For instance, ESGUI still exerts a negative effect on the cryptocurrency volatility.

Hence, we can conclude that our results are robust as they are mostly consistent regardless of the measures used.

⁴ [Figures 3 and 4](#) plot the RV of Bitcoin and Ethereum ETFs. These graphs indicate that the RV of Ethereum ETF experiences more fluctuations than the Bitcoin ETF.

Table 2
MIDAS analysis using the measure of Rogers & Satchell.

	Equally-weighted ESGUI		GDP-weighted ESGUI	
	Estimate	S.E.	Estimate	S.E.
Panel A: Bitcoin ETF				
α	0.0017***	0.0005	0.0017***	0.0005
δ	-0.0031	0.0371	-0.0084	0.0374
β	-0.0006	0.0004	-0.0006**	0.0003
θ_1	1.2431***	0.0527	1.2393***	0.0322
θ_2	19.9975***	0.0015	19.9990***	0.0009
Log-likelihood	2121.58		2123.44	
Panel B: Ethereum ETF				
α	0.0011***	0.0001	0.0010***	0.0001
δ	0.2586***	0.0359	0.2637***	0.0361
β	-0.0002**	0.0001	-0.0001	0.0001
θ_1	0.9972***	0.2314	1.1591***	0.1218
θ_2	4.0137	18.0876	19.9986***	0.0012
Log-likelihood	3509.28		3507.88	

Notes: This Table reports the findings of our MIDAS analysis: Panel A shows the results for the Bitcoin ETF, while Panel B presents the findings for the Ethereum ETF. The parameter β measures the effect of ESG uncertainty index (ESGUI) on the realized volatility (RV) of cryptocurrency exchange-traded funds (ETFs). θ_1 and θ_2 refer to the Beta distribution parameters. *** and ** imply statistical significance at 1 % and 5 % levels, respectively.

Table 3
MIDAS analysis of realized volatility: Parkinson’s measure.

	Equally-weighted ESGUI		GDP-weighted ESGUI	
	Estimate	S.E.	Estimate	S.E.
Panel A: Bitcoin ETF				
α	0.0212***	0.0012	0.0209***	0.0012
δ	0.2086***	0.0368	0.2104	0.0367
β	-0.0017**	0.0008	-0.0008*	0.0005
θ_1	1.2113***	0.0435	1.2107***	0.0338
θ_2	19.9993***	0.0023	19.9978***	0.0010
Log-likelihood	1845.67		1845.04	
Panel B: Ethereum ETF				
α	0.0219***	0.0013	0.0215***	0.0013
δ	0.3329***	0.0350	0.3395***	0.0353
β	-0.0006**	0.0004	-0.0001	0.0001
θ_1	0.9978***	0.0876	1.1784***	0.0724
θ_2	2.8275***	0.0381	19.9984***	0.0011
Log-likelihood	1923.74		1922.08	

Notes: This Table reports the findings of our MIDAS analysis for the realized volatility (\sqrt{RV}): Panel A shows the results for the Bitcoin ETF, while Panel B presents the findings for the Ethereum ETF. The parameter β measures the effect of ESG uncertainty index (ESGUI) on the realized volatility (RV) of cryptocurrency exchange-traded funds (ETFs). θ_1 and θ_2 refer to the Beta distribution parameters. *** and ** imply statistical significance at 1 % and 5 % levels, respectively.

5.2. Estimates of the MIDAS regressions: realized volatility (\sqrt{RV})

Tables 3 and 4 report the findings of the MIDAS model for the realized volatility measure (i.e., \sqrt{RV}). These results are usually in line with those shown in Tables 1 and 2. For example, the impact of ESGUI is mostly significant and negative. Hence, consistent with our previous analysis, we document a similar relationship between ESGUI and realized volatility of the digital assets under study. One notable difference is that the realized volatility of Bitcoin ETF is now sensitive to its lagged value, suggesting the existence of volatility persistence in each cryptocurrency.

Note that the relationship between sustainability uncertainty and

Table 4
MIDAS analysis of realized volatility: Rogers & Satchell’s measure.

	Equally-weighted ESGUI		GDP-weighted ESGUI	
	Estimate	S.E.	Estimate	S.E.
Panel A: Bitcoin ETF				
α	0.0235***	0.0014	0.0236***	0.0014
δ	0.1343***	0.0370	0.1307	0.0373
β	-0.0018**	0.0009	-0.0014**	0.0006
θ_1	1.2121***	0.0313	1.2179***	0.0260
θ_2	19.9978***	0.0012	19.9982***	0.0006
Log-likelihood	1633.16		1634.02	
Panel B: Ethereum ETF				
α	0.0220***	0.0014	0.0215***	0.0014
δ	0.3359***	0.0350	0.3430***	0.0353
β	-0.0016**	0.0006	-0.0007*	0.0004
θ_1	0.9944***	0.1119	1.1711***	0.0792
θ_2	3.1753	7.8471	19.9979***	0.0010
Log-likelihood	1912.11		1910.28	

Notes: This Table reports the findings of our MIDAS analysis for the realized volatility (\sqrt{RV}): Panel A shows the results for the Bitcoin ETF, while Panel B presents the findings for the Ethereum ETF. The parameter β measures the effect of ESG uncertainty index (ESGUI) on the realized volatility (RV) of cryptocurrency exchange-traded funds (ETFs). θ_1 and θ_2 refer to the Beta distribution parameters. *** and ** imply statistical significance at 1 % and 5 % levels, respectively.

cryptocurrency volatility serves as a critical nexus point for various stakeholders. Understanding this association is essential for developing strategies that mitigate risks, foster sustainable practices, and ultimately create a more stable cryptocurrency market. Addressing sustainability concerns proactively could enhance the legitimacy of cryptocurrency and contribute to its long-term success as a viable digital asset.

5.3. Robustness analysis

So far, we have used different realized variance (volatility) measures in our analysis. We now replace RV with the conditional variance (CV) of the cryptocurrency ETFs. To estimate the CV of these digital assets, we consider applying the EGARCH process as follows:

$$\ln(h_t^2) = \omega + \alpha \left| \frac{\varepsilon_{t-1}}{h_{t-1}} \right| + \gamma \frac{\varepsilon_{t-1}}{h_{t-1}} + \beta \ln(h_{t-1}^2) \tag{7}$$

where h_t^2 is the conditional variance (i.e., CV) for the digital assets, γ is the asymmetric parameter and β measures the persistence of volatility. Note that we consider student’s t -distribution for the errors.

Table 5 reports the findings of our MIDAS regression given in Equation 1, with RV being replaced by CV. These findings are consistent with those reported in Tables 1 and 2. The only discrepancy is that the volatility of Ethereum ETF now reacts significantly to both equally- and GDP-weighted sustainability uncertainty indexes.

Our findings conform to Gaies et al. (2025), Olanrewaju et al. (2025) and Zhao et al. (2025) which also show that ESGUI has predictive contents for various financial markets. Gaies et al. (2025), for example, find that the European stock markets are highly influenced by this ESG-based sustainability uncertainty indicator under different market conditions. In addition, Olanrewaju et al. (2025) indicate that ESGUI generally exerts a negative short-term influence on the prices of oil, heating oil, and natural gas, particularly in bearish or moderately active market environments. In contrast, over the long term, ESG uncertainty tends to drive up prices across all three fuels, likely due to market adaptations to regulatory risks, supply disruptions, and increased hedging activity. Our study extends this scarce literature by documenting a significant relationship between ESGUI and digital asset class.

Table 5
Robustness analysis.

	Equally-weighted ESGUI		GDP-weighted ESGUI	
	Estimate	S.E.	Estimate	S.E.
Panel A: Bitcoin ETF				
α	0.0017***	0.00002	0.0017***	0.0002
δ	0.3457***	0.0198	0.3362***	0.0201
β	-0.00003	0.00002	-0.00002**	0.0001
θ_1	4.5949***	0.7891	4.9653***	0.9237
θ_2	1.4384***	0.2683	1.2876***	0.2704
Log-likelihood	4415.03		4416.32	
Panel B: Ethereum ETF				
α	0.0029***	0.00004	0.0029***	0.00005
δ	0.2172***	0.0608	0.2068***	0.0541
β	-0.0010**	0.0004	-0.00004**	0.00002
θ_1	3.8124***	0.6663	0.9604***	0.0529
θ_2	0.9384***	0.2439	1.1697**	0.5175
Log-likelihood	4054.70		4051.05	

Notes: This Table reports the findings of the additional analysis using GARCH estimates: Panel A shows the results for the Bitcoin ETF, while Panel B presents the findings for the Ethereum ETF. The parameter β measures the effect of ESG uncertainty index (ESGUI) on the conditional volatility (CV) of cryptocurrency exchange exchange-traded funds (ETFs). θ_1 and θ_2 refer to the Beta distribution parameters. *** and ** imply statistical significance at 1 % and 5 % levels, respectively.

5.4. Additional analysis: Good and bad realized volatilities

In this section, we aim at predicting the good and bad volatilities for the crypto assets using the information on ESGUI. This strand of investigation is important given that good and bad volatilities, which are linked to positive and negative cryptocurrency returns respectively, could have heterogeneous influences on price changes, thereby playing a pivotal role in digital asset pricing. Previous articles (Ang, 2006; BenSaïda, 2019; Farago and T'edongap, 2018; Lyu et al., 2021; Patton and Sheppard, 2015) also reveal that bad volatility has higher effects on asset returns compared to good volatility, which offers key implications to market participants.

Following BenSaïda (2019) and Lyu et al. (2021), we define the realized good and bad volatilities as follows:

$$\text{Good volatility : } RV_t^+ = RV_t \cdot 1\{r_t > 0\} \tag{8}$$

Table 6
Impact of ESGUI on good volatility: Parkinson's measure.

	Equally-weighted ESGUI		GDP-weighted ESGUI	
	Estimate	S.E.	Estimate	S.E.
Panel A: Bitcoin ETF				
α	0.0003***	0.0001	0.0003***	0.0001
δ	0.2330***	0.0356	0.2302***	0.0358
β	-0.0001	0.0001	-0.0020*	0.0011
θ_1	0.7949	9.1679	1.2751***	0.0923
θ_2	0.8099	9.1680	19.9999***	0.0014
Log-likelihood	4115.56		4116.48	
Panel B: Ethereum ETF				
α	0.0007***	0.0001	0.0006***	0.0001
δ	0.0587	0.0365	0.0620*	0.0365
β	-0.0003***	0.0001	-0.00009***	0.00003
θ_1	1.0512***	0.0559	1.0524***	0.0565
θ_2	2.2818***	1.6785	3.5019	3.8998
Log-likelihood	3806.48		3805.47	

Notes: This Table reports the effect of sustainability uncertainty on good volatility: Panel A shows the results for the Bitcoin ETF, while Panel B presents the findings for the Ethereum ETF. The parameter β measures the effect of ESG uncertainty index (ESGUI) on the good volatility of cryptocurrency exchange exchange-traded funds (ETFs). θ_1 and θ_2 refer to the Beta distribution parameters. *** and ** imply statistical significance at 1 % and 5 % levels, respectively.

Table 7
Impact of ESGUI on good volatility: Rogers & Satchell's measure.

	Equally-weighted ESGUI		GDP-weighted ESGUI	
	Estimate	S.E.	Estimate	S.E.
Panel A: Bitcoin ETF				
α	0.0004***	0.0001	0.0003***	0.0001
δ	0.2216***	0.0357	-0.2245	0.0358
β	-0.0006**	0.0003	-0.00003	0.00002
θ_1	1.0846***	0.1198	1.2700***	0.0812
θ_2	4.4145	7.2372	19.9997***	0.0009
Log-likelihood	4124.67		4123.82	
Panel B: Ethereum ETF				
α	0.0007***	0.0001	0.0006***	0.0001
δ	0.0705*	0.0367	0.0788**	0.0366
β	-0.00014**	0.00005	-0.00006**	0.00003
θ_1	1.0674***	0.0610	1.2542***	0.0393
θ_2	3.0493	2.2013	19.9979***	0.0010
Log-likelihood	3875.02		3872.59	

Notes: This Table reports the effect of sustainability uncertainty on good volatility: Panel A shows the results for the Bitcoin ETF, while Panel B presents the findings for the Ethereum ETF. The parameter β measures the effect of ESG uncertainty index (ESGUI) on the good volatility of cryptocurrency exchange exchange-traded funds (ETFs). θ_1 and θ_2 refer to the Beta distribution parameters. *** and ** imply statistical significance at 1 % and 5 % levels, respectively.

$$\text{Bad volatility : } RV_t^- = RV_t \cdot 1\{r_t < 0\} \tag{9}$$

where $1\{\cdot\}$ refers to an indicator function which equals 1 for good volatility if the asset return at time t is positive. For bad volatility, on the other hand, $1\{\cdot\}$ is equal to 1 if the asset return at time t is negative.

Tables 6–9 present the results of the good and bad volatility analysis. These findings show that the information content of ESGUI is useful for predicting the good and bad volatilities of various crypto assets, although the results tend to vary with the changes in the RV measures. For instance, the good volatility of the Bitcoin ETF does not react to the fluctuations in the ESGUI when Parkinson's measure is employed. However, when the Rogers and Satchell's estimator is used to measure the RV, we find significant results. For the Ethereum market, such variations are also observed for the bad volatility analysis.

Overall, our analysis confirms that ESGUI has predictive contents for both good and bad volatilities⁵. These results have key implications for cryptocurrency investors given that they prefer to differentiate between good and bad volatilities as the former is directional, persistent, moderately easy to foresee and associated with sufficiently high volume, whereas the latter is linked to frequent jumps, accompanied by low volume and critical to predict (Çepni et al., 2022). Therefore, it is crucial to develop precise econometric approaches to accurately model the good and bad volatilities, which would help market participants make proper investment decisions under varied market conditions.

5.5. Discussions

The inverse relationship between sustainability uncertainty and cryptocurrency market volatility can be complex and influenced by various factors. For instance, with the increase in sustainability uncertainty, participants in cryptocurrency markets might adopt a more vigilant approach. In particular, such investors may be less likely to engage in speculative trading based on hype or rapid price movements. This would result in more stable trading behavior, thereby lowering the volatility. Moreover, if investors are uncertain about the sustainability of digital assets in the long run, they may focus on holding strategies rather than aggressive trading strategies. This long-term attitude could lead to fewer drastic buy or sell actions, which can also reduce volatility.

⁵ Table 10 provides a summary of our analysis.

Table 8
Impact of ESGUI on bad volatility: Parkinson’s measure.

	Equally-weighted ESGUI		GDP-weighted ESGUI	
	Estimate	S.E.	Estimate	S.E.
Panel A: Bitcoin ETF				
α	0.0007***	0.0002	0.0008***	0.0002
δ	-0.0045	0.0366	-0.0091	0.0367
β	-0.00036**	0.00018	-0.0003***	0.0001
θ_1	1.0013***	0.0372	1.0217***	0.0382
θ_2	1.1371***	0.2767	1.1600***	0.2101
Log-likelihood	2884.22		2885.88	
Panel B: Ethereum ETF				
α	0.0006***	0.0001	0.0009***	0.0001
δ	0.0861**	0.0364	0.0864**	0.0365
β	-0.0001	0.0001	-0.00004	0.00003
θ_1	0.9860***	0.0454	0.9869***	0.0532
θ_2	1.1718*	0.6164	1.1662*	0.6545
Log-likelihood	3781.42		3781.31	

Notes: This Table reports the effect of sustainability uncertainty on bad volatility: Panel A shows the results for the Bitcoin ETF, while Panel B presents the findings for the Ethereum ETF. The parameter β measures the effect of ESG uncertainty index (ESGUI) on the bad volatility of cryptocurrency exchange-traded funds (ETFs). θ_1 and θ_2 refer to the Beta distribution parameters. *** and ** imply statistical significance at 1 % and 5 % levels, respectively.

Table 9
Impact of ESGUI on bad volatility: Rogers & Satchell’s measure.

	Equally-weighted ESGUI		GDP-weighted ESGUI	
	Estimate	S.E.	Estimate	S.E.
Panel A: Bitcoin ETF				
α	0.0012**	0.0005	0.0013***	0.0005
δ	-0.0070	0.0366	-0.0115	0.0366
β	-0.0008**	0.0004	-0.0007**	0.0003
θ_1	1.0052***	0.0430	1.0341***	0.0554
θ_2	1.1359***	0.2916	1.1623***	0.2161
Log-likelihood	2190.18		2191.84	
Panel B: Ethereum ETF				
α	0.0007***	0.0001	0.0006***	0.0001
δ	0.1287***	0.0363	0.1268***	0.0362
β	-0.0001*	0.00006	-0.00007**	0.00003
θ_1	0.9862***	0.0386	0.9834***	0.0374
θ_2	1.1668**	0.5721	1.1495**	0.4381
Log-likelihood	3695.94		3696.58	

Notes: This Table reports the effect of sustainability uncertainty on bad volatility: Panel A shows the results for the Bitcoin ETF, while Panel B presents the findings for the Ethereum ETF. The parameter β measures the effect of ESG uncertainty index (ESGUI) on the bad volatility of cryptocurrency exchange-traded funds (ETFs). θ_1 and θ_2 refer to the Beta distribution parameters. *** and ** imply statistical significance at 1 % and 5 % levels, respectively.

Besides, as the market matures and responds to sustainability issues, institutional investors may become more involved. These investors often have a longer-term view compared to retail traders, possibly contributing to a more stable market environment and lower volatility. Moreover, in times of high sustainability uncertainty, investors may prefer stable and sustainable investments over more volatile options. This could drive up the prices of cryptocurrencies with clearer sustainability credentials while increasing volatility in less sustainable assets. To sum up, while one might presume that higher sustainability uncertainty would increase the volatility of digital assets due to unpredictability, the potential for reduced speculative behavior, a shift towards long-term holding strategies, and a more stable group of investors could collectively lead to reduced volatility in the cryptocurrency markets.

Note that such inverse association between sustainability uncertainty and cryptocurrency market volatility may lead to several policy implications. For example, policymakers might introduce specific

Table 10
Summary of the key findings.

Models	Volatility measures	Key findings	Sources
Realized variance: RV	Parkinson; Rogers & Satchell	GDP-weighted (equally-weighted) ESGUI has a negative effect on the realized variance of Bitcoin (Ethereum) ETF.	Tables 1–2
Realized variance: \sqrt{RV}	Parkinson; Rogers & Satchell	Both equally- and GDP-weighted ESGUI impact the realized volatility of cryptocurrency ETFs negatively.	Tables 3–4
Good volatility	Parkinson; Rogers & Satchell	In case of Ethereum ETF, good volatility reacts significantly to each type of ESGUI. The Bitcoin ETF, the impact depends on the type of ESGUI.	Tables 6–7
Bad volatility	Parkinson; Rogers & Satchell	In case of Bitcoin ETF, bad volatility is sensitive to each type of ESGUI irrespective of the volatility measures used. For the Ethereum ETF, however, the impact of ESGUI is significant only when we employ the Rogers & Satchell’s measure.	Tables 8–9
Conditional volatility	GARCH	While only GDP-weighted ESGUI impacts the conditional volatility of Bitcoin ETF, the Ethereum market volatility is sensitive to each type of ESGUI. More importantly, the effect is negative.	Table 5

Notes: This Table summarizes the key findings of our empirical analysis.

regulations for addressing sustainability practices within the cryptocurrency space. By promoting sustainable mining practices and eco-friendly technologies, regulators could reduce sustainability-related uncertainties, potentially stabilizing the market. In addition, establishing frameworks for transparency and reporting on sustainability metrics in the cryptocurrency industry can help reduce uncertainty further. If stakeholders have better access to information about the sustainability practices of different cryptocurrencies, it could lead to more informed investment decisions and potentially decrease overall volatility. Besides, to encourage sustainable practices in the cryptocurrency sector, governments could offer incentives for projects that prioritize sustainability. This might include tax breaks or grants for companies that demonstrate environmentally friendly practices in their operations. Moreover, governments and organizations could focus on education initiatives to raise awareness about the importance of sustainability in the cryptocurrency market. Better-informed investors may behave more rationally, contributing to reduced volatility. For market participants, developing frameworks for assessing the risks associated with sustainability uncertainties in cryptocurrency investments can help them opt better choices. This may lead to a more stable market as investors become more aware of how these factors affect pricing. Additionally, incorporating cryptocurrency into broader environmental and economic sustainability goals can help mitigate the volatility associated with sudden shifts in investor sentiment driven by sustainability issues. By aligning cryptocurrency market practices with national and global sustainability targets, markets may stabilize over time. Overall, the inverse relationship between sustainability uncertainty and cryptocurrency market volatility leads to heightened awareness and influence over investment decisions. Investors may prioritize sustainability as a critical factor, thus reshaping their strategies, risk profiles, and asset allocations in favor of cryptocurrencies that align with sustainable practices. This shift not only affects individual investment decisions but also has broader implications for market dynamics, potentially fostering a more stable and responsible cryptocurrency ecosystem.

6. Conclusions

This empirical research, unlike the existing literature, investigates if the volatility dynamics of digital assets are driven by the changes in sustainability uncertainty. In doing so, we use a recently developed ESG-based sustainability uncertainty index (i.e., ESGUI) and examine its effect on the volatility dynamics of Bitcoin and Ethereum ETFs. Applying the mixed data sampling (MIDAS) approach shows that ESGUI exerts a negative impact on the RV of cryptocurrency markets. One possible explanation for this linkage is that as sustainability-related uncertainty rises, investors tend to adopt sustainability practices and initiatives. This shift towards sustainable practices can result in more consistent and foreseeable long-term economic conditions, ultimately reducing the volatility of cryptocurrency markets.

Our results carry important implications for participants in cryptocurrency markets. The sensitivity of digital asset volatility to sustainability-related uncertainty suggests that investors should monitor the ESGUI closely when making decisions involving crypto-asset risk. This also indicates that the information contained in the ESGUI may help investors more accurately forecast the risks associated with cryptocurrency investments. Researchers, in turn, can leverage the ESGUI to develop more effective volatility models for risk management purposes. Moreover, the connection between cryptocurrency volatility and sustainability uncertainty is likely to influence traditional financial markets as digital assets continue to mature as an investment class. Financial instruments linked to Bitcoin may experience parallel fluctuations, with potential consequences for broader market stability. This implies that the pronounced influence of sustainability uncertainty on cryptocurrency volatility could spill over into other sectors (e.g., particularly energy markets) potentially triggering a chain reaction of price volatility across multiple markets.

Future studies could thus examine whether ESGUI affects the interconnectedness between cryptocurrencies and other asset classes. Such analysis is crucial for designing hedging strategies and policy making for the global financial system.

Author contributions

This paper is solely authored.

CRedit authorship contribution statement

Anupam Dutta: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Ethical statement

As this manuscript does not involve research on humans or animals, nor does it include vulnerable populations, an ethical statement is not applicable.

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