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Are green bonds and sustainable cryptocurrencies truly sustainable? Evidence from a wavelet coherence analysis

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ABSTRACT

This article aims to explore the co-movement of daily returns among S&P green bonds (GB/GBs), the top five sustainable cryptocurrencies, Bitcoin, the Dow Jones Sustainability World Index (DJSWI) and the Dow Jones Sustainability Emerging Market Index (DJSEMI) to determine whether GBs, Bitcoin and sustainable cryptocurrencies are truly sustainable; in addition, it investigates hedging and diversification opportunities. Using a partial wavelet coherence framework to capture the bivariate co-movement, our findings show strong (weak) positive co-movements among GB (sustainable cryptocurrencies) and DJSWI returns, where GBs (sustainable cryptocurrencies) have a heterogeneous leading role in the short-term and long-term horizons. Results indicate moderate positive (negative) co-movement among GBs and sustainable cryptocurrencies (Bitcoin) and DJSWI in the short run (long run). Overall, the results show GB (sustainable cryptocurrencies) acts as a diversifier for Bitcoin and sustainable cryptocurrencies in most cases (DJSWI). However, increasing Bitcoin returns adversely impacts the DJSWI in the long run. Findings are equally imperative for green investors, crypto traders and policymakers, where investors and traders can earn financial and social returns, and policy-makers can deploy suitable policies for the development of sustainable cryptocurrency mining processes. The role of Bitcoin is alarming for the United Nations Sustainable Development Goals and global greener economy.

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Green bonds; sustainable cryptocurrencies; Bitcoin; sustainability world index; wavelet coherence; diversifier

JEL CLASSIFICATIONS
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1. Introduction

Sustainability is a key antecedent of sustainable social, environmental and economic development. The Department of Economics and Social Affairs of the United Nations launched the 2030 Agenda for Sustainable Development in 2015. It expounds 17

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development goals and 169 targets. The mission of the sustainable development goals (SDGs) is to transform the worldwide society to a better sustainable future for the entire planetary ecosystem by 2030. Addressing sustainability challenges requires an enormous effort (de Oliveira et al., 2020). According to an estimate by Trade and Development, US$5 to 7 trillion is indispensable to achieve the forecasted targets and goals (de Oliveira et al., 2020). Therefore, the role of individual and institutional investors is crucial to mobilize resources and sustainable investments.

Climate change has become an existential challenge for people living around the globe (Xuefeng et al., 2021). Currently, greenhouse gas emissions are playing a devastating role in fostering global warming due to the increasing pace of their rise. Rising emissions could have irreversible consequences in damaging the ecosystem and life on earth. These challenges are alarming and require immediate action to mitigate the carbon emission rate and to circumvent environmental disasters. Hence, mobilizing substantial capital flows is required to tackle climate challenges and to institute a low-carbon economy. A serious global climate change movement requires approximately US$3.5 trillion every year from the energy sectors from 2020 to 2050 (Naeem et al., 2021) and approximately US$110 trillion in total to reach the targets set by the Paris climate change agreement by 2050 (Ferrer et al., 2021). In addition, the challenges of climate change, greenhouse emissions and global warming have turned the attention of individual and institutional investors toward financial innovations to promote a greener global economy and sustainable development. The development of energy technologies can promote environmental protections and decarbonize the energy system (Van Hoang et al., 2019). Therefore, GBs and sustainable cryptocurrencies are promising innovations and avenues for the massive reallocation of funds.

Since the first green bond was issued in 2017 by the European Investment Bank (EIB), the GB market has become a rapidly growing segment of the capital markets. The role of GBs is vital in the fund collections related to environmentally friendly projects to combat climate change (Baker et al., 2018). It is a fixed-income capital market security and differs from other fixed-income instruments due to its environmental protections and sustainable features. The scope of GB is wider. A majority of the GBs issued between 2010 and 2019 were related to renewable energy, energy efficiency, clean transportation, green buildings, pollution prevention and control. According to the International Capital Market Association, the global bond market reached US$128.3 trillion in August 2020[1], and the GB market increased from US$11 billion in 2011 to US$349.1 in June 2020 (Naeem et al., 2021). However, the GB market accounts for less than 5% of the total bond market and is still in its infancy (Naeem et al., 2021). A huge potential avenue for future growth has spotlighted the GB market, and investors (individual and institutional) foresee GB as a sustainable risk management tool in finance and economics (Haq et al., 2021; Huynh et al., 2020; Le et al., 2021; Liu et al., 2021; Nguyen et al., 2021; Pham, 2021; Reboredo, 2018; Reboredo & Ugolini, 2020; Reboredo et al., 2020; Saeed et al., 2020). Thus, it is of interest to investigate the GB market to validate the sustainable development impact and risk management possibilities in the current market.

Sustainable cryptocurrency is an emerging buzzword in modern sustainable finance. Sustainable cryptocurrencies and eco-friendly crypto options have received enormous attention since Elon Musk (chief executive of Tesla) announced that they are not going to accept Bitcoin as payment for electric vehicles. Bitcoin has a severe impact on carbon emissions and sustainability. The mining process of conventional cryptocurrencies involves high-powered computer systems, huge electricity requirements to run algorithms, and uses nonrenewable resources such as coal and fossil fuels. In addition, these nonrenewable resources produce the worst consequences for the environment and carbon footprints. The SolarCoin (SLR) generates 1 SolarCoin for each megawatt hour by employing solar technology. The BitGreen (BITG) mining process involves a low-energy proof of stake algorithm to ensure eco-friendly actions. The cryptocurrency network utilizes a minimal power of 6 GWh only for Cardano (ADA), and it is more energy efficient than Bitcoin. ADA was introduced by the co-founder of Ethereum. Moreover, Steller (XLM) has its own consensus protocol (SCP). Due to its personal SCP, the authentication cycle becomes shorter, which makes it an energy-efficient and low-cost crypto asset. However, Ripple (XRP) uses an algorithm called the Ripple protocol consensus algorithm (RPCA). Therefore, RPCA provides a low cost and a secure rapid transaction speed.[2] The mining processes of sustainable cryptocurrencies are reliant on sustainable and environmentally beneficial systems. Therefore, the idea to create sustainable cryptocurrencies seems plausible, and the future of modern sustainable finance and the cryptocurrency market lie in sustainable cryptocurrencies.

Our motivations are as follows: First, participants in cryptocurrency and sustainable financial markets have heterogeneous investment horizons (e.g., amateur traders versus informed long-term institutional investors) and investment objectives (conventional (black) versus green investors) (Broadstock & Cheng, 2019), which not only requires a differentiation between social returns and financial returns (Lucey et al., 2021) due to environmental consequences (Y. Wang et al., 2022) but also the application of a wavelet-based approach to make inferences in a time–frequency setting (Bouri et al., 2020). Second, the academic hedging literature highlights potential differences between conventional cryptocurrencies (e.g., Bitcoin and Ethereum) (Haq et al., 2021; Koumba et al., 2020; Rubbaniy et al., 2021). In addition, the hedging and diversifier roles of Bitcoin and other cryptocurrencies have increased in the last five years (Haq et al., 2021); however, the hedge and diversifier role of GB with sustainable cryptocurrencies remains overlooked. Thus, the current research seeks to answer two questions: Are GBs and sustainable cryptocurrencies truly sustainable? Does GB act as a hedge or a diversifier for sustainable cryptocurrencies and Bitcoin? In addition, in exploring these questions, we explore the leading and lagging roles of all asset classes.

The current research contributes to the inclusive body of the literature in a few ways. First, to the best of our knowledge, this is the first study to investigate the co-movement among GB, sustainable cryptocurrencies, Bitcoin, DJSWI and DJSEMI returns over the short and long run. Second, it contributes to the hedge and diversifier literature (Arif et al., 2021; Hung, 2021; Le et al., 2021; Maltais & Nykvist, 2020; Naeem et al., 2022; Naeem et al., 2021; Nguyen et al., 2021; Reboredo et al., 2020). Third, it adds knowledge to the current debate concerning the negative consequences of the accelerating Bitcoin mining practices (Naeem & Karim, 2021). Finally, it prompts an inquiry of whether GBs and sustainable cryptocurrency are truly sustainable and improves sustainability around the globe.

Using a partial wavelet coherence framework, our empirical analysis presents five significant outcomes. First, it finds that GB is positively correlated (in-phase) with the DJSWI and DJSEMI, where the GB market leads the DJSWI and DJSEMI (lagging). Second, it reveals the financial impact of COVID-19 by considering COVID-19 episode data, where GB is positively correlated (in-phase) with DJSWI and DJSEMI and GB is leading the other two sustainability indices. Third, it adds knowledge to the inclusive debate about sustainable cryptocurrencies. The top five sustainable cryptocurrencies do not present any pronounced strong positive (in-phase) correlation with GB. Thus, GBs act as diversifiers for sustainable cryptocurrencies or weak hedge. Fourth, it notices a positive (in-phase) relationship between sustainable cryptocurrencies and DJSWI. It reveals a negative impact of increasing returns on the DJSWI in the long run. The outputs show evidence of a moderate positive co-movement of Bitcoin and GB returns.

The rest of this article unfolds as follows. Section 2 provides an overview of the related literature. Section 3 describes the methods employed, and Section 4 presents the data and an empirical analysis. Finally, Section 5 concludes this article and suggests future research avenues.

2. Review of related studies

The earlier academic literature is divided into several parts, GB premium and yields, volatility comparison, benefits of GB, price efficiency dynamics, and co-movements between GB and conventional assets.

Many previous studies have focused on the yield and premium of GB (Ferrer et al., 2021). Overall, researchers have found mixed GB outcomes. Previous studies reported a positive GB premium, suggesting that GBs have the option to earn financial gains (Gianfrate & Peri, 2019; Zerbib, 2019). However, the premium of GBs reported a negative moderate; hence, investors have to scarify the returns in the name of the sustainability and environmental protection characteristics of GBs (Bachelet et al., 2019). The recent literature has captured a wide picture of the premium and yields avenues (MacAskill et al., 2020). In short, the discussion of the GB premium is still inclusive (Ferrer et al., 2021).

From another perspective, volatility comparisons and spillovers between GBs and other fixed income asset markets have been studied earlier. Similarly, Pham (2016) investigated the relationship between GB and standard fixed income markets, finding a strong spillover risk between GBs and conventional fixed-come markets. Moreover, volatility clustering is much stronger in green markets than in standard fixed income markets. Another study by Broadstock and Cheng (2019) documented that the relationship between U.S. GBs and standard bonds is sensitive, where crude oil, news-based risk proxies and economic conditions predict the association between both markets. Recently, the connectedness between GB and equity markets was investigated by Park et al. (2020), who reported the existence of volatility spillovers using a multivariate GARCH model. A similar nature of research was conducted from the

Chinese perspective (Gao et al., 2021) but reported an insignificant spillover between GBs and the equity market in China.

Another relevant body of the literature explores the benefits of GB issuance, not from the issuer and investor perspective but for national benefit (Naeem et al., 2021). The announcements about GB issuance increased the shareholder's return (Lautsi, 2019) and stock prices positively pinned with the announcement of GB issuance (Tang & Zhang, 2020). Likewise, the issuance of GBs adds value to Chinese shareholders (J. Wang et al., 2020). In addition, the announcement of GB environmental issuances (Flammer, 2020) as well as the financial performance of firms and the funding cost to climate change is another compelling advantage of GBs (Flaherty et al., 2017). Similarly, GBs proved to be a potential avenue to achieve sustainable development goals (Banga, 2019).

One additional area of research is price efficiency dynamics. Until lately, only limited studies have examined the multifractal features (Naeem et al., 2021). They conclude that the GB market is highly efficient and reacts more efficiently in black swan events or periods of higher uncertainty, such as COVID-19. In contrast, a lack of efficiency was found in green and other bonds (Karginova-Gubinova et al., 2020). Furthermore, Karginova-Gubinova et al. (2020) suggested that the GB market is yet immature; hence, institutional and regulatory changes should be made to improve efficiency in Russian settings.

Several studies have investigated the co-movements and dependencies between GBs and other asset classes or financial markets (Huynh et al., 2020; Le et al., 2021; Liu et al., 2021; Nguyen et al., 2021; Pham, 2021; Reboredo, 2018; Reboredo & Ugolini, 2020; Reboredo et al., 2020; Saeed et al., 2020). In an earlier contribution, the dependencies were gauged by Reboredo (2018) between GB, conventional bonds and fixed-income, energy and equity markets. They found that the GB market is cointegrated with other corporate bonds using the bivariate. However, the GB prices positively but not perfectly co-move with energy and stock markets. Therefore, ample diversification potential exists in the GB market. In a similar domain, Reboredo and Ugolini (2020) studied the price transmissions of several financial markets and the GB market. Using a VAR (vector autoregressive) model, they concluded that the GB market is more cointegrated with the U.S. currency markets and government bonds. Similarly, another study by Reboredo et al. (2020) investigated network connectedness, where the number of asset classes and the GB market were studied over multiple investment horizons in the U.S. and European Union. Another recent study by Liu et al. (2021) investigated the dynamic dependency structure between GB and global energy clean energy markets using a copula approach alongside a conditional value at risk model. The outputs reported a positive time-varying dependence.

Another promising area is focusing on the dynamic linkage between GBs and other financial markets considering the unprecedented global episode of COVID-19 (Shahzad et al., 2021). For instance, Haq et al. (2021) investigated the dynamic conditional correlation between GB, rare earth metals, clean energy stocks and the economic policy uncertainty (EPU) index during the COVID-19 pandemic. They found that the GB acted more as a hedge than a safe haven during the pandemic for EPU but as a diversifier for other asset classes, such as clean energy stocks and rare earth metals. In contrast, Gupta et al. (2021) have studied the impact of financial uncertainty (news-based index) on U.S. interest rates (term structure). They concluded that U.S. treasury securities proved to be a safe-haven during the pandemic period. Similarly, Bouri et al. (2021) found the GB market to be a main transmitter of volatility during the coronavirus period. They have investigated the connectedness between bonds, currencies, crude oil, equities and gold during the pandemic. A similar set of asset classes were considered by Arif et al. (2021) to explore the hedging and safe-haven properties of the GB market.

From the above discussion, we conclude that the body of the literature on diversification and hedging is advancing tremendously. However, the earlier literature remains silent on exploring the socially and environmentally sustainable features of GBs and cryptocurrencies. To the best of our knowledge, no study has investigated the hedging and sustainability features of sustainable cryptocurrencies. Therefore, this article seeks to fill the current literature gap in the existing studies.

3. Wavelet coherence

The wavelet coherence approach combines the time and frequency of the time series in itself. It serves to estimate the association or co-movement between two time series over time and frequency bands. This research considers the wavelet coherency as defined by Torrence and Compo (1998) under the smoothing technique in both domains. Here, there are two time series a(t) and b(t) and the cross-wavelet transforms for them $W_a(u, s)$ and $W_b(u, S)$. Hence, the cross-wavelet transform can be written as follows in Equation (1).

$$W_{a,b}(u, s) = W_a(u, s)\ W_b^*(u, s) \quad (1)$$

In Equation (1),'s' and 'u' are the scale and position index, respectively. Given any two time series 'a' and 'b', a continuous wavelet transform can be written for time series 'a' and 'b' as $W_a(u, s)$ and $W_b^*(u, s)$, respectively. A symbol on any series 'b', as given in equation W_b^*, demonstrates a complex conjugate. Hence, a wavelet transform gauges the association between any two time series 'a' and 'b'.

Torrence and Compo (1998) introduced a wavelet coherence approach that was used to estimate cross-wavelet power. The purpose of the wavelet coherence approach is to identify a notable covariance between any two times through the cross-wavelet power series at each scale. Likewise, the purpose of wavelet coherence is quite similar to the cross-wavelet power. However, it may not have high wavelet power. Hence, this study followed the Torrence and Webster (1999) method to estimate the squared wavelet coherence between pairs. It is an extension of the Torrence and Compo (1998) method. Therefore, squared wavelet coherence can be written as follows in Equation (2):

$$R^2(u, s) = \frac{\left|S\left[s^{-1}W_{a,b}(u, s)\right]\right|^2}{S\left[s^{-1}|W_a(u, s)|^2\right]S\left[s^{-1}|W_b(u, s)|^2\right]} \quad (2)$$

In Equation (2), the smoothing operator is 's' over time as well as space, and an inconclusive $R^2(u, s)$ defines the localized correlation in a squared form over the time and frequency domains. In addition, the squared correlation coefficient ranges from $0 \le R^2(u, s) \le 1$. The value of $R^2(u, s)$ determines the co-movement between any two time series, and a higher (lower) value of $R^2(u, s)$ denotes a higher (lower) co-movement. However, squared wavelet coherence faces an issue. It remains unable to differentiate between positive or negative associations and is thus limited to capturing co-movements from 0 to 1 only. Ultimately, Torrence and Compo (1998) developed a solution to resolve this issue and recommended using the phase difference. The core purpose of phase difference is detecting different directions (positive/negative) of co-movements between pairs. Hence, the phase difference can be written as follows in Equation (3):

$$\varnothing_{a,b}(u, s)\ \tan^{-1}\left(\frac{Im\left\{S\left(s^{-1}W^{a,b}(u, s)\right)\right\}}{Re\left\{S\left(s^{-1}W^{a,b}(u, s)\right)\right\}}\right) \tag{3}$$

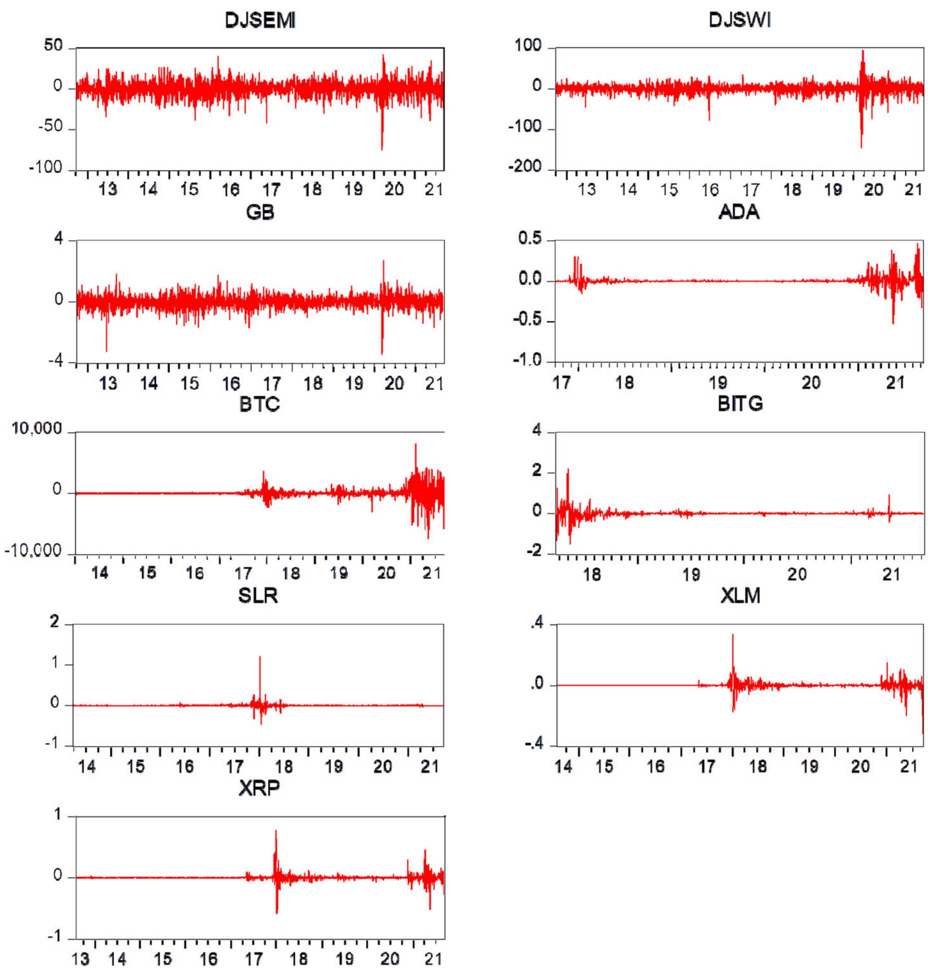

Figure 1. First difference return series.
Source: Authors' estimations.

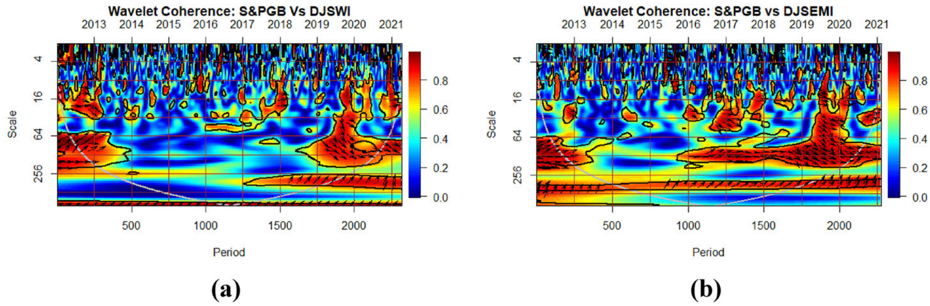

Figure 2. Wavelet coherence among green bond, sustainability world index and sustainability emerging market index.

Note: The figure indicates the wavelet coherency plot among the Green bond, Sustainability World Index and Sustainability Emerging Market Index where the horizontal axis presents the time in days. The vertical axis depicts the period (frequency) classified in 4, 8, 16, 32, 64, 128 and 256 days). The correlation (coherency band) is flaunted on the right side of the figure in blue (0.0) to red (1.0) colours indicating the correlation range and the highest and lowest correlation value (R^2). The cone of influence is displayed in a curved solid white colour. Black-coloured contours at different spots demonstrate the significance of the results at the 0.05 (5%) level. The arrows signal the phase differences, where forward arrows (→) are in the phase (positive relationship) connectedness and vice versa. Upward arrows (↑) indicate that the first time series is leading the other (lagging) and vice versa. Forward upward and downward arrows (↘,↗) denotes a phase (positive relationship) and the first time series is leading other (lagging) and (↙,↖) vice versa.

Source: Authors' estimations and drawing.

In Equation (3), *lm* expresses the imaginary smoothed part and *Re* expresses the real part of the smoothed cross-wavelet transform.

Generally, the analysis of a cross-wavelet coherence estimation produces a figure. The colourful figure has five key chunks (see Figures 2–5), colours from red to blue (warm and cold colours), uniquely directed eight arrows in the black colour (←, →, ↑, ↓, ↘, ↗, ↙, ↖), black contours, a cone of influence and two axes (x-axis and y-axis). The ← (→) arrows indicate an out-of-phase (in-phase) association between two time series or a negative (positive) correlation direction. Moreover, ↗ (↙) denotes that the first time series variable leads the second time series. For example, the ↖ arrow in the figure (see Figures 2–5) denotes a negative correlation or out-of-phase association between any two series 'a' and 'b' under the leading effect of any first-time series 'a'. In contrast, ↘ has the reverse explanation. Generally, a zero phase difference indicates that both time series 'a' and 'b' move in inhomogeneous directions. Black coloured curves in Figures (2–5) show the black contours. These black contours indicate that the results (coherence regions) are statistically significant at a significance level of 0.05 (5%), and an ultimate u-shaped white solid line is the cone of influence in Figures (2–5).

4. Data descriptions and an empirical analysis

4.1. Data description

The research follows daily values (five days a week) for all variables. The sample period for S&P GB, DJSWI, and DJSEMI is 1 September 2012 to 9 September 2021. The sample period for the five sustainable cryptocurrencies SolarCoin, BitGreen, Cardano, Steller and Ripple commence from different starting points due the latest inception on 29 March 2014, 22 March 2018, 1 October 2017, 5 August 2014, 4

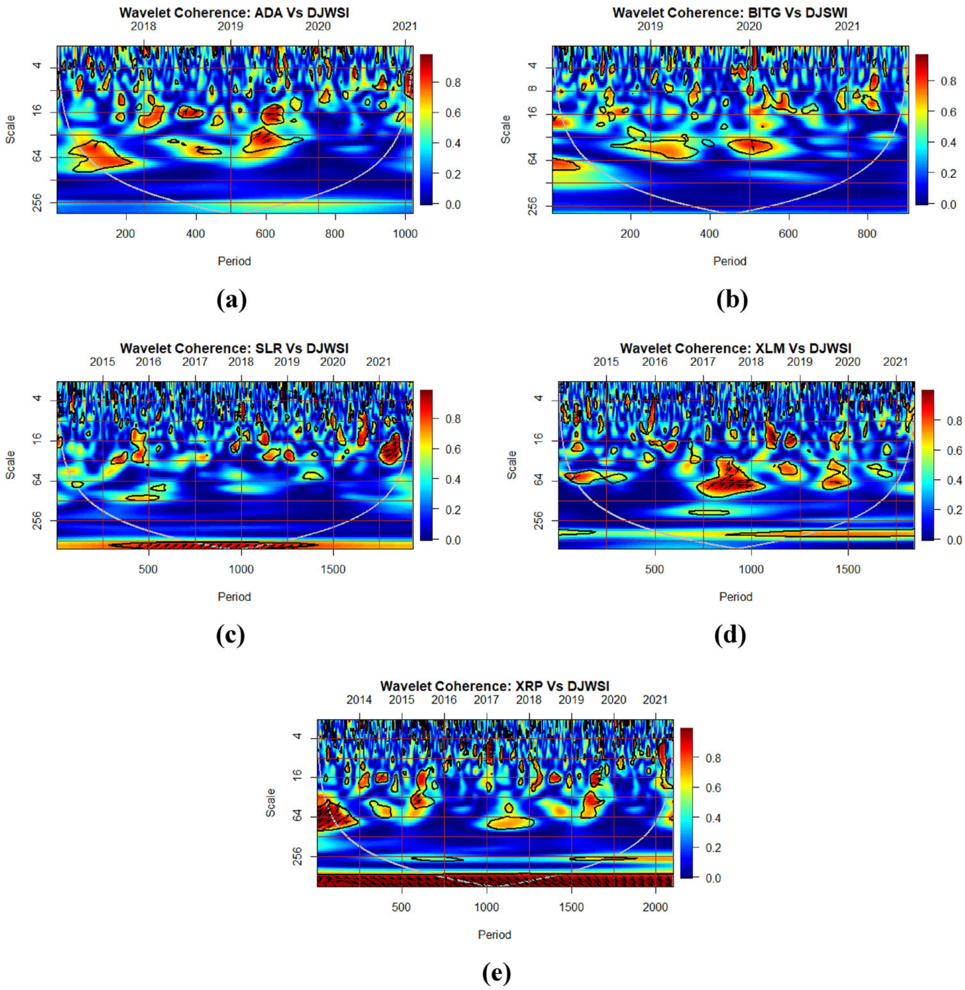

Figure 3. Wavelet coherence of sustainable cryptocurrencies and the world sustainability index.
The figure indicates the wavelet coherency plot between sustainable cryptocurrencies and world sustainability index. Refer Figure 1 for interpretations of the wavelet coherence output.
Source: Authors estimations and drawing.

August 2013 to 9 September 2021, respectively. In addition, the dataset covers the data for Bitcoin from 1 January 2014 to 9 September 2021. First, (1st) difference daily values are calculated for wavelet coherence analysis. The studied cryptocurrencies are the top five sustainable cryptocurrencies[3] and the largest capped cryptocurrency, Bitcoin. The data for GB, DJSWI and DJSEMI are given according to the available cryptocurrency data. The data for cryptocurrencies (GB, DJSWI and DJSEMI) were sourced from coinmarketcap.com (www.spglobal.com).

4.2. Basic statistics

The descriptive statistics for the level series and first difference are illustrated in Table 1. The statistics in Table 2 show that all-time series positive means, except

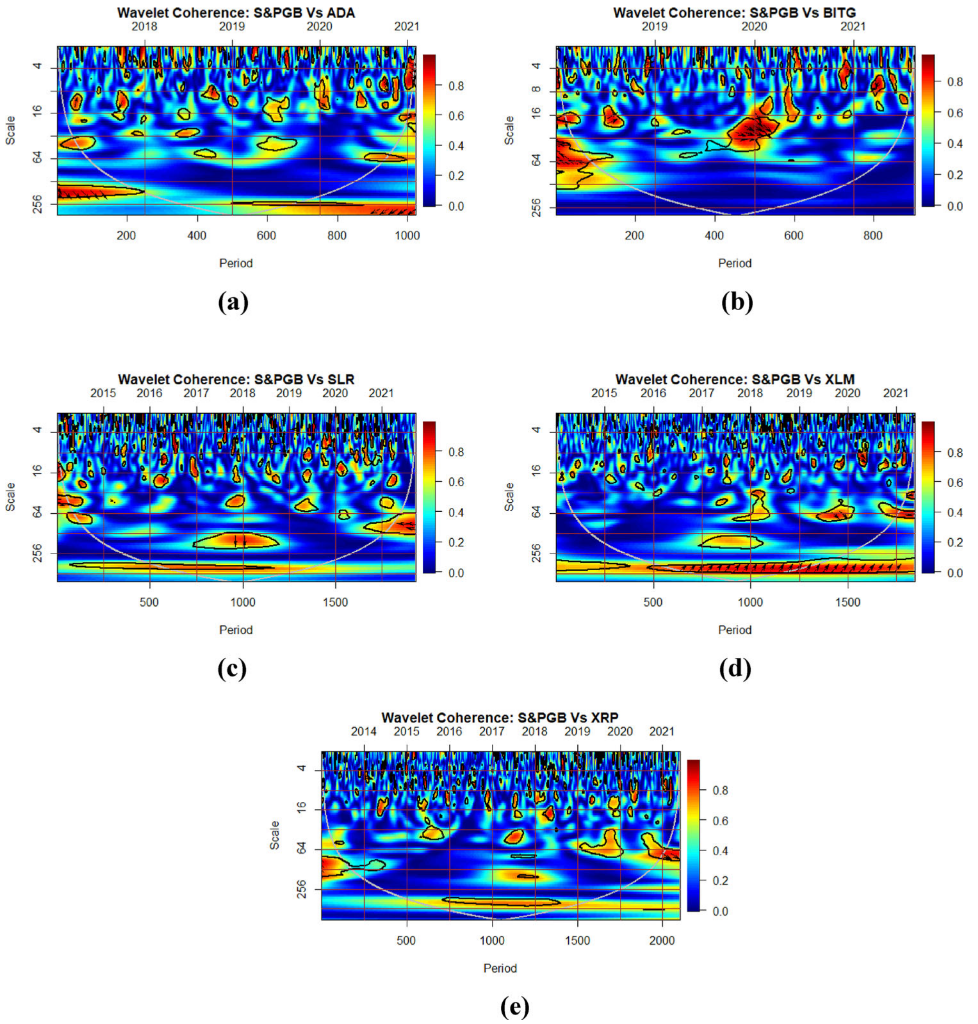

Figure 4. Wavelet coherence of green bonds and cryptocurrencies.
Figure indicates the wavelet coherency plot between Green bonds and cryptocurrencies. Refer Figure 1 for interpretations of wavelet coherence output.
Source: Authors' estimations and drawing.

BITG. Bitcoins is the most volatile cryptocurrency with a standard deviation of 755.947; however, BITG is more volatile among the sustainable cryptocurrencies with a standard deviation of 0.187. Interestingly, the DJSEMI proves more volatile than the DJSWI, which obviates the fact that emerging markets are more volatile. All first difference series are leptokurtic, indicating the presence of higher tail risks. The coefficients of Jarque–Bera validates that all first difference series are non-normally distributed. (Table 3)

Figure A.1 (see Appendix A) and Figure 1 depict the level series and first difference return series, respectively, for all indices. Figure 1 delineates the presence of momentous growth in GB, sustainability indices, and sustainable cryptocurrencies except SLR and BITG. In addition, it also depicts the huge price appreciation in Bitcoins, ADA, XLM and XRP since COVID-19 (December 2019).

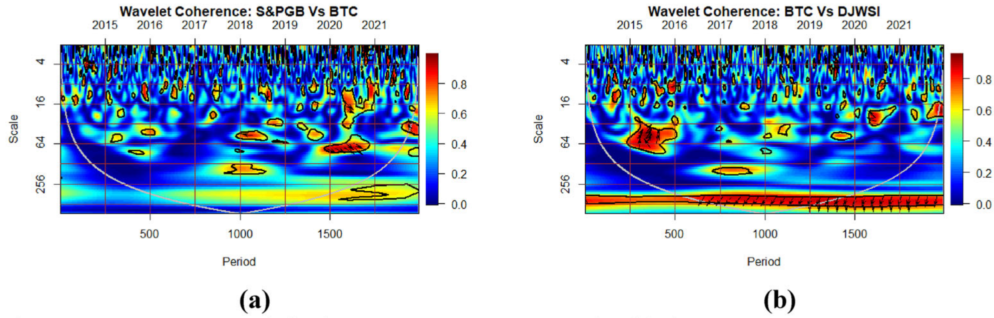

Figure 5. Wavelet coherence of Bitcoin, green bonds and world sustainability index.
The figure indicates the wavelet coherency plot between Bitcoin, green bonds and the world sustainability index. Refer Figure 1 for interpretations of wavelet coherence output.
Source: Authors' estimations and drawing.

4.3. Wavelet coherence

Current research investigates the co-movement of sustainable cryptocurrencies with GB and DJSWI using the wavelet coherence approach by Torrence and Webster (1999). In addition, it captures the relationship (co-movements) between GB and sustainability indices for world and emerging markets in the full sample and during the COVID-19 period. The leading and lagging relationship is estimated by using the in-phase and out-phase arrows in the wavelet coherence. The scale is divided into four levels: 1–4 days, 4–8 days, 8–16 days, 16–32 days, 32–64 days, 64–128 days, 128–256 days and scales above 256 days.

Figure 2 displays the outcomes of wavelet coherence for the GB, DJSWI and the DJSEMI considering the full sample estimation. Subfigure 2a shows that the right-directed upward and downward arrows (↘,↗) indicate an in-phase relationship (positive correlation) between GB and DJSWI from 2012 to 2014 and 2017 to 2021 on all scales. The subfigure further validates that GB is leading DJSWI. The black contours on the left and right sides at multiple scales show a positive co-movement at the 5% significance level. The results indicate that regardless of the hedge and diversifier, GB increased world sustainability. In addition, Subfigure 2 b shows a homogeneous co-movement to Subfigure 2a. However, the black contours indicate that a positive correlation (in-phase) between GB and DJSEMI is more pronounced in 2012 to 2013 and 2016 to 2021 at all scales. The outcome indicates that GBs are not the only source of increasing world sustainability and sustainability in emerging markets.

In sum, the findings show a strong positive co-movement over short- and long-term investment horizons between GB and sustainability indices (DJSWI and DJSEMI). Moreover, GBs have a leading role in increasing the sustainability of the world and emerging markets. Therefore, GB is not only a suitable risk management tool but also positively associated with sustainability indices. It is evidence for the idea that GBs are sustainable for the environment and key financial market participants (Ferrer et al., 2021). Additionally, the GB demonstrated an even stronger association and impact on sustainability during the unprecedented COVID-19 period than in the full sample estimation. The current findings fill several research gaps

Table 1. Descriptive statistics.

	Mean	Std. Dev.	Skewness	Kurtosis	Jarque–Bera	Probability	Observations
DJSEMI	0.152	9.618	−0.682	7.898	2502.56*	0.000	2323
DJSWI	0.487	12.128	−1.469	21.705	34699.04*	0.000	2323
GB	0.008	0.419	−0.702	9.858	4742.962*	0.000	2323
ADA	0.000	0.093	−16.45	434.175	7994020*	0.000	1025
BTC	22.089	755.947	−0.706	31.677	68596.07*	0.000	1997
BITG	−0.005	0.187	1.677	46.270	71026.67*	0.000	904
SLR	0.000	0.037	16.032	583.876	27287104*	0.000	1934
XLM	0.000	0.020	0.291	101.067	739747.2*	0.000	1845
XRP	0.000	0.054	−2.198	125.371	1315086*	0.000	2104

Note: The table reports the descriptive statistics of the differenced return of closing prices. * denotes the rejection of the null hypothesis at the 1% significance level. Dow Jones Sustainability Emerging Market Index (DJSEMI). Dow Jones Sustainability World Index (DJSWI), S&P Green Bonds (GB), Cardano (ADA), Bitcoin (BTC), BitGreen (BITG), SolarCoin (SLR), Stellar (XLM), and Ripple (XRP).
Source: Authors' estimations.

highlighted in previous research (Broadstock & Cheng, 2019; Haq et al., 2021) and demonstrate the significant utility of GBs in terms of social and financial returns. The current results establish GB as a sustainable investment for global investors and investors from emerging markets to build a greener economy, as emphasized in earlier research (Arif et al., 2021; Ferrer et al., 2021; Naeem et al., 2021; Naeem et al., 2021) GBs are similar to conventional bonds, but they mainly focus on green and sustainable projects that are thus friendly to the environment (Saeed et al., 2020). Current findings disagree with Maltais and Nykvist (2020), who argued that GBs have a false image of being more sustainable or impactful toward the environment than other municipal and corporate bonds.

Figure 3 depicts the outcomes of the wavelet coherency between the top five sustainable cryptocurrencies and DJSWI. The right-directed arrows in the middle of Subfigure 3a from 2019 to 2020 show a positive relationship or co-movement (in-phase) between ADA and DJSWI on 16–32-day and 32–64-day scales. They also indicate that ADA is leading the DJSWI. Black contours in the subfigure validate that positive co-movements are significant at the 5% significance level. Backward arrows on the left side, middle and right side on the 64-day scale in Subfigure 3 b show a marginally positive correlation (out of the phase) between BITG and DJSWI in the short term (16–32-day and 32–64-day scales). Although several black contours show a zero phase difference at the 5% significance level, the relationship is not pronounced through multiple scales and time periods. Subfigure 3c and Subfigure 3e show a homogenous co-movement pattern, where both SLR and XRP show a positive relationship (in-phase) co-movement with DJWSI. The right-directed arrows (→,↘,↗) at the bottom, left and right side at 16 days, 64 days and ahead of the 256-day scale confirm the position relationship, and the black contours validate that the outcomes are significant at the 5% significance level. In addition, the right-directed arrows confirm that SLR and XRP lead the DJWSI in the short and long term. Subfigure 3d shows a positive relationship (in-phase) between XLM and DJWSI on 16-day and 64-day scales from 2017 to 2019. Right directed arrows (→,↘,↗) confirm the positive association, where black contours show results that are significant at the 5% significance level. These findings indicate that sustainable cryptocurrencies increased the DJSWI, except for BITG. The relationship between sustainable

Table 2. Philips–Perron test of unit root (1st difference returns).

Index	t-statistics	P value
BTC	−46.685*	0.000
BITG	−27.497*	0.000
XLM	−40.854*	0.000
SLR	−51.045*	0.000
ADA	−35.869*	0.000
XRP	−34.045*	0.000
GB	−42.237*	0.000
DJSWI	−43.941*	0.000
DJSEMI	−38.793*	0.000

Note: The table represents the results of the unit root test. * denotes the rejection of the null hypothesis at the 1% significance level. Refer Table 1 for abbreviations.
Source: Authors' estimations.

Table 3. Portmanteau (Q) test for serial correlation.

Index	t-statistics	Probability
BTC	214.1909*	0.000
BITG	225.8032*	0.000
XLM	162.7755*	0.000
SLR	448.6706*	0.000
ADA	111.9378*	0.000
XRP	459.6799*	0.000
GB	75.7123**	0.006
DJSWI	203.6113*	0.000
DJSEMI	100.6810*	0.000

Note: The table reports results for the Ljung-Box statistics of autocorrelation of t returns for serial correlation. * (**) denotes the rejection of the null hypothesis at the 1% (10%) significance level. Refer Table 1 for abbreviations.
Source: Authors' estimations.

cryptocurrencies and DJSWI remains low in most cases, but several red, light red and yellow spots with black borders show a significant relationship on different scales.

In summary, the outputs show mixed co-movement patterns between sustainable cryptocurrencies and DJSWI. The dynamic co-movement over different investment horizons and time periods supports the idea that sustainable cryptocurrencies were prompted as a source of increasing global sustainability. Sustainable cryptocurrencies (SLR and XRP) have strong long-term co-movements, and BITG, SLR and XRP co-move positively with DJSWI on 16–32-day and 32–64-day scales, particularly in 2021 and 2013, respectively. XLM and ADA also have a short-term co-movement with DJSWI on 16–32-day and 32–64-day scales; moreover, XLM also has a long-term co-movement.

Overall, all selected sustainable cryptocurrencies have strong positive co-movement in the short run. Only two sustainable cryptocurrencies (SLR and XRP) co-move (in-phase) with DJSWI in the long run (ahead of a 256-day scale). These outcomes answer the difficult question raised by Arps (2018) that cannot be answered by investing in the role of sustainable cryptocurrencies in terms of global and social sustainability. These results are novel because no study has investigated the co-movement between sustainable cryptocurrencies and DJSWI through the wavelet coherence approach.

Figure 4 shows the wavelet coherency between GB and the top five sustainable cryptocurrencies (ADA, BITG, SLR, XLM and XRP). Subgroup 4a demonstrates wavelet coherence between GB and ADA. The black contours at the lower left corner show a positive co-movement between GB and ADA, where GB leads the ADA price. Several other spots highlighted in yellow and light-red confirm moderate co-movement at the 5% significance level. However, several backward arrows (↙) ahead of the 256 scale demonstrate a negative co-movement (out-phase) during the COVID-19 period. Subfigure 4 b also portrays backward arrows (↙,↖) where BITG is leading the GB. In contrast, the forward arrows in the middle indicate a positive co-movement (in-phase). More areas are shown in blue, which indicates a low co-movement between the GB and BITG. Subfigure 5c demonstrates several black contours filled with a light-red colour, which show a co-movement between GB and SLR; however, most of the area remains blue except a few backward and downward (←,↓), indicating a negative co-movement (in-phase). In Subfigure 4d, the right upward directed arrows (↗) indicate that GB and XLM have a positive relationship or co-movement (in-phase) ahead of the 256 scale and that GB leads XLM returns in the long run. In addition, several other black contours filled with the light-red colour validate the moderate co-movement at a 5% significance. Black contours filled with light-red and yellow colours show a moderate co-movement in Subfigure 4e on different scales. There is no phase; thus, both series are moving in the same direction, and the series is now leading or lagging. All these findings demonstrate that GB acts as a diversifier with sustainable cryptocurrencies because the GB showed a moderate co-movement or correlation but not a perfect correlation except with SLR and ADA. ADA and SLR showed few moderate negative co-movements in the long run; therefore, GB evidenced hedging properties for ADA and SLR. In summary, the pronounced blue colour in all subfigures indicates that GB and sustainable cryptocurrencies have a weak or no co-movement; therefore, GB acts as a weak hedge against sustainable cryptocurrencies.

Overall, our results reveal a positive moderate and weak co-movement between GB and sustainable cryptocurrencies on short-term investment horizons (1–4-day, 4–16-day and 16–64-day scales), except SLR, where it negatively co-moves with GB from 2017 to 2018 and from mid-2020 to 2021. Therefore, GB acts as a hedge for the SLR 64–128-day and 128–256-day scales for SLR, and previous studies found GB to be a hedge (Arif et al., 2021; Naeem et al., 2021; Naeem et al., 2021). The light red colour shows a moderate correlation (but not perfect), and the blue colour indicates no co-movement; therefore, GB acts as a diversifier in the short-term investment horizon and as a weak hedge where no correlation exists (blue colour). These findings partially match previous research by Haq et al. (2021).

Figure 5 captures the wavelet coherence output of Bitcoin with GB and DJSWI. Black contours are present in Subfigure 5a, and most of them are light red and yellow. A black contour in light red with right-directed arrows (↘) on the 32–64-day scale during 2020 indicates that GB and Bitcoin returns have positive (in-phase) co-movements during 2020. However, Figure 5b shows several light-red and yellow contours outlined in black validate a moderate data co-movement during the entire sample period. These findings show that GBs act as diversifiers of Bitcoin. Interestingly, the left-directed arrows (↙) in the right bottom corner above the 256-day scale show a negative relationship or co-movement (out of phase). These arrows also confirm that the DJSWI is leading, and Bitcoin is lagging. The black contour on the subfigure validates the results at the 5% significance level. Current output shows that world sustainability and Bitcoin have a negative relationship, indicating that price increases for Bitcoin decrease sustainability.

In summary, our results express a moderate co-movement between GB and Bitcoin in the long-term investment horizon (ahead of the 256-day scale) from 2020 to 2021 and a strong positive leading impact on Bitcoin returns in the short-term investment horizon in 2020. The moderate co-movement suggests that diversification avenues exist between Bitcoin and GBs in the long-term investment horizon; however, there is no significant correlation in the short-term investment horizon. This may be due to the long-term investment nature of the GB asset class (Haq et al., 2021). Interestingly, the wavelet coherency showed a strong-negative co-movement between Bitcoin returns and DJSWI in the long-term investment horizon (ahead of a 256-day scale). Additionally, this co-movement remained strong at the 4–16-day and 16–64-day scales from 2016 and 2020 to 2021. These findings suggest that the increasing Bitcoin value and returns have a negative impact on world sustainability. This outcome is consistent with previous studies (De Vries, 2018; Li et al., 2019), where they found that increased Bitcoin is harmful for sustainability due to high energy consumption and carbon emissions around the globe (Gallersdörfer et al., 2020; Onat et al., 2021). Recently, Elon Musk also announced that Tesla will no longer accept Bitcoin because Bitcoins are using massive amounts of fossil fuel for transactions and mining. Although cryptocurrencies have a promising future, they produce severe negative externalities to sustainable ecosystems and greener global economies.

5. Concluding remarks

This article investigates the co-movement among GB, DJSWI and Dow Jones sustainability emerging markets indices. In addition, this study investigates the co-movement among five sustainable cryptocurrencies, Bitcoin and DJSWI. The wavelet coherence approach captures co-movements over multiple scales and time. The main results reveal several conclusions. First, we find a strong positive co-movement of GB with both indices, i.e., DJSWIDJSWI and DJSEMI. Generally, the wavelet coherence shows strong co-movement over the short and long run among GB, DJSWI and DJSEMI. In addition, GB returns lead both sustainability indices over short- and long-term investment horizons. This indicates that GBs are sources of increasing global sustainability as well as increasing sustainability in emerging markets. Second, sustainable cryptocurrencies and DJSWI show strong but heterogeneous co-movement in both short-term and long-term horizons, except for BITG. Institutional investors, speculators, Bitcoin accepting companies and other market participants accelerate the use and investment of sustainable cryptocurrencies other than Bitcoin, as sustainable cryptocurrencies to ensure a sustainable global environment and achieve sustainable development goals. Third, the co-movements of the GB remain heterogeneous and intermittent with the top five sustainable cryptocurrencies, i.e., SLR, BITG, ADA, XLM and XRP, over the short and long run, indicating diversification benefits for GB for sustainable cryptocurrencies (except for SLR) due to the internal short- and long-term wavelet coherence. GB is more like a diversifier with ADA in the short run and a hedge in the long run and a diversifier with XRP in the short run and a hedge for

SLR on the 64–128-day scale (short-term). In addition, wavelet coherence presents a strong positive co-movement between GB and Bitcoin in short horizons up to the 64-day scale from 2018 to 2021 but with a moderate co-movement (correlation) but it is not perfectly positive, suggesting that GB acts as a diversifier with Bitcoin in the long-term investment horizon from 2018 to 2021 (COVID-19). Moreover, a strong negative relationship between Bitcoin and DJSWI in the long run alone shows an unstable strong negative relationship in the short run, suggesting that increasing Bitcoin returns are deteriorating world sustainability.

Our findings offer several key policy implications for crypto traders, green investors, and sustainability stakeholders in terms of hedging strategies and sustainability policy. First, green investors and sustainability stakeholders need to understand that it is perfectly possible to fight against climate change through investment in GBs and sustainable cryptocurrencies to promote a sustainable global economy. Moreover, policy-makers should look into the role of sustainable cryptocurrencies and deploy policies in support of developing systems for sustainable cryptocurrencies. Second, Bitcoin is a serious detriment to the world's sustainability, which should compel major improvements to the mining process. Hence, the mining process must refrain from worsening global sustainability to ensure a greener global economy. Third, aside from environmental and social benefits, GBs appear to be a potential diversification avenue against sustainable cryptocurrencies for green, conventional, amateur crypto traders and informed long-term institutions. However, GB and sustainable cryptocurrencies do not offer significant hedging benefits for sustainability investors (emerging and global) and sustainable crypto traders (except SLR) in the short- and long-run investment horizons. Fourth, despite the adverse role of Bitcoin toward sustainability, Bitcoin proves to be a hedge against DJSWI, suggesting that crypto traders can earn hedging benefits when considering Bitcoin against the DJSWI in the long-term investment horizon. In summary, beyond the diversification and hedging gains, these sustainable financial assets can help mitigate the climate change crisis and meet the rising demand for environmentally and socially responsible investments.

This research was conducted while the COVID-19 pandemic was not yet over. In addition, it is not exclusively based on a COVID-19 event-specific dataset. Moreover, the time period significantly differs for cryptos due to different inception times and data availability. Hence, future research should explore the safe-haven properties of GBs and sustainable cryptocurrencies using the same time spans. We suggest investigating the price efficiency and inefficiency of sustainable cryptocurrencies. In addition, direct portfolio implications, such as hedging effectiveness should be considered. Sustainable cryptocurrencies are understudied; hence, they provide ample research opportunities to academicians, young scholars and students.

Notes

1. https://www.icmagroup.org/Regulatory-Policy-and-Market-Practice/Secondary-Markets/bond-market-size/
2. See for more details; https://ripple.com/files/ripple_consensus_whitepaper.pdf/
3. See the list of sustainable cryptos; https://www.leafscore.com/blog/the-9-most-sustainable-cryptocurrencies-for-2021/

Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix A

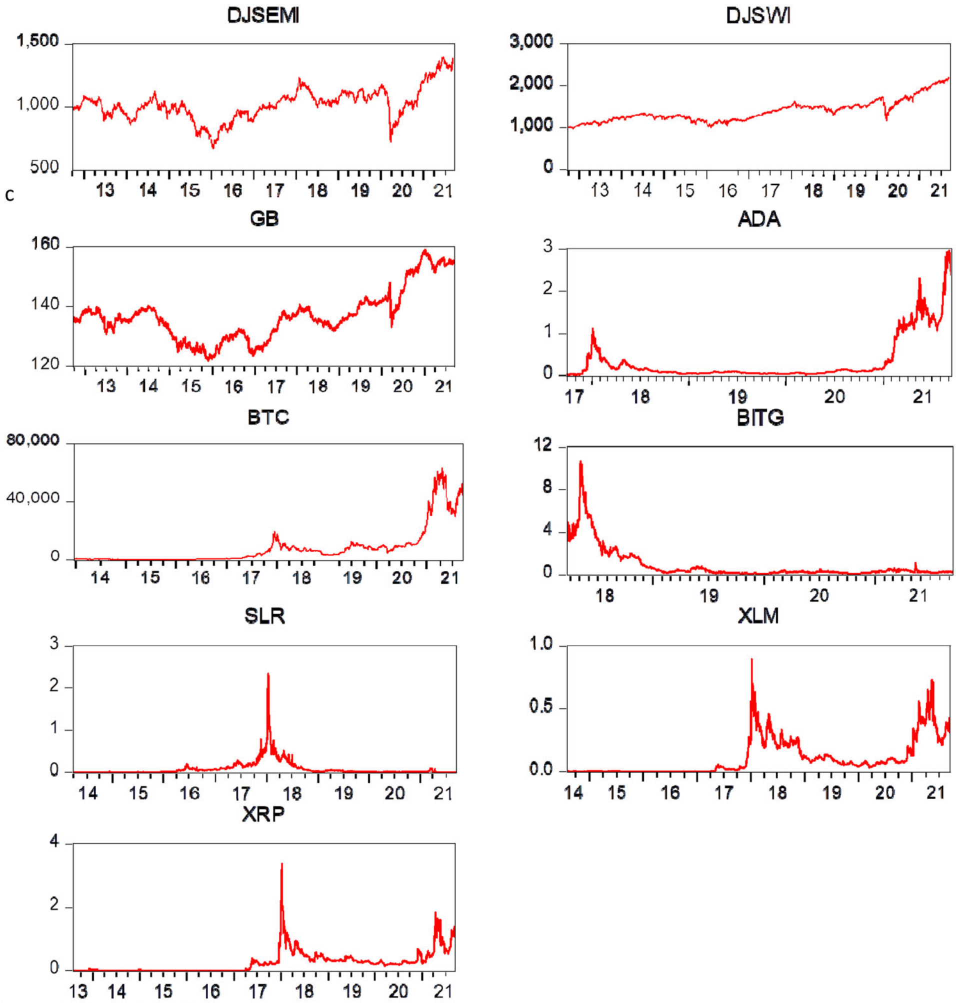

Figure A.1. Original data.
Source: Coinmarketcap and S&P Global.