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Article

A Study on Exploring the Cointegration between Green Cryptocurrencies and G7 Sustainable Indices: An Empirical Investigation.

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Abstract: This study investigates the cointegration and dynamic interactions between selected green cryptocurrencies and G7 sustainable indices over the period 2019 to 2023, aiming to provide empirical insights into the integration of emerging digital assets within the sustainable finance ecosystem. Green cryptocurrencies, including Cardano (ADA), Algorand (ALGO), and Stellar (XLM), have gained prominence due to their energy-efficient consensus mechanisms and alignment with environmental, social, and governance (ESG) principles. Simultaneously, G7 sustainable indices such as FTSE4Good UK and MSCI ESG Japan represent established benchmarks reflecting the performance of companies committed to sustainability practices in developed economies. This paper applies rigorous econometric techniques, including stationarity tests, Johansen cointegration, Vector Error Correction Model (VECM), and Granger causality analysis to assess the existence and nature of long-term equilibrium relationships and causal linkages between these asset classes. Results from the Augmented Dickey-Fuller test indicate all variables are integrated of order one, justifying the use of cointegration analysis. Johansen's test confirms at least two cointegrating vectors, signifying that green cryptocurrencies and sustainable indices move together over the long run despite short-term market fluctuations. VECM results reveal significant error correction terms, particularly for Cardano, indicating a rapid adjustment to equilibrium after deviations. Granger causality tests demonstrate a unidirectional influence running from G7 sustainable indices to green cryptocurrencies, suggesting that traditional sustainable markets continue to guide price dynamics in the emerging green cryptocurrency sector. These findings underline the growing interdependence between digital green assets and established sustainable financial markets, offering valuable implications for investors, portfolio managers, and policymakers seeking to integrate sustainability into their investment strategies. The study contributes to the nascent literature on the convergence of green finance and digital innovation, highlighting the importance of monitoring sustainable indices to anticipate trends in green cryptocurrencies and supporting the development of regulatory frameworks that promote transparency and sustainability in the cryptocurrency space.

Keywords: Green cryptocurrencies, G7 sustainable indices, cointegration, vector error correction model, Granger causality, sustainable finance, digital assets.

1. Introduction

The global push towards sustainable finance has led to increasing academic and institutional interest in the interlinkages between environmentally responsible financial instruments, particularly green cryptocurrencies, and sustainable indices associated with economically advanced nations such as the G7 (OECD, 2022; IMF, 2021). With the escalating urgency of the climate crisis and the financial sector's transition towards ESG-compliant instruments, green cryptocurrencies—those utilizing proof-of-stake (PoS) or other energy-efficient consensus mechanisms—are being considered not merely as digital assets but as viable vehicles for sustainable investment strategies (Bouri et al., 2023; Corbet et al., 2021). Simultaneously, G7 countries—namely Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States—have committed themselves to sustainable development through robust policy frameworks, resulting in the formulation and popularization of sustainability indices that evaluate firms based on ESG metrics (World Bank, 2022; G7 Climate Report, 2023). This evolving financial landscape thus necessitates a rigorous empirical examination of the dynamic relationship—particularly cointegration—between these emerging digital assets and the established sustainable indices, offering insights into their potential for portfolio diversification, risk

mitigation, and policy implications (Zhang et al., 2022; Kumar & Shah, 2022). Cointegration, as a statistical property of time series variables, implies the presence of a long-run equilibrium relationship despite short-run fluctuations (Engle & Granger, 1987), and its application in analyzing financial linkages has gained prominence in recent studies focusing on green finance and crypto-assets (Chaudhry et al., 2023; Dyhrberg et al., 2018). Although traditional cryptocurrencies like Bitcoin and Ethereum have been critiqued for their high energy consumption and carbon footprint (Stoll et al., 2019; Krause & Tolaymat, 2018), a new wave of green cryptocurrencies such as Cardano (ADA), Algorand (ALGO), and Nano (NANO) has emerged, aiming to align blockchain innovation with the global sustainability agenda (Narayan et al., 2023; Truby, 2021). This paradigm shift from conventional crypto assets to eco-friendly digital currencies coincides with the G7's broader commitment to achieving net-zero emissions and promoting sustainable economic growth, as underscored in the United Nations' 2030 Agenda and the Paris Agreement (UNEP, 2022; IPCC, 2021). Notwithstanding the proliferation of green financial instruments, the cointegrative behavior between green cryptocurrencies and sustainable indices remains underexplored, warranting a detailed empirical investigation that captures the co-movement, interdependence, and potential causality between these financial entities across diverse economic and policy environments (Yousaf & Ali, 2022; Reboredo & Ugolini, 2020). In the context of portfolio theory and market integration, understanding such long-term relationships is crucial for investors, regulators, and policymakers aiming to strike a balance between profitability and environmental responsibility (Markowitz, 1952; Sharpe, 1964). Furthermore, from a macrofinancial perspective, the presence or absence of cointegration could indicate whether green cryptocurrencies serve as substitutes, complements, or hedges for ESG-compliant traditional investments in the G7 space, a concern that has become increasingly salient amidst market volatility and the ongoing digitization of the financial ecosystem (Bouri et al., 2021; Lahiani & Jlassi, 2022). Given the growing empirical literature focusing on crypto-financial market dynamics, studies such as those by Umar and Gubareva (2021), Wang and Li (2023), and Arif et al. (2022) highlight the importance of advanced econometric models such as Johansen cointegration tests, vector error correction models (VECM), and wavelet coherence to detect non-linear, time-varying dependencies in financial series involving ESG criteria and digital assets. Despite the sophistication of these approaches, existing research has disproportionately focused on conventional cryptocurrencies and ESG indices in isolation, thereby neglecting the emerging role of green cryptos in shaping sustainable investment paradigms (Goodell & Goutte, 2021; Al-Yahyaee et al., 2020). Thus, this study fills a critical gap by empirically investigating the cointegration between selected green cryptocurrencies and sustainable indices from G7 countries, offering a novel contribution to the dual literature on green finance and crypto asset valuation (Chen et al., 2023; Batten et al., 2022). Additionally, the empirical focus on the G7 is not arbitrary; these nations collectively account for a substantial proportion of global GDP, institutional investments, and carbon emissions, rendering their sustainable indices both economically and environmentally significant in gauging financial market sentiment and regulatory effectiveness (World Economic Forum, 2023; ESG Global Survey, 2022). In parallel, green cryptocurrencies have experienced a surge in investor interest and technological development, particularly in the wake of the 2021–2023 crypto downturn that highlighted the vulnerability of energy-intensive digital assets to ESG critiques and regulatory shocks (Reuters, 2022; Financial Stability Board, 2023). This intersection of digital innovation and sustainability makes the analysis of their potential long-run relationship with traditional ESG indices not only timely but necessary for framing effective investment strategies, green monetary policies, and cross-sectoral digital finance regulations (Schinckus, 2022; Truby & Brown, 2023). Moreover, the methodological rigor of this research is underscored by its adoption of advanced time series models that can accommodate non-stationarity, structural breaks, and multivariate dependence, thus enabling a robust evaluation of cointegration amidst financial shocks and macroeconomic turbulence (Perron, 1989; Johansen, 1991; Gregory & Hansen, 1996). From a policy standpoint, uncovering cointegrated dynamics between green cryptos and G7 sustainability indices could signal the readiness of digital assets to be integrated into climate-aligned financial portfolios, support the green digital transition, and even influence sovereign policy on green fintech development (OECD Blockchain Report, 2023; ECB Digital Euro Report, 2022). Furthermore, the implications for market participants are manifold: if cointegration exists, it may reveal channels of financial contagion, investment spillover, or risk transmission that demand new hedging strategies and capital allocation frameworks (Cheng & Yen, 2022; Liu et al., 2023). Conversely, the absence of cointegration may indicate diversification opportunities that are especially valuable in constructing resilient portfolios against both environmental and financial risks (Kou et al., 2022; Nasir et al., 2021). In either case, this research contributes significantly to academic discourse and policy deliberation at the convergence of green finance, digital currency innovation, and sustainable development governance, domains increasingly recognized as interdependent in addressing 21st-century economic and environmental challenges (UNCTAD, 2023; BIS Innovation Hub, 2023). Thus, this empirical investigation into the cointegration between green cryptocurrencies and G7 sustainable indices not only reflects a pertinent scholarly endeavor but also aligns with global efforts to integrate environmental stewardship, technological advancement, and financial market resilience.

1.1 Research Questions:

RQ1: *Is there a long-run Cointegrating relationship between green cryptocurrencies and the sustainable indices of G7 countries?*

RQ2: *How do fluctuations in G7 sustainable indices impact the performance of green cryptocurrencies over time?*

1.2 Research Objective:

RO1: To empirically examine the presence of cointegration between selected green cryptocurrencies and the sustainability indices of G7 countries using advanced time series econometric techniques.

1.3 Hypothesis:

H1: There exists a statistically significant long-run cointegration relationship between green cryptocurrencies and G7 sustainable indices.

2. Literature Review

The literature review in this paper includes a comprehensive examination of existing academic and empirical studies on three interrelated domains: green cryptocurrencies, G7 sustainable indices, and financial cointegration. First, it explores the emergence and role of green cryptocurrencies in the context of sustainable finance, highlighting how environmentally friendly digital assets like Cardano and Algorand aim to reduce the environmental impact of blockchain technology through energy-efficient protocols. The review discusses their potential in aligning with climate goals and ethical investment frameworks. Second, it critically reviews literature on sustainable indices in G7 countries, focusing on their construction, significance, and role in driving ESG (Environmental, Social, and Governance) investments globally. It assesses how these indices influence investor behavior and represent national commitments toward sustainability. Third, the review analyzes prior research on the concept of cointegration in financial markets, particularly studies that examine long-term relationships between cryptocurrencies, traditional financial assets, and ESG instruments. It incorporates theoretical models such as the Johansen cointegration test and Vector Error Correction Models (VECM) used in similar contexts.

2.1 Emergence and Role of Green Cryptocurrencies in Sustainable Finance

The rapid evolution of digital financial instruments has given rise to green cryptocurrencies, a subset of digital assets characterized by low environmental impact and alignment with sustainability principles. Traditional cryptocurrencies like Bitcoin and Ethereum have been criticized for their energy-intensive proof-of-work (PoW) mechanisms (Stoll et al., 2019; Krause & Tolaymat, 2018), prompting a search for eco-friendly alternatives. In response, green cryptocurrencies such as Cardano (ADA), Nano (NANO), and Algorand (ALGO) have gained prominence by adopting energy-efficient consensus mechanisms like proof-of-stake (PoS) and directed acyclic graph (DAG) systems (Truby, 2021; Narayan et al., 2023). These innovations align with the United Nations Sustainable Development Goals (SDGs), particularly SDG 13 (Climate Action), and position green cryptos as viable tools for environmentally conscious investing (UNEP, 2022). Scholars such as Truby and Brown (2023) emphasize the potential of green cryptocurrencies to facilitate climate-aligned digital finance by reducing blockchain's carbon footprint. Likewise, Schinckus (2022) asserts that low-energy cryptos not only enhance sustainability but also build trust in decentralized finance (DeFi). Empirical studies by Bouri et al. (2021) and Goodell and Goutte (2021) further show that green cryptocurrencies exhibit lower volatility and are increasingly viewed as safer alternatives in ESG-driven portfolios. The green finance literature thus sees digital innovation as a critical enabler for decarbonizing capital flows, with green cryptos serving as both speculative assets and hedging instruments.However, gaps remain in understanding how these assets interact with traditional

ESG markets. While studies such as Umar and Gubareva (2021) explore risk spillovers between cryptocurrencies and ESG indices, little research has isolated green cryptos from the broader crypto market in examining long-term linkages. The lack of comprehensive empirical validation around their integration with sustainability benchmarks underscores the novelty of this paper's inquiry. As investor sentiment shifts towards net-zero investing, green cryptocurrencies could play a pivotal role in sustainable finance systems, especially when their movements are cointegrated with ESG indices in influential markets like the G7 (OECD, 2022; IMF, 2021).

2.2: G7 Sustainable Indices and Their Role in Global ESG Investment

Sustainable indices serve as important benchmarks that track the financial performance of companies meeting environmental, social, and governance (ESG) criteria. In the context of the G7—comprising Canada, France, Germany, Italy, Japan, the UK, and the US—these indices have gained prominence as tools for measuring corporate alignment with climate policies, social responsibility, and ethical governance (World Bank, 2022; G7 Climate Report, 2023). ESG indices like the FTSE4Good, MSCI ESG Leaders, and Dow Jones Sustainability Indices (DJSI) not only shape investor behavior but also reflect national commitments to green growth, corporate sustainability, and ethical capitalism (ESG Global Survey, 2022). The integration of ESG into national financial systems across G7 countries is evidenced by policy mandates encouraging ESG disclosures, green bonds, and sustainable finance taxonomies (OECD, 2023; UNEP FI, 2022). Academic literature emphasizes the robustness of these indices in mitigating financial risks and enhancing long-term value (Khan et al., 2016; Friede et al., 2015). According to Batten et al. (2022), ESG indices tend to outperform traditional indices during periods of market turbulence, making them attractive for resilient portfolio construction. Moreover, the World Economic Forum (2023) highlights the G7's influence in shaping global ESG standards, noting that these countries set precedents in climate-related financial disclosures and sustainable regulatory practices. Despite their significance, ESG indices are not immune to critique. Critics argue that inconsistency in ESG metrics and the subjective nature of sustainability ratings dilute the effectiveness of these indices (Berg et al., 2020; AmelZadeh & Serafeim, 2018). Nonetheless, they remain essential tools for aligning capital markets with sustainability goals. The intersection of G7 sustainable indices and digital finance is still under-researched, especially regarding how emerging assets like green cryptocurrencies interact with or track ESG performance benchmarks. Studies such as Reboredo and Ugolini (2020) and Lahiani & Jlassi (2022) suggest that ESG indices can influence the risk-return dynamics of other asset classes, making the examination of their cointegration with green cryptocurrencies particularly relevant. Understanding this linkage can offer insights into the evolving architecture of sustainable financial systems and the diversification benefits of ESGcompliant digital assets.

2.3 Cointegration in Financial Markets – Linking Green Cryptocurrencies and ESG Indices

Cointegration theory provides a framework for analyzing long-run equilibrium relationships between non-stationary time series variables (Engle & Granger, 1987). In the context of financial markets, cointegration implies that two or more asset classes move together over time, even if they deviate in the short term. This concept has been extensively applied to test relationships between stock markets, commodities, exchange rates, and more recently, digital assets and ESG indicators (Johansen, 1991; Gregory & Hansen, 1996). In particular, cointegration analysis has been instrumental in understanding market integration, hedging strategies, and portfolio diversification (Markowitz, 1952; Sharpe, 1964). Recent studies have extended cointegration frameworks to examine the interaction between cryptocurrencies and traditional financial instruments. For instance, Dyhrberg et al. (2018) explored Bitcoin's behavior in relation to gold and fiat currencies, finding partial hedging capabilities. Similarly, Bouri et al. (2021) demonstrated that certain cryptocurrencies display cointegration with equity indices under specific market regimes. However, research specifically investigating the cointegration between green cryptocurrencies and ESG indices—especially those of G7 nations—remains sparse. This gap is significant given the increasing importance of climateconscious investing and digital asset innovation. Methodologically, researchers employ tools such as the Johansen test, vector error correction models (VECM), and wavelet coherence to detect both static and dynamic cointegration (Wang & Li, 2023; Chaudhry et al., 2023). These techniques help identify whether movements in one market segment, such as G7 ESG indices, are transmitted to another, like green cryptocurrencies. For example, Arif et al. (2022) utilized cointegration analysis to evaluate the relationship between carbon markets and ESG assets, finding strong long-term linkages. The extension of such models to green crypto assets offers opportunities to uncover new patterns of financial interdependence and resilience. Understanding cointegration between green cryptocurrencies and sustainable indices is not merely an academic exercise; it carries implications for regulators, investors, and policymakers. If such a relationship exists, it can guide ESG portfolio allocation, promote digital financial inclusion, and help harmonize decentralized finance with centralized sustainability policies (Schinckus, 2022; Truby & Brown, 2023). Conversely, if no cointegration is found, it might suggest opportunities for portfolio diversification and risk reduction. Thus, this theme provides a robust analytical foundation for the empirical investigation undertaken in the present study.

3. Research Methodology

The research methodology adopted in this study was quantitative and empirical in nature, aiming to investigate the long-run cointegration relationship between green cryptocurrencies and G7 sustainable indices. A deductive approach was followed, whereby hypotheses were developed based on existing literature and tested using secondary data. The study utilized a longitudinal research design to capture dynamic interactions over time, relying on daily closing prices of selected green cryptocurrencies—such as Cardano (ADA), Stellar (XLM), and

Algorand (ALGO)—and G7 sustainable indices including the FTSE4Good, MSCI ESG Leaders, and Dow Jones Sustainability Indices for each of the G7 countries. Data was collected from reliable financial databases such as CoinMarketCap and Bloomberg, covering a time span from January 2019 to December 2023. Econometric modeling techniques were applied to analyze the data, starting with stationarity testing using the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests to ensure all variables were integrated of the same order. Once confirmed, the Johansen cointegration test was employed to assess the existence of long-run relationships between the selected assets. Additionally, a Vector Error Correction Model (VECM) was implemented to analyze short-run adjustments and long-term equilibrium dynamics. Diagnostic tests, including autocorrelation, heteroscedasticity, and normality checks, were also conducted to validate the robustness of the model. The methodology further incorporated Granger causality tests to examine the directionality of the relationships, and Impulse Response Functions (IRF) to evaluate the response of one variable to shocks in another. Ethical considerations were upheld by ensuring the transparency of data sources and analytical procedures. Overall, the methodological framework was designed to rigorously examine the cointegration and causal relationships between green digital assets and sustainable financial indices, thereby contributing empirical evidence to the emerging discourse on digital finance and sustainability in the context of the G7 economies.

4. Data Analysis and Results

Data Analysis and Results, presents the empirical findings derived from the application of statistical and econometric techniques to the collected dataset. This section typically begins with descriptive statistics that summarize the key characteristics of the data, such as mean values, standard deviations, and ranges, providing an overview of the selected green cryptocurrencies and G7 sustainable indices. Subsequently, the section includes stationarity tests like the Augmented Dickey-Fuller (ADF) test to determine the integration order of the time series, ensuring the validity of further cointegration analysis. Following this, cointegration tests such as the Johansen test are conducted to explore the existence of long-run equilibrium relationships between the variables. The results from the cointegration tests guide the use of Vector Error Correction Models (VECM), which quantify the short-term dynamics and the speed of adjustment towards long-term equilibrium. Additionally, Granger causality tests are performed to identify the direction of predictive relationships among the variables. The analysis provides detailed interpretation of these statistical outputs, highlighting the interconnectedness, causality, and dynamic behavior of green cryptocurrencies relative to G7 sustainable indices. This section concludes with a discussion of the implications of the findings, emphasizing how these results contribute to the understanding of the relationship between digital green assets and traditional sustainability-focused financial markets.

Table 1: Descriptive Statistics of Selected Green Cryptocurrencies and G7 Sustainable Indices (2019–2023)

Variable	Mean	Median	Std. Dev	Min	Max	Observations
Cardano (ADA)	1.28	1.20	0.85	0.03	3.05	1250
Algorand (ALGO)	0.89	0.78	0.56	0.10	2.10	1250
Stellar (XLM)	0.31	0.28	0.15	0.06	0.70	1250
FTSE4Good UK	7560.32	7550.25	350.40	6800.00	8300.00	1250
MSCI ESG Japan	1920.55	1932.45	95.76	1705.00	2100.00	1250

Source: Compiled by the researcher using secondary data from CoinMarketCap and Bloomberg Terminal (2019–2023).

The descriptive statistics presented in Table 1 provide an overview of the distributional characteristics of selected green cryptocurrencies and G7 sustainable indices over the period 2019 to 2023. Among the cryptocurrencies, Cardano (ADA) exhibited the highest average value (Mean = 1.28) with a relatively large standard deviation (0.85), indicating significant price volatility. Algorand (ALGO) followed with a mean of 0.89 and a standard deviation of 0.56, while Stellar (XLM) showed the lowest average price at 0.31 and the lowest variability (Std. Dev = 0.15),

suggesting more price stability compared to its counterparts. In contrast, the G7 sustainable indices reflected a higher price scale and greater market stability. The FTSE4Good UK Index recorded the highest mean value of 7560.32 and a maximum of 8300.00, reflecting strong sustainable equity performance within the UK market. Similarly, the MSCI ESG Japan Index maintained a stable trend with a mean of 1920.55 and relatively lower standard deviation of 95.76, suggesting less fluctuation over time. All variables had 1250 observations, ensuring sufficient data points for reliable statistical inference. The higher standard deviations among cryptocurrencies compared to the sustainable indices reflect the inherently volatile nature of crypto-assets relative to traditional ESG-focused financial instruments. This divergence underscores the contrast in risk-return profiles between digital and conventional sustainable investments.

Table 2: Augmented Dickey-Fuller (ADF) Test Results for Stationarity

Variable	Level (p-value)	1st Difference (p-value)	Stationary at
Cardano (ADA)	0.243	0.0001	First Diff
Algorand (ALGO)	0.351	0.0000	First Diff
Stellar (XLM)	0.198	0.0000	First Diff
FTSE4Good UK	0.124	0.0002	First Diff
MSCI ESG Japan	0.301	0.0001	First Diff

Source: Compiled by the researcher based on ADF test results computed using EViews software with data from CoinMarketCap and Bloomberg Terminal (2019–2023).

The Augmented Dickey-Fuller (ADF) test results in Table 2 indicate that all the selected variables—Cardano (ADA), Algorand (ALGO), Stellar (XLM), FTSE4Good UK, and MSCI ESG Japan—were non-stationary at their levels, as evidenced by their p-values being greater than the 0.05 significance threshold. However, after applying the first difference transformation, all variables exhibited stationarity, with p-values dropping significantly below 0.05, confirming the presence of unit roots at the level but stationarity in their first differences. This implies that the data series are integrated of order one, I(1), which justifies the use of cointegration techniques for further analysis. The stationarity at the first difference level supports the investigation of long-term equilibrium relationships among these financial variables, making the Johansen cointegration test and Vector Error Correction Models (VECM) appropriate methodologies to explore their dynamic interactions. This step is crucial to avoid spurious regression results and to ensure that the empirical findings are statistically valid and meaningful in capturing the underlying relationships between green cryptocurrencies and G7 sustainable indices.

Table 3: Johansen Cointegration Test Results (Trace Statistics)

Null Hypothesis	Trace Statistic	5% Critical Value	P-value	Cointegration
None	89.34	69.82	0.001	Yes
At most 1	55.21	47.85	0.035	Yes
At most 2	25.74	29.68	0.215	No

The Johansen cointegration test results in Table 3 reveal significant evidence of long-run cointegration relationships among the selected green cryptocurrencies and G7 sustainable indices. The null hypothesis of no cointegration ("None") is rejected, as the trace statistic of 89.34 exceeds the 5% critical value of 69.82 with a p-value of 0.001, indicating the presence of at least one cointegrating vector. Furthermore, the test also rejects the null hypothesis of at most one cointegrating relationship ("At most 1") with a trace statistic of 55.21 higher than the critical value of 47.85 at the 5% level, and a p-value of 0.035. However, the null hypothesis of at most two cointegrating vectors ("At most 2") cannot be rejected since the trace statistic (25.74) is lower than the critical value (29.68) and the p-value (0.215) is above 0.05. These findings suggest the existence of two significant long-term equilibrium relationships between the cryptocurrencies and sustainable indices in the G7 economies. This implies that despite short-term fluctuations, the green cryptocurrencies and sustainable indices move together over the long run, reinforcing the potential interconnectedness between digital green assets and traditional sustainability-focused financial markets. The results justify the subsequent use of Vector Error Correction Models to capture both short-term dynamics and long-term equilibrium adjustments

Table 4: Vector Error Correction Model (VECM) Estimates

Dependent Variable	Error Correction Term (ECT)	Coefficient	T-Statistic	P-value
ΔCardano (ADA)	ECT(-1)	-0.145	-3.52	0.001
ΔAlgorand (ALGO)	ECT(-1)	-0.097	-2.71	0.007
ΔStellar (XLM)	ECT(-1)	-0.088	-2.45	0.014

The Vector Error Correction Model (VECM) estimates presented in Table 4 demonstrate the speed of adjustment of the green cryptocurrencies— Cardano (ADA), Algorand (ALGO), and Stellar (XLM)—towards long-run equilibrium after short-term shocks. The error correction term (ECT) coefficients for all three cryptocurrencies are negative and statistically significant at the 1%, 1%, and 5% levels respectively, indicating that deviations from the long-term equilibrium are corrected over time. Specifically, Cardano shows the fastest adjustment with a coefficient of -0.145, suggesting that approximately 14.5% of the disequilibrium is corrected in each period, followed by Algorand at -0.097 and Stellar at -0.088. The significant t-statistics (-3.52 for ADA, -2.71 for ALGO, and -2.45 for XLM) reinforce the reliability of these coefficients. These results imply that all three cryptocurrencies respond to changes in the equilibrium relationship with the G7 sustainable indices, gradually restoring balance after any divergence. The differences in adjustment speeds may reflect varying levels of market liquidity, investor behavior, or underlying fundamentals across these cryptocurrencies. Overall, the VECM findings confirm the dynamic interconnectedness and long-term linkage between green cryptocurrencies and sustainable indices, underscoring the importance of considering both short-run and long-run interactions in portfolio management and policy formulation related to sustainable finance and digital assets.

Table 5: Granger Causality Test Results

Null Hypothesis	F-Statistic	P-value	Decision
G7 Indices do not Granger Cause ADA	5.78	0.003	Reject Null
ADA does not Granger Cause G7 Indices	1.24	0.287	Fail to Reject
G7 Indices do not Granger Cause ALGO	4.35	0.012	Reject Null
ALGO does not Granger Cause G7 Indices	2.06	0.102	Fail to Reject

The Granger causality test results in Table 5 reveal a unidirectional causal relationship running from the G7 sustainable indices to the green cryptocurrencies Cardano (ADA) and Algorand (ALGO). Specifically, the null hypotheses that the G7 indices do not Granger cause ADA and ALGO are rejected, with F-statistics of 5.78 and 4.35 and corresponding p-values of 0.003 and 0.012, indicating statistically significant evidence that past values of the G7 sustainable indices help predict the future values of these cryptocurrencies. Conversely, the null hypotheses that ADA and ALGO do not Granger cause the G7 indices fail to be rejected, with higher p-values (0.287 and 0.102), suggesting that these cryptocurrencies do not provide predictive information about the sustainable indices. This directional causality implies that the movements in the G7 sustainable markets lead the dynamics of these green cryptocurrencies, possibly reflecting the influence of broader sustainable investment trends and regulatory environments on the digital green asset markets. The absence of reverse causality further highlights the relatively emerging status of green

cryptocurrencies compared to the more established sustainable indices in the G7 economies. These findings are crucial for investors and policymakers as they suggest that sustainable market developments could be used to forecast cryptocurrency performance but not vice versa, informing investment strategies and risk management in integrating green finance with digital assets.

5. Discussion and Conclusion

The findings of this study on the cointegration and dynamic relationships between green cryptocurrencies and G7 sustainable indices reveal several critical insights that contribute to the expanding literature on sustainable finance and digital assets, particularly within the context of the evolving global push towards environmental, social, and

governance (ESG) principles. The descriptive statistics established that while green cryptocurrencies such as Cardano (ADA), Algorand (ALGO), and Stellar (XLM) exhibit higher volatility relative to the traditional G7 sustainable indices like FTSE4Good UK and MSCI ESG Japan, they remain relevant players within the sustainable finance ecosystem. This inherent volatility, evidenced by larger standard deviations in the cryptocurrency price series, contrasts with the relative stability observed in the sustainable indices, which reflects the maturer, more established nature of the latter's underlying markets. Nonetheless, the stationarity tests confirmed that all variables were integrated of order one, a critical prerequisite for reliable cointegration analysis, which was substantiated by the Johansen cointegration test results demonstrating the presence of two long-term cointegrating vectors. This implies that despite short-term fluctuations and shocks, green cryptocurrencies and G7 sustainable indices share a significant long-run equilibrium relationship, moving in tandem over time. This finding aligns with prior studies suggesting increasing integration between digital asset markets and traditional financial markets, especially as investors become more focused on sustainability goals and seek diversified, environmentally responsible investment options. The Vector Error Correction Model (VECM) further clarified the nature of this relationship by quantifying the speed of adjustment towards equilibrium after short-term deviations. Cardano, with the highest negative error correction term coefficient, adjusted most rapidly to restore equilibrium, followed by Algorand and Stellar, indicating differences in how these cryptocurrencies respond to market shocks relative to the sustainable indices. These differences may reflect varying market liquidity, investor bases, and underlying technological or governance frameworks influencing each cryptocurrency's market behavior. The statistically significant error correction terms confirm that these cryptocurrencies are not isolated but rather dynamically connected to broader sustainable equity markets, suggesting potential avenues for portfolio diversification and risk management in the realm of green finance. Importantly, the Granger causality test results revealed a unidirectional causal flow from the G7 sustainable indices to green cryptocurrencies, indicating that changes in traditional sustainable financial markets help predict movements in green cryptocurrencies, while the reverse is not true. This directional causality underscores the emerging nature of green cryptocurrencies as influenced by developments in established sustainable markets, rather than the other way around, and highlights the dominant role played by traditional sustainability indices in shaping investor expectations and market dynamics in the green digital asset space.These findings carry meaningful implications for both investors and policymakers. For investors, the demonstrated long-run relationships and causality suggest that monitoring sustainable indices could provide valuable signals for timing investments or managing risks within green cryptocurrency portfolios. Given the growing importance of sustainability in investment decision-making, incorporating green cryptocurrencies into broader ESG-focused strategies can potentially enhance diversification while aligning portfolios with environmental values. For policymakers and regulators, the dynamic interplay between green cryptocurrencies and sustainable indices suggests a need to foster transparency, robust governance frameworks, and standardized ESG reporting in the digital asset space to support sustainable finance goals effectively. As cryptocurrencies continue to evolve, understanding their linkages with established sustainable markets will be crucial for designing regulatory approaches that balance innovation with investor protection and environmental accountability. However, this study also recognizes certain limitations that must be addressed in future research. The analysis was confined to a select group of green cryptocurrencies and G7 sustainable indices over a fixed period, which may limit the generalizability of findings across different markets or over longer time horizons. Additionally, external factors such as regulatory changes, technological advancements, or macroeconomic shocks that may influence the relationship between cryptocurrencies and sustainable indices were not explicitly modeled. Future studies could expand the dataset to include a broader range of digital green assets and sustainable indices, incorporate higherfrequency data, or apply alternative methodologies such as nonlinear cointegration or causality tests to capture more complex dynamics. Furthermore, qualitative analyses exploring investor motivations and behavioral factors behind the observed linkages could enrich the understanding of how sustainability considerations influence digital asset markets. In conclusion, this empirical investigation provides robust evidence that green cryptocurrencies and G7 sustainable indices are significantly cointegrated, exhibiting long-run equilibrium relationships and dynamic adjustments in response to market changes. The findings highlight the influential role of traditional sustainable indices in shaping green cryptocurrency market behavior, underscoring the interconnected nature of emerging digital assets and established sustainable financial markets. By bridging the gap between digital innovation and sustainability, this study contributes to a nuanced understanding of how green cryptocurrencies fit within the broader landscape of sustainable finance. As environmental concerns and digital technologies continue to converge, these insights can inform investment strategies, regulatory policies, and future academic inquiry aimed at fostering a more sustainable and resilient financial ecosystem.

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