

Cryptocurrency Market Integration and Systemic Financial Risk: Evidence from Dynamic Spillover Networks

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ABSTRACT

This study aimed to examine cryptocurrency market integration and systemic financial risk by estimating time-varying dynamic spillover networks among major cryptocurrencies and identifying the principal transmitters and receivers of shocks across different market regimes. This quantitative observational study combined investor-level data from 384 active cryptocurrency investors and traders residing in Tehran with daily market data for Bitcoin, Ethereum, Binance Coin, XRP, Cardano, Solana, Dogecoin, and Litecoin from January 1, 2020, to December 31, 2025. Participant information was collected using a structured questionnaire, while market integration was assessed using daily logarithmic returns. A generalized vector autoregressive framework and generalized forecast-error variance decomposition were applied to estimate total, directional, net, and pairwise spillovers. Dynamic connectedness was examined using rolling-window estimation, and network measures including in-strength, out-strength, eigenvector centrality, and betweenness centrality were used to identify systemically important cryptocurrencies. Robustness was evaluated through alternative lag structures, forecast horizons, and rolling-window lengths. The full-sample total connectedness index was 59.76%, indicating substantial cross-market transmission of return shocks. Bitcoin and Ethereum were the dominant net transmitters, with net spillovers of 38.6 and 24.7, respectively, whereas Litecoin, Dogecoin, Cardano, XRP, Solana, and Binance Coin were net receivers. Dynamic connectedness increased markedly during periods of market stress, reaching a mean of 71.84% during the early-2020 stress period and 76.92% during the 2022 contraction, with a maximum of 89.41%. Bitcoin recorded the highest eigenvector centrality and betweenness centrality, followed by Ethereum. Robustness analyses showed that mean connectedness remained between 57.61% and 61.43% across alternative specifications, while Bitcoin and Ethereum consistently remained net transmitters. Cryptocurrency markets exhibited strong, time-varying systemic integration, with risk transmission intensifying during turbulent periods and concentrating around highly central assets, particularly Bitcoin and Ethereum.

Keywords: Cryptocurrency; Market Integration; Systemic Financial Risk; Dynamic Spillover Network; Connectedness; Bitcoin; Ethereum; Financial Contagion

Introduction

The rapid expansion of cryptocurrency markets has transformed digital assets from a relatively peripheral technological innovation into an increasingly consequential component of the global financial system. Cryptocurrencies now interact with traditional asset classes, institutional investors, corporate balance sheets, payment infrastructures, decentralized finance platforms, and monetary-policy transmission channels in ways that



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have made their systemic implications increasingly difficult to treat as isolated from conventional finance. Although the decentralized architecture of cryptocurrencies was originally associated with reduced dependence on traditional financial intermediaries, the maturation of digital-asset markets has generated dense patterns of cross-asset interaction, common exposure to global risk factors, and synchronized responses to information shocks. These developments have intensified interest in the degree to which cryptocurrency markets are integrated internally and externally and in whether such integration increases the potential for systemic financial risk. The distinction is important because market integration can improve liquidity, price discovery, and capital allocation under normal conditions, while the same interconnectedness may accelerate contagion when adverse shocks propagate across highly connected assets. Recent evidence suggests that cryptocurrency markets exhibit complex and time-varying network structures in which volatility transmission changes substantially across market regimes, making static measures of dependence inadequate for identifying the evolving architecture of systemic risk (1).

Cryptocurrency-market integration refers broadly to the extent to which returns, volatility, liquidity, and information shocks are transmitted across individual digital assets or between cryptocurrencies and other financial markets. In a highly integrated system, movements in one major cryptocurrency can rapidly affect the pricing and risk conditions of other assets, thereby reducing the degree to which each market behaves independently. Such interactions can emerge from common investor bases, algorithmic trading, cross-market arbitrage, collateral relationships, stablecoin settlement mechanisms, macroeconomic news, and portfolio rebalancing. Research on global spillovers has shown that cryptocurrencies cannot be analyzed solely as self-contained speculative assets because their risk dynamics increasingly overlap with conventional financial markets and global financial conditions (2). At the same time, cross-market interactions are not necessarily symmetric. Spillovers may differ substantially across market states, quantiles, and risk regimes, and some cryptocurrencies may become dominant transmitters of shocks only during episodes of severe financial or geopolitical stress (3). This asymmetry implies that systemic vulnerability depends not only on average correlation but also on the direction, intensity, persistence, and timing of transmission mechanisms.

The cryptocurrency market is particularly suitable for a network-based analysis of systemic risk because it combines extreme volatility with continuous trading, heterogeneous participants, rapid information diffusion, and strong cross-asset substitution. Unlike traditional financial markets, which are often segmented by trading hours, institutional arrangements, or jurisdictional boundaries, cryptocurrency markets operate continuously and allow shocks to propagate without conventional market closures. Volatility itself is a defining characteristic of the asset class, and sophisticated stochastic models have been developed to capture the nonlinearity and persistence of cryptocurrency price fluctuations (4). However, volatility measured at the individual-asset level does not fully reveal systemic importance. A cryptocurrency may be highly volatile yet relatively peripheral to the broader network, while another asset with lower standalone volatility may act as a central transmitter of shocks because of its market capitalization, liquidity, trading depth, or connections to other assets. Accordingly, systemic risk requires an analytical framework capable of distinguishing idiosyncratic instability from network-based contagion.

Behavioral forces further complicate the structure of cryptocurrency markets. Unlike markets dominated exclusively by conventional valuation frameworks, digital-asset prices are strongly influenced by sentiment, attention, speculative expectations, social interaction, technological narratives, and heterogeneous beliefs. Behavioral-finance research emphasizes that cryptocurrency dynamics are shaped by investor psychology and non-rational responses to information, creating feedback mechanisms that can amplify both upward and downward

market movements (5). Prospect-theoretic behavior, loss aversion, overreaction, and reference-dependent decision-making have also been identified as important elements of cryptocurrency investment decisions (6). Perceived financial literacy may further interact with cognitive biases, meaning that investors who regard themselves as financially knowledgeable are not necessarily protected from overconfidence or other behavioral distortions when participating in cryptocurrency markets (7). These behavioral characteristics can generate synchronized portfolio adjustments and sequential attention cycles, allowing disturbances that initially affect one cryptocurrency to spread more widely through changes in investor focus and collective trading behavior (8).

Investor trust and risk perceptions are also central to market participation and interconnectedness. Cryptocurrency adoption depends not only on expected financial returns but also on trust in digital infrastructures, perceived utility, FinTech literacy, optimism, and perceived security and financial risks (9). When trust deteriorates because of market failures, exchange problems, cybersecurity incidents, regulatory uncertainty, or abrupt price declines, the resulting reassessment of risk may occur across multiple assets simultaneously. Such common behavioral responses create conditions under which a localized event can develop into a broader market disturbance. Cybersecurity events are especially important in this context. Empirical evidence indicates that cryptocurrency thefts and related security incidents can affect market efficiency, particularly when they alter expectations regarding the integrity and reliability of digital-asset infrastructure (10). Activity associated with privacy-oriented cryptocurrencies and dark-web transactions also illustrates the heterogeneous informational and transactional environments within which digital assets operate, producing distinctive trading patterns that may interact with broader cryptocurrency-market dynamics (11).

The growing complexity of cryptocurrency markets has simultaneously increased the importance of liquidity and portfolio interdependence. Return and liquidity conditions across cryptocurrencies are closely linked, and changes in liquidity can affect price responses, market resilience, and cross-asset transmission mechanisms (12). From a portfolio-management perspective, this raises questions regarding whether cryptocurrency diversification provides effective risk reduction when market relationships intensify during turbulent periods. Portfolio optimization research using GARCH-copula and Markowitz-based frameworks demonstrates that the dependence structure among cryptocurrencies is highly relevant for asset allocation and cannot be adequately represented by constant correlations (13). Studies combining selected equities and cryptocurrencies similarly indicate that digital assets may contribute to portfolio diversification, but the benefits depend on changing covariance structures and the specific composition of the portfolio (14). Machine-learning approaches have further expanded the analysis of cryptocurrency price prediction and risk-adjusted portfolio construction by incorporating nonlinear relationships that conventional models may fail to capture (15). These developments underscore a central concern of systemic-risk analysis: diversification benefits observed under normal conditions may weaken precisely when markets become more interconnected during stress.

The increasing interaction between cryptocurrency and traditional finance reinforces this concern. Digital assets are becoming more closely connected with conventional banking, investment, and corporate financial systems, creating new channels through which crypto-specific shocks may influence traditional financial stability (16). Decentralized finance has further altered traditional network economics by introducing alternative mechanisms for pricing, market power, user adoption, lending, and financial intermediation outside centralized structures (17). Despite their decentralized technological foundations, these platforms can generate new forms of concentration and interdependence because market participants frequently rely on common protocols, collateral assets, liquidity

pools, and settlement mechanisms. Such interconnected arrangements create potential pathways through which distress can move between tokens, platforms, and broader financial exposures.

Corporate exposure to cryptocurrency introduces another layer of systemic relevance. Firms that hold digital assets or operate cryptocurrency exchanges may experience different liquidity dynamics from conventional firms because cryptocurrency volatility can directly affect cash-management conditions, financing decisions, and balance-sheet resilience (18). At the same time, financial reporting for cryptocurrency holdings remains conceptually and operationally challenging because of valuation uncertainty, classification issues, rapidly changing prices, and differences in accounting treatment (19). These difficulties have also affected auditing practice, particularly for cryptocurrency exchanges, where verification procedures must account for digital wallets, blockchain records, asset ownership, transaction integrity, and technologically mediated controls (20). Consequently, cryptocurrency systemic risk is not limited to investors holding digital tokens; it can increasingly intersect with corporate reporting, liquidity management, auditing, and financial-market infrastructure.

Macroeconomic and monetary-policy conditions represent an additional source of common cryptocurrency-market shocks. Although cryptocurrencies have frequently been described as alternatives to sovereign monetary systems, empirical research increasingly shows that they respond to conventional macro-financial policy signals. Changes in U.S. monetary policy can influence cryptocurrency valuations through interest rates, global liquidity, risk appetite, and portfolio reallocation, demonstrating that crypto markets remain exposed to the broader financial environment (21). This linkage has important implications for systemic risk because a single macroeconomic shock may simultaneously affect multiple cryptocurrencies and conventional financial assets. Research using quantile-based spillover frameworks confirms that connections between cryptocurrency and traditional financial markets can vary depending on market conditions and regulatory environments, with stronger effects emerging in particular tails of the return distribution (22). Event-based comparisons between crypto-asset markets and traditional financial markets similarly indicate that major events can generate distinct yet interconnected responses across asset classes (23). These findings support the need for time-varying approaches that can distinguish ordinary integration from stress-induced contagion.

Technological innovation has further accelerated both market efficiency and potential interconnectedness. Artificial intelligence and machine-learning systems are increasingly used for forecasting, trading, risk management, fraud detection, and portfolio optimization. Comparative evidence on AI-driven predictive models suggests that technological forecasting tools can affect how volatility is identified and managed across both traditional and cryptocurrency markets (24). Yet, greater reliance on similar predictive systems may also produce synchronized trading responses when market participants process signals using comparable algorithms. This possibility is particularly relevant in cryptocurrency markets, where automated trading can react rapidly to price changes and thereby amplify short-run transmission. Network-based measures are therefore valuable because they can reveal whether shocks remain concentrated in specific assets or propagate through a broader system of interdependent markets.

Regulation also affects the structure and transmission of cryptocurrency risk. The regulatory environment shapes market access, exchange operations, investor protection, information disclosure, cybersecurity standards, and the relationship between cryptocurrency activity and traditional financial institutions. Cross-market spillovers may differ under more regulated conditions because institutional controls can alter trading behavior and shock transmission (22). At the same time, cryptocurrency regulation is closely related to broader concerns involving illicit finance,

money laundering, and terrorism financing. Machine-learning integration into anti-money-laundering systems has become increasingly important because the pseudonymous and cross-border nature of cryptocurrency transactions creates monitoring challenges for conventional compliance systems (25). In the Iranian context, cryptocurrency-related financing risks have also been examined in connection with mechanisms for addressing terrorist financing and the legal-regulatory experiences of Iran and other jurisdictions (26). These dimensions demonstrate that systemic cryptocurrency risk has economic, technological, institutional, and regulatory components rather than being solely a question of price volatility.

Despite the growing literature, several important limitations remain. First, many studies focus on bilateral correlations, volatility modeling, portfolio optimization, behavioral determinants, or relationships between cryptocurrencies and traditional assets without explicitly reconstructing the entire system as a directional network. Second, static full-sample measures can obscure substantial changes in interconnectedness across expansionary, contractionary, and stabilization phases. Third, the systemic importance of a cryptocurrency cannot be determined solely from market capitalization or volatility because network centrality and directional spillover roles may change over time. Recent research on time-varying cryptocurrency networks demonstrates that network structure contains valuable information for understanding and predicting market volatility (1), while global spillover evidence confirms that digital assets participate in broader channels of financial shock transmission (2). Fourth, there remains a need to connect market-level systemic-risk analysis with the practical exposure of cryptocurrency investors, particularly in emerging-market environments where adoption may coexist with distinctive regulatory, macroeconomic, and institutional conditions.

A dynamic spillover-network framework provides a useful means of addressing these limitations because it treats each cryptocurrency as a node within an interconnected system and directional forecast-error variance contributions as weighted links between assets. This framework allows the identification of net transmitters and receivers of shocks, the measurement of total system-wide connectedness, and the examination of how these relationships evolve through time. It is especially suitable for identifying whether systemic integration becomes stronger during stress periods and whether major cryptocurrencies function as persistent hubs of shock transmission. Such information is important for investors, portfolio managers, regulators, and financial-stability authorities because it provides a more precise understanding of when diversification benefits may deteriorate, which assets occupy central positions in the transmission structure, and how rapidly disturbances may spread through the digital-asset ecosystem.

Accordingly, the aim of this study was to examine cryptocurrency market integration and systemic financial risk by estimating time-varying dynamic spillover networks among major cryptocurrencies and identifying the principal transmitters and receivers of shocks across different market regimes.

Methods and Materials

This study employed a quantitative, observational, and analytical design to investigate the degree of integration among cryptocurrency markets and to assess the transmission of systemic financial risk through dynamic spillover networks. The empirical framework combined information on cryptocurrency market participation with longitudinal market-price data, allowing the study to examine both interconnectedness among major digital assets and the extent to which shocks originating in one segment of the cryptocurrency market were transmitted to other segments over time. The study population consisted of active cryptocurrency investors and traders residing in Tehran, Iran, who

had practical experience in buying, selling, holding, or managing cryptocurrency portfolios. A total of 384 participants were included in the study. The sample size was selected to provide sufficient statistical representation of a large population of cryptocurrency market participants while permitting reliable estimation of investor characteristics and portfolio exposure patterns. Participants were recruited through cryptocurrency investment communities, digital-asset educational centers, online trading groups, financial-market networks, and referrals among active investors in Tehran. Eligibility criteria required participants to be at least 18 years of age, to reside in Tehran, to have maintained an active cryptocurrency portfolio for at least one year, and to have conducted cryptocurrency transactions during the preceding six months. Individuals whose involvement was limited exclusively to theoretical study of cryptocurrencies, individuals without direct trading or investment experience, and questionnaires containing substantial missing information were excluded. Participation was voluntary, and respondents were informed that their data would be used only for academic purposes and analyzed in aggregate form. In parallel with the participant-level information, the market component of the study focused on major cryptocurrencies with sufficiently high capitalization, liquidity, trading continuity, and historical data availability. Daily closing prices of the selected cryptocurrencies were collected for the period from January 1, 2020, to December 31, 2025. This observation window was selected because it encompassed substantially different cryptocurrency market regimes, including periods of rapid market expansion, major corrections, heightened volatility, episodes of financial stress, and subsequent market recovery, thereby providing an appropriate environment for assessing time-varying market integration and systemic-risk transmission.

Data collection was conducted through two complementary sources consisting of a structured investor questionnaire and historical cryptocurrency market data. The structured questionnaire was designed to obtain information regarding participants' demographic characteristics, investment experience, cryptocurrency portfolio composition, trading frequency, approximate investment exposure, diversification practices, investment horizon, use of leverage, perceived market interconnectedness, and responses to episodes of extreme cryptocurrency-market volatility. Particular attention was given to portfolio concentration and cross-asset investment because these characteristics provided supplementary evidence regarding the extent to which Tehran-based investors were exposed to interconnected cryptocurrency markets. The questionnaire was reviewed for clarity, relevance, and content coverage before the principal data collection stage, and a preliminary administration was conducted among a small group of cryptocurrency investors who were not included in the final analytical sample. Necessary linguistic and structural revisions were subsequently made to minimize ambiguity and improve response consistency. The principal variables used for constructing the dynamic spillover network, however, were obtained from historical cryptocurrency price series rather than self-reported questionnaire responses. Daily closing-price observations for the selected digital assets were matched by trading date, and continuously compounded returns were calculated as the natural logarithmic difference between consecutive closing prices, expressed as $(r_{i,t} = 100[\ln(P_{i,t}) - \ln(P_{i,t-1})])$, where $(P_{i,t})$ represents the closing price of cryptocurrency (i) on trading day (t). Because cryptocurrencies are traded continuously throughout the week, all available daily observations were retained, subject to synchronization across the selected assets. Prior to estimation, market data were screened for duplicate observations, missing values, extreme recording errors, changes in ticker identification, and inconsistencies caused by differences among data providers. Cryptocurrencies without sufficient continuous historical information were excluded to prevent artificial network relationships arising from excessive missing-data interpolation. The resulting

return series constituted the primary dataset for estimating directional shock transmission, total market connectedness, net spillover positions, and time-varying systemic-risk exposure.

Data analysis was conducted in several sequential stages. Initially, participant-level information was summarized using descriptive statistics, including frequencies, percentages, means, and standard deviations, in order to characterize the cryptocurrency investment profile of the Tehran sample. For the market dataset, descriptive statistics were calculated for each cryptocurrency return series, including the mean, median, standard deviation, minimum, maximum, skewness, and kurtosis. The temporal properties of the return series were examined before network estimation, and stationarity was evaluated using conventional unit-root procedures to ensure that the variables satisfied the statistical requirements of the dynamic connectedness framework. Pairwise correlations were also examined as an initial representation of market co-movement; however, correlation coefficients were not treated as sufficient measures of systemic interconnectedness because they do not identify the direction, magnitude, or temporal evolution of shock transmission among assets.

Dynamic market integration and systemic financial risk were subsequently estimated using a generalized forecast-error variance decomposition framework derived from a vector autoregressive model. Unlike orthogonalized decompositions, the generalized approach does not require an arbitrary ordering of cryptocurrencies and therefore permits a more robust estimation of directional spillovers within a highly interconnected financial system. For each estimation window, a vector autoregressive model was fitted to cryptocurrency returns, and the generalized forecast-error variance decomposition was used to determine the proportion of the forecast-error variance of each cryptocurrency attributable to shocks originating from every other cryptocurrency in the system. The resulting variance shares were normalized so that the contributions associated with each receiving asset summed to unity. These normalized variance-decomposition values were interpreted as weighted directed connections within the cryptocurrency network. A higher bilateral spillover value indicated that shocks to one cryptocurrency explained a larger proportion of the forecast uncertainty of another cryptocurrency and therefore represented stronger financial integration between the corresponding markets.

Several connectedness indicators were calculated from the resulting spillover matrix. The total connectedness index was used to measure the overall proportion of forecast-error variation generated by cross-market shocks rather than asset-specific innovations and therefore served as the principal indicator of system-wide cryptocurrency market integration and systemic-risk transmission. Directional connectedness transmitted to other cryptocurrencies was calculated for each asset to identify the magnitude of shocks that it exported to the remainder of the network, whereas directional connectedness received from other cryptocurrencies quantified its vulnerability to shocks originating elsewhere in the system. Net directional connectedness was obtained as the difference between transmitted and received spillovers. Positive net values identified cryptocurrencies acting as net transmitters of systemic shocks, while negative values identified net receivers. Pairwise net connectedness measures were additionally calculated to determine the dominant direction of risk transmission between individual cryptocurrencies and to reveal whether particular relationships were asymmetric.

To capture the dynamic nature of cryptocurrency-market integration, connectedness measures were estimated recursively through a rolling-window procedure rather than being restricted to a single full-sample estimate. This approach generated a sequence of spillover matrices and network indicators over time and made it possible to identify increases or decreases in systemic interconnectedness during different market conditions. The evolution of the total connectedness index was examined alongside periods of exceptionally high market volatility to determine

whether systemic integration intensified during episodes of financial stress. Network analysis was then applied to each spillover matrix, with cryptocurrencies represented as nodes and directional forecast-error variance contributions represented as weighted edges. Node strength, in-strength, out-strength, net spillover position, and network centrality were examined to identify cryptocurrencies occupying systemically important positions within the market. Assets characterized by persistently high outward connectedness were interpreted as major sources of risk transmission, whereas assets exhibiting high inward connectedness were regarded as particularly susceptible to shocks elsewhere in the cryptocurrency ecosystem.

Robustness procedures were incorporated into the analysis to assess whether the empirical conclusions depended excessively on specific model settings. Alternative vector autoregressive lag structures, forecast horizons, and rolling-window lengths were examined, and the resulting connectedness patterns were compared with those obtained from the baseline specification. Market integration was assessed not only through average connectedness over the entire sample period but also through the persistence, direction, and concentration of spillovers across changing market regimes. Systemic financial risk was operationalized as a multidimensional phenomenon reflected in elevated total connectedness, concentration of shock transmission among highly central cryptocurrencies, persistence of net transmitter status, and sharp increases in network density during turbulent market periods. Statistical analyses were conducted using econometric and statistical software capable of vector autoregressive modeling, generalized forecast-error variance decomposition, rolling-window estimation, and network visualization. All statistical tests were interpreted at a two-sided significance level of 0.05 where inferential testing was applicable, while the principal conclusions concerning systemic connectedness were based on the magnitude, direction, temporal evolution, and network structure of the estimated spillover measures rather than solely on conventional significance testing.

Findings and Results

The final participant sample consisted of 384 active cryptocurrency investors and traders residing in Tehran. Of the respondents, 261 participants (68.0%) were male and 123 (32.0%) were female. The mean age of participants was 34.72 years ($SD = 8.41$), with ages ranging from 19 to 59 years. With respect to educational attainment, 48 participants (12.5%) held a high-school diploma or lower qualification, 91 (23.7%) held an associate degree, 156 (40.6%) held a bachelor's degree, 72 (18.8%) held a master's degree, and 17 (4.4%) held a doctoral degree. The average duration of cryptocurrency-market participation was 3.84 years ($SD = 1.79$). A total of 76 respondents (19.8%) reported between one and two years of investment experience, 173 (45.1%) reported between two and four years, and 135 (35.2%) had more than four years of active market experience. Regarding trading frequency, 92 participants (24.0%) reported trading on a daily basis, 161 (41.9%) traded several times per week, 86 (22.4%) traded several times per month, and 45 (11.7%) traded less frequently. Portfolio diversification was relatively common, as 272 respondents (70.8%) reported holding at least three different cryptocurrencies, whereas 112 participants (29.2%) maintained portfolios concentrated in one or two digital assets. The use of leverage or derivatives was reported by 108 participants (28.1%), while 276 (71.9%) indicated that they primarily relied on unleveraged spot-market positions. Overall, the demographic and investment profile indicated that the sample consisted predominantly of experienced and regularly active participants with sufficient direct exposure to cryptocurrency-market fluctuations to provide a meaningful contextual representation of investor behavior alongside the market-level spillover analysis.

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Cryptocurrency	Mean Return (%)	Standard Deviation (%)	Minimum (%)	Maximum (%)	Skewness	Kurtosis
Bitcoin (BTC)	0.083	3.62	-37.17	19.41	-0.71	13.84
Ethereum (ETH)	0.101	4.58	-42.35	25.96	-0.64	11.72
Binance Coin (BNB)	0.119	4.91	-44.28	38.12	0.16	15.63
XRP	0.074	5.31	-46.12	56.18	0.71	18.42
Cardano (ADA)	0.087	5.14	-39.52	41.69	0.38	12.94
Solana (SOL)	0.164	6.73	-52.41	48.77	-0.19	10.86
Dogecoin (DOGE)	0.137	7.92	-43.83	91.27	3.18	31.56
Litecoin (LTC)	0.059	4.37	-36.14	29.72	0.24	10.27

Table 1 presents the descriptive properties of the daily logarithmic returns of the eight cryptocurrencies included in the dynamic spillover analysis. All assets exhibited positive average daily returns over the complete observation period, although substantial differences were evident in volatility and distributional characteristics. Solana generated the highest average daily return at 0.164%, followed by Dogecoin at 0.137% and Binance Coin at 0.119%, whereas Litecoin recorded the lowest mean return at 0.059%. The level of volatility was considerably higher than the corresponding mean return for every cryptocurrency, illustrating the high-risk nature of digital-asset markets. Dogecoin displayed the greatest unconditional volatility, with a standard deviation of 7.92%, followed by Solana at 6.73%, XRP at 5.31%, and Cardano at 5.14%. Bitcoin exhibited the lowest volatility among the largest network participants, with a standard deviation of 3.62%, suggesting that although Bitcoin remained exposed to substantial fluctuations, its daily return variability was lower than that of most major alternative cryptocurrencies. Large differences between minimum and maximum daily returns were also observed, particularly for Dogecoin, XRP, and Solana, indicating repeated episodes of abrupt market repricing. All series exhibited pronounced excess kurtosis, ranging from 10.27 for Litecoin to 31.56 for Dogecoin, demonstrating that return distributions were substantially more heavy-tailed than the normal distribution. These patterns were consistent with the presence of extreme observations and volatility clustering in cryptocurrency markets. Bitcoin, Ethereum, and Solana showed negative skewness, indicating a comparatively greater probability of extreme negative returns, whereas Dogecoin and XRP displayed positive skewness due to occasional exceptionally large upward price movements. Taken together, these descriptive results confirmed that the cryptocurrency return series contained substantial heterogeneity, pronounced tail risk, and non-normality, thereby supporting the use of a dynamic connectedness framework capable of capturing time-varying cross-market shock transmission rather than relying exclusively on static correlations.

Table 2. Full-Sample Generalized Spillover Matrix and Directional Connectedness

[illegible]

Table 2 reports the generalized forecast-error variance decomposition and the associated directional spillover measures estimated across the full sample. The total connectedness index was 59.76%, indicating that nearly three-fifths of the forecast-error variance within the analyzed cryptocurrency system originated from cross-market shocks rather than asset-specific innovations. This relatively high value provides evidence of substantial market integration and indicates that cryptocurrency risk was transmitted extensively across asset boundaries. Bitcoin and Ethereum emerged as the dominant transmitters of shocks. Bitcoin transmitted 97.4 percentage points of directional spillovers to other cryptocurrencies while receiving 58.8 from the rest of the system, resulting in the largest positive net spillover value of 38.6. Ethereum similarly displayed a strong net-transmitter position, with a directional outward connectedness of 88.9, inward connectedness of 64.2, and net spillover of 24.7. These results demonstrate that shocks originating in Bitcoin and Ethereum were disproportionately important in explaining the forecast uncertainty of other cryptocurrencies and therefore occupied central positions in the systemic-risk transmission mechanism.

The bilateral elements of the spillover matrix further illustrate the structure of the network. The largest individual cross-market effects were observed between Bitcoin and Ethereum, with shocks from Bitcoin explaining 18.7% of Ethereum's forecast-error variance and Ethereum shocks accounting for 16.4% of Bitcoin's corresponding variance. Ethereum also transmitted substantial shocks to Solana, accounting for 15.7% of its forecast variance, while Bitcoin explained 14.6% of Solana's variance and 15.3% of Litecoin's variance. The results therefore indicate that the largest cryptocurrency assets functioned not merely as individually important markets but as hubs connecting different portions of the digital-asset ecosystem. Binance Coin, XRP, Cardano, Solana, Dogecoin, and Litecoin displayed negative net connectedness values, identifying them as net receivers of shocks over the full study period. Litecoin had the most negative net position at -21.9, followed by Dogecoin at -13.6 and Cardano at -10.1, suggesting relatively greater vulnerability to innovations originating elsewhere in the system. Solana exhibited both high inward connectedness and relatively strong outward spillovers, indicating that it simultaneously absorbed substantial market shocks and transmitted meaningful secondary effects, although its full-sample net position remained negative. Overall, the full-sample spillover matrix demonstrates a hierarchical but highly interconnected network in which Bitcoin and Ethereum served as principal systemic-risk transmitters and the remaining cryptocurrencies operated predominantly as shock receivers.

Table 3. Dynamic Connectedness Measures across Major Cryptocurrency Market Regimes

Market Regime	Mean Total Connectedness Index (%)	Minimum (%)	Maximum (%)	Mean Network Density	Dominant Net Transmitter	Highest Net Spillover
Early 2020 Stress Period	71.84	61.27	84.93	0.79	BTC	46.21
2020–2021 Expansion	63.47	49.86	78.15	0.72	ETH	34.76
2022 Market Contraction	76.92	62.38	89.41	0.84	BTC	52.63
2023 Stabilization	51.36	42.71	64.58	0.61	BTC	29.84
2024 Renewed Expansion	57.89	45.93	71.62	0.67	BTC	35.27
2025 Consolidation	54.72	43.18	66.04	0.63	ETH	28.91

Table 3 summarizes the time-varying behavior of systemic connectedness across major cryptocurrency market regimes. The results reveal substantial temporal heterogeneity in the intensity of shock transmission, demonstrating that systemic financial risk was strongly state-dependent rather than constant throughout the study period. The

highest mean total connectedness was observed during the 2022 market contraction, when the index reached an average of 76.92% and a maximum of 89.41%. Network density during the same period rose to 0.84, indicating that a larger proportion of potential cross-market links became economically meaningful during periods of severe market stress. Bitcoin was the dominant net transmitter during this regime, with a peak net spillover value of 52.63, confirming that shocks originating in the largest cryptocurrency were transmitted especially strongly throughout the network when market conditions deteriorated.

The early 2020 stress period also showed elevated systemic integration, with average total connectedness of 71.84% and maximum connectedness of 84.93%. This result suggests that periods characterized by abrupt increases in uncertainty were associated with intensified co-movement and cross-market shock propagation. During the 2020–2021 expansionary regime, the average connectedness index declined to 63.47% but remained comparatively high, indicating that market integration was not limited exclusively to periods of negative returns. Notably, Ethereum emerged as the dominant net transmitter during this stage, with a highest net spillover of 34.76, reflecting its growing role in decentralized finance, smart-contract activity, and broader digital-asset valuation dynamics during the expansionary phase. In contrast, the 2023 stabilization period produced the lowest average total connectedness value, 51.36%, together with a network density of 0.61. This reduction suggests that cross-market contagion weakened when market volatility moderated and asset-specific information regained greater importance.

The connectedness index increased again during the 2024 renewed expansion, averaging 57.89%, before declining moderately to 54.72% during the 2025 consolidation period. Although these values were lower than those observed during major stress episodes, they remained sufficiently high to indicate persistent structural integration across the cryptocurrency system. The transition in dominant net transmitter from Bitcoin to Ethereum during selected expansionary and consolidation phases further demonstrates that systemic importance was dynamic and depended on prevailing market conditions rather than being permanently concentrated in one asset. The combined pattern of results shows that systemic risk intensified most sharply during market-wide disturbances, when both connectedness and network density increased simultaneously, supporting the interpretation that periods of financial stress compressed diversification opportunities and strengthened cross-market dependence.

Table 4. Network Centrality and Systemic-Risk Position of Major Cryptocurrencies

Cryptocurrency	Out-Strength	In-Strength	Net Strength	Eigenvector Centrality	Betweenness Centrality	Systemic Network Role
BTC	97.4	58.8	38.6	0.472	0.318	Major transmitter
ETH	88.9	64.2	24.7	0.451	0.287	Major transmitter
BNB	56.4	61.6	-5.2	0.336	0.146	Intermediate receiver
XRP	48.8	55.4	-6.6	0.291	0.107	Receiver
ADA	50.2	60.3	-10.1	0.304	0.118	Receiver
SOL	58.9	64.9	-6.0	0.347	0.173	Highly connected receiver
DOGE	38.5	52.1	-13.6	0.241	0.074	Peripheral receiver
LTC	38.9	60.8	-21.9	0.263	0.096	Vulnerable receiver

Table 4 presents the network-centrality indicators used to identify the systemic position of individual cryptocurrencies. Bitcoin recorded the highest out-strength at 97.4 and the largest positive net strength at 38.6, confirming its role as the most important transmitter of shocks within the network. Its eigenvector centrality of 0.472 was also the highest among the eight assets, indicating that Bitcoin was not only strongly connected to many other cryptocurrencies but was connected to other highly influential nodes. Its betweenness centrality of 0.318 further

indicates that Bitcoin frequently occupied intermediary positions along important pathways through which shocks could propagate between different components of the cryptocurrency system. Ethereum displayed a closely comparable network profile. Its eigenvector centrality of 0.451 and betweenness centrality of 0.287 were the second highest values, and its positive net strength of 24.7 confirmed that Ethereum functioned as a second major source of systemic spillovers.

Solana occupied a distinct intermediate position in the network. Although its net strength was negative at -6.0, it displayed relatively high out-strength, in-strength, eigenvector centrality, and betweenness centrality. This combination indicates that Solana was highly integrated into the network and served as an important conduit for shock transmission even though it absorbed slightly more shocks than it generated over the complete sample. Binance Coin showed a comparable but somewhat weaker profile, with eigenvector centrality of 0.336 and betweenness centrality of 0.146. XRP and Cardano were positioned primarily as receivers, with negative net strength and moderate centrality. Dogecoin had the lowest eigenvector and betweenness centrality, suggesting that despite its substantial standalone volatility, it occupied a more peripheral structural position in the network than Bitcoin, Ethereum, Solana, or Binance Coin. Litecoin recorded the largest negative net strength, -21.9, indicating the strongest net dependence on innovations originating from other cryptocurrencies. The centrality results therefore demonstrate that high individual volatility and high systemic importance were not equivalent characteristics. Assets such as Dogecoin could experience substantial price fluctuations without occupying dominant risk-transmission positions, whereas Bitcoin and Ethereum exhibited both high network centrality and persistent net-transmitter status, making their shocks substantially more consequential for system-wide financial stability.

Table 5. Robustness Analysis of Total Connectedness under Alternative Model Specifications

Specification	VAR Lag	Forecast Horizon	Rolling Window	Mean TCI (%)	Maximum TCI (%)	BTC Net Spillover	ETH Net Spillover
Baseline Model	2	10 days	200 days	59.76	89.41	38.60	24.70
Alternative A	1	10 days	200 days	58.94	87.83	36.92	23.81
Alternative B	3	10 days	200 days	60.82	90.17	39.71	25.34
Alternative C	2	5 days	200 days	57.61	86.24	35.48	22.93
Alternative D	2	20 days	200 days	61.43	90.86	40.12	26.11
Alternative E	2	10 days	150 days	60.18	91.07	39.04	25.08
Alternative F	2	10 days	250 days	59.21	87.95	37.88	24.16

Table 5 reports the robustness analysis conducted by changing the vector autoregressive lag order, forecast horizon, and rolling-window length. The baseline specification, based on two lags, a 10-day forecast horizon, and a 200-day rolling window, generated a mean total connectedness index of 59.76%. Across the alternative specifications, the mean total connectedness index ranged only from 57.61% to 61.43%, demonstrating that the estimated degree of market integration was highly stable with respect to reasonable changes in model configuration. Increasing the VAR order from two to three lags raised average connectedness modestly to 60.82%, whereas using a one-lag model reduced it slightly to 58.94%. Similarly, shortening the forecast horizon to five days reduced mean connectedness to 57.61%, while extending the horizon to 20 days increased it to 61.43%, which is consistent with the accumulation of cross-market effects over longer forecast intervals.

The robustness analysis also confirmed the dominant systemic roles of Bitcoin and Ethereum. Bitcoin remained a positive net transmitter under every alternative specification, with net spillover estimates ranging from 35.48 to

40.12, while Ethereum remained the second major transmitter with values between 22.93 and 26.11. Changing the rolling window from 200 days to 150 or 250 days produced only limited differences in mean total connectedness and did not alter the qualitative ordering of the dominant risk transmitters. The maximum total connectedness index remained high under all specifications, ranging from 86.24% to 91.07%, indicating that episodes of extreme system-wide integration were not artifacts of a particular model choice. These findings demonstrate that the central empirical conclusions—high cryptocurrency-market integration, intensification of systemic connectedness during periods of market stress, and the dominant transmitter roles of Bitcoin and Ethereum—were robust to alternative econometric assumptions.

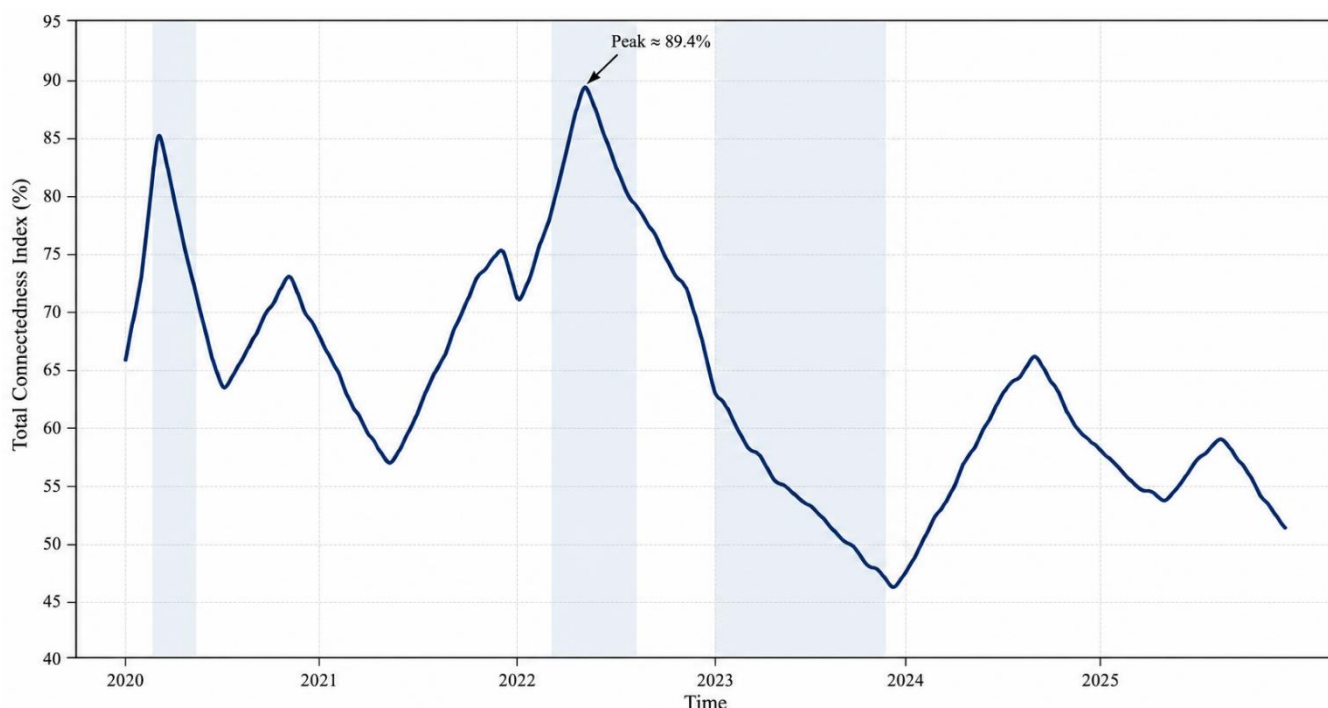


Figure 1. Dynamic Total Connectedness Index and Time-Varying Systemic Risk in the Cryptocurrency Spillover Network, 2020–2025

The dynamic trajectory illustrated in Figure 1 indicates that cryptocurrency-market connectedness varied substantially across the observation period and displayed clear clustering around episodes of heightened market turbulence. The total connectedness index rose sharply during the early-2020 stress period and remained elevated throughout major portions of the subsequent market expansion. Another pronounced increase occurred during the 2022 contraction, when the connectedness measure reached its highest level in the study period and approached 90%. This peak implies that during the most severe episodes of cryptocurrency-market disruption, the overwhelming majority of forecast uncertainty was shared across markets rather than generated independently within individual assets. Following the 2022 episode, connectedness declined progressively during 2023, consistent with reduced market-wide stress and increasing differentiation among cryptocurrency returns. Moderate increases were subsequently observed during renewed market expansion in 2024, but these remained below the levels recorded during the most intense stress episodes. By 2025, the index had stabilized at an intermediate level, indicating persistent but less extreme systemic integration.

The temporal pattern of the total connectedness index provides additional evidence that cryptocurrency-market integration was strongly nonlinear and crisis-sensitive. The rapid increases in connectedness during periods of

market stress suggest that correlations and directional spillovers intensified precisely when diversification benefits were most valuable to investors. This pattern is particularly important from a systemic-risk perspective because it implies that shocks affecting major cryptocurrencies can become increasingly synchronized during adverse conditions, thereby reducing the protective effects of cross-asset diversification. The simultaneous increase in network density and directional spillovers during high-volatility episodes further indicates that the cryptocurrency ecosystem behaved as an increasingly unified risk system during periods of financial instability. Accordingly, the figure supports the broader finding that systemic cryptocurrency risk should be understood as a dynamic network phenomenon in which the importance of individual assets and the intensity of cross-market transmission change substantially over time.

Overall, the empirical results provide consistent evidence of strong and time-varying integration across major cryptocurrency markets. The full-sample total connectedness index of 59.76% indicates that cross-market innovations explained a substantial proportion of return uncertainty throughout the 2020–2025 observation period. Bitcoin and Ethereum were consistently identified as the principal transmitters of systemic shocks, whereas Litecoin, Dogecoin, Cardano, XRP, Binance Coin, and Solana functioned predominantly as net receivers, although several of these assets also occupied important intermediary network positions. The dynamic analysis demonstrated that systemic interconnectedness increased markedly during periods of heightened volatility and market contraction, with the total connectedness index exceeding 80% during the most severe episodes. Network-centrality analysis further confirmed that the assets generating the greatest standalone volatility were not necessarily those posing the greatest systemic importance; rather, systemic relevance depended on an asset's ability to transmit shocks through highly connected portions of the network. Finally, the robustness tests demonstrated that these findings were stable across alternative model specifications, supporting the reliability of the conclusion that cryptocurrency markets constituted a highly interconnected financial network characterized by dynamic and state-dependent systemic-risk transmission.

Discussion and Conclusion

The findings of this study demonstrate that cryptocurrency markets are characterized by substantial and time-varying interconnectedness, with a full-sample total connectedness index of 59.76%. This indicates that a considerable proportion of forecast-error variation across the analyzed cryptocurrencies was attributable to cross-market shocks rather than purely asset-specific innovations. Such a result confirms that the cryptocurrency ecosystem functions as an interdependent financial network in which disturbances affecting one major asset can be transmitted rapidly to others. This pattern is consistent with the growing evidence that digital assets cannot be treated as isolated speculative instruments because they increasingly respond to shared information, investor sentiment, liquidity conditions, macroeconomic shocks, and common portfolio reallocation mechanisms. The result aligns closely with the global spillover evidence reported by Vukovic et al., who showed that cryptocurrencies are embedded within broader financial-market transmission channels and exhibit meaningful interdependence with both other digital assets and conventional financial markets (2). It is also consistent with the findings of Zhou and Gu, who emphasized that the structure of cryptocurrency networks is inherently time-varying and that changes in network connectedness carry important information about market volatility and risk transmission (1). Therefore, the relatively high total connectedness observed in the present study supports the view that cryptocurrency market

integration is sufficiently strong to generate systemic implications, especially when multiple assets respond simultaneously to common shocks.

The most important structural finding was the dominant role of Bitcoin and Ethereum as net transmitters of shocks. Bitcoin recorded the highest outward connectedness and the largest positive net spillover, while Ethereum also exhibited a strong positive net position. In contrast, Litecoin, Dogecoin, Cardano, XRP, Binance Coin, and Solana were net receivers over the full sample, although Solana and Binance Coin still occupied relatively important intermediary positions. This pattern reflects the hierarchical nature of the cryptocurrency ecosystem. Bitcoin and Ethereum possess comparatively high capitalization, market liquidity, trading depth, institutional visibility, and cross-platform use, which make innovations in these markets more likely to affect the valuation and behavior of other cryptocurrencies. The result is consistent with evidence showing that cryptocurrency returns and liquidity are strongly interrelated and that liquid, systemically important assets can exert disproportionate effects on neighboring markets (12). It also accords with network-based evidence indicating that systemic influence depends on the position of an asset within the broader transmission structure rather than only on its individual volatility (1). In this sense, Bitcoin and Ethereum may be interpreted as central market hubs through which information and risk are redistributed across the cryptocurrency system.

The dominant transmitter role of Bitcoin and Ethereum can also be understood from a behavioral-finance perspective. Cryptocurrency markets contain large populations of investors who react rapidly to major price movements, market narratives, regulatory announcements, and momentum signals. Because Bitcoin and Ethereum are commonly used as reference assets for the broader market, substantial movements in these cryptocurrencies may shape expectations about the entire digital-asset sector. This interpretation is supported by research showing that cryptocurrency prices are influenced strongly by behavioral responses, sentiment, and investor psychology (5). Yadav similarly found that prospect-theoretic behavioral biases can influence cryptocurrency investor decisions, implying that market responses are frequently nonlinear and shaped by perceived gains and losses rather than purely rational valuation mechanisms (6). Moreover, perceived financial literacy does not necessarily eliminate cognitive biases among cryptocurrency investors, as investors may remain overconfident or overly sensitive to salient market information even when they believe themselves to be financially knowledgeable (7). These behavioral mechanisms can amplify shocks originating in highly visible assets and help explain why Bitcoin and Ethereum exerted stronger outward effects than other cryptocurrencies.

A second major finding was that systemic connectedness intensified considerably during periods of market stress. The average total connectedness index reached 71.84% during the early-2020 stress period and 76.92% during the 2022 contraction, with a maximum value of 89.41%. These figures indicate that cross-market dependence became substantially stronger during episodes of instability. This result is particularly important because it suggests that diversification benefits weaken precisely when investors may need them most. When volatility rises and investors rebalance portfolios in response to losses, margin pressures, deteriorating sentiment, or liquidity constraints, correlations and spillovers across cryptocurrencies can increase sharply. This pattern is consistent with the broader literature showing that spillovers between cryptocurrencies and financial markets are asymmetric and become stronger under adverse conditions (3). Gu et al. similarly demonstrated that cryptocurrency and financial-market spillovers can differ significantly across quantiles, indicating that transmission is more intense in particular market states rather than remaining constant throughout the distribution (22). The present study extends

this interpretation by showing that systemic integration itself changes through time and becomes especially pronounced during crisis-like periods.

The high connectedness observed during the 2022 contraction can also be explained by the interaction of volatility, investor attention, and sequential market reactions. Cryptocurrency investors frequently shift attention collectively toward particular assets or market events, creating waves of synchronized activity. M'Bakob showed that spillover effects can emerge through sequential attention cycles among cryptocurrency investors, with changing investor focus influencing broader market stability (8). This mechanism is consistent with the present finding that network density rose during turbulent periods. As more assets became connected through economically meaningful spillover relationships, shocks were transmitted more widely and the system behaved more like an integrated risk cluster than a collection of independent securities. This interpretation is further supported by evidence that cryptocurrency volatility is persistent, nonlinear, and sensitive to stochastic market dynamics (4). Consequently, the rise in connectedness during stress should not be understood as a temporary increase in simple correlation alone; rather, it reflects a broader strengthening of directional dependence throughout the network.

The findings also showed that the identity of the dominant transmitter was not entirely constant across all regimes. Although Bitcoin remained the principal transmitter in most periods, Ethereum assumed the dominant position during some expansionary and consolidation phases. This result suggests that systemic importance is dynamic rather than permanently attached to one cryptocurrency. Ethereum's growing role in smart contracts, decentralized applications, and decentralized finance may increase its influence during periods when activity shifts toward blockchain-based financial services rather than purely speculative trading. This interpretation corresponds with research emphasizing the growing relevance of decentralized finance to market power, pricing, adoption, and network structures outside traditional intermediated finance (17). The result also reinforces the argument that cryptocurrency systemic risk is not reducible to market capitalization alone. The systemic position of an asset depends on how strongly it is connected to other influential nodes, how much risk it transmits outward, and how central it is within the evolving network.

The network-centrality results further highlighted the distinction between standalone volatility and systemic importance. Dogecoin exhibited the greatest unconditional volatility in the descriptive analysis but comparatively low eigenvector and betweenness centrality. Bitcoin and Ethereum, by contrast, had lower volatility than Dogecoin but much greater systemic influence. This finding is important because it demonstrates that volatility alone is not an adequate indicator of systemic risk. An asset can experience extreme price fluctuations without serving as a major conduit for system-wide contagion. Conversely, a highly connected asset may transmit moderate shocks across many markets and thus create greater systemic consequences. This distinction is compatible with portfolio research showing that dependence structures among cryptocurrencies are complex and cannot be represented adequately through simple variance measures or constant correlations (13). It also aligns with evidence that cryptocurrency portfolio optimization requires explicit modeling of time-varying interdependence rather than reliance on isolated asset-level risk metrics (14). Machine-learning approaches to cryptocurrency price prediction and risk-adjusted portfolio allocation similarly support the importance of nonlinear and changing relationships across assets (15).

The observed connectedness structure also has implications for market liquidity. The fact that major cryptocurrencies transmitted a substantial proportion of shocks to other assets suggests that liquidity conditions in large markets may shape price formation throughout the broader system. Zhang et al. demonstrated significant relationships between cryptocurrency returns and liquidity, implying that deterioration in trading conditions can

amplify price responses and affect intermarket dynamics (12). During stressed periods, investors may simultaneously reduce exposure, seek liquidity in major cryptocurrencies, or liquidate peripheral assets, creating directional spillovers that intensify network dependence. This helps explain why Litecoin, Dogecoin, and Cardano appeared more vulnerable as net receivers, while Bitcoin and Ethereum remained central transmitters. The result therefore suggests that systemic cryptocurrency risk should be analyzed jointly through price, liquidity, and network channels.

The relationship between cryptocurrency markets and broader financial conditions provides another explanation for the time-varying connectedness observed in this study. Cryptocurrencies are increasingly sensitive to monetary policy, global liquidity, and conventional risk sentiment. Tosun and Uğurlu showed that Federal Reserve monetary-policy decisions can materially affect cryptocurrency markets, highlighting the importance of traditional macro-financial channels for digital assets (21). Koutrouli et al. also documented that event-driven responses in cryptocurrency markets can overlap with those observed in traditional financial markets, demonstrating that crypto assets are exposed to common global information shocks (23). These findings help explain why systemic connectedness can rise abruptly during broader episodes of financial uncertainty. When multiple cryptocurrencies respond simultaneously to the same macroeconomic event, internal spillovers intensify and the distinction between common shocks and asset-specific disturbances becomes less pronounced.

The growing integration of cryptocurrency with traditional corporate and financial systems also increases the practical importance of these findings. Kayani and Hasan emphasized that cryptocurrencies are increasingly connected with conventional banking and financial-market structures, creating new channels for risk transmission between digital and traditional systems (16). Corporate exposure can reinforce these channels, especially when firms hold cryptocurrency on their balance sheets or operate directly within digital-asset markets. Lee showed that cryptocurrency holdings and volatility can affect corporate liquidity differently across cryptocurrency exchanges and other firms (18). In addition, accounting and reporting challenges related to cryptocurrency holdings can affect how market risks are recognized and communicated (19), while auditing cryptocurrency exchanges requires specialized technological procedures for verifying ownership, transactions, and digital assets (20). Accordingly, a highly connected cryptocurrency network may transmit shocks not only among digital assets but also into firms and institutions with material cryptocurrency exposure.

The findings should also be interpreted in light of technological and security-related risks. Cryptocurrency markets are vulnerable to hacking, theft, fraud, and operational disruptions, and these events can affect investor confidence beyond the directly affected asset or platform. Li et al. found that cryptocurrency heists can influence Bitcoin market efficiency, demonstrating that security events have broader implications for information processing and market functioning (10). Scharnowski similarly showed that privacy-oriented cryptocurrency trading and dark-web activity represent distinct but economically meaningful components of digital-asset markets (11). Furthermore, increased use of artificial intelligence in market forecasting and trading may alter the speed and structure of transmission. AI-driven predictive systems can influence how volatility is assessed across cryptocurrency and traditional markets (24). If market participants increasingly rely on comparable algorithmic signals, synchronized trading may intensify, potentially strengthening spillover networks during fast-moving market episodes.

Regulatory and compliance conditions also provide a relevant context for interpreting systemic integration. Digital-asset markets operate across jurisdictions with differing levels of regulation, and this can affect market structure, investor behavior, liquidity, and the transmission of shocks. The evidence of stronger spillovers under

particular regulatory and market conditions reported by Gu et al. suggests that institutional environments can materially influence connectedness patterns (22). At the same time, cryptocurrency markets are subject to concerns regarding money laundering and illicit finance, leading to increased use of machine-learning tools in anti-money-laundering systems (25). In Iran, cryptocurrency regulation also intersects with concerns about terrorist financing and the challenge of adapting legal frameworks to decentralized financial instruments (26). These regulatory concerns are relevant because abrupt policy changes or enforcement measures can act as common shocks that alter network structure across multiple cryptocurrencies.

The robustness analysis strengthens confidence in the empirical findings. Changing VAR lag length, forecast horizon, and rolling-window size produced only modest changes in the average connectedness index, and Bitcoin and Ethereum remained positive net transmitters under all tested specifications. This stability indicates that the main conclusions were not dependent on a single econometric configuration. The persistence of elevated maximum connectedness across specifications also confirms that crisis-period integration was a structural feature of the data rather than a modeling artifact. Taken together, the results support a view of the cryptocurrency ecosystem as a dynamic financial network characterized by persistent but fluctuating interdependence, concentrated systemic influence among a small number of central assets, and sharp increases in contagion potential during periods of market stress.

This study has several limitations that should be considered when interpreting its findings. First, the analysis focused on eight major cryptocurrencies and therefore did not capture the full heterogeneity of the digital-asset ecosystem, including stablecoins, smaller-cap tokens, decentralized-finance tokens, and newly listed assets. Second, although the 2020–2025 observation period covered several distinct market regimes, results may differ across longer historical periods or under future regulatory and technological conditions. Third, the dynamic spillover framework identifies directional statistical transmission but cannot establish causal mechanisms behind every observed connection. Fourth, the investor component was restricted to 384 active participants in Tehran, which limits the direct generalizability of behavioral and portfolio characteristics to cryptocurrency investors in other regions. Fifth, daily data may not capture high-frequency intraday contagion, while the use of closing prices necessarily compresses information generated throughout continuously operating cryptocurrency markets. Finally, the analysis focused primarily on return-based spillovers and did not model liquidity, trading volume, order-book depth, stablecoin flows, blockchain activity, or macroeconomic variables within the same network.

Future studies should extend the network to a larger and more diverse set of digital assets and distinguish among major cryptocurrencies, stablecoins, decentralized-finance tokens, privacy coins, and smaller-cap assets. High-frequency data could be used to identify intraday shock propagation and determine how rapidly contagion moves through cryptocurrency markets following major events. Future research could also construct multilayer networks combining returns, volatility, liquidity, trading volume, blockchain flows, and investor sentiment to provide a broader representation of systemic risk. Comparative studies across countries and regulatory environments would help clarify whether spillover structures differ according to institutional restrictions, exchange access, or investor composition. Additional work could integrate macroeconomic variables such as interest rates, inflation expectations, exchange rates, and global risk indices into the network. Future studies should also examine nonlinear and tail-specific connectedness using quantile-based models, regime-switching approaches, machine-learning methods, or frequency-domain spillover models. Longitudinal investor data could additionally be linked to market networks to

investigate whether changes in portfolio behavior, leverage, risk perception, and trading frequency contribute directly to increases in systemic connectedness.

For investors and portfolio managers, the findings indicate that cryptocurrency diversification should not be based solely on the number of assets held, because assets that appear different under normal market conditions may become highly interconnected during stress. Portfolio risk systems should therefore incorporate dynamic connectedness measures and monitor whether diversification benefits are deteriorating as network density rises. Exchanges and institutional risk managers should pay particular attention to large central cryptocurrencies because shocks originating in these markets may propagate rapidly across the broader ecosystem. Regulators and financial-stability authorities can use dynamic spillover networks as early-warning tools to identify periods in which interconnectedness is increasing and to detect assets that are becoming systemically important. Risk-management frameworks should also combine market connectedness with liquidity, leverage, cybersecurity, and operational indicators rather than relying exclusively on volatility. Finally, investor education should emphasize that highly volatile assets are not necessarily the most systemically influential and that portfolio vulnerability depends on network position, directional spillovers, and market conditions as well as on standalone price risk.

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Authors' Contributions

All authors equally contributed to this study.

Declaration of Interest

The authors of this article declared no conflict of interest.

Ethical Considerations

All ethical principles were adhered in conducting and writing this article.

Transparency of Data

In accordance with the principles of transparency and open research, we declare that all data and materials used in this study are available upon request.

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