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Sustainable versus Conventional Cryptocurrencies in the Face of Cryptocurrency Uncertainty Indices: An Analysis across Time and Scales

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Abstract: Are conventional and sustainable cryptocurrencies effective hedging instruments for high cryptocurrency uncertainty? This paper examines co-movements between conventional (Bitcoin, Ethereum, Binance Coin, Tether) and sustainable (Cardano, Powerledger, Stellar, Ripple) cryptocurrencies and two cryptocurrency uncertainty indices (UCRY price and UCRY policy). Using weekly returns from 1 October 2017 to 30 March 2021, the paper employs the bivariate wavelet coherence method considering three investment horizons, short-term, medium-term, and long-term. The results confirm that conventional and sustainable cryptocurrencies show consistent positive and identical co-movements with both cryptocurrency uncertainty indices at the short-term horizon during COVID-19 and negative co-movement at the medium-term investment horizon, suggesting the short-term hedging ability of dirty/green cryptocurrencies for high UCRY price and policy. Evidence of negative coherences shows that higher cryptocurrency prices and policy uncertainties lead to lower cryptocurrency returns, reflecting the adverse impact of higher uncertainties on the trust of crypto traders and investors. Weak co-movement is found between dirty/green cryptocurrencies and UCRY price/policy indices, which suggests the possible role of dirty/green cryptocurrencies as a weak hedge for UCRY price and policy indices. These findings provide potential avenues to hedge cryptocurrency uncertainties using conventional and sustainable cryptocurrencies across multiple investment horizons.

Keywords: cryptocurrency uncertainty indices; sustainable cryptocurrency; dirty cryptocurrency; hedge; COVID-19; wavelet coherence

JEL Classification: C22; D81; G1

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1. Introduction

Sustainability has become a serious concern in finance for investors and policymakers (Mishra and Kaushik 2021; Wiek and Weber 2014). The rate of climate change is increasing and companies are considering green investments for better financial, social, and environmental returns (Khalil and Nimmanunta 2022; Tuhkanen and Vulturius 2020). Governments around the globe, such as the USA (Ul Haq et al. 2022), China (Zhang 2020; Saravade et al. 2022), Japan (Schumacher et al. 2020), India (Shanmugam et al. 2022), as well as developing countries (Banga 2019) and South-Asian countries (Azhgaliyeva et al. 2020), focus on issuing green bonds and other sustainable financial investments to promote energy efficiency, environmental quality, and sustainable financial practice[1].

The development of sustainable or green cryptocurrencies is a notable concern in the current era (Pham et al. 2022) because conventional or dirty cryptocurrencies such as Bitcoin require high energy consumption in the mining process (Ul Haq et al. 2022) and have high carbon footprints (Ghosh and Bouri 2022; Wang et al. 2022) which increase the vulnerability to climate change risk. In such a scenario, policymakers must incentivise and ease the transition of dirty cryptocurrency mining mechanisms from a proof of work (PoW) consensus to non-PoW or energy-efficient consensus (Ren and Lucey 2022a). In addition, investment flow in sustainable assets, i.e., green cryptocurrencies, can support the allocation of funds and achieve the Sustainable Development Goals of the United Nations (Chen et al. 2021). Hence, investors should prioritise green cryptocurrencies rather than conventional cryptocurrencies (Ren and Lucey 2022a).

In addition to gold, cryptocurrencies represent an attractive alternative asset due to blockchain technological innovation, decentralization, acting as a store of value, high divisibility, and price resilience during crisis periods (Shahzad et al. 2020). The positive relationship between major cryptocurrencies and some uncertainty indices and, therefore, the hedging ability of cryptocurrencies for the US implied volatility (VIX) (Raheem 2021), economic policy uncertainty (EPU) (Cheng and Yen 2020), cryptocurrency implied volatility index (VCRIX) (Rubbaniy et al. 2021), and Twitter-based EPU (Aharon et al. 2022) are well documented. However, cryptocurrency policy uncertainty (UCRY policy) and cryptocurrency price uncertainty (UCRY price), newly introduced by Lucey et al. (2022), are more relevant to crypto traders and investors (who have heterogeneous investment horizons) than VIX, EPU (Haq et al. 2021), or other uncertainty indices (Dai et al. 2021; Lucey et al. 2022; Rubbaniy et al. 2021). The current debate has turned towards sustainable cryptocurrency investment (Ren and Lucey 2022a) due to numerous benefits such as greener funds offering excess returns (Chen et al. 2021). Moreover, the role of sustainable cryptocurrencies as hedging instruments is under-studied in earlier literature (Ul Haq et al. 2022). Therefore, empirical investigation of the co-movement between conventional and sustainable cryptocurrencies and UCRY uncertainties is required. In this paper, we draw the first inferences on co-movement and hedging in a time–frequency domain between various cryptocurrencies (conventional and sustainable) and cryptocurrency uncertainty indices using the wavelet approach, which extends the above studies.

Generally, a strong (weak) hedge is an asset or cryptocurrency that is positively correlated (uncorrelated) with volatility or risk measures, on average, in a normal economic period (Bouri et al. 2017a, 2017b; Iqbal 2017). So, our motivations are, firstly, that cryptocurrency market participants have various investment horizons (e.g., novice traders versus knowledgeable long-term institutional investors), which necessitates not only differentiating between policy and price uncertainty and differentiating between financial and environmental gains (Ul Haq et al. 2022; Lucey et al. 2022; Wang et al. 2022), but also the use of a wavelet-based approach to make inferences in a time–frequency setting (Bouri et al. 2020). Secondly, there may be discrepancies between conventional cryptocurrencies such as Bitcoin and Ethereum and green cryptocurrencies such as Cardano, Ripple, and Stellar, as highlighted in the academic hedging literature (Ul Haq et al. 2022). Finally, investors and crypto traders need to know the existing crypto asset or portfolio UCRY price and policy exposure to use crypto as a hedge against UCRY price and policy. Although UCRY itself is not a risk, a portfolio can incur losses resulting from higher URCY, which is a risk which needs to be hedged.

By considering various conventional and sustainable cryptocurrencies and accounting for the heterogeneity of market participants across scales, we extend previous findings (Hassan et al. 2021; Karaömer 2022; Ah Mand 2021; Ren and Lucey 2022a; Ul Haq et al. 2022; Haq 2022; Haq et al. 2022) on gold, and conventional and sustainable cryptocurrencies. Accordingly, our contributions concern: (1) the growing literature on the hedging ability of conventional cryptocurrencies and sustainable cryptocurrencies (e.g., Ul Haq et al. 2022); (2) the ongoing debate on the hedging instruments for cryptocurrency uncertainty indices (e.g., Hassan et al. 2021; Hasan et al. 2022; Karim et al. 2022; Karaömer 2022; Ah Mand 2021) beyond gold, Islamic indices, bond markets and Bitcoin, and (3) inferences in both time and frequency, which are necessary to account for the heterogeneity of investment horizons between the short, medium, and long term (Ul Haq et al. 2022; Bouri et al. 2020; Rubbaniy et al. 2021).

Our main empirical results indicate that the dependence structure of conventional cryptocurrencies and sustainable cryptocurrencies are significantly heterogeneous over time and frequency domains against UCRY price and policy indices. Generally, the wavelet coherence graphs validate a weak dependence structure at the long-term investment horizon. This finding may be attributed to the weak hedging properties of cryptocurrencies against UCRY price and policy indices. Interestingly, the extent of dependence between conventional/sustainable cryptocurrencies and UCRY price and policy indices is notably higher at the 1–4-week and 4–8-week frequency bands. Furthermore, the analysis shows that both conventional and sustainable cryptocurrencies prove to be strong hedges against both UCRY policy and price indices at the short-term investment horizon. UCRY uncertainty indices (lead) have negative co-movement with dirty/green cryptocurrencies (lag), hence failing to act as a hedging instrument in the medium term. Overall, UCRY uncertainty indices show an identical leading role to dirty/green cryptocurrencies.

The remainder of the article is organised as follows. Section 2 reviews the most relevant literature on the association between cryptocurrencies and policy uncertainty indices. Section 3 delineates the data description and wavelet coherence method. Section 4 reports the main empirical results. Section 5 presents the discussion. Finally, Section 6 concludes the study.

2. Related Studies

This section critically discusses related studies from the literature. Previous research documents controversial and inclusive findings on the co-movement of green/dirty cryptocurrencies and policy uncertainties. For instance, Wu et al. (2019) investigate the hedge and safe-haven properties of Bitcoin and gold against EPU using a combined GARCH-based quantile regression. They reveal that both gold and Bitcoin are not effective hedges nor safe-havens in average market conditions, however, their weak hedging properties are more pronounced in highly uncertain times. In a similar domain, Cheng and Yen (2020) and Yen and Cheng (2021) investigate the relationship between cryptocurrency returns and volatility, respectively, with EPU. Cheng and Yen (2020) state that EPU significantly positively predicts monthly cryptocurrency returns. Yen and Cheng (2021) show that EPU negatively predicts cryptocurrency volatility. In a comprehensive review, Haq et al. (2021) discuss the link between the cryptocurrency market and EPU risk during recent years and argue that the hedging and diversification properties of crypto assets are heterogeneous across national EPU.

Interestingly, Kim et al. (2021) suggest that the VCRIX can serve as a pertinent proxy for the cryptocurrency uncertainty, unlike the EPU. Addressing these issues, Rubbaniy et al. (2021) study the safe-haven opportunities in individual cryptocurrency returns (i.e., Bitcoin, Ethereum, and Ripple) against the VCRIX and the Global COVID-19 Fear Index, employing wavelet coherence methods. They conclude that cryptocurrencies are safe-havens for non-financial risk proxies only, and do not show safe-haven properties for financial proxies. This supports the findings of Kim et al. (2021) that the safe-haven properties of the crypto market are contingent upon the risk proxy (EPU, VIX, Global COVID-19 Fear Index, VCRIX) used for market turbulence or uncertainty.

Given the paucity of crypto policy uncertainty indices, Lucey et al. (2022) develop a new weekly risk measure, called UCRY, for cryptocurrency uncertainty. This index uses a news-based article methodology following Baker et al. (2016) and measures two types of uncertainty, UCRY price and UCRY policy. This proxy captures economic shocks and high uncertainty events from the cryptocurrency market such as hacking attacks. Hassan et al. (2021) study the time-varying correlation and asymmetric effect between the volatility of precious metals and UCRY uncertainty indices. By employing the DCC-GJR-GARCH method, the authors reveal that only gold among the top four precious metals works as an effective and reliable safe-haven. In a similar domain, Karim et al. (2022) examine the hedge and safe-haven opportunities of the bond market against UCRY policy using the ADCC-GARCH model. They state that the bond market is neither a hedge nor a safe-haven against UCRY policy, except SKUK (S&P green bond) which is a safe-haven (hedge) investment for UCRY policy. More closely related to our research, Hasan et al. (2022) explore the hedge and safe-haven properties of gold, Bitcoin, the US dollar, crude oil, the DJ Islamic index, and sukuk, applying a quantile-on-quantile regression model. The findings show that Bitcoin and crude oil act as hedges but neither is a safe-haven, however, gold, the DJ Islamic index, and sukuk are effective hedge investments against UCRY policy. Karaömer (2022) studies the time-varying connectedness between cryptocurrency volatility and UCRY policy using the DDC-GARCH model. The results indicate that cryptocurrency returns have a negative correlation with UCRY policy. In other words, crypto's conditional volatility is negatively correlated with UCRY policy, which delineates those crypto assets which fail to act as hedge instruments or safe-havens for UCRY policy.

A few studies in the earlier literature investigate the role of sustainable or green cryptocurrencies. However, the connectedness between sustainable cryptocurrencies has not been studied. For instance, Ul Haq et al. (2022) analyses the co-movement among the S&P Green Bonds Index, Dow Jones Sustainability World Index, and sustainable cryptocurrencies such as Cardano, Solar Coin, Ripple, Stellar, and BitGreen using the wavelet coherence method. Sustainable cryptocurrencies are shown to have a positive impact on world sustainability and can be used in portfolios as diversifiers with green bonds. Similarly, Ren and Lucey (2022a) examine the relationship between clean energy and dirty and clean or green cryptocurrencies using the dynamic connectedness approach of Diebold and Yilmaz (2012)[2] and the DCC-GARCH framework. They conclude that both clean/green and dirty cryptocurrencies fail to hedge against clean energy. Ren and Lucey (2022b) study herding behaviour in both dirty and clean cryptocurrencies and find significant herding behaviour in the dirty crypto market. In a similar domain, Pham et al. (2022) investigate the tail dependence among the prices of carbon, green cryptocurrencies, and non-green cryptocurrencies, using a quantile connectedness framework. They show that green cryptocurrencies are weakly connected to conventional or dirty cryptocurrencies and investors can achieve time-variant diversification and hedging benefits using carbon emission allowance against climate risks.

From the above discussion, we infer two observations. Firstly, the previous hedging literature shows inclusive findings about the hedging or safe-haven properties of cryptocurrencies for the UCRY indices. Secondly, the co-movement and dependence structure between conventional cryptocurrencies, sustainable cryptocurrencies, and UCRY price and policy uncertainties considering multiple wavelet investment horizons are ignored. Therefore, we hypothesise the following:

H1. *There is significant co-movement between conventional cryptocurrency returns and UCRY indices (policy and price) across investment horizons.*

H2. *There is significant co-movement between sustainable cryptocurrency returns and UCRY indices (policy and price) across investment horizons.*

3. Materials and Methods

3.1. Data Description

We use the closing prices of the top four conventional cryptocurrencies, and four sustainable cryptocurrencies by market capitalization, and two risk measures for cryptocurrency uncertainty, the UCRY policy index and the UCRY price index, constructed by Lucey et al. (2022) based on news articles. Data on cryptocurrencies and uncertainty measures are sourced from www.coinmarketcap.com and brianmlucey.wordpress.com, respectively. The conventional cryptocurrencies are Bitcoin (BTC), Ethereum (ETH), Binance Coin (BNB), and Tether (USDT), and the sustainable cryptocurrencies are Cardano (ADA), Powerledger (POWR), Stellar (XLM), and Ripple (XRP). Data are collected weekly according to the frequency of uncertainty indices, and the period was 17 October 2017 to 2

March 2021, covering the COVID-19 episode and several hacking attacks (Lucey et al. 2022). The daily values are converted to returns to find the logarithm and first difference using:

$$R_{i,t} = (\ln(P_{i,t}) - \ln(P_{i,t-1})) \quad (1)$$

where $R_{i,t}$ indicates the logarithm daily differenced returns, and $P_{i,t}$ and $P_{i,t-1}$ denote the daily values of the index i (green financial assets and VCRIX) at the time t and $t-1$, respectively.

Series log returns (Hassan et al. 2021) are presented in Table 1. The most (least) volatile cryptocurrency is BNB (USDT). The distribution of log-returns is high-peaked, asymmetric, and, thus, non-normal. All return series are stationary. Appendix A, Figure A1, plots the level series of the data, and Figure 1 plots the return series and shows large fluctuations around the COVID-19 outbreak.

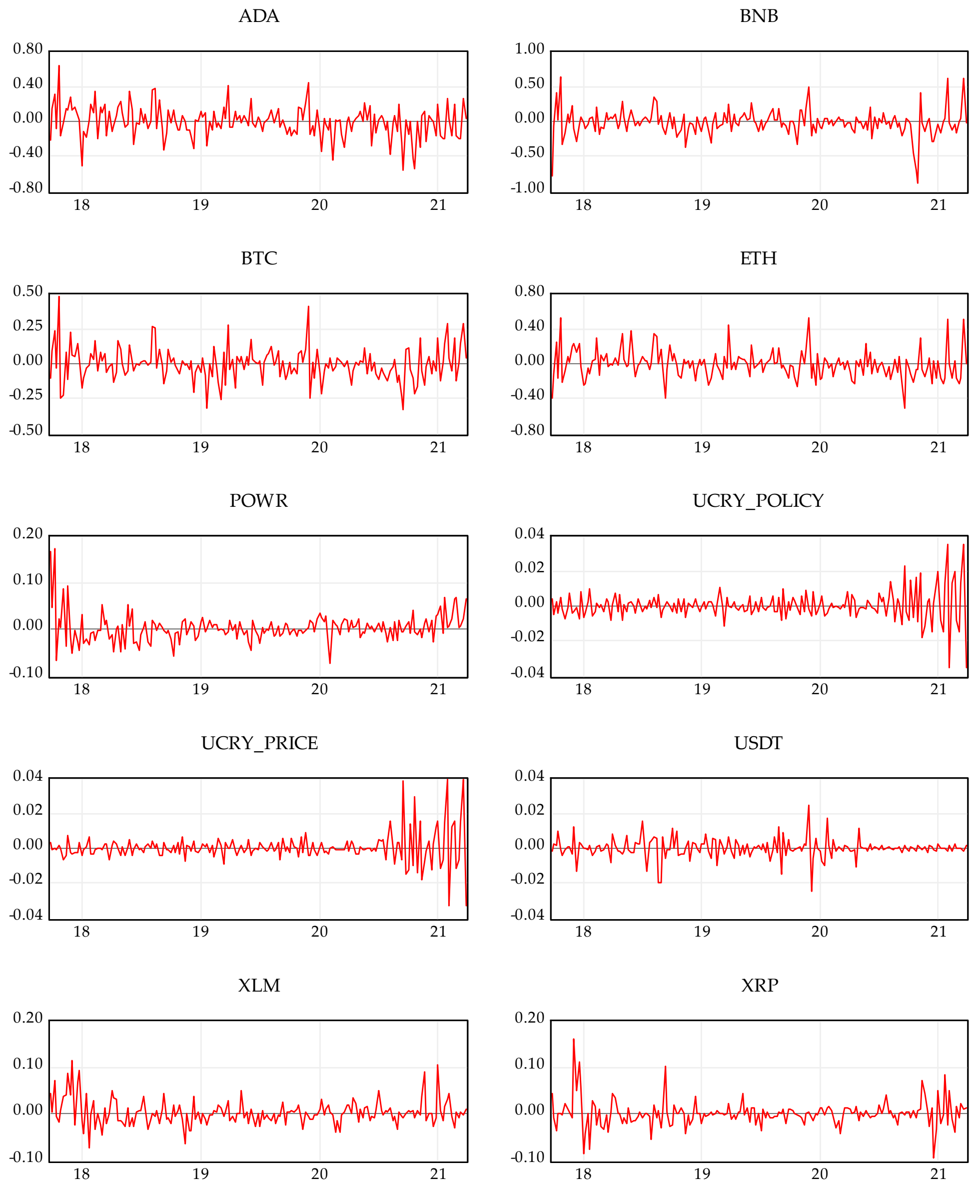

Figure 1. Plots of log returns.

Table 1. Summary statistics.

	M.	Max.	Min.	SD.	Skew.	Kurt.	JB.	PP.	ADF.
ADA	−0.0056	0.6438	−0.5555	0.1789	−0.0851	4.3562	14.245 [a]	−12.417 [a]	−12.326 [a]
BNB	−0.0184	0.6438	−0.8874	0.1880	−0.3540	8.5978	242.750 [a]	−13.056 [a]	−13.056 [a]
BTC	−0.0029	0.4850	−0.3285	0.1193	0.5508	5.0578	41.542 [a]	−12.926 [a]	−12.927 [a]
ETH	−0.0071	0.5288	−0.5165	0.1616	0.7420	5.0882	50.043 [a]	−20.791 [a]	−18.542 [a]
POWR	0.0028	0.1739	−0.0731	0.0309	1.8714	11.7267	687.502 [a]	−14.521 [a]	−15.348 [a]
USDT	0.0001	0.0249	−0.0247	0.0057	−0.2427	8.2488	211.865 [a]	−20.684 [a]	−18.178 [a]
XLM	0.0027	0.1149	−0.0743	0.0273	1.1786	6.3049	125.655 [a]	−11.420 [a]	−10.736 [a]
XRP	0.0008	0.1602	−0.0965	0.0282	1.3289	10.9611	537.129 [a]	−13.791 [a]	−12.121 [a]
UCRYP	0.0003	0.0353	−0.0358	0.0083	0.1962	8.9634	272.340 [a]	−12.610 [a]	−12.608 [a]
UCRYPR	0.0004	0.0392	−0.0327	0.0084	1.1719	11.9044	646.465 [a]	−19.384 [a]	−17.264 [a]

Notes: ADA (Cardano), BNB (Binance Coin), BTC (Bitcoin), ETH (Ethereum), POWR (Powerledger), USDT (Tether), XLM (Stellar), XRP (Ripple), UCRYP (UCRY Policy), UCRYPR (UCRY Price). "[a]" denotes statistical significance at the 1% level.

Table 2 presents the unconditional correlations among the cryptocurrencies and UCRY indices at zero lag. The unconditional correlation coefficients are significant at a 1% level and the correlation signs of UCRY uncertainty indices are predominantly positive with conventional cryptocurrencies and negative with sustainable cryptocurrencies, i.e., ADA, XLM, and XRP. The correlation among conventional and sustainable cryptocurrencies is positive, except for POWR which has a negative unconditional correlation with a majority of cryptocurrencies. The output of unconditional correlation demonstrates hedging and diversification opportunities for crypto traders.

Table 2. Unconditional correlations.

	ADA	BNB	BTC	ETH	POWR	USDT	XLM	XRP	UCRYP	UCRYPR
ADA	1	0.5814	0.7016	0.7832	−0.0212	0.0982	0.0594	−0.0177	−0.0315	−0.0977
BNB	0.5814	1	0.6813	0.7062	−0.1017	0.1080	0.0057	−0.0749	0.2184	0.2000
BTC	0.7016	0.6813	1	0.8077	0.0111	0.1694	0.0241	0.0175	0.1390	0.0675
ETH	0.7832	0.7062	0.8077	1	−0.0917	0.1303	0.0237	−0.0197	0.1449	0.0867
POWR	−0.0212	−0.1017	0.0111	−0.0917	1	−0.0695	0.1361	−0.0203	0.0329	0.0076
USDT	0.0982	0.1080	0.1694	0.1303	−0.0695	1	0.1000	0.0667	0.0136	0.0020
XLM	0.0594	0.0057	0.0241	0.0237	0.1361	0.1000	1	0.6952	0.0190	−0.0002
XRP	−0.0177	−0.0749	0.0175	−0.0197	−0.0203	0.0667	0.6952	1	−0.0925	−0.0938
UCRYP	−0.0315	0.2184	0.1390	0.1449	0.0329	0.0136	0.0190	−0.0925	1	0.9324
UCRYPR	−0.0977	0.2000	0.0675	0.0867	0.0076	0.0020	−0.0002	−0.0938	0.9324	1

Notes: refer to Table 1.

3.2. Wavelet Coherence

According to previous studies (e.g., Jiang and Yoon 2020), the wavelet coherency technique (Grinsted et al. 2004) captures co-movements between two time series, $x(t)$ and $y(t)$, over both time and frequency domains.[3] The cross-wavelet transform of $i(t)$ and $j(t)$ is:

$$W_{i,j}(u,\ s) = W_i(u,\ s)^* W_j(u,\ s) \tag{2}$$

where $W_i(u, s)$ and $W_j(u, s)$ are the cross-wavelet transforms of $i(t)$ and $j(t)$, respectively, 's' and 'u' are the scale and position index, respectively, and * denotes a complex conjugate.

The squared wavelet coherence between $i(t)$ and $j(t)$ identifies notable co-movement through cross-wavelet power series at each scale:

$$R^2(u,\ s) = \frac{\left|S\left[s^{-1}W_{i,j}(u,\ s)\right]\right|^2}{S\left[s^{-1}|W_i(u,\ s)|^2\right]S\left[s^{-1}|W_j(u,\ s)|^2\right]},\ \text{with } R^2(u,\ s) \in [0,1] \tag{3}$$

where $R^2(u,\ s)$ defines the localised correlation in a squared form in the time–frequency domain.

Since $R^2(u,\ s)$ is restricted to only positive values, the wavelet coherence phase difference is used to reflect both positive and negative co-movements:

$$\rho_{i,j}(u,\ s) = tan^{-1}\left(\frac{lm\{S(s^{-1}W^{i,j}(u,\ s))\}}{Re\{S(s^{-1}W^{i,j}(u,\ s))\}}\right),\ \text{with } \rho_{ij} \in [-\pi, \pi] \quad (4)$$

where lm expresses the imaginary smoothed part and Re is the real part of the smoothed cross-wavelet transform.

The results for both wavelet coherence and phase difference are shown in a scalogram, bearing in mind, firstly, that the frequency is on the vertical axis. Short-term refers to the 1–4-week bands; medium-term refers to 4–8-week and 8–16-week bands, and long-term refers to 16–32-week and 32–64-week bands. Secondly, warmer red (colder blue) colours represent regions with higher (lower) co-movement. Thirdly, the lead/lag phase (i.e., causality) link and correlation are shown by the direction of the oriented arrows (Jiang and Yoon 2020). The two series move in unison when there is no phase gap between them. The arrows, when the two series are in-phase (out-of-phase), point to the right, "→" (left, "←"). A positive (negative) link between cryptocurrency and UCRY index returns is shown when they are in-phase (out-of-phase). Arrows pointing right-up, "↗" or left-down, "↙" suggest that cryptocurrency returns lag those of UCRY uncertainties, while those pointing right-down, "↘" or left-up, "↖" imply the opposite. Arrows pointing straight up and down "↑" and "↓", respectively, show that cryptocurrency returns are leading and lagging. Fourthly, black curves show the statistically significant coherence at the 5% level. Finally, the area affected by edge effects is shown by the u-shaped solid white line.

4. Empirical Results

Evidence from Wavelet Coherence

The wavelet coherence among conventional cryptocurrencies and UCRY uncertainty indices are illustrated in Figures 2 and 3 across short-term, medium-term, and long-term investment horizons. In Figure 2, there are positive co-movements between the conventional cryptocurrencies, Bitcoin, Binance Coin, and Tether, and the UCRY policy index in the 1–4-week and 8–16-week frequency bands (see subfigures (a), (c), and (d)), but not Ethereum (subfigure (b)) where the coherence follows heterogeneous movement, negative in the early days of the sample and positive during COVID-19. The positive association also exists in the pandemic period, reflecting a hedging ability of the conventional cryptocurrencies, except Tether. Bitcoin, Binance Coin, and Tether lead the UCRY policy index at short-term investment horizons during normal and uncertain periods. Conversely, a negative correlation (out-of-phase) exists between Ethereum and the UCRY policy index (subfigure (b)). Additionally, Ethereum returns lag those of the UCRY policy index and lead UCRY policy during the COVID-19 episode.

Figure 3 shows that the most significant coherence and correlation between each of the four conventional cryptocurrencies and the UCRY price index are seen in the 1–4-week and 4–8-week frequency bands. Bitcoin and Ethereum are negatively correlated with the UCRY price uncertainty index (see subfigures (b) and (e)) in the early weeks of the sample; however, the (→) arrows describe a positive correlation (in-phase) for Binance Coin and Tether in the majority of cases (see subfigures (c) and (d)). Interestingly, Bitcoin and Ethereum show positive co-movement with the UCRY price index during the COVID-19 period. Bitcoin and Ethereum returns lag those of the UCRY price index in the early sample and lead during the COVID-19 episode, whereas Binance Coin returns predominantly lead the UCRY price index. During the pandemic, the hedging ability of Binance Coin, Bitcoin, and Ethereum for the UCRY price index became stronger.

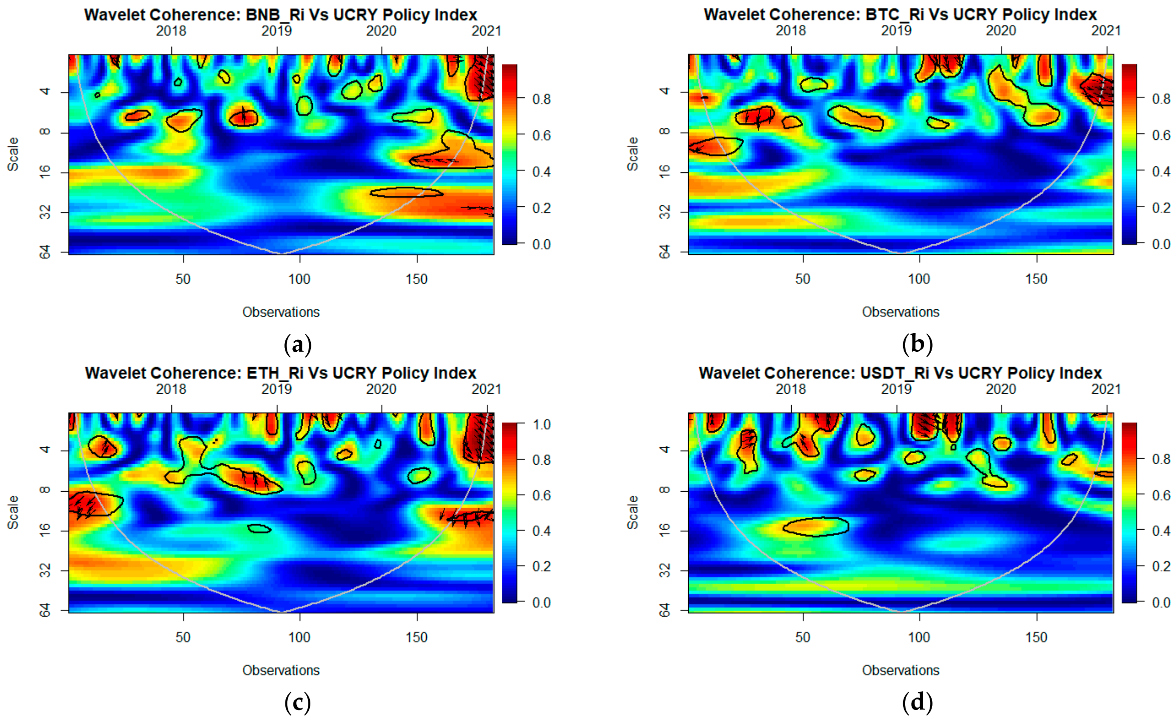

Figure 2. Wavelet coherence between conventional cryptos and UCRY policy index. Note: (**a**) = wavelet coherence between Binance Coin and UCYR Policy Index, (**b**) = wavelet coherence between Bitcoin and UCYR Policy Index, (**c**) = wavelet coherence between Ethereum and UCYR Policy Index, (**d**) = wavelet coherence between Tether and UCYR Policy Index.

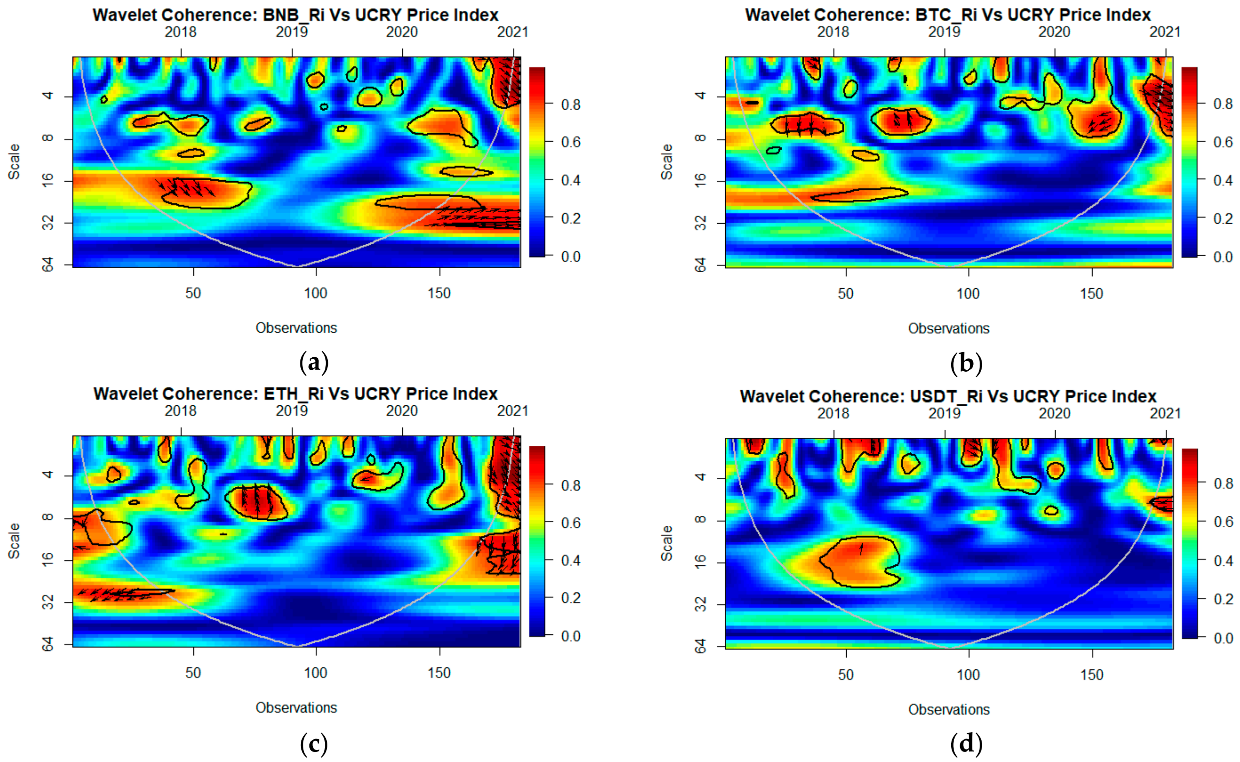

Figure 3. Wavelet coherence between conventional cryptos and UCRY price index. Note: (**a**) = wavelet coherence between Binance Coin and UCYR Price Index, (**b**) = wavelet coherence between Bitcoin and UCYR Price Index, (**c**) = wavelet coherence between Ethereum and UCYR Price Index, (**d**) = wavelet coherence between Tether and UCYR Price Index.

Overall, conventional cryptocurrencies have an identical or similar association with both cryptocurrency uncertainty indices, i.e., UCRY price and UCRY policy. These findings corroborate Hassan et al. (2021) who show that precious metals demonstrate a similar impact on UCRY Policy and Price indices. The co-movement between conventional cryptocurrencies and the UCRY indices is more pronounced at short-term investment horizons (1–4-week and 4–8-week scales). Interestingly, the prevailing blue area at medium-term and long-term investment horizons presents a weak or zero phase difference. Therefore, the prospects of higher financial gains for crypto traders and investors are short-lived and there are lower financial benefits at medium-term and long-term investment horizons against an increasing UCRY policy index.

Figures 4 and 5 represent the output of the wavelet coherence analysis between sustainable cryptocurrencies and UCRY uncertainty indices at the 1–4-week, 4–8-week, 8–16-week, 16–32-week, and 32–64-week bands. Figure 4 indicates a heterogeneous association between sustainable cryptocurrency returns and the UCRY policy index. More specifically, Cardano has a positive (in-phase) relationship with the UCRY policy index in the short term, a negative (out-of-phase) relationship in the medium term, and a moderately significant (zero phase difference) relationship at the long-term investment horizon. In comparison, Powerledger follows positive co-movement with UCRY policy in the medium term during the COVID-19 period, but negative (out-of-phase) co-movement throughout the sample period at the long-term investment horizon. Stellar and Ripple have heterogeneous correlation patterns and phase differences, as the backward (forward) arrows in subfigures (c) and (d) indicate a negative (positive) or out-of-phase (in-phase) relationship between XLM (XRP) returns and the UCRY policy index. Sustainable cryptocurrencies (Cardano, Powerledger, Stellar) lead the UCRY policy index at the 2–4-week scale and Cardano and Ripple returns lag the UCRY policy index at the 4–8-week frequency scale. Overall, the co-movement between sustainable cryptocurrencies and UCRY policy is marginal at long-term investment horizons, except for Powerledger.

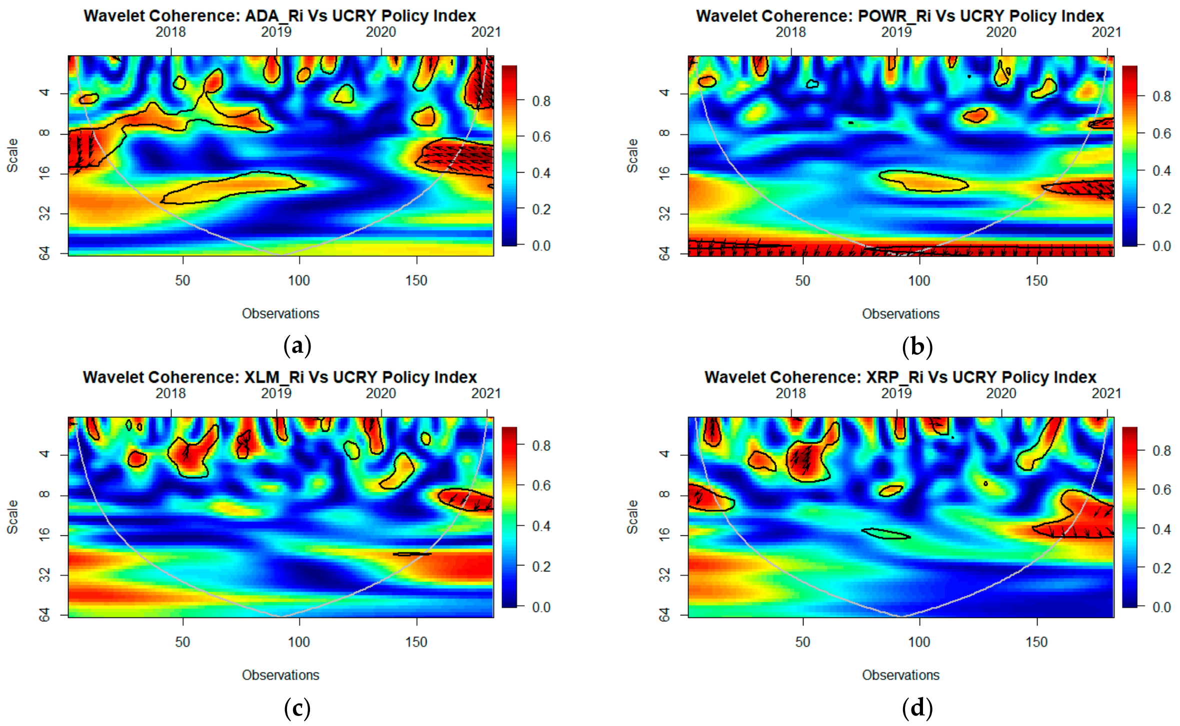

Figure 4. Wavelet coherence between sustainable cryptos and UCRY policy index. Note: (**a**) = wavelet coherence between Cardano and UCYR Policy Index, (**b**) = wavelet coherence between Powerledger and UCYR Policy Index, (**c**) = wavelet coherence between Stellar and UCYR Policy Index, (**d**) = wavelet coherence between Ripple and UCYR Policy Index.

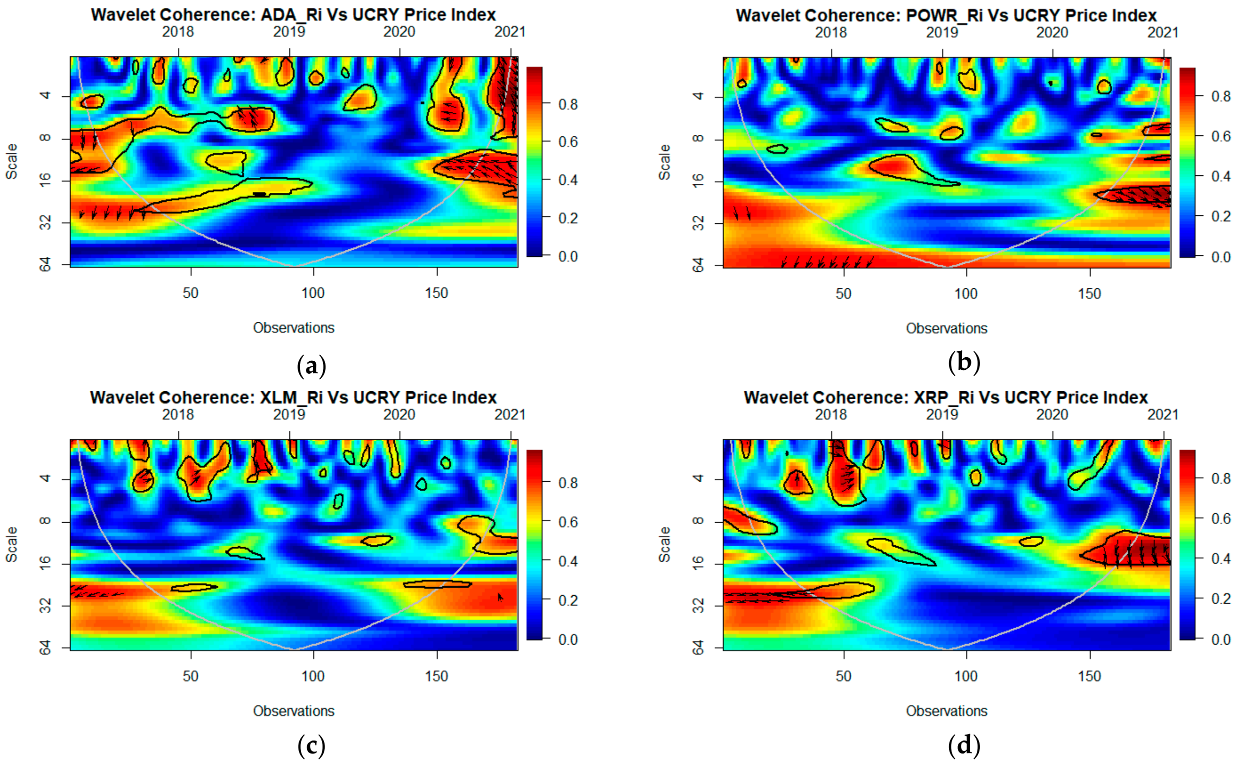

Figure 5. Wavelet coherence between sustainable cryptos and UCRY price index. Note: (**a**) = wavelet coherence between Cardano and UCYR Price Index, (**b**) = wavelet coherence between Powerledger and UCYR Price Index, (**c**) = wavelet coherence between Stellar and UCYR Price Index, (**d**) = wavelet coherence between Ripple and UCYR Price Index.

Figure 5 represents the output of the wavelet coherence approach and presents the co-movement between sustainable cryptocurrencies and the UCRY price index. Generally, the co-movement between green financial assets (i.e., Cardano, Stellar, and Ripple) and the UCRY price index is positive (in-phase) at the 2–4-week frequency band during COVID-19 in particular, but not Powerledger which shows positive co-movement at the 16–32-week scale. Therefore, sustainable cryptocurrency returns lead the UCRY price index at short-term investment horizons, particularly during the COVID-19 episode. The co-movement is generally negative (out-of-phase) in the rest of the frequency bands, or medium-term and long-term investment horizons, suggesting that sustainable cryptocurrencies lag the UCRY price index in the medium and long term.

In overview, the hedging ability of sustainable cryptocurrencies is short-lived against increasing UCRY policy and price uncertainty, therefore investors need to design a timely hedging strategy to earn financial gains. In addition, the dominant blue areas suggest weak coherence or co-movement, indicating that sustainable cryptocurrencies can serve as weak hedging instruments for high UCRY policy risk at the long-term investment horizon. Importantly, investors and crypto traders can protect their portfolios from high UCRY policy and price risk by including sustainable cryptocurrencies.

5. Discussion and Implications

This research paper examines the wavelet coherence between conventional cryptocurrencies, sustainable cryptocurrencies, and UCRY policy and price indices, allowing for capturing potential heterogeneous relationship over time and frequency domains. Cryptocurrency returns are found to be more strongly associated with UCRY price index than the UCRY policy index, which may be due to investor's type (Lucey et al. 2022) and investor's trust (Haq et al. 2021). Specifically, the returns of conventional cryptocurrencies show positive co-movement with the UCRY policy index in the short-term and weak co-movement in the medium-term and long-term investment horizons, which are consistent with (Karaömer 2022; Ah Mand 2021). Conversely, the co-movement between the returns of conventional cryptocurrencies and the UCRY price index is more significant across all investment horizons. These findings suggest the hedging ability of conventional cryptocurrencies against UCRY policy and price indices (Hasan et al. 2022; Karaömer 2022). Interestingly, conventional cryptocurrencies lead UCRY policy and price uncertainties dominantly at the short-term horizon, and weakly lead/lag the relationship at the medium-term and long-term investment horizons. These findings indicate the hedging ability of cryptocurrencies and corroborate earlier research (Hassan et al. 2021; Hasan et al. 2022; Ah Mand 2021; Karim et al. 2022; Karaömer 2022). Specifically, the results partially corroborate Hassan et al. (2021), in so much as UCRY policy and price indices have a positive effect on gold returns, suggesting that gold is a suitable hedge for UCRY uncertainty, and partially contradict them as Bitcoin fails to hedge UCRY price and policy. The findings align with Ah Ah Mand (2021) who finds a stronger dependence structure between cryptocurrency returns and the UCRY policy index across investment horizons. The results contradict Karaömer (2022) who finds a consistent negative correlation between cryptocurrencies and UCRY policy and that no conventional cryptocurrency among the top six can act as a hedge or safe-haven for UCRY policy.

In short, the findings of this paper suggest that the hedging ability of conventional cryptocurrencies, including Bitcoin, is a short-lived or low-frequency hedging ability (Chan et al. 2019; Majdoub et al. 2021) because cryptocurrencies are traded at very high frequencies (Dyhrberg 2016). In addition, UCRY uncertainties are mainly reliant upon the major conventional cryptocurrencies, i.e., Bitcoin, Ethereum, Litecoin, Tether, and Ripple (Lucey et al. 2022). Therefore, UCRY price and policy uncertainties cannot be hedged in the long term using conventional cryptocurrencies. This is supported by the previous findings of Karaömer (2022), that UCRY policy fosters volatility among conventional cryptocurrencies, thus conventional cryptocurrencies are not effective hedges against the highly uncertain cryptocurrency market. In addition, as argued by Koumba et al. (2020), cryptocurrency-specific features, such as protocols and administration, affect their price dynamics and, thereby, their hedging abilities.

The role of sustainable cryptocurrencies is under-studied from a hedging and safe-haven perspective (Ul Haq et al. 2022). The wavelet coherence findings suggest positive co-movement between sustainable cryptocurrencies and UCRY policy and price indices at the short-term investment horizon (2–4-week scale) and negative co-movement at the medium-term and long-term investment horizons, except for Cardano, Stellar, and Ripple, which show zero phase difference and weak dependence structure at the 16–32-week and 32–64-week frequency scales (long-term investment horizons). Thus, sustainable cryptocurrencies are a strong hedge for high UCRY price and policy at short-term investment horizons. These findings corroborate earlier research which finds that sustainable cryptocurrencies are diversifiers for green bonds and the Dow Jones Sustainability Index (Ul Haq et al. 2022). Moreover, positive co-movement between sustainable cryptocurrencies and UCRY policy and price indices in the long term indicates that increasing UCRY policy and price uncertainty might damage the green role of sustainable cryptocurrencies, because conventional or dirty cryptocurrencies consume huge amounts of electricity and cause climate change and carbon emissions (Ul Haq et al. 2022; Pham et al. 2022; Naeem and Karim 2021).

Overall, the co-movement of conventional cryptocurrencies and sustainable cryptocurrencies with UCRY policy and price indices follows almost identical coherence patterns, indicating that UCRY policy and price indices have a strong lagging role in both sustainable and conventional cryptocurrencies. This might be because the herd flows from green/clean cryptocurrency investors to dirty crypto markets/currencies, particularly when both generate positive returns (Ren and Lucey 2022b). In other words, clean crypto investors tend to follow identical actions to dirty crypto investors. In addition, investors and crypto traders seem indifferent to investing in green or sustainable cryptocurrencies or dirty or conventional cryptocurrencies (Ren and Lucey 2022a). Both cryptocurrency uncertainty indices behave similarly. The heterogeneity of co-movements and hedging properties of cryptocurrencies for both cryptocurrency uncertainty indices might be driven by the heterogeneity of traders and investors. Lucey et al. (2022) indicate that amateur investors (traders) are more sensitive to price fluctuations and general media attention, unlike informed institutional investors, who care more about changes in cryptocurrency policy uncertainty.

6. Conclusions

Using the bivariate wavelet coherence method, this paper provides the first empirical evidence of co-movements of conventional and sustainable cryptocurrencies with cryptocurrency policy uncertainty and cryptocurrency price uncertainty indices, and makes hedging inferences in the time–frequency domain. Previous studies, such as Ren and Lucey (2022a) and Haq et al. (2022) state that sustainable or green cryptocurrencies could be used as diversification and hedge instruments by green crypto investors. However, this paper shows consistent positive co-movement between cryptocurrencies and UCRY indices (policy and price) regardless of cryptocurrency type (conventional or sustainable) conditional on a short-term investment horizon. Firstly, conventional cryptocurrencies can hedge either cryptocurrency policy or cryptocurrency price uncertainty indices at a high-frequency scale, however, Binance Coin shows consistent positive co-movement, which implies that Binance Coin is the most effective hedge among the conventional cryptocurrencies against the UCRY policy index. Secondly, rising UCRY policy and UCRY price lead Bitcoin, Ethereum, and Cardano returns, while UCRY policy and UCRY price lag Binance Coin returns. Despite being the largest cryptocurrency, Bitcoin is not the leading in terms of cryptocurrency policy uncertainty across medium-term and long-term investment horizons. Thirdly, sustainable cryptocurrencies can be used as hedging tools for either type of cryptocurrency uncertainty, limited to a short-term investment horizon. In particular, Cardano is the most effective hedge for increasing UCRY price and policy uncertainty. However, the hedging properties of sustainable cryptocurrencies disappear at the medium-term investment horizon. Fourthly, when UCRY policy and price increase, it leads to an increase in the returns of sustainable cryptocurrencies (except Powerledger) in the short term, signifying a hedging ability in the short term only. These findings have policy implications for informed institutional investors who can hedge the price and policy uncertainty of the cryptocurrency market, during normal and COVID-19 periods, using Binance Coin and Cardano under specific time-horizon conditions. The negative influence of price and policy cryptocurrency uncertainties on Bitcoin and Ethereum in the medium term concerns policymakers who should consider taking timely countermeasures.

This study has several key implications for investors, including amateur traders, informed long-term institutional investors (Lucey et al. 2022), and sustainable/green investors (Ren and Lucey 2022a). The outputs of wavelet coherence analysis show heterogenous co-movements over multiple investment horizons, hence crypto traders and investors can consider the current findings (conventional and sustainable cryptos) to avoid or diversify UCRY policy and price exposure at the short-term horizon. Furthermore, crypto traders and global investors need to understand that cryptocurrency price and policy uncertainty, in itself, is not a risk, but a portfolio can incur losses resulting from higher URCY (price and policy), which is a risk which needs to be hedged. Hence, conventional and sustainable cryptocurrencies provide hedging opportunities and can thus be used by portfolio managers and crypto traders. Additionally, policy and price uncertainties adversely affect sustainable cryptocurrency returns in the long run, hence policymakers need to take countermeasures to protect investments and cryptocurrency portfolios. The weak dependence structure at the long-term investment horizon suggests that investors can consider conventional and sustainable cryptocurrencies to hedge UCRY price and policy uncertainties, but the hedging properties are more pronounced at the short-term investment horizon. Finally, the development of sustainable cryptocurrencies can bring significant social, environmental, and financial benefits, unlike conventional cryptocurrencies. Investors need to invest in sustainable cryptocurrencies rather than dirty or conventional cryptocurrencies. Therefore, greater effort is needed in making the global economy greener and more sustainable, and in raising environmental awareness.

This research has been conducted while the COVID-19 pandemic is not yet over, therefore future research might consider studying the connectedness in an exclusive data sample. Future research should consider direct portfolio implications such as hedging effectiveness. In addition, the application of blockchain has enormous benefits and challenges for the financial sector (Mishra and Kaushik 2021; Najjar et al. 2022), therefore, it is timely to study the connectedness between sustainable cryptocurrencies and the Index of Cryptocurrency Environmental Attention (ICEA) (Wang et al. 2022) due to its relevance to the environmental concerns of cryptocurrencies.

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Appendix A

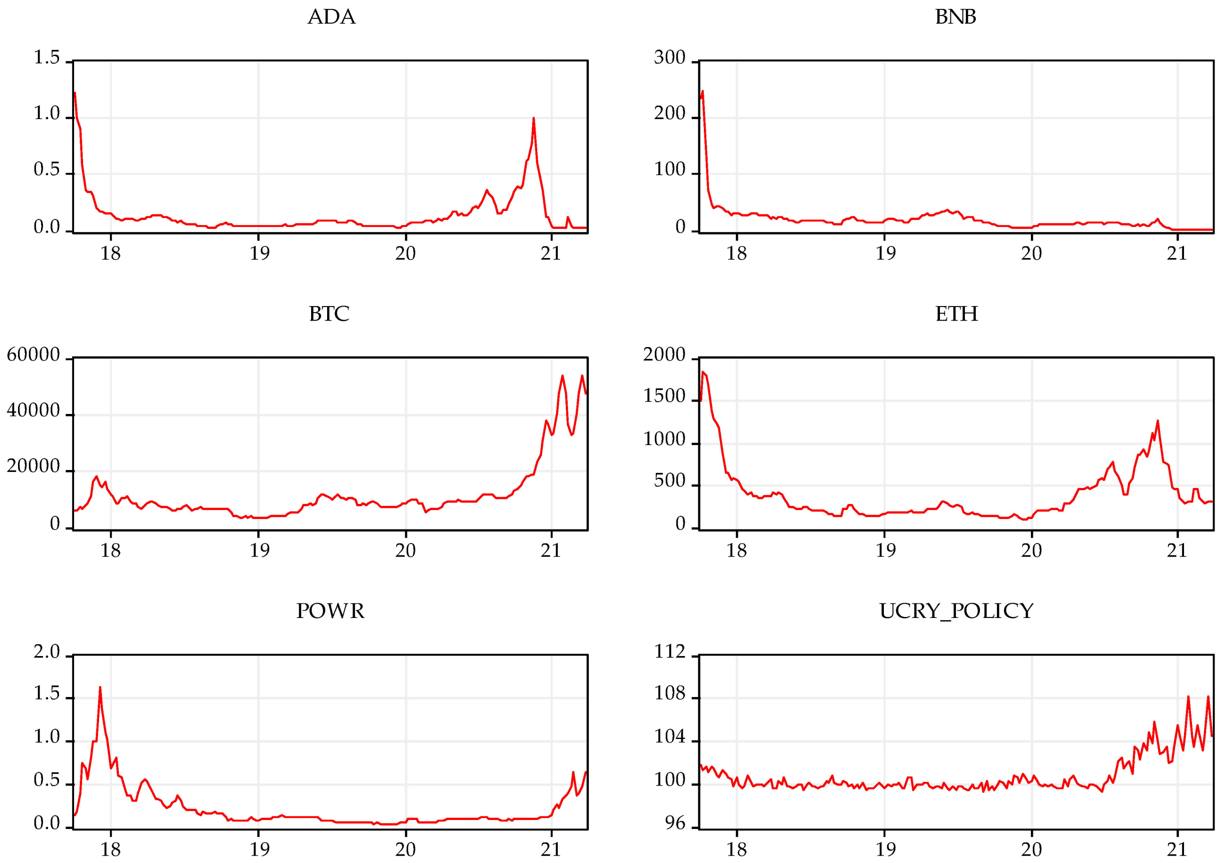

Figure A1. *Cont.*

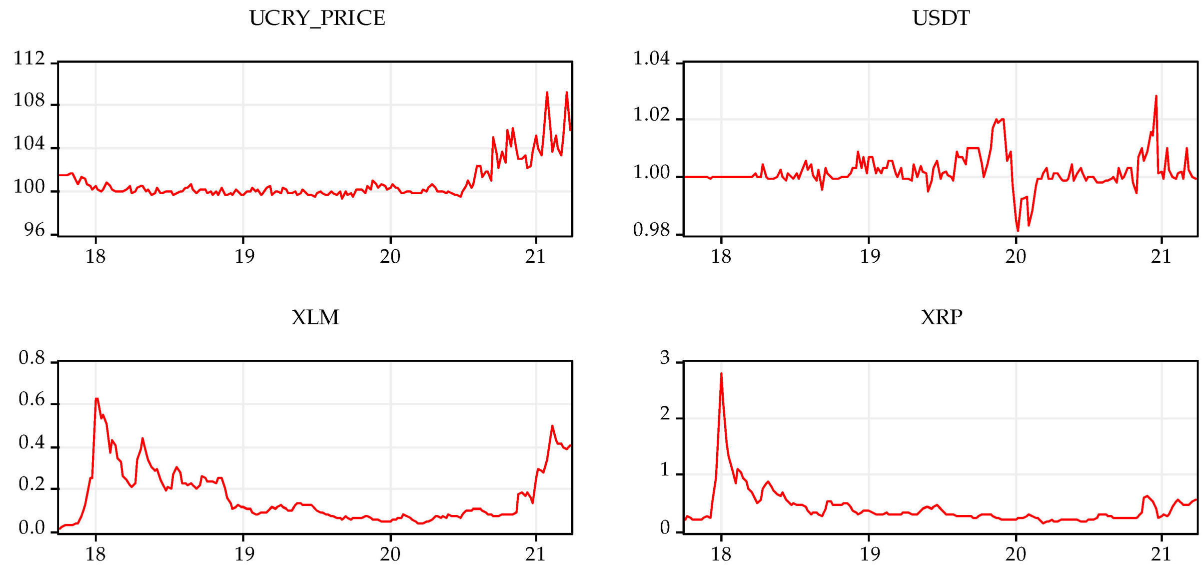

Figure A1. Plots for level series.

Notes

1. Some studies consider environmental movements (Saplie 2011), climate change challenges (Salpie 2021), environmental policy objectives (Hilmi et al. 2021), and emission taxes (Marrouch and Sinclair-Desgagné 2012), bearing in mind that monetary policies are affected by a changing financial environment (Shahin Wassim 2017).
2. A related strand of literature considers the connectedness across major cryptocurrencies (Bouri Elie et al. 2021; Shahzad et al. 2021; Ashish et al. 2022), and the presence of time-varying jumps (Dutta Anupam 2022).
3. Wavelet-based methods are applied in various research fields (Katicha et al. 2017, 2021).

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