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Crypto-driven growth: A comparative study of Bitcoin and Ethereum on economic growth for multi-country analysis

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Abstract

Despite the growing emphasis on the nexus between growth and macroeconomic indicators, research on the influence of cryptocurrencies on economic performance remains limited. This study compares the impact of two leading cryptocurrencies, Bitcoin and Ethereum, on economic growth, alongside inflation, market uncertainty, and oil and gold prices, using panel data from 14 countries between Q3 2015 and Q3 2023. The results demonstrate robust cross-sectional dependence, indicating that economic shocks in one country affect the entire group. Therefore, second-generation tests are employed to confirm the presence of stationarity in the variables. Except for Bitcoin's trading volume, panel fully modified ordinary least squares estimations reveal a significantly positive impact of cryptocurrencies on growth. Cointegration is present in the long run, while in the short run, strong bi- and unidirectional causality is found for all cryptocurrency proxies. The study provides insights that can help policymakers develop strategies to align economic growth with the crypto market, benefiting the broader economy.

Keywords: cryptocurrency, economic growth, panel data models, Bitcoin, Ethereum.
JEL classification: C33, E44, G15, O11.

1. Introduction

The digital transformation of the financial system spurred the creation of decentralized digital currencies known as cryptocurrencies. Nakamoto (2008) introduced the concept of a cryptographic-based electronic payment system to replace the trust-based model of traditional banking. The current financial system was criticized for its costliness, inefficiency, and transaction limits. Therefore,

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Bitcoin (BTC), a virtual currency and a payment form without third-party involvement, was introduced. Since then, BTC's success has driven the development of numerous other cryptocurrencies and blockchain projects (Joshi et al., 2018). Correspondingly, the number of cryptocurrencies has grown significantly since 2013, reaching nearly 20,000 by 2024 (Best, 2024).

Many cryptocurrencies were designed to replace the traditional financial system (Vora, 2015) but are often viewed by investors as speculative investment tools rather than innovative payment methods due to their high returns, decentralized nature, and underlying blockchain technology. Furthermore, the volatility of the crypto market created a suitable environment for speculators, providing opportunities to gain profits within short periods despite significant risks.

Even with this backdrop, cryptocurrencies also serve purposes beyond investment. In El Salvador, the government adopted them as legal tender to stimulate growth and address high public debt. El Salvador's president, Bukele, stated that BTC adoption would encourage economic development and boost innovation and financial inclusion (Alfaro et al., 2022). China, by contrast, has banned cryptocurrencies due to security concerns and the perception that they pose a threat to the monetary system (Wulandari, 2022). There is still no global consensus on the reliability of cryptocurrencies, as regulations remain ambiguous and their economic effects uncertain. As a result, some countries consider them a solution and a growth driver, while others regard them as a major risk and a potential source of financial instability. Given this global uncertainty, we analyze the impact of the two leading cryptocurrencies, BTC and Ethereum (ETH), on economic indicators within a multi-country framework. In doing so, it is important to acknowledge the contradicting results in the existing literature regarding whether cryptocurrencies affect economic growth.

To clarify the ambiguity in prior studies, this paper addresses the following question: *Do cryptocurrencies have a substantial effect on economic growth in the long run?* To this end, we first adopt panel fully modified ordinary least squares (FMOLS) due to its superior properties in handling complex datasets compared to time series models. Specifically, we employ panel cointegration tests to capture long-term relationships and panel Granger causality tests to identify short-term effects of both BTC and ETH on *growth*. Second, given the lack of comparable multi-country studies, we analyze 14 countries, systematically discussing the determinants of growth by integrating key economic, crypto-related, and financial market indicators. Considering the disparities among these 14 countries, analyzing the impact of cryptocurrencies on growth provides a broader and more reliable perspective than single-country analyses. Third, while most studies have focused solely on BTC or on macroeconomic determinants affecting it (Panagiotidis et al., 2018; Shaikh 2020; Vo et al., 2021), we also include ETH — the second most valuable and dominant cryptocurrency. As of December 2023, BTC and ETH accounted for more than half of the crypto market, with a combined dominance of 69%. Their respective market prices reached approximately $43,060 and $2,250.[1] To our knowledge, this is the first study that jointly examines both leading cryptocurrencies and their impacts on economic growth within a multi-country analysis.

[1] https://coinmarketcap.com/currencies/ethereum/historical-data/

The remainder of this paper is structured as follows: Section 2 presents a comprehensive review of the existing literature; Section 3 describes the data and methodology; Section 4 reports and discusses the empirical results; and Section 5 concludes the study.

2. Literature review

The rapid development of cryptocurrency has attracted increasing attention from scholars over the last decade, making it important to investigate the interaction between the crypto market and the broader economy. Earlier studies focused primarily on exploring the conceptual foundations and technological design of cryptocurrency systems. However, with the rising number of cryptocurrency users, attention has shifted toward examining the economic implications of the crypto market.

Most research has centered on BTC as a representative of the cryptocurrency market, since it was the first cryptocurrency introduced and remains dominant due to its popularity, high market capitalization, and trading volume. Although BTC's dominance in the cryptocurrency market is undisputed, there is a growing need for more studies on ETH, the second most traded cryptocurrency.

Fig. 1 illustrates the rate of return (RoR, %) and trading volumes for BTC and ETH from Q3 2015 to Q3 2023, highlighting the high volatility and speculative nature of these assets. Many investors rely on RoR to assess investment efficiency and profitability, and it plays a significant role in shaping investment decisions and allocation of capital. The RoR graph reveals substantial fluctuations, with notable peaks in Q4 2017 Q1 and 2021 indicating sharp price increases. Conversely, periods of negative returns appear around Q1 2018 and Q2 2022, reflecting major value declines. In 2022, as central banks worldwide raised interest rates to curb inflation, investor appetite for speculative and risky assets diminished. Consequently, demand for BTC and ETH fell, leading to a decline in their prices and a negative RoR. These fluctuations underscore the inherent risk — return dynamics of the cryptocurrency market, where steep gains are often followed by abrupt corrections.

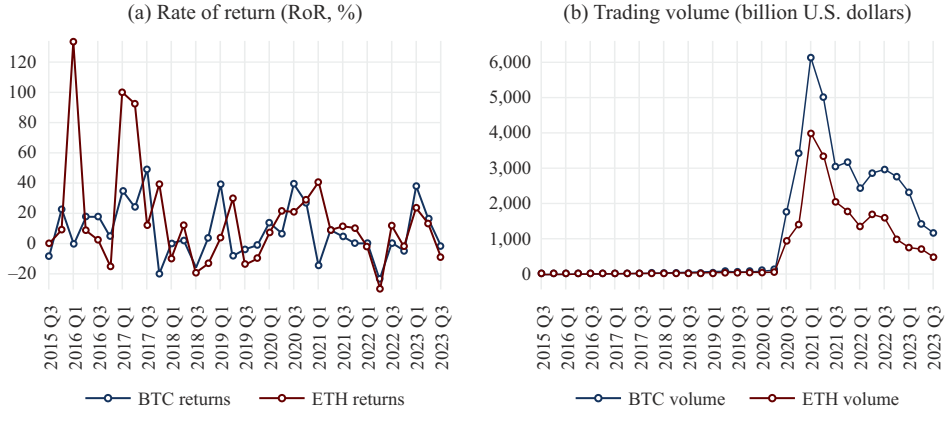

Fig. 1. Trends in BTC and ETH returns and trading volumes from 2015 Q3 to 2023 Q3.

Source: Compiled by the authors.

The trading-volume graph shows a significant spike in early 2021. This surge was followed by a marked decline in trading activity after 2021 — approximately 30% for BTC and 23% for ETH. The downturn coincides with periods of lower RoR, suggesting that reduced returns disincentivized trading activity. These observations highlight the close linkage between trading activity and price movements, emphasizing the speculative and reactive nature of the cryptocurrency market.

The volatility of BTC and ETH prices, trading volumes, and returns — together with their rising popularity and market capitalization — has intensified academic interest in understanding their potential effects on the economy. Whether the crypto market plays a significant role in fostering economic growth and financial stability remains an open question. Existing studies on the relationship between cryptocurrencies and the economy employ diverse economic indicators and econometric models, often yielding contradictory results.

2.1. Cryptocurrencies and growth

Some investors and policymakers view cryptocurrency as a speculative tool or an investment instrument influenced by various economic factors (Kristoufek, 2015), while others regard it as an independent medium of exchange (Baek and Elbeck, 2014). Multiple studies have examined how the crypto market interacts with different economic variables. Vo et al. (2021) found that BTC evolved from a speculative instrument into an independent investment tool that responds to economic stability, monetary policy, and investor sentiment indicators. Their study used real GDP growth as a measure of economic growth because it reflects the overall health of the economy while accounting for price fluctuations and adjusting for inflation or deflation. Additionally, it assists policymakers in adjusting monetary and fiscal policies to achieve economic objectives.

Only a few studies have explored the direct link between cryptocurrencies and growth. Both Al-Qudah and Aloulou (2020) and Alqatan (2022) found no connection between GDP and BTC prices. Conversely, Loseva (2016) highlighted the importance of legalizing BTC trading in Russia, arguing that it slows inflation and decreases money supply without harming growth. Panigrahi (2023) analyzed the effects of BTC prices on India's growth and financial stability using the FMOLS model. The estimations showed that, in the long run, BTC prices have a positive effect of 0.003% on growth, while a 1% increase in BTC prices reduces financial stability by 5%. Using FMOLS and DOLS models, Miśkiewicz et al. (2022) found that increased crypto trading boosts the GDP of seven European countries by 0.017%.

Applying annual data in a multi-country analysis, Utomo (2018) found that Bitcoin and technology negatively affect growth, while labor and capital positively influence GDP. Similarly, Abdelkaoui et al. (2024) found that BTC significantly and negatively affects GDP in ten Asian countries. However, Titalessy and Situmeang (2024) reported a positive relationship between BTC and GDP, suggesting that although BTC's impact is not yet comparable to that of traditional capital, it contributes positively to overall economic development.

Scholars have sought to clarify the effects of cryptocurrency on various economic and financial factors to derive conclusions that could enhance economic development and policy decision-making. Some countries impose absolute bans on cryptocurrency trading and use; however, many researchers argue that the crypto market can support economic growth and revitalize financial markets.

Cryptocurrencies are highly volatile due to multiple factors such as unexpected events in the crypto market and cybercrimes. Some authors used cryptocurrency volatility rather than prices when studying economic effects, as BTC volatility is often easier to forecast than BTC returns (Malladi et al., 2019). Astuti and Nadia (2018) found that an increase in BTC volatility leads to currency appreciation. The volatility of cryptocurrencies increases investment risk; therefore, investors often prefer to allocate capital to their domestic currencies instead.

Financial markets promote economic growth and stability by allocating resources and providing liquidity and capital. The stock market is regarded as a vital economic indicator. Risk and volatility, trading mechanisms, and investor bases are among the commonalities between stocks and cryptocurrencies. These similarities have raised questions about whether the two markets are connected, prompting many studies on the link between stock and crypto markets. Sami and Abdallah (2020) discovered that in MENA countries, stock-market performance increases by 0.13% with a 1% rise in crypto returns, whereas in Gulf countries, the same rise in returns leads to a 0.15% decline in stock markets. In Japan, South Korea, Sweden, and the United States, there is bidirectional causality between stock-market indices and BTC prices; however, no such relationship was observed in Russia (Akinci and Li 2018). Conversely, Ünvan (2019) argued that there is no causality between BTC prices and the S&P 500 index, but there is unidirectional causality from the Nikkei 225 index to BTC prices. Additionally, Erdaş and Caglar (2018) and Güleç et al. (2018) examined the connection between stock and crypto markets in Türkiye and concluded that no causality exists between BTC prices and the BIST 100 index.

2.2. Price levels and growth

Many central banks around the world have maintained strategic ambiguity toward the cryptocurrency market because of the unclear effects of cryptocurrencies on the economy. Providing policy recommendations for achieving price stability, Narayan et al. (2019) concluded that BTC price growth leads to currency appreciation, reduced money velocity, and higher inflation, thereby negatively affecting GDP growth. Gul et al. (2023) stated that inflation, exchange rates, and GDP account for 46% of BTC price variation, showing a positive relationship between inflation and exchange rates with BTC prices, and a negative relationship with GDP.

Inflation's effect on growth is theoretically mixed: classical and Keynesian views, along with Tobin's (1972) portfolio-balance model, argue that moderate inflation can stimulate activity by lowering real interest rates, whereas monetarist theory and Friedman (1977) emphasize that higher inflation raises uncertainty and discourages investment. More recent evidence points to a non-linear relationship in which low or moderate inflation may support growth, while high

inflation becomes harmful, particularly in developing economies. In a study by Panigrahi (2023), the impact of inflation on India's GDP was analyzed for the period 2015–2022. The results indicated that a 1% increase in inflation results in a 6.8% increase in GDP. Shiferaw (2023) also found that for every 1% rise in inflation, Ethiopia's GDP increases by 0.47%. On the other hand, a study by Lubeniqi, Haziri, and Avdimetaj (2023) on 20 developing European countries from 1995 to 2022 showed that a 1% increase in inflation negatively affects growth by 0.017%. Using the ARDL bounds approach on data covering 1970–2019, Saungweme and Odhiambo (2021) found that inflation has a statistically significant negative effect on Kenya's real GDP. Similarly, Mandeya and Ho (2021) observed that inflation negatively impacts South Africa's GDP in both the short and long run. In agreement, Olugbenga Adaramola and Dada (2020) and Dada (2020) found that inflation exerts a significant negative impact on Nigeria's GDP during 1980–2018. In contrast, Salamai et al. (2022), examining Saudi Arabia's GDP and inflation from 1969 to 2020 using the OLS model, reported that inflation does not significantly affect GDP. Živkov et al. (2020) found that inflation has a slight negative effect on GDP growth in eight Central and Eastern European countries.

Several scholars have analyzed the inflation–growth relationship using panel cointegration methods such as FMOLS, dynamic ordinary least squares (DOLS), or common correlated effects (CCE). Uddin and Rahman (2022) used panel FMOLS and DOLS methods to estimate the influence of inflation on the growth of 79 developing countries from 2002 to 2018 and found that inflation has a significantly positive effect on growth. Yahyaoui and Bouchoucha (2021) also reported a significant positive effect of inflation on growth in 48 African countries, using FMOLS and DOLS estimations for the period 1996–2014. Similarly, using panel ARDL, FMOLS, and DOLS methods, Taderera et al. (2021) confirmed that inflation positively affects GDP growth in SACU countries. In contrast, Panigrahi et al. (2020), analyzing ASEAN-5 countries for 1995–2018, found that inflation has a small negative impact on GDP growth.

2.3. Market volatility and growth

Examining the connection between the crypto market and stock indices has clarified that cryptocurrencies are perceived more as investment instruments rather than as mediums of exchange like fiat money (Baur, Hong, and Lee 2018). An important measure of stock-market volatility is the Chicago Board Options Exchange Volatility Index (*VIX*), which has drawn considerable attention because it captures market uncertainty. Using pairwise Granger causality tests on data from 1990 to 2022, Chatterjee (2023) found that *VIX* is negatively correlated with U.S. GDP. However, when in-sample and out-of-sample forecast evaluations were applied, the study concluded that *VIX* does not have predictive power for GDP. Investigating the impact of financial-cycle variables on GDP growth in 31 countries from 2002 to 2021, Wang and Xiao (2023) found that an increase in *VIX* negatively affects GDP growth. In another study based on 70 countries, Alaminos et al. (2021) concluded that *VIX* is one of the most significant variables for predicting GDP growth in emerging economies — being

significant in six of the seven models developed. The same study found *VIX* significant in two out of seven models for developed countries and in four out of seven for global samples.

2.4. Commodity prices and growth

The commodity market is another key financial market and among the most volatile and sensitive economic indicators, as commodity prices respond sharply to global economic events and carry high risk. Brent and WTI crude oils, natural gas, and gold are the four most traded commodities worldwide (Thaxton, 2022). Consequently, many studies have explored the relationship between these commodities and growth.

Jiménez-Rodríguez and Sanchez (2005) examined the impact of oil-price shocks on economic activity in industrialized countries from 1980 to 2003. Using multivariate VAR analysis, they found that increases in oil prices have a negative effect on growth. Through multivariate threshold analysis, Huang et al. (2005) demonstrated that oil-price fluctuations have greater explanatory power for economic indicators than oil-price volatility in Canada, the United States, and Japan. Rafiq et al. (2009) emphasized that oil prices in Thailand are a key factor for macroeconomic stability by affecting investment and unemployment. Bildirici and Sonustun (2018) applied an MS-VAR model to analyze the effects of oil and gold volatility on growth in eight oil-exporting countries and highlighted the significant role of oil prices in driving business cycles in these economies. Similarly, Çemrek and Bayraç (2021) used a random-effects model on data from OPEC countries for 2000–2017 and found that increasing oil prices and exports have a positive impact on GDP growth.

Gold serves dual roles as both a commodity and a monetary asset with intrinsic value. Its importance is reinforced by its store-of-value function, which becomes particularly relevant during periods of economic or political turbulence. Baur and McDermott (2010) identified a negative relationship between gold returns and periods of high economic volatility. Khan (2015) demonstrated the significant impact of oil and gold prices on Pakistan's growth during 1997–2014. Guan et al. (2021) found that in the short term, gold has a significant positive effect on GDP growth in 17 countries, while both oil and gold exert adverse effects in the long term. Salisu et al. (2022) showed that gold-price volatility has negatively affected the growth of eight developed countries.

3. Data and methodology

The purpose of this study is to investigate whether cryptocurrencies have a notable effect on countries' economic growth. Furthermore, it examines the relationships among various economic and financial indicators and cryptocurrencies, and their combined effect on the economy. The dataset covers 14 countries from Q3 2015 to Q3 2023.

The country selection was informed by prior studies in the field. While Panigrahi (2023) focused exclusively on time-series data for India, Miśkiewicz et al. (2022) analyzed a panel of seven countries. To broaden these approaches, we assembled a heterogeneous panel dataset including 14 countries. This wider scope provides

a stronger empirical basis for analysis and enhances the generalizability of the results, thereby strengthening the study's contribution to the literature.

To estimate the panel data regression, we apply the group-mean fully modified ordinary least squares (GM-FMOLS) cointegration model, along with several pre- and post-estimation tests: cross-sectional dependence, unit-root, cointegration, and panel Granger causality tests. Since BTC and ETH hold the largest market shares in the crypto market, their trading volumes and rates of return are used as the main cryptocurrency indicators.

Real GDP growth serves as the dependent variable and proxy for economic growth. The RoR and trading volumes of BTC and ETH are selected as crypto-related variables. In addition, the consumer price index (CPI) measures inflation, *VIX* represents financial-market uncertainty, and both WTI and GOLD capture commodity-market dynamics. Table 1 presents a summary of the selected variables. The selection of these macroeconomic indicators was guided by their relevance to the research objectives and their ability to capture key economic dimensions that influence — and are influenced by — the activities of economic agents, including those engaging in cryptocurrency transactions. This selection also aligns with earlier research, particularly Panigrahi (2023), who employed similar indicators.

Accurate measurement of growth is essential. Although several forms of GDP are used in the literature, this study employs the real GDP growth rate, consistent with contemporary research (Evans, 2019; Jati et al., 2022; Chatterjee, 2023).

CPI provides key information on price changes that governments and firms use to make informed economic decisions (U.S. Bureau of Labor Statistics, 2023). In addition to serving as an inflation gauge, it can also indicate the effectiveness of government economic policy. The choice of *CPI* as the inflation proxy follows prior studies (Kremer et al., 2012; Barro, 2013; Saymehet et al., 2013; Evans, 2019).

VIX is a real-time market indicator that forecasts volatility expectations for the next 30 days based on S&P 500 option prices. As the S&P 500 is widely regarded as a leading barometer of global financial conditions, *VIX* (% change) is used here to represent both stock-market volatility and risk.

Table 1
Definition of variables.

Measurement	Code	Description	Source
Economic growth	GDP	Real gross domestic product growth, change from the previous period, seasonally adjusted (%)	OECD
Inflation	CPI	Consumer Price Index, quarterly growth rate (%)	OECD
Uncertainty	VIX	Percentage change of the closing price of the Chicago Board Options Exchange Volatility Index (%)	Yahoo Finance
Energy prices	WTI	Percentage change of Cushing, OK, West Texas Intermediate crude-oil spot prices (%)	EIA
Commodity prices	GOLD	Gold price per troy ounce, change (%)	WGC
Bitcoin volume	BTCV	Percentage change of Bitcoin trading volume (%)	CMC
Bitcoin return	BTCR	Bitcoin rate of return (%)	CMC
Ethereum volume	ETHV	Percentage change of Ethereum trading volume (%)	CMC
Ethereum return	ETHR	Ethereum rate of return (%)	CMC

Note: EIA — U.S. Energy Information Administration; WGC — World Gold Council; CMC — CoinMarketCap.
Source: Compiled by the authors.

WTI is included as a benchmark for global crude-oil price changes, given its importance for oil-exporting countries such as Canada, Colombia, Indonesia, Saudi Arabia, and the United States, all of which are part of the dataset. Together with gold, the percentage change in WTI spot price serves as a commodity-market indicator; a positive correlation between WTI and growth is expected (Chatterjee, 2023).

Among the 14 countries in our dataset, seven (Australia, Canada, China, Colombia, Indonesia, South Africa, and the United States) have significant gold-mining and export sectors. The relationship between growth and gold prices is often inverse: during periods of strong economic expansion, investors prefer higher-return assets, reducing demand for gold and lowering its price (Wang and Lee, 2016). Conversely, gold acts as a safe-haven asset during downturns, increasing both demand and prices (Triki and Ben Maatoug, 2021). These dynamics highlight gold's role as a hedge against macroeconomic instability and currency depreciation, making it a key variable for understanding economic sentiment.

The descriptive statistics for the selected variables are presented in Table 2. *ETHV* exhibits the largest mean value (approximately 1.75) compared with *BTCV* (0.94), and both variables display the highest standard deviations among the sample. The standard deviation of *BTCR* is lower than that of *ETHR*, indicating that Ethereum is riskier to invest in than Bitcoin. However, the maximum value of *ETHR* is substantially higher than that of *BTCR*, which may make Ethereum more attractive to certain investors seeking higher potential returns. The Jarque–Bera test results indicate that the data for all variables are normally distributed, except for *GOLD*.

Panel data are the most suitable for this study, as they provide greater variability and reliability than either cross-sectional or time-series data alone. Panel regression captures both the time dimension and the cross-country differences within the sample (Zulfikar, 2018), allowing us to address the research question effectively. This approach also controls for unobserved heterogeneity, such as country-specific characteristics — including economic structure, geographic location, and institutional classification — that could otherwise bias the results.

Table 2
Descriptive statistics.

Variable	Mean	Median	Max.	Min.	Std. dev.	Skewness	Kurtosis	Jarque–Bera
GDP	0.0072	0.0064	0.2256	−0.2255	0.0311	−0.6674	21.8760	6893.137*
CPI	0.0258	0.0194	0.1329	−0.0320	0.0261	1.0695	4.3706	124.234*
VIX	0.0472	−0.0633	1.8392	−0.3635	0.3976	2.9182	13.0712	2608.250*
WTI	0.0550	0.0400	1.4598	−0.7123	0.3159	2.1748	13.1036	2329.308*
GOLD	−0.0177	−0.0058	0.0848	−0.1246	0.0506	−0.0863	2.6579	2.826
BTCR	0.0803	0.0346	0.4854	−0.2355	0.1788	0.4952	2.5360	23.030*
BTCV	0.9054	0.0809	14.8589	−0.3922	2.6777	4.3592	22.5798	8843.082*
ETHR	0.1556	0.0876	1.3391	−0.3024	0.3396	1.9052	6.6692	538.667*
ETHV	1.6975	0.1328	19.1452	−0.8507	4.1986	2.8956	10.8876	1843.205*

Note: Table 2 presents descriptive statistics for 14 countries from 2015 Q3 to 2023 Q3 (462 observations). Among all variables, only *GOLD* does not follow a normal distribution. * Denotes significance at the 1% level.
Source: Authors' calculations.

The general panel regression model can be expressed as follows:

$$Y_{it} = \alpha_i + \beta_1 X_{1it} + \beta_2 X_{2it} + \ldots + \beta_n X_{3nit} + \varepsilon_{it}, \quad (1)$$

where Y_{it} represents the dependent variable (GDP growth), and α_i is the country-specific intercept. β_1, β_2, …, β_n denote the coefficients measuring the change in Y_{it} resulting from a one-unit change in the respective explanatory variables X_{1it}, X_{2it}, …, X_{3nit}. The error term ε_{it} captures random disturbances not explained by the model. Index i refers to cross-sections (i = 1, 2, …, n), and t denotes time periods (t = 1, 2, …, T).

Based on this framework, six models (Models 1–6) are constructed, each with different combinations of cryptocurrency indicators to compare their respective effects.

$$\text{Model (1): } GDP_{it} = \alpha_i + \beta_1 CPI_{it} + \beta_2 VIX_{it} + \beta_3 WTI_{it} + \beta_4 GOLD_{it} + \\ + \beta_5 BTCR_{it} + \varepsilon_{it}, \quad (2)$$

$$\text{Model (2): } GDP_{it} = \alpha_i + \beta_1 CPI_{it} + \beta_2 VIX_{it} + \beta_3 WTI_{it} + \beta_4 GOLD_{it} + \\ + \beta_5 BTCV_{it} + \varepsilon_{it}, \quad (3)$$

$$\text{Model (3): } GDP_{it} = \alpha_i + \beta_1 CPI_{it} + \beta_2 VIX_{it} + \beta_3 WTI_{it} + \beta_4 GOLD_{it} + \\ + \beta_5 ETHR_{it} + \varepsilon_{it}, \quad (4)$$

$$\text{Model (4): } GDP_{it} = \alpha_i + \beta_1 CPI_{it} + \beta_2 VIX_{it} + \beta_3 WTI_{it} + \beta_4 GOLD_{it} + \\ + \beta_5 ETHV_{it} + \varepsilon_{it}, \quad (5)$$

$$\text{Model (5): } GDP_{it} = \alpha_i + \beta_1 CPI_{it} + \beta_2 VIX_{it} + \beta_3 WTI_{it} + \beta_4 GOLD_{it} + \\ + \beta_5 BTCR_{it} + \beta_6 ETHR_{,it} + \varepsilon_{it}, \quad (6)$$

$$\text{Model (6): } GDP_{it} = \alpha_i + \beta_1 CPI_{it} + \beta_2 VIX_{it} + \beta_3 WTI_{it} + \beta_4 GOLD_{it} + \\ + \beta_5 BTCV_{it} + \beta_6 ETHV_{it} + \varepsilon_{it}. \quad (7)$$

Here, β_1–β_6 are the estimated coefficients showing the marginal effects of each independent variable on GDP growth. The sample covers 14 countries over the period Q3 2015– Q3 2023 (32 quarters).

As a proxy for economic performance, GDP_{it} represents real GDP growth (%). $BTCR_{it}$ and $ETHR_{it}$ denote the rate of return on Bitcoin and Ethereum (%), while $BTCV_{it}$ and $ETHV_{it}$ represent their respective trading volumes (% change). *WTI* and *GOLD* capture energy and commodity price variations, *VIX* measures market uncertainty, and *CPI* proxies inflation.

Before estimating the panel regression model, several diagnostic and specification tests were performed, including checks for cross-sectional dependence, slope homogeneity, and unit-root properties. After these steps, the panel cointegration and Granger-causality tests were conducted to evaluate both long-run and short-run relationships among the variables.

Table 3
Correlation matrix.

	GDP	*CPI*	*VIX*	*WTI*	*GOLD*	*BTCR*	*BTCV*	*ETHR*	*ETHV*
GDP	1								
CPI	0.0201	1							
VIX	−0.0698	0.0048	1						
WTI	0.5656	0.0063	0.0216	1					
GOLD	0.0506	0.0401	−0.1125	−0.0393	1				
BTCR	0.1113	−0.0754	−0.1739	0.0727	−0.4001	1			
BTCV	0.4081	−0.0394	−0.1101	0.7588	−0.2801	0.2951	1		
ETHR	0.0108	−0.0641	−0.1350	−0.1088	−0.1485	0.2551	0.1900	1	
ETHV	0.3350	−0.0583	−0.0944	0.5190	−0.3368	0.2960	0.7779	0.6149	1

Source: Authors' calculations.

Table 4
Cross-sectional dependence test results.

Test	Statistic	Degrees of freedom	Prob.
Breusch−Pagan LM	1457.8780	91	0.0000*
Pesaran scaled LM	101.3197	–	0.0000*
Bias-corrected scaled LM	101.1010	–	0.0000*
Pesaran CD	31.3624	–	0.0000*

Note: * $p < 0.01$, ** $p < 0.05$, *** $p < 0.1$.
Source: Authors' calculations.

3.1. Correlation analysis

Correlation coefficients are moderate across variables, indicating that multicollinearity should not distort the estimation results (Table 3).

3.2. Cross-sectional dependence

Cross-sectional dependence occurs when observations are correlated across countries due to unobserved common shocks or spillover effects. Given the multi-country sample, this issue must be addressed to obtain reliable inferences (Breusch and Pagan, 1980; Pesaran, 2004; Baltagi et al., 2012). All tests reject the null of no cross-sectional dependence, indicating the presence of common shocks and interdependence among countries (Table 4).

These results confirm that shocks in one economy — such as financial crises, commodity-price swings, or crypto-market fluctuations — propagate across others, justifying the use of estimators robust to cross-dependence.

3.3. Panel unit-root tests

Non-stationarity can bias coefficient estimates and inference. Because the panel exhibits cross-dependence, second-generation unit-root tests (CIPS and truncated CIPS) were applied following Pesaran (2007).

The results show that most variables are stationary in levels or become stationary after minimal detrending (Table 5). This indicates that the data are either I(0) or borderline I(1), validating the use of estimators capable of handling mixed

Table 5
Panel unit-root tests.

Statistic	Non-deterministic		Constant		Constant and trend	
CIPS	−1.68005**		−2.76603*		−3.78911*	
Truncated CIPS	−1.68005**		−2.39629**		−3.41114*	
CIPS Critical Values	CIPS	T-CIPS	CIPS	T-CIPS	CIPS	T-CIPS
1%	−1.89	−1.89	−2.47	−2.47	−2.98	−2.98
5%	−1.66	−1.66	−2.27	−2.27	−2.78	−2.78
10%	−1.54	−1.54	−2.15	−2.15	−2.67	−2.67

Note: $T = 32$ and $N = 14$ (448 observations). * $p < 0.01$, ** $p < 0.05$, *** $p < 0.1$.
Source: Authors' calculations.

Table 6
Swamy S homogeneity test.

Models with GDP as dependent variable	χ^2 value	p-value
Model (1)	199.25	0.0000*
Model (2)	206.95	0.0000*
Model (3)	199.10	0.0000*
Model (4)	195.93	0.0000*
Model (5)	204.60	0.0000*
Model (6)	213.55	0.0000*

Note: * $p < 0.01$, ** $p < 0.05$, *** $p < 0.1$.
Source: Authors' calculations.

integration orders and cross-sectional dependence — such as the GM-FMOLS approach.

3.4. Slope-homogeneity test

The Swamy S test (Swamy, 1970) was applied to examine slope homogeneity. All models reject the null of slope homogeneity ($p < 0.01$), implying that coefficients differ across countries (Table 6). Heterogeneous estimators such as GM-FMOLS or CCEMG are thus preferred.

3.5. Estimation method

Pedroni (2001) investigates the asymptotic characteristics of cointegrating regressions in dynamic panels with heterogeneous dynamics and fixed effects across members that share a common cointegrating vector. He demonstrates why traditional OLS is inconsistent in this situation and creates a fully modified OLS estimator that accounts for serial correlation and endogeneity, enabling consistent estimate in spite of cross-member variability. For a panel of $i = 1, ..., N$ members, the following cointegrated system was taken into consideration:

$$\begin{aligned} y_{it} &= \alpha_i + \beta x_{it} + \mu_{it}, \\ x_{it} &= x_{it-1} + \varepsilon_{it} x_{it} = x_{it-1} + \varepsilon_{it}, \end{aligned} \tag{8}$$

where the vector error process $\xi_{it} = (\mu_{it}, \varepsilon_{it})'$ is stationary with asymptotic covariance matrix λ_i. Thus, the variables x_{it} and y_{it} are said to cointegrate for each member of

the panel, with cointegrating vector β if y_{it} is integrated of order one. The term α_i allows the cointegrating relationship to include member-specific fixed effects. No exogeneity of regressors is required. The vector error process $\xi_{it} = (\mu_{it}, \varepsilon_{it})'$ was later partitioned such that μ_{it} is a scalar series and ε_{it} is an m-dimensional vector of first differences of the regressors, where $\varepsilon_{it} = x_{it} - x_{it-1} = \Delta x_{it}$.

Thus, the long-run covariance matrix λ_i can be written as:

$$\lambda_i = \begin{bmatrix} \lambda_{11i} & \lambda'_{21i} \\ \lambda_{21i} & \lambda_{22i} \end{bmatrix}. \tag{9}$$

Here, λ_{11i} is the scalar long-run variance of μ_{it}, and λ_{21i} is the m × 1 long-run covariance between μ_{it} and ε_{it}. $\lambda'_{21i} = \lambda_{12i}$, is the long-run covariance between the cointegrating error μ_{it} and the changes in the regressors ε_{it}. Just like λ_{21i}, the term λ'_{21i} quantifies the endogeneity in the system. λ_{22i} is the $m \times m$ long-run covariance matrix among ε_{it}. Using these long-run covariance components, Pedroni (2001) introduced the group-mean FMOLS (GM-FMOLS), which averages country-specific estimates while adjusting for endogeneity and serial correlation:

$$\hat{B}_{FG} = \frac{1}{N}\sum_{i=1}^{N} \left\{ \left(\sum_{t=1}^{T} \tilde{X}_{it}\tilde{X}_{it}' \right)^{-1} \sum_{t=1}^{T} \left(\tilde{X}_{it}\tilde{y}_{it} - \hat{\lambda}_{21i} \right) \right\}, \tag{10}$$

where $\hat{B}_{FG}$ is the estimator; $\tilde{X}_{it}$ and $\tilde{y}_{it}$ are demeaned values of the regressors and dependent variable; T and N are the time-series and cross-sectional dimensions; i and t index country and time; and $\hat{\lambda}_{21i}$ denotes the estimated long-run covariance adjustment term.

The group-mean estimator provides consistent estimates of the sample mean of the cointegrating vectors, unlike weighted or pooled estimators that impose parameter homogeneity. The main advantage of GM-FMOLS lies in its inclusion of common time dummies, which helps control for possible regressor endogeneity, serial correlation, and cross-sectional dependence while ensuring consistent parameter estimates (Mohey-ud-Din and Siddiqi, 2013).

The panel FMOLS method is therefore employed to estimate the long-run effects of the independent variables on the dependent variable by deriving cointegration coefficients without the need to first-difference the data. In contrast, standard pooled OLS may yield biased estimates when cointegration exists among variables, particularly under serial correlation and endogeneity (Akpolat, 2014).

GM-FMOLS estimations were implemented for Models (1)–(6), allowing a comparative analysis of their long-run relationships and consistency across specifications.

4. Empirical results

The panel GM-FMOLS estimation results for the six models (Table 7) provide insights into the relationships between *GDP* growth and the explanatory variables.

The impact of Bitcoin trading volume is particularly noteworthy. In Models 2 and 6, *BTCV* negatively and significantly affects growth, highlighting the poten-

Table 7
Results of panel GM-FMOLS estimations.

Variables	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)
CPI	0.1137*	0.1408*	0.1171*	0.1289*	0.0988*	0.1337*
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0002)	(0.0000)
VIX	−0.0040**	−0.0070*	−0.0052*	−0.0052*	−0.0037**	−0.0068*
	(0.0385)	(0.0004)	(0.0054)	(0.0073)	(0.0494)	(0.0002)
WTI	0.0555*	0.0606*	0.0575*	0.0514*	0.0560*	0.0637*
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
GOLD	0.0721*	0.0228	0.0483*	0.0588*	0.0742*	0.0390*
	(0.0000)	(0.1525)	(0.0009)	(0.0002)	(0.0000)	(0.0098)
BTCV	–	−0.0005	–	–	–	−0.0027*
		(0.3221)				(0.0000)
BTCR	0.0252*	–	–	–	0.0203*	–
	(0.0000)				(0.0000)	
ETHV	–	–	–	0.0008*	–	0.0016*
				(0.0002)		(0.0000)
ETHR	–	–	0.0088*	–	0.0057*	–
			(0.0000)		(0.0073)	
R^2	0.3430	0.3271	0.3381	0.3343	0.3490	0.3414
Adjusted R^2	0.3370	0.3210	0.3321	0.3283	0.3416	0.3339

Note: Coefficients are followed by *p*-values in parentheses. * $p < 0.01$, ** $p < 0.05$, *** $p < 0.1$.
Source: Authors' calculations.

tial risks associated with cryptocurrency markets. High Bitcoin trading volumes may signal speculative surges that increase financial uncertainty and potential losses, thereby discouraging investment and economic activity. This result aligns with concerns about the destabilizing role of speculative trading in emerging digital-asset markets.

In contrast, Ethereum trading volume shows a positive and significant effect on growth in Models 4 and 6. This pattern suggests that the ETH market may be perceived differently from BTC, possibly reflecting market innovation and a broader integration of Ethereum-based applications into economic activity. The positive association between *ETHV* and growth implies that rising activity in the Ethereum ecosystem may accompany expansion in productive investment and technology-driven sectors.

Regarding returns, the RoR of Bitcoin (*BTCR*) is positively and significantly related to growth in Models 1 and 5. Higher Bitcoin returns appear to stimulate aggregate output, possibly through wealth effects or investment spillovers. Similarly, the RoR of Ethereum (*ETHR*) positively influences growth in Models 3 and 5, reinforcing the view that favorable cryptocurrency performance can coincide with improved macroeconomic outcomes. Collectively, these results indicate that cryptocurrency markets can contribute positively to economic development when returns are high, but elevated trading activity — particularly in Bitcoin — may introduce volatility that dampens stability.

Across all models, *CPI* shows a consistent and significant positive relationship with growth, suggesting that moderate inflation, as captured by consumer-price changes, coincides with stronger output. This outcome may reflect expansionary conditions where rising prices accompany higher aggregate demand. It also underscores the dual role of inflation—as both a potential stimulus to activity and a variable that must be carefully managed by policymakers to avoid overheating.

The *VIX*, often termed the "fear gauge," exerts a negative and significant effect on growth in every model. Higher *VIX* levels, which capture global financial uncertainty, are associated with lower GDP growth, consistent with the view that market volatility discourages investment and consumption. These findings reinforce the broader economic principle that stability supports growth, while uncertainty constrains it.

Energy-market dynamics, represented by *WTI*, exhibit a uniformly positive and highly significant relationship with growth. This pattern suggests that higher oil prices benefit oil-exporting economies in the sample and may also reflect global demand expansion during growth periods. The positive link highlights how energy prices influence aggregate activity through both revenue channels and investment in energy-related industries.

Gold prices (*GOLD*) are positively associated with GDP growth in most models, although the effect in Model 2 is statistically insignificant. The generally positive coefficients may indicate that gold, while often viewed as a safe-haven asset, also contributes to economic stability and investor confidence during uncertain periods. Thus, fluctuations in gold prices can serve as a proxy for shifts in market sentiment and the broader macro-financial environment.

Overall, the empirical evidence suggests that cryptocurrency variables (*BTCR*, *BTCV*, *ETHR*, *ETHV*) interact with traditional macroeconomic indicators in a manner consistent with partially integrated financial markets. Favorable returns are growth-enhancing, whereas excessive trading activity — particularly in Bitcoin — may amplify volatility risks. Macroeconomic variables (*CPI*, *VIX*, *WTI*, and *GOLD*) behave as expected, confirming that the model captures both financial and real-sector linkages across the 14-country panel.

4.1. Panel cointegration test

Panel cointegration tests are used to evaluate whether a long-run equilibrium relationship exists among variables while accounting for temporal dynamics and cross-sectional dependence. Pedroni (1999, 2004) extended the Engle and Granger (1987) framework to panel settings, incorporating unit-root behavior and country-specific heterogeneity. In Pedroni's formulation, cointegration implies the existence of a stable long-term equilibrium among variables even though short-term fluctuations may occur.

The Pedroni residual-based tests comprise seven statistics grouped into two categories:

(1) within-dimension tests (assuming a homogeneous alternative) and

(2) between-dimension tests (assuming a heterogeneous alternative).

Following Pedroni (2004), the null hypothesis of no cointegration is rejected when at least four of the seven statistics are significant at the 5% level.

As shown in Table 8, at least four or five statistics per model reject the null hypothesis. Hence, a long-run equilibrium relationship exists between GDP growth and the set of explanatory variables — cryptocurrency returns and trading volumes, inflation, financial-market volatility, and commodity prices — across the 14-country panel.

These outcomes confirm the presence of long-term relationships among the variables, consistent with the GM-FMOLS framework adopted earlier.

Table 8
Pedroni panel cointegration test results.

	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)
Panel	−3.9972	−3.9956	−4.0073	−3.9325	−4.4335	−4.6242
v-statistic	(1.0000)	(1.0000)	(1.0000)	(1.0000)	(1.0000)	(1.0000)
Panel	−2.1669**	−2.2066**	−2.3033**	−2.0068**	−0.9726	−0.5902
rho-statistic	(0.0151)	(0.0137)	(0.0106)	(0.0224)	(0.1654)	(0.2775)
Panel	−13.7479**	−15.6035**	−13.4308**	−13.7813**	−11.6003**	−15.1817**
PP-statistic	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Panel	−11.5787**	−12.6508**	−11.7805**	−11.7222**	−10.5521**	−12.5684**
ADF-statistic	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Group	−0.1971	−0.5129	−0.5096	−0.3083	1.0957	1.3238
rho-statistic	(0.4219)	(0.3040)	(0.3052)	(0.3789)	(0.8634)	(0.9072)
Group	−16.8574**	−20.1376**	−16.3987**	−17.4447**	−13.3838**	−20.0739**
PP-statistic	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Group	−11.1466**	−13.5229**	−11.7275**	−11.7465**	−9.6796**	−12.9229**
ADF-statistic	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
	Cointegrated	Cointegrated	Cointegrated	Cointegrated	Cointegrated	Cointegrated

Note: PP = Phillips–Perron (non-parametric); ADF = Augmented Dickey–Fuller (parametric). Statistics are asymptotically normal. Values in parentheses are *p*-values; ** $p < 0.05$ indicates rejection of H0 (no cointegration). The optimal lag length (maximum 6) is automatically selected via the Schwarz information criterion (SIC).
Source: Authors' calculations.

4.2. Panel Granger-causality test

To explore causal link between variables, the Dumitrescu and Hurlin (2012) panel Granger-causality test was employed. This approach identifies the direction of predictive relationships between variables while allowing heterogeneity across countries. The findings — presented in Appendix A — show both unidirectional and bidirectional causal links. Fig. 2 summarizes the principal causality flows between cryptocurrency indicators and GDP growth.

The results reveal several key short-run relationships. *BTCR* exhibits unidirectional causality toward *CPI*, implying that Bitcoin returns can help predict inflationary movements. At the same time, causality runs from *VIX* to *BTCR*, indicating that Bitcoin performance responds to shifts in market sentiment and financial stability. Moreover, a bidirectional relationship between *BTCR* and *WTI* underscores the mutual influence between cryptocurrency and oil markets.

For Ethereum, *ETHR* shows unidirectional causality from *GDP* and *VIX*, suggesting that macroeconomic growth and financial-market volatility drive short-term Ethereum returns. In addition, *ETHR* responds to changes in oil prices (*WTI*), emphasizing the relevance of energy-market conditions for cryptocurrency dynamics.

The analysis of trading volumes yields further insights. *BTCV* demonstrates bidirectional causality with *GDP* and *WTI*, implying a two-way feedback mechanism between Bitcoin market activity, real-sector performance, and global energy prices. *BTCV* also shows unidirectional causality toward *VIX* and *GOLD*, suggesting that Bitcoin trading intensity can forecast movements in market volatility and gold prices.

In contrast, *ETHV* exhibits unidirectional causality from *GDP* and *WTI*, highlighting the influence of economic growth and energy conditions on Ethereum trading activity. Additionally, *ETHV* shows bidirectional causality with *GOLD*, reflecting their interplay as alternative investment assets.

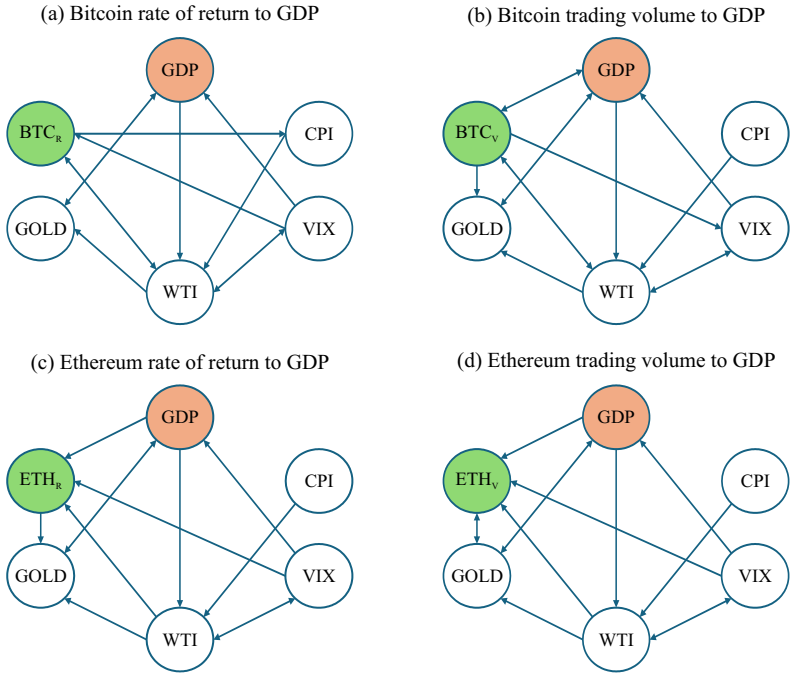

Fig. 2. Causality relationships between cryptocurrency variables and GDP growth.

Note: → = unidirectional causality; ↔ = bidirectional causality.
Source: Authors' calculations.

Taken together, these findings illustrate that cryptocurrency variables and macroeconomic indicators are closely interconnected. Bitcoin appears more sensitive to financial-market volatility, while Ethereum's linkages seem stronger with real-economic and commodity-market dynamics. The combination of bidirectional and unidirectional relationships underscores the dual role of cryptocurrencies — as both transmitters and receivers of macro-financial shocks within the global economic system.

5. Discussion and policy implications

The analysis presented in this study underscores the intricate interdependencies between macroeconomic indicators and cryptocurrencies. The regression results for Bitcoin's impact on growth are broadly consistent with previous studies (Jati et al., 2022; Panigrahi, 2023). According to the findings, Bitcoin's rate of return (*BTCR*) contributes positively to GDP growth, suggesting that increases in Bitcoin value support economic expansion, while Bitcoin's trading volume (*BTCV*) — a proxy for volatility — exerts a negative effect. Similarly, Ethereum's rate of return (*ETHR*) has a positive impact on growth, whereas its trading volume (*ETHV*) is associated with higher volatility and potential downside risk. These results highlight that cryptocurrency returns can enhance growth when markets are stable, but their volatility poses substantial macro-financial risks.

The bidirectional causality between *BTC* and *GDP* further suggests mutual feedback: economic conditions influence Bitcoin's market performance, while fluctuations in Bitcoin activity affect real economic outcomes. Consequently,

policymakers should develop regulatory frameworks to stabilize cryptocurrency markets, and investors should adopt diversified portfolio strategies to mitigate volatility-related risks.

Policymakers should also design a comprehensive legal framework classifying cryptocurrencies as investment assets to channel their growth potential into the formal economy. Such measures would enhance legal clarity, improve investor protection, and ensure proper tax compliance. Establishing clear standards for different cryptocurrency categories could reduce market uncertainty and promote responsible trading practices (Al-Qahtani and Albakjaji, 2023). Implementing licensing and supervision for crypto exchanges — alongside stronger anti-money-laundering (AML) and counter-terrorism financing (CTF) regulations — would further enhance market integrity.

In the short term, authorities can deploy real-time market surveillance, conduct public-education campaigns, and introduce temporary transaction limits during extreme volatility. These actions could mitigate systemic risk and prevent economic downturns linked to crypto-market collapses (Bouoiyour et al., 2019; Ünvan, 2019; Sami and Abdallah, 2020; Moussa et al., 2021).

Inflation also exhibits a lasting influence on GDP growth, confirming the existence of a long-run equilibrium relationship. This suggests that policymakers should prioritize inflation-targeting frameworks to maintain price stability, while investors should closely monitor inflation trends to inform asset-allocation decisions. The negative coefficients for *VIX* indicate that heightened financial-market volatility correlates with slower growth. The confirmed cointegration implies that sustained volatility can have persistent effects on economic performance. The bidirectional causality between *GDP* and *VIX* further indicates that shifts in macroeconomic activity influence market volatility and vice versa. To minimize volatility spillovers, policymakers should promote macro-financial stability, and investors should account for volatility indices in portfolio-risk management.

The significant effects of *WTI* crude oil and *GOLD* prices on growth emphasize the importance of commodity markets in overall economic performance. Policymakers should therefore consider commodity-price dynamics when designing fiscal and monetary policies, while investors can use oil and gold as hedging instruments against macroeconomic risk.

Encouraging economic diversification toward sectors less dependent on commodities, such as technology and manufacturing, can further strengthen resilience. In the short term, mechanisms like hedging contracts, stabilization funds, and flexible policy adjustments can help moderate the impact of commodity-price fluctuations on the broader economy.

6. Conclusion

This study examined the dynamic relationships between economic growth, inflation, financial-market volatility, commodity prices, and cryptocurrency metrics — specifically the trading volumes and returns of Bitcoin and Ethereum — using quarterly panel data for 14 countries from Q3 2015 to Q3 2023. Unlike previous studies, it compared the top two cryptocurrencies simultaneously to evaluate their combined and distinct effects on economic performance.

Panel-data regression was implemented with cross-sectional dependence and second-generation unit-root tests. Short-run relationships were further analyzed using panel Granger-causality tests. The empirical results confirmed significant cross-sectional dependence, justifying the use of advanced estimators. The GM-FMOLS results demonstrated robust relationships between GDP growth and macroeconomic indicators, including a notable influence of cryptocurrency metrics. The presence of cointegration supports the existence of a long-run equilibrium among the variables, reflecting the interconnectedness of global financial and real sectors.

Causality analysis revealed bidirectional relationships between Bitcoin trading volume (*BTCV*) and GDP, and unidirectional causality from GDP to both Ethereum's rate of return (*ETHR*) and trading volume (*ETHV*). Additional findings include unidirectional causality from *VIX* to growth, from growth to oil prices, and bidirectional causality between growth and gold prices. The sensitivity of cryptocurrency returns to financial volatility and the unidirectional causality from Bitcoin returns (*BTCR*) to inflation highlight the growing integration of digital assets into the macroeconomic system.

These results confirm that cryptocurrencies and growth are interlinked, carrying important policy implications. To mitigate the destabilizing effects of crypto-market volatility, policymakers must establish robust regulatory frameworks. Integrating cryptocurrency oversight into broader monetary-policy strategies can enhance financial stability and strengthen inflation-targeting regimes. For investors, incorporating cryptocurrencies into diversified portfolios may offer effective hedging opportunities, but such exposure requires disciplined risk-management practices.

Overall, the findings emphasize the complex and evolving relationships among macroeconomic variables, cryptocurrency markets, and GDP growth. The positive effects of Bitcoin and Ethereum returns point to a potentially constructive role for digital assets in economic development. However, the adverse effects of cryptocurrency volatility highlight the inherent uncertainties of this market. Understanding these dual dynamics is crucial for both policymakers and investors.

Future research could expand on these findings by employing dynamic panel estimators that integrate additional dimensions such as market sentiment indices, technological innovation, and financial inclusion metrics to further clarify the multifaceted role of cryptocurrencies in global economic systems.

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Appendix A. Panel causality test results

Hypotheses	W-bar stat.	Z-bar stat.	Prob.	Conclusion
VIX ⇏ GDP	21.4418	47.4077	0.0000*	*VIX → GDP*
GDP ⇏ WTI	8.7538	17.8751	0.0000*	*GDP → WTI*
GDP ⇏ GOLD	0.1926	−2.0517	0.0402**	*GDP ↔ GOLD*
GOLD ⇏ GDP	4.2127	7.3055	0.0000*	
CPI ⇏ WTI	2.5479	3.4304	0.0006*	*CPI → WTI*
WTI ⇏ VIX	0.0381	−2.4114	0.0159**	*WTI ↔ VIX*
VIX ⇏ WTI	8.3125	16.8481	0.0000*	
WTI ⇏ GOLD	2.8541	4.1431	0.0000*	*WTI ↔ GOLD*
Hypotheses for BTCR				
BTCR ⇏ CPI	2.1647	2.5385	0.0111**	*BTCR → CPI*
VIX ⇏ BTCR	2.8541	4.1431	0.0000*	*VIX → BTCR*
BTCR ⇏ WTI	0.0027	−2.4936	0.0126**	*BTCR ↔ WTI*
WTI ⇏ BTCR	0.0095	−2.4780	0.0132**	
Hypotheses for BTCV				
BTCV ⇏ GDP	2.8560	4.1476	0.0000*	*BTCV ↔ GDP*
GDP ⇏ BTCV	43.0501	97.7028	0.0000*	
BTCV ⇏ VIX	0.0858	−2.3004	0.0214**	*BTCV → VIX*
BTCV ⇏ WTI	4.0095	6.8325	0.0000*	*BTCV ↔ WTI*
WTI ⇏ BTCV	22.6643	50.2530	0.0000*	
BTCV ⇏ GOLD	0.0531	−2.3764	0.0175**	*BTCV → GOLD*
Hypotheses for ETHR				
GDP ⇏ ETHR	0.1131	−2.2369	0.0253**	*GDP → ETHR*
VIX ⇏ ETHR	2.8541	4.1431	0.0000*	*VIX → ETHR*
WTI ⇏ ETHR	0.0082	−2.4809	0.0131**	*WTI → ETHR*
Hypotheses for ETHV				
GDP ⇏ ETHV	18.6639	40.9420	0.0000*	*GDP → ETHV*
WTI ⇏ ETHV	8.5672	17.4410	0.0000*	*WTI → ETHV*
ETHV ⇏ GOLD	0.0001	−2.5000	0.0124**	*ETHV ↔ GOLD*
GOLD ⇏ ETHV	0.0132	−2.4693	0.0135**	

Note: (⇏) denotes "no Granger causality from A to B" under the Dumitrescu–Hurlin panel test (Dumitrescu and Hurlin, 2012) with two lags. → and ↔ denote unidirectional and bidirectional causality, respectively. * $p < 0.01$, ** $p < 0.05$, *** $p < 0.1$.

Source: Authors' calculations.