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Connectedness of cryptocurrency markets to crude oil and gold: an analysis of the effect of COVID-19 pandemic

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Abstract

The notion that investors shift to gold during economic market crises remains unverified for many cryptocurrency markets. This paper investigates the connectedness between the 10 most traded cryptocurrencies and gold as well as crude oil markets pre-COVID-19 and during COVID-19. Through the application of various statistical techniques, including cointegration tests, vector autoregressive models, vector error correction models, autoregressive distributed lag models, and Granger causality analyses, we explore the relationship between these markets and assess the safe-haven properties of gold and crude oil for cryptocurrencies. Our findings reveal that during the COVID-19 pandemic, gold is a strong safe-haven for Bitcoin, Litecoin, and Monero while demonstrating a weaker safe-haven potential for Bitcoin Cash, EOS, Chainlink, and Cardano. In contrast, gold only exhibits a strong safe-haven characteristic before the pandemic for Litecoin and Monero. Additionally, Brent crude oil emerges as a strong safe-haven for Bitcoin during COVID-19, while West Texas Intermediate and Brent crude oils demonstrate weaker safe-haven properties for Ether, Bitcoin Cash, EOS, and Monero. Furthermore, the Granger causality analysis indicates that before the COVID-19 pandemic, the causal relationship predominantly flowed from gold and crude oil toward the cryptocurrency markets; however, during the COVID-19 period, the direction of causality shifted, with cryptocurrencies exerting influence on the gold and crude oil markets. These findings provide subtle implications for policymakers, hedge fund managers, and individual or institutional cryptocurrency investors. Our results highlight the need to adapt risk exposure strategies during financial turmoil, such as the crisis precipitated by the COVID-19 pandemic.

Keywords: Cryptocurrency market, Connectedness, Safe-haven, Gold, Crude oil, Time-series models, COVID-19 pandemic

JEL Classification: C32, G01, G15, Q02

Introduction

The extensive shutdown of industrial operations and travel restrictions imposed by lockdown measures during the COVID-19 pandemic profoundly impacted global crude oil demand, leading to sharp price decreases and increased financial market risk (Qin et al. 2020; Le et al. 2021). For the first time in history, the price of West Texas Intermediate

(WTI) oil dipped below − 37 US dollars (USD) on April 20, 2020, due to significant abnormal market pressures, geopolitical tensions, and global concerns about the severity of the COVID-19 pandemic[1] (Le et al. 2021). The COVID-19 pandemic had far-reaching effects on various financial markets, including stocks, commodities, exchange rates, and cryptocurrency markets (Ozili 2020; Lahmiri 2023a, b; Lahmiri and Bekiros, 2020a, b, c, d; Lahmiri et al. 2022a; Naeem et al. 2021; Le et al. 2021; Drake 2022).

The COVID-19-related changes in economic and financial market dynamics are expected to have significant implications for hedge fund managers, cryptocurrency market investors, and policymakers (Khelifa et al. 2021; Corbet et al. 2021). Financial market players and investors must account for the changes in market dynamics due to the pandemic and diversify their investment portfolios with suitable hedge and safe-haven assets to reduce risk.

The intrinsic value of commodities makes them less vulnerable to inflations or financial crises; thus, they are considered a potential hedging candidate for other markets (Disli et al. 2021). Crude oil is a key commodity traded internationally that significantly influences macroeconomic factors such as inflation, exchange rates, and economic growth. For example, Bashiri Behmiri and Pires Manso (2013) demonstrate that crude oil prices are influenced by various economic, political, environmental, financial, and technological factors. In contrast, gold has historically been attractive as a financial asset due to its tangible ability to maintain its value, particularly in times of financial, political, and economic uncertainty (Baur and Lucey 2010). Thus, numerous financial researchers have suggested that gold (as well as holding USD) can serve as a reliable safe-haven asset for other markets, including stock and bond markets, protecting against macroeconomic risks during financial crises (Baur and Lucey 2010; Reboredo 2013; Junttila et al. 2018; Baek 2019). For instance, Akhtaruzzaman et al. (2021) examine the role of gold as a hedge or safe-haven asset during the COVID-19 crisis, finding evidence that gold initially served as a safe-haven for stock markets at the onset of the pandemic; however, during the second phase of the crisis (March 17 to April 24, 2020), there was no clear evidence of gold's safe-haven properties. Additionally, Nkrumah-Boadu et al. (2022) discovered that gold and cryptocurrency markets provide safe-haven characteristics for investors in the African stock market.

The literature extensively examines crude oil's hedging and safe-haven properties for stock markets; however, few studies have examined the safe-haven effect of crude oil on cryptocurrency markets. Park and Ratti (2008) examined the impact of oil price shocks on American and 13 European stock markets, revealing significant short- and medium-term effects of oil prices on stock returns in these countries. Creti et al. (2013) also reported a significant shift from no correlation between crude oil and US stock market prices to positive correlation values during the global financial crisis in 2008. Śmiech and Papież (2017) expanded on Baur and Lucey (2010) by investigating the hedging and safe-haven roles of gold and crude oil for stock and currency markets, finding that only gold played a weak hedging role for equity. Junttila et al. (2018) explored the relationship between oil, gold, and stock market prices. They identified a positive correlation

[1] https://www.investopedia.com/articles/investing/100615/will-oil-prices-go-2017.asp.

between crude oil and the US equity market, while the correlation for gold futures was negative, confirming its safe-haven properties. Elie et al. (2019) studied the potential safe-haven roles of gold and crude oil against extreme downward trends in clean energy stock indices. Their analysis used daily price data to demonstrate that crude oil and gold exhibited weak safe-haven characteristics for clean energy indices. Building upon this body of evidence, we investigate whether the hedging or safe-haven effects of gold and crude oil are also evident in cryptocurrency markets.

Cryptocurrencies have emerged as a recent financial asset that enables direct, transparent, and secure electronic payments through blockchain technology. Xu et al. (2019) provide a review of cryptocurrencies and blockchain. Cryptocurrencies' decentralized and secure nature has attracted investors worldwide, but holding these assets for extended periods can expose investors to high risks. Therefore, diversification and hedging strategies beyond cryptocurrency markets are necessary to safeguard investments, particularly during economic uncertainty. Recognizing hedge assets uncorrelated with cryptocurrencies or safe-haven assets exhibiting a positive correlation during cryptocurrency downturns is a plausible approach to mitigating risks and maintaining profits (Nedved and Kristoufek 2023). This situation has led to a growing interest in exploring the interactions between cryptocurrencies and traditional financial assets, such as gold and crude oil. Consequently, a growing body of literature has emerged to explore the interactions between cryptocurrencies as investment assets and other financial assets (Khelifa et al. 2021; Lahmiri and Bekiros 2020c; Conlon and McGee 2020; Mnif et al. 2020; Corbet et al. 2020; Goodell and Goutte 2021).

Researchers have employed various statistical and econometrics models to study the dynamics of cryptocurrency markets. For instance, Katsiampa (2019) applied a bivariate diagonal Baba, Engle, Kraft, and Kroner model to find the interdependency of volatility dynamics between Bitcoin and Ether, showing that Ether can be used as a hedge against Bitcoin. Using a vector autoregressive-generalized autoregressive conditional heteroskedasticity model on Bitcoin, Ether, and Litecoin, Yousaf and Ali (2020) investigated the return and volatility spillover between these cryptocurrencies. Furthermore, Yousaf et al. (2021) examined cryptocurrency markets' fundamental and nonfundamental herding behavior during the COVID-19 pandemic. Similarly, Mariana et al. (2021) conducted a dynamic conditional correlation analysis to suggest the hedging effect of Bitcoin and Ether as a short-term safe-haven for the stock market. In another study, Khelifa et al. (2021) employed vector autoregressive (VAR) models, vector error correction models (VECM), and autoregressive distributed lag (ARDL) models to examine the relationship between cryptocurrency hedge funds and traditional hedge fund strategies and the impact of COVID-19 on hedge fund values. Shahzad et al. (2021) investigated extreme return spillovers among US stock market sectors during the COVID-19 pandemic, while Hui et al. (2022) explored its effect on the connectedness of global equity markets. Cevik et al. (2022) documented the impact of the pandemic on the relationship between investor sentiments and stock markets. Recently, Foroutan and Lahmiri (2022) utilized an exponential general autoregressive conditional heteroskedastic in mean model and Granger causality tests to investigate the effect of the COVID-19 pandemic on return-volatility and return-volume relationships of 10 cryptocurrency markets. The findings from Drake (2022) raise doubts about gold's role

as a hedge for stock market returns during the 2008 financial crisis and the COVID-19 pandemic. Furthermore, other scholars found that deep and machine learning systems are effective in forecasting cryptocurrency prices (Lahmiri & Bekiros 2019; 2020d; 2021b), returns (Sebastião and Godinho 2021; Liu et al. 2023), trading volume (Lahmiri et al. 2020, 2022b) and volatility (Wang et al. 2023a, b). In this regard, Fang et al. (2022) provided a comprehensive survey on cryptocurrency trading.

Recent studies show that the relationship between commodities, such as gold and crude oil, and cryptocurrency markets has gained significant attention. For instance, Owusu Junior et al. (2020) employed an ensemble empirical mode decomposition-based quantile-on-quantile regression model with the data on gold and eight cryptocurrencies (Bitcoin, Ethereum, Dash, Litecoin, Ripple, Stellar, NEM, and Monero) from April 2013 to April 2019. Their findings show that cryptocurrencies and gold can serve as both hedge and diversification assets for each other across various conditional distributions of their returns. González et al. (2021) examined the relationship between gold and cryptocurrency returns, highlighting an asymmetric connectedness of cryptocurrencies to gold returns during economic disturbances. Similarly, Barson et al. (2022) conducted a causality analysis to study the relationship between gold and cryptocurrencies during the COVID-19 pandemic. Their empirical results suggest that gold exhibits weak safe-haven characteristics during the COVID-19 pandemic while acting as a hedge during normal cryptocurrency market conditions.

Several recent studies have examined the interdependence between crude oil and cryptocurrencies. Selmi et al. (2018) compared the hedging and safe-haven properties of Bitcoin and gold for oil markets and concluded that gold and Bitcoin could serve as hedges, safe-havens, and diversifiers against crude oil. Okorie and Lin (2020) explored the volatility connectedness between crude oil and cryptocurrencies, finding a unidirectional volatility spillover from Ethereum, XRP, and ReddCoin to the crude oil markets. The assessment by Disli et al. (2021) rejects the safe-haven characteristics of gold, oil, and Bitcoin for the stock market during the COVID-19 pandemic. Moreover, the study of the hedging effect of cryptocurrencies for Brent crude oil price movements during the COVID-19 pandemic shows that only stablecoins protect against plunging oil price movements; however, they do not reduce investment volatility (Będowska-Sójka and Kliber 2022). Furthermore, Wang et al. (2023a, b) revealed that Bitcoin has a limited safe-haven effect on the crude oil market, whereas gold demonstrates a strong safe-haven ability for crude oil before and after the COVID-19 pandemic. This finding supports Wen et al. (2022), who concluded that Bitcoin is not a safe-haven for oil markets. Nedved and Kristoufek (2023) investigated the safe-haven role of gold, crude oil, and stock markets for Bitcoin. They concluded that while Bitcoin movements positively correlated with the stock market, oil and gold demonstrated safe-haven characteristics, with gold being a strong safe-haven for Bitcoin.

As the pioneering cryptocurrency, Bitcoin was created out of the turmoil of the 2008 Great Recession; the economic recession due to the COVID-19 pandemic was the first financial crisis after the inception of cryptocurrency markets. This section shows that most research on the connectedness between cryptocurrencies and other financial markets is limited to one or two cryptocurrencies, namely Bitcoin and Ether (Katsiampa 2019; Conlon and McGee 2020; Goodell and Goutte 2021). Thus, the crypto literature

must extend its attention to other prominent cryptocurrencies that have gained traction in recent years. This broader examination will enhance our comprehension of the relationship between cryptocurrency markets and various domains, such as commodities. Limited knowledge exists regarding the safe-haven effect of gold or crude oil on cryptocurrency markets during financial crises. This current study attempts to fill this gap in the literature. In this context, we examine dynamic short-term and long-term relationships and potential hedging effects of gold and crude oil markets for the 10 most traded cryptocurrencies. Specifically, we aim to investigate whether the safe-haven potential of gold or crude oil for cryptocurrency remains consistent before and during the COVID-19 pandemic. During the COVID-19 pandemic, gold played a significant safe-haven for Bitcoin, Litecoin, and Monero, while crude oil was a weak safe-haven for Ether, Bitcoin Cash, EOS, and Monero. Among the crude oil assets, Brent was a strong safe-haven for Bitcoin during the COVID-19 pandemic. Our causality analyses indicate a bidirectional relationship between gold and cryptocurrencies such as Bitcoin and Monero during the pandemic. Indeed, knowing this relationship holds profound implications for hedge fund managers and investors for altering their risk exposure and modifying a cryptocurrency portfolio's return. Our findings aim to serve as a basis for future discussions about safe-haven for cryptocurrencies, which are becoming increasingly popular in individual and institutional investors' portfolios. This study is crucial in foreseeing the behavior of cryptocurrency markets and protecting investors against extreme price movements, especially during global pandemics.

This study makes the following significant contributions to the existing literature on the connectedness of cryptocurrencies with other markets:

i. This study employs VAR, VECM, ARDL, and Granger causality analyses to examine the relationship between 10 cryptocurrency markets with commodity markets, such as gold and crude oil, and find whether a hedging or safe-haven role exists.
ii. We analyze the effect of the COVID-19 pandemic as the first economic distress after the emergence of cryptocurrencies on the hedging opportunity of gold and crude oil for cryptocurrency markets dynamics before and during the COVID-19 pandemic periods. This situation has received limited attention compared to the conventional financial markets.
iii. This study conducts a comprehensive analysis of cryptocurrency markets. Contrary to the existing literature that restricts their analysis to a limited number of cryptocurrency markets, mainly Bitcoin and Ether, our study seeks to find the hedging effect of gold and crude oil on the 10 most traded cryptocurrency markets. Our findings will contribute to a comprehensive understanding of the interconnectedness between gold and crude oil markets and digital currencies.
iv. We explore the safe-haven effects on cryptocurrencies. While prior literature primarily investigates the safe-haven effect of Bitcoin on the crude oil market, this study examines the contrary safe-haven effect of crude oil for cryptocurrency markets. To enhance the robustness of our findings, we investigate the safe-haven effect of two widely traded oils, specifically WTI and Brent, on cryptocurrencies.

By incorporating the analysis of these oils, we aim to strengthen the validity and reliability of our results.

The remainder of this manuscript is organized as follows. Sect. "Methodology" describes the methodology, and Sect. "Data" describes our datasets. The empirical results and discussions on their implications are provided in Sect. "Empirical Results", and we conclude the paper in Sect. "Conclusion".

Methodology

Our empirical analysis begins with preliminary tests to confirm the presence of nonlinearities and the stationarity properties in the variables used in this study. We employ the Augmented Dickey–Fuller (ADF) test (Cheung and Lai 1995) on each series in levels to determine whether a series has a unit root. The Johansen and Bounds cointegration tests examine the co-movement between cryptocurrency and oil and gold markets. These tests help identify the appropriate econometric model for analyzing these markets' short-term and long-term relationships. Following the results of the ADF test, one of the following three cases may apply. (i) Series are integrated of order 0 (stationary in level); thus, a cointegration test is unnecessary. (ii) Series are integrated of order 1 (stationary after first difference); thus, a cointegration test is necessary to establish a long-run relationship. A Johansen cointegration test (Johansen 1991) can be performed on the level. If any cointegration equation is found, we estimate both VAR (Sims 1980) for short-term relationships and VECM (Engle and Granger 1987) for long-term relationships. Only the VAR (for the first difference) model should be estimated if no cointegration equation is found. (iii) Series are integrated of different orders; in this case, the bounds test for cointegration (Pesaran et al. 2001) can be performed on the level. After conducting the bounds cointegration test, we determine the applicable model based on the results. Without cointegration, we estimate the short-term relationships using the ARDL (Pesaran and Shin 1995) model. If cointegration exists, we estimate the long-term VECM model.

This rigorous methodology enhances the reliability and validity of our analysis. Following the cointegration tests, one of the below models is applicable.

The equations for VAR(p) model for the first difference of series in this study:

$$\Delta P_t = a_{0,p} + \sum_{i=1}^{p} b_{p,i} \Delta P_{t-i} + \sum_{i=1}^{p} c_p \Delta x_{t-i} + u_{p,t} \tag{1}$$

$$\Delta x_t = a_{0,x} + \sum_{i=1}^{p} b_{x,i} \Delta P_{t-i} + \sum_{i=1}^{p} c_x \Delta x_{t-i} + u_{x,t}. \tag{2}$$

Here, $a_{0,p}$ and $a_{0,x}$ are constants, P_t is the log of cryptocurrency price at time t, P_{t-i} is the i^{th} lag of cryptocurrency price, and x_{t-j} is the j^{th} lag of the gold, WTI, or Brent price log. Finally, $u_{p,t}$ and $u_{x,t}$ are the error terms for the cryptocurrency and crude oil or gold markets, respectively.

The equation for the long-term VECM(p, q) model in this study is expressed:

$$\Delta P_t = \alpha_0 + \sum_{i=1}^{p} \varphi_i \Delta P_{t-i} + \sum_{j=1}^{q} \beta_j \Delta x_{t-j} + \lambda ECT_{t-1} + \varepsilon_{t,vecm} \tag{3-a}$$

$$ECT_{t-1} = c + \gamma P_{t-1} + \theta x_{t-1}. \tag{3-b}$$

Here, α_0 is a constant, P_t is the log of cryptocurrency price at time t, P_{t-i} is the ith lag of cryptocurrency log price, x_{t-j} is the jth lag of the log of gold, WTI, or Brent price, and $\varepsilon_{t,vecm}$ is the error term in the VECM model. The ECT_{t-1} term in Eq. (3-a) captures the long-term effect between markets, and λ is the adjustment coefficient. This cointegrating term represents the long-term equilibrium relationship between cryptocurrency and other markets, while λ shows the convergence speed toward the long-term equilibrium. The lag structures of the VAR(p) and VECM(p, q) models for each market are determined according to the Akaike information criterion (Akaike 1974).

An ARDL model is an ordinary least squares model applicable for non-stationary time series and time series with mixed order of integration. An ARDL(p, q) model is shown below:

$$P_t = \alpha_0 + \sum_{i=1}^{p} \varphi_i P_{t-i} + \sum_{j=0}^{q} \beta_j x_{t-j} + \varepsilon_{t,ardl}. \tag{4}$$

Here, α_0 is a constant, P_t is the log of cryptocurrency price at time t, P_{t-i} is the ith lag of cryptocurrency log price, x_{t-j} is the jth lag of the log of gold, WTI, or Brent price, and $\varepsilon_{t,ardl}$ is the error term in the ARDL model. The proper lag structure in the ARDL model is selected by the Schwarz criterion (Schwarz 1978).

The estimated regression coefficients from Eqs. 1 to 4 are then used to conduct pairwise Granger causality tests (Granger 1969) to determine whether an endogenous variable can be treated as exogenous. We then use the Wald chi-square test for the null hypothesis that gold, WTI, or Brent do not cause the cryptocurrency market. A bidirectional Granger causality exists between variables if both null hypotheses are rejected. Granger causality analysis adopted in the current work was successful in various financial problems, including the studying causality between stock prices and economic activity (Yilanci et al. 2021), insurance market density and economic growth (Pradhan et al. 2017), dynamic price changes in securities (Virgilio 2022), banking activities and economic growth (Mushtaq 2016), Bitcoin market and internet attention (Zhang et al. 2021), pricing dynamics of cryptocurrencies (Kristoufek 2022), and foreign direct investment and economic growth (Sarker 2020).

Data

In line with the previous discussions, both gold and crude oil are popular hedges and safe-haven assets for many financial markets. This study broadly investigates the relationship between cryptocurrencies and the gold and crude oil markets. Following the literature review process, we found that most studies on cryptocurrencies only focus on a limited number of cryptocurrencies, namely Bitcoin and Ether, as they dominate the cryptocurrency market capitalization; however, many new cryptocurrencies have been introduced to the market in recent years, and market players are more eager to trade

Table 1 Cryptocurrency market capitalization

Markets	Tether (USDT)	Bitcoin (BTC)	Ether (ETH)	Ripple (XRP)	Litecoin (LTC)	Bitcoin Cash (BHC)	EOS	Chainlink (LINK)	Cardano (ADA)	Monero (XMR)
Market Share (%)	4.49	41.90	18.45	1.70	0.44	0.31	0.13	0.46	2.03	0.15

Fig. 1 Cryptocurrency, crude oil, and gold prices in pre-COVID-19 and during the COVID-19 periods

Table 2 Augmented Dickey–Fuller test results (*p* values)

Markets	Pre-COVID-19 (2019) 2019/01/01–2019/12/31		During COVID-19 (2020) 2020/01/01–2020/12/31	
	Return	Log price	Return	Log price
Tether	**0.000**	**0.007**	**0.000**	**0.000**
Bitcoin	**0.000**	0.574	**0.000**	0.994
Ether	**0.000**	0.626	**0.000**	0.837
Ripple	**0.000**	0.686	**0.000**	0.169
Litecoin	**0.000**	0.537	**0.000**	0.805
Bitcoin Cash	**0.000**	0.607	**0.000**	0.116
EOS	**0.000**	0.609	**0.000**	0.091
Chainlink	**0.000**	0.427	**0.000**	0.455
Cardano	**0.000**	0.743	**0.000**	0.729
Monero	**0.000**	0.765	**0.000**	0.739
Gold	**0.000**	0.819	**0.000**	0.397
WTI	**0.000**	**0.008**	**0.000**	0.181
Brent	**0.000**	**0.032**	**0.000**	0.133

Bold indicates significant result at 5% level

for other cryptocurrencies. Thus, it is essential to consider the cryptocurrencies that have gained prominence in recent years. To address this gap, we considered the 10 most traded cryptocurrencies based on their average trading volume during the final quarter of 2020. This approach allows us to capture a more diverse range of cryptocurrencies and provide timely and relevant insights for market participants interested in these specific cryptocurrencies.

This study examines the connections between the 10 most traded cryptocurrency markets and gold, WTI, and Brent crude oil markets. The cryptocurrencies studied in this paper are Tether, Bitcoin, Ethereum, Ripple, Litecoin, Bitcoin Cash, EOS, Chainlink, Cardano, and Monero. As of January 31, 2022, the global cryptocurrency market capitalization is about 1740 billion USD with more than 8700 active cryptocurrencies (www.coinmarketcap.com), among which Bitcoin has the highest market capitalization of 729 billion USD (41.9% of the total cryptocurrency market capitalization). Table 1 presents the percentage of cryptocurrency market capitalization. Daily closing prices of cryptocurrencies, daily spot prices of gold and WTI, and Brent crude oil prices are collected from January 1, 2019, to December 31, 2020. In January 2022, the cryptocurrencies' data were extracted from Yahoo Finance (finance.yahoo.com), the gold price data from the World Gold Council (www.gold.org), and the crude oil price drawn from the US Energy Information Administration (www.eia.gov). According to a report submitted to the World Health Organization by the Wuhan Municipal Health Commission, the first COVID-19 verified cases occurred on December 31, 2019. Therefore, the whole sample for each market is divided into two subsamples. The pre-COVID-19 period runs from January 1, 2019, to December 31, 2019, and the COVID-19 period runs from January 1, 2020, to December 31, 2020. The pandemic period is only considered during 2020 to ensure similar sample sizes for pre-pandemic and pandemic periods. Cryptocurrency prices are generally available seven days a week, while the WTI, Brent, and gold spot prices are only available five days a week; thus, we matched the trading days of cryptocurrencies following the

Table 3 Bounds or Johansen cointegration test

Market pairs	Pre-COVID-19 (2019)		During COVID-19 (2020)	
	Bounds test	Johansen test	Bounds test	Johansen test
Tether-Gold	**6.56**		**60.09**	
Tether-WTI			**56.97**	
Tether-Brent			**56.71**	
Bitcoin-Gold		0.502		0.710
Bitcoin-WTI	1.12			0.393
Bitcoin-Brent	1.52			0.568
Ether-Gold		0.664		0.725
Ether-WTI	0.91			0.440
Ether-Brent	1.70			0.514
Ripple-Gold		0.763		0.231
Ripple-WTI	0.78			0.079
Ripple-Brent	1.08			0.107
Litecoin-Gold		0.254		0.735
Litecoin-WTI	0.76			0.430
Litecoin-Brent	1.36			0.637
Bitcoin cash-Gold		0.725		0.193
Bitcoin cash-WTI	1.61			**0.029**
Bitcoin cash-Brent	1.89			**0.040**
EOS-Gold		0.594		0.174
EOS-WTI	0.84			0.068
EOS-Brent	1.84			0.117
Chainlink-Gold		0.207		**0.029**
Chainlink-WTI	2.04			0.274
Chainlink-Brent	1.65			0.289
Cardano-Gold		0.630		0.552
Cardano-WTI	0.42			0.233
Cardano-Brent	0.99			0.210
Monero -Gold		0.420		0.707
Monero -WTI	0.63			0.259
Monero -Brent	0.85			0.274

Bold indicates significant result at 5% level

Values in bold are significant at a 5% significance level. Values for the Bounds test are F-statistic for the null hypothesis that there is no cointegration in levels. F- critical values for lower and upper bounds are I(0) = 3.62, I(1) = 4.16 at a 5% significance level. Values for the Johansen Unrestricted Cointegration Rank Test (Trace) are *p* values for the null hypothesis that there is no Cointegration equation

trading days of gold and crude oil markets. Our sample size is 248 and 246 daily prices for the pre-COVID-19 and during the COVID-19 periods, respectively. Figure 1 illustrates the price movements of each cryptocurrency market along with the gold, WTI, and Brent crude oil prices in the pre-COVID-19 and during the COVID-19 periods.

Empirical results

We first conduct the ADF test to determine whether the price time series contains a unit root. The *p* values from Table 2 indicate that the logarithmic price series of Tether in both pre-COVID-19 and during COVID-19 periods, and WTI and Brent in the pre-COVID-19 period are stationary. For all other markets, only the return series, the first difference of the logarithmic price series, are stationary. The Johansen and Bounds cointegration tests examine short-term and long-term relationships between cryptocurrency, crude oil, and gold markets. Cointegration refers to the long-term

Table 4 Selected econometrics models to investigate market co-movement

Markets	Models	
	Pre-COVID-19 (2019)	During COVID-19 (2020)
Tether-Gold	VECM	VECM
Bitcoin-Gold Ether-Gold Ripple-Gold Litecoin-Gold Bitcoin Cash-Gold EOS-Gold Cardano-Gold Monero-Gold	VAR-first D	VAR-first D
Chainlink-Gold	VAR-first D	VECM
Tether-WTI/ Brent	VAR- level	VECM
Bitcoin cash-WTI/Brent	ARDL	VECM
Bitcoin-WTI/Brent Ether-WTI/Brent Ripple-WTI/Brent Litecoin-WTI/Brent EOS-WTI/Brent/Brent Chainlink-WTI/Brent Cardano-WTI/Brent Monero-WTI/Brent	ARDL	VAR-first D

equilibrium relationship between variables, indicating that they move together over time despite short-term deviations (Jansen et al. 1993). Table 3 shows the F-values of the bounds test and the *p* values of the Johansen test for the null hypothesis of no cointegration between market pairs. The F-value for Tether-gold market pairs in the pre-COVID-19 period and Tether-gold, Tether-WTI, and Tether-Brent pairs during the COVID-19 period is greater than I(1) critical value; hence, we can conclude that the cointegration equation exists between these markets. Therefore, we estimate both ARDL for the short-term and VECM for the long-term relationships among Tether and gold, WTI, and Brent crude oil markets. The *p* values from the Johansen test verify that the cointegration equation only exists among Bitcoin Cash–WTI, Bitcoin Cash–Brent, and Chainlink–gold market pairs during COVID-19. Table 4 summarizes the suitable models following the results of cointegration tests for each market.

Following the cointegration tests, the VECM model can only analyze the potential long-term relationship between Tether–gold, Tether–WTI, Tether–Brent, Chainlink–gold, Bitcoin Cash–WTI, and Bitcoin Cash–Brent market pairs. Moreover, short-term relationships between cryptocurrency markets and crude oil as well as gold will be explored by utilizing the ARDL or VAR-in-first-difference models. According to the results of VECM models in Table 5, during the COVID-19 period, the λ_{Gold}, λ_{WTI}, and λ_{Brent} coefficients for Tether market are significantly negative. Thus, during COVID-19, a significant long-term negative relationship exists between the Tether market and the gold, WTI, and Brent markets at a 5% level. The negative long-term λ coefficient in Eq. 3-a shows that series are convergent in the long run to their long-term equilibrium relationship when deviations occur in the short term. Baur and McDermott (2010) defined a strong safe-haven as an asset negatively correlated with equities,

Table 5 Estimated coefficients in vector error correction models models

	Tether		Bitcoin Cash	Chainlink
	Pre-COVID-19	During COVID-19	During COVID-19	
λ_{Gold}	**−0.2623 (−5.365)**	**−0.8122 (−9.742)**		**−0.0574 (−2.917)**
θ_{Gold}	0.0173 (1.343)	−0.002 (−0.467)		**−8.1508 (−9.257)**
$\beta_{1,Gold}$	−0.0179 (−0.551)	0.0027 (0.107)		−0.3408 (−0.800)
λ_{WTI}		**−0.8187 (−9.923)**	**−0.0331 (−1.919)**	
θ_{WTI}		0.0011 (1.108)	**−0.693 (−4.716)**	
$\beta_{1,WTI}$		0.0002 (0.125)	−0.0144 (−0.764)	
λ_{Brent}		**−0.8241 (−10.046)**	**−0.0718 (−2.967)**	
θ_{Brent}		0.0016 (1.470)	**−0.465 (−3.265)**	
$\beta_{1,Brent}$		0.0063 (1.475)	−0.0145 (−0.246)	

Bold indicates significant result at 5% level

This table presents the coefficients in Eq. 3-a and Eq. 3-b. Values in parentheses are t-statistics. Significant coefficients at a 0.05 level are in bold

whereas a weak safe-haven asset is uncorrelated with equities during corresponding periods. Here, we consider an asset with a significant negative relationship as a strong safe-haven and an asset with an insignificant negative coefficient as a weak safe-haven. The coefficient of lagged gold, $\beta_{1,Gold}$, for Tether is negative but not statistically significant, indicating that gold can be a weak safe-haven for Tether during the stable markets before the pandemic.

In contrast, the short-term effects of gold, WTI, and Brent crude oil on Tether, $\beta_{1,Gold}$, $\beta_{1,WTI}$, and $\beta_{1,Brent}$, are positive and insignificant, showing that gold, WTI, and Brent do not show any safe-haven properties for Tether during the pandemic. Similarly, significant long-term negative relationships are found between Bitcoin Cash and WTI as well as Bitcoin Cash and Brent crude oil markets. This finding indicates that Bitcoin Cash will converge to long-term equilibrium with WTI and Brent crude oil when deviations occur in the short term. Regarding the safe-haven effects, the insignificant negative coefficients of crude oil lag for Bitcoin Cash, $\beta_{1,WTI}$, and $\beta_{1,Brent}$, show a weak safe-haven property during the COVID-19 pandemic. Our results also show a significant long-term negative relationship, λ_{Gold}, between the Chainlink and gold markets and a weak safe-haven characteristic of gold, $\beta_{1,Gold}$, for the Chainlink market during the COVID-19 pandemic.

Comparing the results of the VECM model in the pre-COVID-19 period shows that the long-term relationship, λ_{Gold}, is only available between Tether and gold markets. Our results suggest that gold can have a weak safe-haven effect for Tether in the pre-COVID-19 period and for Chainlink during the COVID-19 period. Furthermore, during COVID-19, crude oil markets such as WTI and Brent can play an investment-hedging role in the Bitcoin Cash market. Thus, our findings suggest diversifying the Bitcoin Cash portfolios with crude oil assets during COVID-19 to minimize the investment risk; however, during the stable markets (pre-COVID-19 period), it is suggested that investors in Tether diversify their portfolios with gold assets.

Table 6 and 7 present the results of the estimated short-term relationships between cryptocurrency markets and crude oil and gold markets with ARDL and VAR models, respectively. As indicated in Table 6, our findings did not suggest any short-term

Table 6 Estimated coefficients in autoregressive distributed lag models

Tether	Bitcoin	Ether	Ripple	Litecoin	Bitcoin Cash	EOS	Chainlink	Cardano	Monero
Pre-COVID-19 (2019)									
WTI	0.0302 (0.722)	0.0481 (0.977)	− 0.0073 (− 0.169)	0.0003 (0.005)	**0.1069 (1.727)**	0.0533 (0.839)	− 0.0885 (− 1.132)	0.0158 (0.272)	0.0003 (0.006)
Brent	0.0529 (1.312)	**0.0848 (1.821)**	0.0400 (0.970)	0.0737 (1.335)	**0.1129 (1.950)**	**0.1209 (1.918)**	− 0.0271 (− 0.348)	0.0782 (1.332)	0.0380 (0.797)

Bold indicates significant result at 5% level

This table presents the β_0 coefficients in ARDL model (Eq. 10). Values in the parentheses are associated t-statistic. Significant coefficients at 0.1 level are in bold

relationship between cryptocurrency and crude oil markets before the COVID-19 pandemic at a 5% significance level. Nonetheless, considering a 10% level, a significant positive effect of Brent price, represented by β_0 coefficient, on the price of Ether, Bitcoin Cash, and EOS was evident before the pandemic. Likewise, the WTI price significantly positively affects the Bitcoin Cash price at a 10% level. These findings show that crude oil price movements are similar to the price movements of Ether, Bitcoin Cash, and EOS and that crude oil is not a safe-haven for these cryptocurrencies during the stable markets; however, the negative insignificant WTI and Brent crude oil coefficients for other assets in Table 6 indicate that crude oil can be a short-term weak safe-haven asset for Ripple and Chainlink.

Furthermore, the findings in Table 7 provide evidence that no statistically significant short-term connectedness exists between cryptocurrencies and WTI, Brent, and gold markets in the pre-COVID-19 period, as their coefficients are not significant at a 5% level; however, with a 10% significance level, we observe a negative relationship between lagged gold returns and Litecoin and Monero before the COVID-19 pandemic. Moreover, gold's first lag has an insignificant negative relationship with all cryptocurrency markets before the COVID-19 pandemic. These results confirm the weak safe-haven properties of gold for all ten cryptocurrencies in the periods of financial stability. Likewise, the insignificant negative lagged WTI and Brent coefficients for the Tether market in Table 7 suggest that crude oil can serve as a weak safe-haven for Tether in stable periods.

Conversely, during the COVID-19 pandemic, lagged gold returns have a significant negative relationship with Bitcoin, Litecoin, and Monero at a 5% level. Thus, gold is a strong safe-haven asset for Bitcoin, Litecoin, and Monero during the financial crisis and the COVID-19 pandemic. Meanwhile, the lagged WTI has a significant direct association with Bitcoin returns, while the lagged Brent crude oil returns have a significant negative relationship with Bitcoin returns at the 5% level. Therefore, during the COVID-19 pandemic, Brent crude oil can be considered a strong safe-haven for Bitcoin, whereas WTI is not a safe-haven for Bitcoin during this period. This study found no significant relationship between WTI and Brent crude oil markets and Ripple, Litecoin, Bitcoin Cash, EOS, Chainlink, and Cardano during the COVID-19 pandemic. Furthermore, we found no significant relationship between gold and Ether, Ripple, Bitcoin Cash, EOS, Chainlink, and Cardano markets in our sub-sample periods. Conversely, due to insignificant negative coefficients, WTI is a weak safe-haven for Ether, Ripple, EOS, Chainlink, and Monero; Brent is a weak safe-haven for Ether, Cardano, and Monero; and gold is a weak safe-haven for Bitcoin Cash, EOS, and Cardano during the COVID-19 crisis. Our findings indicate that gold exhibits stronger safe-haven characteristics for cryptocurrencies than the crude oil markets, particularly during the COVID-19 pandemic. Furthermore, the safe-haven characteristics of gold and crude oil markets for most cryptocurrencies have improved during the COVID-19 pandemic when we compare it with the prior to the COVID-19 pandemic.

Table 8 presents the p values for unidirectional Granger causality tests, examining the causal effect of gold, WTI, and Brent return series toward cryptocurrency returns. The results reveal that during the COVID-19 pandemic, gold returns Granger caused Bitcoin, Litecoin, and Monero returns at a 5% significance level; however, we found no

Table 7 Estimated coefficients in vector autoregressive -in-first-difference models

	Bitcoin	Ether	Ripple	Litecoin	Bitcoin Cash	EOS	Chainlink	Cardano	Monero
Pre-COVID-19 (2019)									
DGold (−1)[#]	−0.0182 (−0.048)	−0.2414 (−0.550)	−0.4658 (−1.215)	−0.9277* (−1.862)	−0.7199 (−1.342)	−0.5940 (−1.118)	−0.8389 (−1.215)	−0.6112 (−1.259)	−0.1457 (−0.326)
DGold (−2)	0.2184 (0.579)								−0.3361 (−0.758)
DGold (−3)	−0.4527 (−1.188)								−0.7621* (−1.697)
DGold (−4)	−0.0527 (−0.138)								−0.2142 (−0.475)
Tether in level									
WTI (−1)	0.0007 (0.066)	Brent (−1)	0.0031 (0.273)						
WTI (−2)	0.0026 (0.177)	Brent (−2)	−0.0019 (−0.123)						
WTI (−3)	−0.0073 (−0.670)	Brent (−3)	−0.0029 (−0.261)						
During COVID− 19 (2020)									
DGold (−1)	−0.1958 (−0.822)	0.0694 (0.220)	0.1246 (0.313)	0.0241 (0.078)	−0.2345 (−0.689)	−0.0842 (−0.268)		−0.1067 (−0.298)	0.1217 (0.417)
DGold (−2)	0.2062 (0.864)	0.3666 (1.162)	0.2859 (0.718)	0.2297 (0.756)					0.2833 (0.969)
DGold (−3)	**−0.6566 (−2.813)**			**−0.936 (−3.087)**					**−0.7307 (−2.552)**
DGold (−4)	**−0.4908 (−2.078)**								−0.5394* (−1.865)
DWTI (−1)	0.0140 (1.005)	−0.0005 (−0.029)	0.0019 (0.086)	0.0112 (0.633)		−0.0004 (−0.024)	0.0005 (0.021)	0.0115 (0.611)	0.0067 (0.402)
DWTI (−2)	0.0048 (0.317)	−0.0045 (−0.256)	−0.005 (−0.222)	0.0067 (0.357)			−0.004 (−0.149)		−0.0003 (−0.016)
DWTI (−3)	0.0142 (0.919)			0.0014 (0.077)			0.005 (0.197)		0.0018 (0.098)
DWTI (−4)	0.0205 (1.356)						0.005 (0.203)		0.0038 (0.230)

Table 7 (continued)

	Bitcoin	Ether	Ripple	Litecoin	Bitcoin Cash	EOS	Chainlink	Cardano	Monero
DWTI (− 5)	**0.0272 (1.977)**								
DBrent (− 1)	0.0084 (0.204)	0.0208 (0.374)	0.0086 (0.122)	0.0169 (0.315)		0.0025 (0.045)	0.0019 (0.025)	− 0.0193 (− 0.308)	0.0309 (0.620)
DBrent (− 2)	0.0039 (0.096)	0.0583 (1.056)	0.0356 (0.509)	0.0278 (0.519)			0.0843 (1.148)		− 0.0201 (− 0.406)
DBrent (− 3)	0.0508 (1.231)	0.0345 (0.621)		0.0488 (0.911)			0.1046 (1.423)		0.0438 (0.880)
DBrent (− 4)	0.0289 (0.708)	0.0084 (0.152)					0.0751 (1.023)		0.0122 (0.246)
DBrent (− 5)	**− 0.0845 (− 2.077)**	− 0.1043* (− 1.898)							− 0.0849* (− 1.723)

Bold indicates significant result at 5% level

This table presents the coefficients in VAR model (Eq. (1)). Values in the parentheses are associated t-statistic. Significant coefficients at a 0.05 level are in bold and values with (*) are significant at the 10% level. # DGold (− 1) shows the first difference of gold at the first lag

Table 8 Granger causality from gold, West Texas Intermediate, and Brent toward cryptocurrencies (*p* values)

Markets	H0: Gold Granger causes Cryptocurrency		H0: WTI Granger causes Cryptocurrency		H0: Brent Granger causes Cryptocurrency	
	Pre-COVID-19	During COVID-19	Pre-COVID-19	During COVID-19	Pre-COVID-19	During COVID-19
Tether	0.5819	0.9146	0.7183	0.9008	0.942	0.1403
Bitcoin	0.7788	**0.008**	0.2475	0.4312	0.166	0.2192
Ether	0.5819	0.5017	0.3141	0.9655	0.1389	0.3732
Ripple	0.2244	0.7421	0.8814	0.96	0.384	0.8745
Litecoin	0.0626*	**0.0152**	0.7477	0.9351	0.2312	0.7816
Bitcoin cash	0.1795	0.4904	0.0616*	0.4446	0.0771*	0.8053
EOS	0.2636	0.7883	0.3327	0.9806	0.1424	0.9639
Chainlink	0.2245	0.4236	0.6113	0.9976	0.871	0.4251
Cardano	0.208	0.7656	0.7163	0.541	0.3177	0.758
Monero	0.4355	**0.0313**	0.6177	0.9924	0.3675	0.4436

Bold indicates significant result at 5% level

Values in bold are significant at the 5% level and values with (*) are significant at the 10% level

Table 9 Safe-haven properties of gold, West Texas Intermediate, and Brent crude oil

	Gold		WTI		Brent	
	Pre-COVID-19	During COVID-19	Pre-COVID-19	During COVID-19	Pre-COVID-19	During COVID-19
Tether	Weak	None	Weak	None	Weak	None
Bitcoin	Weak	**Strong**	None	None	None	**Weak**
Ether	Weak	None	None	Weak	None	Weak
Ripple	Weak	None	Weak	Weak	None	Weak
Litecoin	**Strong**	**Strong**	None	None	None	None
Bitcoin cash	Weak	Weak	None	Weak	None	Weak
EOS	Weak	Weak	None	Weak	None	None
Chainlink	Weak	Weak	Weak	Weak	Weak	None
Cardano	Weak	Weak	None	None	None	Weak
Monero	**Strong**	**Strong**	None	Weak	None	Weak

Bold indicates significant result at 5% level

significant Granger causality effect of WTI and Brent crude oil returns on cryptocurrency returns in the same period. In the pre-COVID-19 period, gold returns Granger caused Litecoin returns at a 10% significant level. Similarly, WTI and Brent crude oil prices significantly affect Bitcoin Cash at a 10% level in this period. We found no significant causality relationship between gold, WTI, and Brent crude oil toward other cryptocurrencies in pre-COVID-19 and during COVID-19 periods. These Granger causality test results also confirm our findings about the safe-haven effects discussed previously. More specifically, the significant Granger causality from gold toward Bitcoin, Litecoin, and Monero and the observed adverse effects from Table 7 confirm that gold can serve as a strong safe-haven asset for these markets during the COVID-19 crisis.

This study's analyses suggest that, in general, gold is a better safe-haven asset than crude oil for cryptocurrencies in both periods of pre-COVID-19 and during

Table 10 Granger causality effect from cryptocurrencies toward gold, West Texas Intermediate, and Brent (*p* values)

	Tether	Bitcoin	Ether	Ripple	Litecoin	Bitcoin Cash	EOS	Chainlink	Cardano	Monero
Pre-COVID-19 (2019)										
Gold	0.9795	0.2132	0.3493	0.3299	0.9668	0.2126	0.6046	0.5973	0.3539	0.3508
WTI	0.3032	0.3568	0.395	0.8624	0.868	0.703	0.7711	0.3352	0.497	0.7993
Brent	0.4722	0.0843*	0.181	0.9627	0.48	0.4065	0.9176	0.0593*	0.543	0.4187
During COVID-19 (2020)										
Gold	**0.0112**	**0.0148**	**0.0032**	0.3911	0.1735	0.6464	0.5927	0.968	0.9703	**0.0274**
WTI	0.9636	0.0744*	0.4194	0.9272	0.5077	0.2643	0.4742	0.5105	0.6294	0.1127
Brent	0.077*	**0.0398**	0.0524*	0.5382	0.5229	0.4883	0.3728	0.4528	0.1815	0.1396

Bold indicates significant result at 5% level

Values in bold are significant at the 5% level and values with (*) are significant at the 10% level

Table 11 Summary of significant long-term and short-term relationships

	Pre-COVID-19 (2019)		During COVID-19 (2020)	
	Gold	Crude oil	Gold	Crude oil
Tether	Long-term	–	Long-term	Long-term
Bitcoin	–	–	Short-term	Short-term
Ether	–	–	–	–
Ripple	–	–	–	–
Litecoin	–	–	Short-term	–
Bitcoin Cash	–	Short-term	–	Long-term
EOS	–	–	–	–
Chainlink	–	–	Long-term	–
Cardano	–	–	–	–
Monero	–	–	Short-term	–

COVID-19. Even though crude oil is generally a weak safe-haven for cryptocurrencies, the safe-haven properties of crude oil for Bitcoin, Ether, Bitcoin Cash, EOS, and Monero rose during the COVID-19 pandemic. During the COVID-19 crisis, hedge fund managers could reduce the risk of investing in Bitcoin, Litecoin, and Monero by assigning a portion of their portfolio investments to the gold market. Furthermore, Bitcoin investors could reduce their investment risks during the COVID-19 pandemic by investing in Brent crude oil; however, the absolute value of the coefficients for the effect of gold on Bitcoin is more significant than that of Brent crude oil on Bitcoin. Therefore, gold would be a better hedging asset for Bitcoin during the COVID-19 pandemic.

These results are consistent with prior literature (Owusu Junior et al. 2020; González et al. 2021; Barson et al. 2022; Nedved and Kristoufek 2023), providing evidence of gold's safe-haven properties for cryptocurrency markets. Our results corroborate the findings of Nedved and Kristoufek (2023) regarding the strong safe-haven nature of gold and the weaker safe-haven role of crude oil for the Bitcoin market; however, we could not compare our results on crude oil's safe-haven properties for other cryptocurrencies with prior studies, as we did not find any research on this topic. Table 9 summarizes the

Table 12 Summary of significant Granger causality effects

	Pre-COVID-19 (2019)			During COVID-19 (2020)		
	Gold	**WTI**	**Brent**	**Gold**	**WTI**	**Brent**
Tether	–	–	–	Tether GC Gold		Tether GC Brent*
Bitcoin	–	–	–	Bidirectional GC	Bitcoin GC WTI*	Bitcoin GC Brent
Ether	–	–	–	Ether GC Gold	–	Ether GC Brent*
Ripple	–	–	–	–	–	–
Litecoin	Gold GC Litecoin*	–	–	Gold GC Litecoin	–	–
Bitcoin Cash	–	WTI GC Bitcoin Cash*	Brent GC Bitcoin Cash*	–	–	–
EOS	–	–	–	–	–	–
Chainlink	–	–	Chainlink GC Brent*	–	–	–
Cardano	–	–	–	–	–	–
Monero	–	–	–	Bidirectional GC	–	–

This table shows the significance at the 5% level. Rows with * are significant at the 10% level

existence and the intensity of safe-haven properties of gold, WTI, and Brent crude oil for 10 cryptocurrencies analyzed in this study.

To investigate the possible causal relationships from cryptocurrency markets toward the gold, WTI, and Brent crude oil markets, Table 10 presents the p values of Granger causality tests. These tests consider the cryptocurrency returns as exogenous variables to estimate gold, WTI, and Brent market returns. Our findings suggest that before the COVID-19 pandemic, only Bitcoin and Chainlink prices significantly affected Brent crude oil prices at 0.1 level; however, during the COVID-19 period, Tether, Bitcoin, and Ether returns significantly Granger caused the Brent returns. Likewise, Bitcoin return Granger causes the WTI return at this period.

Our empirical studies show that Tether, Bitcoin, Ether, and Monero returns significantly affect gold market return at a 5% level during COVID-19. Table 8 indicates that the Granger causality relationship between Bitcoin-gold and Monero-gold markets is bidirectional. Table 11 summarizes the significant long-term and short-term relationships between cryptocurrency, gold, and crude oil markets and Table 12 summarizes our findings about significant Granger causal effects between the cryptocurrency markets and gold, WTI, and Brent crude oil markets.

Regarding robustness, our findings were assessed through several methods to ensure the reliability and validity of the results. First, the analysis used different statistical models, including cointegration tests, VAR, VECM, ARDL models, and Granger causality tests, providing consistent and converging outcomes. This cross-validation approach strengthened the confidence in the findings, as they were not reliant on a single model. Additionally, to enhance the generalizability of the findings, we employed a large and diverse dataset, encompassing 10 cryptocurrency markets, two crude oil markets, and the gold market in a sample of 494 daily instances covering the pre-COVID-19 and during COVID-19 periods. Including this comprehensive dataset allowed for a more

comprehensive analysis, reducing potential biases, and increasing the reliability of our findings.

Conclusion

Numerous studies have highlighted the lower volatility of gold markets compared to high frequency traded markets such as stocks and digital currencies (Klein et al. 2018; Dyhrberg 2016; Maghyereh and Abdoh 2022). This study investigated the connectedness between the 10 most traded cryptocurrencies and gold and crude oil markets by employing various statistical and econometrics models. Our findings suggest that, during the COVID-19 pandemic, gold acts as a superior safe-haven asset compared to WTI and Brent crude oil for minimizing the risk of cryptocurrency investments. Similarly, the significant long-term negative relationships between Bitcoin Cash and WTI and Bitcoin Cash and Brent crude oil markets during COVID-19 indicate that crude oil can be a safe-haven for Bitcoin Cash investments. Before the COVID-19 pandemic, we found no significant short-term connectedness between cryptocurrency and crude oil and gold markets; however, during the COVID-19 pandemic, lagged WTI and Brent crude oil returns demonstrated a significant relationship with Bitcoin returns. Overall, our findings suggest that the emergence of the COVID-19 pandemic strengthened the safe-haven effect of gold and crude oil markets for portfolios primarily invested in Bitcoin, Litecoin, Monero, Chainlink, and Bitcoin Cash; however, the magnitude of the effect of gold on these markets is more prominent than the effect of crude oil. We found no significant connection between gold and crude oil markets with Ether, Ripple, EOS, and Cardano, at a 5% significance level, during any of the study periods. Moreover, Granger causality tests were conducted on cryptocurrency, gold, WTI, and Brent crude oil to determine the direction of causal relationships between these markets. Our empirical results show that the direction of significant causal relations is predominantly from cryptocurrencies toward gold or crude oil markets; however, during the COVID-19 pandemic, gold significantly Granger caused Bitcoin, Litecoin, and Monero. This study revealed the availability of the safe-haven effect of gold and crude oil markets for cryptocurrency markets before and during the financial crisis due to the COVID-19 pandemic. This finding can help hedge fund managers and investors in digital currencies balance their risk exposures and maximize their returns in a financial crisis. More specifically, the results indicate that incorporating gold as a safe-haven asset in Bitcoin, Litecoin, Monero, Bitcoin Cash, Chainlink, EOS, and Cardano portfolios can provide risk mitigation benefits, particularly during periods of market turbulence such as the COVID-19 pandemic. Therefore, investors and portfolio managers may consider diversifying their cryptocurrency holdings by including gold to improve portfolio resilience. Additionally, this study shows that the safe-haven characteristics of both gold and Crude oil markets have improved during the COVID-19 pandemic compared to the period before. This finding suggests that market participants should take a long-term perspective when evaluating the safe-haven potential of these assets. Managers should consider the evolving market conditions and reassess the safe-haven properties of gold and crude oil over time.

Abbreviations

AGARCH	Asymmetric General Autoregressive Conditional Heteroskedasticity
VAR	Vector autoregressive
VECM	Vector error correction model
ARDL	Autoregressive distributed lag
WTI	West Texas Intermediate
BEKK	Baba, Engle, Kraft and Kroner
DCC	Dynamic conditional correlation
EGARCH-M	Exponential General Autoregressive Conditional Heteroskedasticity in Mean
ADF	Augmented Dickey–Fuller
AIC	Akaike information criterion
OLS	Ordinary least square
SIC	Schwarz information criterion
WHO	World Health Organization

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