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Research article

Green gold or carbon beast? Assessing the environmental implications of cryptocurrency trading on clean water management and carbon emission SDGs

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ABSTRACT

This study addresses the ongoing debate concerning the environmental implications of cryptocurrencies. Specifically, it investigates the impact of Bitcoin trading volume on water and sanitation (Sustainable Development Goal (SDG) 6) and climate action (SDG 13). The research employs Ordinary Least Squares (OLS) panel data analysis to examine these relationships using a sample of 32 countries with available Bitcoin trading volume data from 2013 to 2020. The findings indicate that Bitcoin trading significantly and positively impacts progress towards SDG 6, suggesting potential benefits for water and sanitation initiatives. However, the study reveals a significant negative impact of higher Bitcoin trading volume on increased carbon emissions, underscoring the environmental costs associated with cryptocurrency activities. Similar impacts are observed for gold reserves, as their mining necessitates substantial energy consumption. These results highlight the need to regulate cryptocurrency trading and promote voluntary sustainable practices, particularly given the disparities between developed and emerging markets based on their governance frameworks. Additionally, the study considers the disparities between countries based on technology exports and economic policy uncertainty as influential determinants. The study's results emphasize the importance of proactive measures to ensure the responsible and sustainable use of cryptocurrencies. While cryptocurrencies offer significant economic returns, their early adoption stage necessitates further investigation into environmentally friendly approaches. Potential strategies include directing financial returns from cryptocurrencies towards alternative energy projects and supporting other environmental SDGs, thereby fostering a positive impact on the overall ecosystem. The study's implications extend to policymakers, regulators, and stakeholders, advocating for comprehensive and collaborative efforts to integrate sustainability into the rapidly evolving cryptocurrency market. This integration is crucial to ensure that the economic benefits of cryptocurrencies do not come at the cost of our environment.

1. Introduction

The Sustainable Development Goals (SDGs) Agenda, comprising 17 goals and 169 targets on economic, social, and environmental issues, has garnered significant attention from scholars and experts since its announcement in 2015 (Ramus et al., 2018; United Nations Development Programme, 2020, [United Nations, 2016). Addressing the long-term viability concerns of human societies has become essential in shaping nations' strategies (Moyer and Hedden, 2020). However, there is a prevailing focus on achieving economic SDGs, often disregarding scientific evidence of compromised SDG coherence and adverse environmental consequences (Arli et al., 2023; Gong et al., 2024; Khalfaoui et al., 2022; Ramírez-Melgarejo and Stringer, 2024). Despite the critical role of environmental indicators, they are underrepresented in leading agendas like the World Development Indicators (WDI) database, where only 138 out of 1600 indicators pertain to environmental aspects (World Bank, 2018). This inconsistency and underrepresentation limit the attainment of the SDGs agenda and cause the loss of track of responses to

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Table 1
Descriptive statistics.

Variables	Obs	Mean	Std. Dev.	Min	Max
Panel A: Descriptive Statistics of the Sample					
SDG 6	256	0.676	0.237	0.144	1.000
SDG13	256	8.289	0.694	7.106	10.028
Bitcoin	256	4.889	1.034	0.000	7.165
GDP	256	28,518	24,186	1354	102,913
Inflation	253	0.033	0.069	−0.169	0.509
Unemployment	256	0.063	0.047	0.003	0.299
G-index	256	35.606	11.019	14.880	50.490
BusDisclosIndx	256	7.180	2.701	0	10
Stock	222	11.119	1.183	8.393	13.624
Gold	256	11.083	0.574	9.819	12.591
RD_GDP	247	0.018	0.018	0.001	0.127
Broadband	254	6.772	0.628	4.870	8.684
Innovation	256	45.52	10.94	24.10	68.40
PolUnc	256	0.262	0.208	0.009	1.27
Panel B: Descriptive Statistics of Emerging Countries					
SDG 6	112	0.479	0.201	0.144	1.000
SDG13	112	8.439	0.679	7.106	10.028
Bitcoin	112	4.913	1.032	0.000	6.886
GDP	112	12,427	14,323	1354	66,679
Inflation	112	0.054	0.096	−0.169	0.509
Unemployment	112	0.068	0.062	0.003	0.299
G-index	112	27.327	7.864	16.804	46.236
BusDisclosIndx	112	7.777	2.312	2	10
Stock	109	11.090	1.034	8.674	13.595
Gold	112	11.134	0.628	9.819	12.591
RD_GDP	103	0.013	0.015	0.001	0.100
Broadband	110	6.781	0.727	4.87	8.684
Innovation	112	37.82	7.49	24.10	59.40
PolUnc	112	0.266	0.219	0.036	0.902
Panel C: Descriptive Statistics of Developed Countries					
SDG6	144	0.829	0.120	0.506	0.992
SDG13	144	8.172	0.684	7.230	9.742
Bitcoin	144	4.871	1.039	2.799	7.165
GDP	144	41,032	22,878	8704	102,913
Inflation	144	0.017	0.028	−0.154	0.100
Unemployment	144	0.060	0.030	0.016	0.173
G-index	144	42.045	8.547	14.88	50.490
BusDisclosIndx	144	6.717	2.892	0	10
Stock	113	11.147	1.314	8.393	13.624
Gold	144	11.044	0.528	10.138	12.143
RD_GDP	144	0.022	0.018	0.004	0.127
Broadband	144	6.765	0.543	5.980	8.083
Innovation	144	51.51	10.21	31.90	68.40
PolUnc	144	0.252	172	0.008	1.27

Notes: Table 1 reports the descriptive statistics results of the variables used in the OLS regression. SDG6 is water and sanitation management measured as the average of the targets 6.1.1–6.1.6, 6.2.1–6.2.9), SDG13 is the climate action measured as the log of the million tons of carbon emission), Bitcoin is measured as a log of Bitcoin trading volume (in USD), GDP (GDP per capita in USD), Inflation (the inflation rate of the country), and Unemployment (the unemployment rate over the percentage of the labour market). G-index (a governance index to capture country-level investor protection). BusDisclosIndx (refers to the extent of business disclosure in the country, it ranges between 1 and 10). Stock is the log of the total value of stock trading volume (in USD), Gold is the log of the total value of the gold reserves (in USD), RD_GDP is the percentage of allocated money for research and development over GDP, Innovation (GII), Broadband is the log of the number of home broadband subscriptions, and PolUnc is the political-economic uncertainty.

environmental challenges (Agrawal et al., 2022; Di Vaio et al., 2020). Moreover, it is observed that prioritizing ecological SDGs may differ between developed and developing countries, with the latter facing significant ecosystem degradation and unsustainable resource use (Allen et al., 2016). Considering global concerns about water pollution and climate emergencies, there is a growing consensus on the need to prioritize SDGs related to water and sanitation (SDG 6) and climate action (SDG 13) due to their impact on pollution, diseases, and other threats (Kim et al., 2022; Swain and Ranganathan, 2021).

Previous research has explored various aspects of environmental SDGs, such as disclosure, policies, green supply chains, monitoring and evaluation of carbon data, and creative funding sources for mitigating obstacles in SDGs' progress (Centobelli et al., 2022; de Villiers et al., 2021; Truby, 2018; Rani et al., 2024; Yin et al., 2023; Zhang et al., 2023). In recent years, there has been increasing interest in studying blockchain technology applications to enhance ecological sustainability (de Villiers et al., 2021). Among these applications, Bitcoin stands out for its corruption-free and high-transparency transactions and its potential to offer a sustainable competitive advantage (Fosso Wamba et al., 2020; Hew et al., 2020; Nandi et al., 2021). By utilizing Bitcoin to fund projects, there is a higher opportunity to allocate funds to SDG initiatives with reduced concerns about governance systems (Li et al., 2019; Oyewo, 2023). However, debates persist regarding early adoption and the high energy consumption associated with cryptocurrencies (Papathanasiou et al., 2020; Yan et al., 2022).

Despite the growing literature on blockchain applications, it remains challenging to generalize the results, particularly regarding the global environmental impact of Bitcoin (Centobelli et al., 2022; Lal et al.,

Table 2
OLS regression results (SDGs 6 and 13)[7]

	SDG 6 Index	SDG 13
Bitcoin	0.040***	0.238***
	(0.001)	(0.000)
GDP	0.000*	−0.000**
	(0.030)	(0.002)
Inflation	−1.008**	−0.381
	(0.008)	(0.737)
Unemployment	0.174	3.537***
	(0.464)	(0.000)
G-index	0.0178***	0.006
	(0.000)	(0.177)
BusDisclosIndx	−0.006	0.023*
	(0.085)	(0.019)
Stock	−0.146***	–
	(0.000)	–
Gold	0.198***	0.835***
	(0.000)	(0.000)
RD_GDP	–	7.393**
	–	(0.026)
Broadband	0.081***	–
	(0.000)	–
Innovation	–	−0.014*
	–	(0.013)
PolUnc	−0.146**	−0.356*
	(0.002)	(0.064)
Constant	−1.23***	−1.901**
	(0.000)	(0.009)
Observations	220	247
R^2	0.746	0.621

Note: Table 2 reports the OLS regression results. SDG6 is water and sanitation management measured as the average of the targets 6.1.1–6.1.6, 6.2.1–6.2.9), SDG13 is the climate action measured as the log of the million tons of carbon emission), Bitcoin is measured as a log of Bitcoin trading volume (in USD), GDP (GDP per capita in USD), Inflation (the inflation rate of the country), and Unemployment (the unemployment rate over the percentage of the labour market). G-index (a governance index to capture country-level investor protection). BusDisclosIndx (refers to the extent of business disclosure in the country, it ranges between 1 and 10). Stock is the log of the total value of stock trading volume (in USD), Gold is the log of the total value of the gold reserves (in USD), RD_GDP is the percentage of allocated money for research and development over GDP, Innovation (GII), Broadband is the log of the number of home broadband subscriptions, and **PolUnc is the political-economic uncertainty.**
***, ** and * indicate that the coefficients are significant at the 1%, 5% and 10% level of significance, respectively. Numbers in brackets are p-values.

2024). While some studies discuss the negative and positive aspects of cryptocurrencies on sustainability (Aalborg et al., 2019; Bouraoui, 2020; Tsolakis et al., 2021), the questions of how Bitcoin trading volume impacts the progress towards SDG 6 (water and sanitation) and SDG 13 (climate action), particularly in terms of carbon emissions and how this impact may vary between countries based on their economic classification (i.e., developed and emerging markets, economic policy uncertainty, and levels of technology exports) remain unanswered. Accordingly, this study seeks to answer these questions comprehensively, offer insights into the varying effects of Bitcoin trading across different economic contexts, and provide recommendations to researchers and policymakers.

We employed a balanced panel of 256 country-year observations from 32 countries to attain the study objectives and answer its questions. The study employs the Resource-Based View (RBV) and Institutional Theory to support the proposed empirical model and answer the questions related to SDGs 6 and 13. The findings reveal that Bitcoin trading volume significantly and positively influences SDG 6, facilitated by utilizing network resources in smart cities and directing funds toward water network expansion and improved water access. However, despite its generated wealth and resources, the study identifies a positive and significant impact of Bitcoin trading volume on SDG 13, contributing to increased CO-2 emissions. These findings highlight the often-unacknowledged effects of increased trading, which could potentially hinder climate actions but still enhance the attainment of other SDGs and levels of sustainability reporting. Moreover, the results provide valuable insights for central banks and policymakers in devising regulatory frameworks for crypto trading, considering the differences between emerging and developed markets and other factors of economic policy uncertainty and technology exports.

The influence of Bitcoin trading on SDGs 6 and 13 encompasses several intricate channels that warrant academic exploration within research discourse (de Villiers et al., 2021). Bitcoin mining, integral to its functioning, raises environmental concerns due to its energy-intensive nature. The substantial energy consumption in Bitcoin mining contributes to carbon emissions, impacting climate change and potentially undermining SDG 13, emphasizing climate action and environmental sustainability. Blockchain technology, underlying Bitcoin transactions, offers potential applications in water management systems (Cui et al., 2018). Innovative blockchain solutions can enhance transparency, efficiency, and accountability in water distribution and management, thereby contributing to achieving SDG 6's objectives.

This research addresses a critical gap by exploring the relationship between cryptocurrency trading, particularly Bitcoin, and the attainment of SDGs 6 and 13. This study represents the first cross-country empirical investigation into how Bitcoin trading volume impacts the achievement of these SDGs. It contributes to the existing literature by providing new insights into the role of cryptocurrency trading in promoting environmental sustainability goals. Furthermore, it offers actionable recommendations and results that could shift current perceptions towards recognizing the potential of digital currencies in achieving the UN's environmental objectives. The findings have significant implications for policymakers, businesses, and investors, guiding them in prioritizing sustainable development strategies. Additionally, this study highlights the importance of integrating innovative technologies and governance practices in achieving the SDGs, presenting an opportunity to foster a greener and more sustainable future. Lastly, offering a methodologically rigorous and theoretically grounded investigation establishes a foundation for future studies about responsible practices and strategies in cryptocurrency adoption and regulation.

The remainder of the paper is structured as follows: Section 2 reviews the relevant literature and outlines the main theories supporting the impact of Bitcoin trading volume on environmental SDGs. Section 3 presents the methodology, followed by the main findings. Lastly, the study concludes with its implications, limitations, and potential directions for future research.

2. Literature and hypotheses development

The UN 2030 Agenda, encompassing 17 goals and 169 targets, aims to achieve sustainability while minimizing trade-offs across countries and goals. The pursuit of economic growth often intersects with environmental concerns, as unchecked economic activities may exacerbate climate change through increased emissions and resource depletion (Chang et al., 2023). Countries frequently prioritize economic aspects of sustainability over environmental and social dimensions, leading to a concentration of resources in the hands of a few (Cui et al., 2018; Wang et al., 2020). Conversely, sustainable economic growth involves mitigating environmental degradation and adopting climate-resilient strategies (de Villiers et al., 2021; Mustafa et al., 2022).

Institutional Theory posits that adopting climate-resilient strategies requires institutional environments to shape organizational behavior and ensure compliance with established norms, rules, and regulations (Di Vaio et al., 2024; Westney, 1993). This theory suggests that organizations are influenced by the institutional context in which they operate, including regulatory frameworks, governance standards, and societal expectations (Escobar and Vredenburg, 2011; Westney, 1993). These institutional pressures can drive organizations to adopt practices

Table 3
Autocorrelation (Serial correlation) Test.

		SDG 6	SDG 13
Wooldridge	**F**	5.18**	23.68***
	Prob > F	0.03	0.00

Note: Table 3 reports the autocorrelation results. SDG6 is water and sanitation management measured as the average target (6.1.1–6.1.6, 6.2.1–6.2.9). SDG 13 is the climate action measured as the log of the million tons of carbon emission). ***, ** and * indicate that the coefficients are significant at the 1%, 5% and 10% level of significance, respectively.

that are deemed legitimate and socially responsible (DiMaggio and Powell, 1983). For instance, in the United Kingdom, policymakers and regulators are pursuing sustainable economic growth by calling for detailed instructions under mandatory standards for firms regarding their carbon emission disclosures (Karim et al., 2021).

Researchers and agencies have highlighted the imbalance in progress toward economic SDGs and emphasized the interdependence of economic development and ecological sustainability, mainly focusing on SDGs 6 and 13. Industry 4.0 technologies have also been recognized for their potential role in promoting progress (Cui et al., 2018). The RBV theory posits that valuable, rare, inimitable, and non-substitutable resources can provide sustainable competitive advantages (Barney, 2001). In this context, Bitcoin and blockchain technology are considered strategic resources that can drive sustainability initiatives if leveraged effectively. Blockchain's decentralized nature can enhance transparency and accountability in environmental projects, while Bitcoin's economic value can fund sustainability efforts.

Hypothesis Development.

2.1. Clean and sustainable water and bitcoin

Challenges in attaining SDG 6, such as water scarcity and inequitable resource distribution, underscore the urgency for sustainable water and sanitation solutions (Roy and Pramanick, 2019; UN, 2015). Around four billion people suffer from severe water scarcity, leading to proper hygiene and sanitation challenges, particularly in low- and middle-income countries (Hannah et al., 2020). In Brazil, the challenge is acute, with limited sewage collection and treatment facilities due to economic constraints (Sampaio and Sampaio, 2020).

Data limitations have hindered progress assessment and relevance of indicators for SDG 6 (Essex et al., 2020; de Villiers et al., 2021; Mustafa et al., 2022; Nath et al., 2022; Parmentola et al., 2022). As the limited progress of SDG 6 indicators varies between developed and emerging markets, the spillover effect from developed to emerging countries by sharing best practices and policies will lead to progress enhancement. According to Kim et al. (2022), the ecological spillover of foreign direct investors in the same industry and city reduces the intensity of local firms' water pollution. Roy and Pramanick (2019) assert that the increasing per capita gross domestic product (GDP) improves sanitation indicators and decreases water-related diseases in India, particularly among children and older people. However, they questioned the sustainability of the results in the absence of an efficacious monitoring system. The need for this monitoring system is aligned with Institutional Theory as the Indian government's environmental policies influence environmental performance and reduce adverse financial outcomes as a normative pressure. The need becomes much more severe when there is a high level of economic policy uncertainty, as countries tend to invest less in SDGs in these cases (Iqbal et al., 2023).

Industry 4.0 provides solutions to reduce water leaks. For instance, it helps save water as it is one of the measures reported and optimized using the Internet of Things (IoT). In detail, IoT water sensors measure progress towards SDG 6 by providing accurate consumption data, stating the calculated savings (e.g., the number of liters), enabling smart contracts, and monitoring environmental standards. Businesses contribute to this as buyers may request that a supplier keep the number of 'liters used per product' below a specific limit and provide feedback to improve water management performance. Enhancing existing performance management systems could improve organizational accountability (de Villiers et al., 2021). Blockchain and IoT, as Parmentola et al. (2022) suggest, streamline the monitoring of water networks, ensuring equitable access to resources. In turn, using Bitcoin can improve the instant reporting of expenditure waste in monetary terms, leading to enhanced disclosure. Similarly, the Bitcoin payment system captures unexpected spending and progress evaluation (Zhang et al., 2023).

According to RBV, these resources can be tangible or intangible assets, including technological innovations and financial capital, which can be strategically leveraged to achieve superior performance and sustainable growth (Mustafa et al., 2022). In the context of this research, Bitcoin and blockchain technology are viewed as strategic resources. As a digital currency, Bitcoin and blockchain technology, as its underlying infrastructure, possess unique attributes that can be harnessed to drive sustainability initiatives. For instance, the decentralized nature of blockchain can enhance transparency and accountability in environmental projects, such as those focused on water management (SDG 6). Additionally, the economic value generated from Bitcoin trading can be redirected to fund sustainability projects, potentially mitigating the negative impacts of traditional funding mechanisms on the environment. In other words, SDG 6 will be attained when wealth is created, and waste is reduced, which can be assigned to water management pipelines, water availability, and hygiene services. As a result of this civilized change, the communities will have better access to clean water. Across the literature, a gap exists in specific studies on Bitcoin. Therefore, the hypothesis is formulated as follows.

H1. Bitcoin trading volume has a positive association with attaining SDG 6.

2.2. Bitcoin and climate action

The profound implications of climate change, precipitated by the elevated rate of greenhouse gas emissions, indicate that a reactive stance towards carbon emissions management is no longer tenable (Chang et al., 2023). The UN agenda for sustainable development has emphatically underscored organizations' need to mitigate environmental pollution (Hui et al., 2024; Ntim and Soobaroyen, 2013; Ullah et al., 2022, 2024a). Specifically, SDG 13 delineates clear responsibilities for both public and private sector entities (Oyewo, 2023). SDG target 13.2 mandates that governments integrate climate change measures into national policies, strategies, and planning (UN, 2023). Concurrently, SDG target 13.3 calls upon private sector organizations and other stakeholders to enhance education, awareness, and human and institutional capacity on climate change mitigation, adaptation, impact reduction, and early warning (Oyewo, 2023; UN, 2023).

Blockchain technology has demonstrated its potential to improve economic and environmental sustainability (Truby, 2018; Sun et al., 2021). However, there is a massive argument about the relevance of this assumption to Bitcoin as one of blockchain's widespread applications. The debate has been raised as Bitcoin requires much energy for the hash rate during mining. According to The Cambridge Bitcoin Electricity Consumption Index (CBECI), mining consumes 114.8 TWh of electricity annually. The consumption is marginally less than the electricity consumption of Norway (125 TWh), home to approximately 5.3 million inhabitants (Yan et al., 2022). The energy consumed by a single Bitcoin transaction is approximately equivalent to the energy a typical American family uses over two months (Howson and de Vries, 2022).

Despite the high energy consumption, Bitcoin also has uncertain economic implications. Yan et al. (2022) reveal a negative correlation between policy uncertainty and investments. On the other hand, digital currency's price volatility is positively associated with the investment

Table 4
Newey Test results (SDGs 6 and 13).

	SDG 6 Index	SDG 13
Bitcoin	0.0407***	0.238***
	(0.001)	(0.000)
GDP	0.000*	−0.000**
	(0.030)	(0.002)
Inflation	−1.008**	−0.381
	(0.008)	(0.737)
Unemployment	0.174	3.537***
	(0.464)	(0.000)
G-index	0.0178***	0.00634
	(0.000)	(0.177)
BusDisclosIndx	−0.00659	0.0234*
	(0.085)	(0.019)
Stock	−0.146***	–
	(0.000)	–
Gold	0.198***	0.835***
	(0.000)	(0.000)
RD_GDP	–	7.393*
	–	(0.026)
Broadband	0.0812***	–
	(0.000)	–
Innovation	–	−0.0140*
	–	(0.013)
PolUnc	−0.146**	−0.356
	(0.002)	(0.064)
Constant	−1.233***	−1.901**
	(0.000)	(0.009)
Observations	220	247

Note: Table 4 reports the Newey test results. SDG6 is water and sanitation management measured as the average of the targets 6.1.1–6.1.6, 6.2.1–6.2.9), SDG13 is the climate action measured as the log of the million tons of carbon emission), Bitcoin is measured as a log of Bitcoin trading volume (in USD), GDP (GDP per capita in USD), Inflation (the inflation rate of the country), and Unemployment (the unemployment rate over the percentage of the labour market). G-index (a governance index to capture country-level investor protection). BusDisclosIndx (refers to the extent of business disclosure in the country, it ranges between 1 and 10). Stock is the log of the total value of stock trading volume (in USD), Gold is the log of the total value of the gold reserves (in USD), RD_GDP is the percentage of allocated money for research and development over GDP, Innovation (GII), Broadband is the log of the number of home broadband subscriptions, and **PolUnc is the political-economic uncertainty.**
***, ** and * indicate that the coefficients are significant at the 1%, 5% and 10% level of significance, respectively.

streams of the youngest black funds with fewer revenue flows. Green funds exhibit no association between their investment flows and digital currencies. Correspondingly, there is an opportunity for better investment implications when mining relies on power derived from greener sources. Thus, digital currencies might replace all existing stores of value (even gold) and open avenues for exchange with a more efficient digital substitute. Howson and de Vries (2022) are not optimistic about this assumption. According to them, Bitcoin's design now supports no more than seven transactions per second, while Visa's network handles 1700–65,000 transactions per second. The average Bitcoin transaction price ranges from $2 to $59. The worst part is that Bitcoin transactions can take 12 min to days to complete. The most crucial reason for Howson and de Vries (2022) is that the benefits of broad environmental, social, and governance are implausible in Bitcoin's current form.

The Institutional Theory explains the variation between the research streams according to how institutional pressures, such as environmental regulations and public demand for sustainability, can influence the behavior of Bitcoin traders and miners. Understanding these institutional factors is crucial for developing policies that promote the responsible use of cryptocurrencies in alignment with sustainability goals. In support of that, Greenberg and Bugden (2019) express fears about the community's economic identity in the United States. Moreover, delays in legalization, resistance, and criticisms of cryptocurrencies due to high energy consumption, illegitimacy, and environmental concerns are worrying examples. Saleem et al. (2023) added another factor to the equation, suggesting that even decisions based on agreeing on more energy consumption to boost GDP growth can be hampered due to uncertainty in policy implementation.

Contrary to previously published studies, Mustafa et al. (2022) conducted a bibliometric analysis and systematic literature review in this context. Their findings support the relationship between cryptocurrency, sustainable energy, and carbon emissions. They found other links to keywords of an arrangement of priorities that can be settled between consumed energy in mining and hash rate operations and the funds allocated to hydroelectricity and wave-power projects. In this case, reducing the gap and studying the link between cryptocurrency trading and achieving energy-focused goals, SDGs 7 and 13, would be possible. Similarly, Truby (2018) concentrates on the advantages of having a governance framework over digital currencies. The author adds that technology models must be created without dependence on energy consumption over economic or social benefits. Thus, their paper proposes a solution to this dilemma: tax ownership and the regulation of their use. MoneyGram supports the proposed solution, a money transfer business that uses Ripple's blockchain technology to cut the time required to send money from almost 1 h to mere seconds worldwide. Still, no lawmaker has attempted to account for the environmental consequences of the technology; instead, they only seek to incorporate digital currencies into the tax system or legitimate their presence. This view is supported by Dogan et al. (2022), who argue that the growing use of solar energy in Bitcoin mining can bring sellers and buyers together. Consequently, it will increase cost efficiency, reduce transmission and energy distribution, and reduce Bitcoin's carbon footprint. Solutions include developing alternative energy- and digital-transaction-efficient algorithms, using the waste heat generated by mining to heat a multifamily house, and designing a heat generator that depends on Bitcoin mining. Similarly, mining might be relocated to cooler regions with less energy.

There is substantial economic potential at the intersection of renewable energy and blockchain applications, such as Bitcoin mining, and it illustrates a pathway toward aligning technological advancements and financial metrics with global sustainability goals. The findings of Lal et al. (2024) indicate that Bitcoin mining is a profitable alternative in 80 of the 83 examined planned renewable installations, with the highest profit reaching $7.68 million. This compelling evidence supports the integration of Bitcoin mining with renewable energy and evaluates it as an opportunity from the perspective of the SDGs. Specifically, integrating Bitcoin mining with renewable energy can significantly contribute towards affordable and clean energy (SDG 7) and SDG 13 by reducing the traditionally high energy consumption and carbon footprint of cryptocurrency mining through renewable energy sources.

According to the above literature and the RBV theory, corruption-free or less corrupted is a rare and inimitable resource capability that makes nations logistically competitive (Di Vaio et al., 2020). Thus, blockchain-based technology, such as Bitcoin, overcomes the main drawback of the RBV, which is its lack of ability to keep resources corruption-free, rare, and unique. In other words, resources are allocated more efficiently when excellent corruption control and governance systems are in place. Bitcoin is unique in transactions and addresses because it runs through a blockchain, and its inimitability is preserved (Di Vaio et al., 2020; Gunawan et al., 2020). Therefore, it achieves sustainability and comparative advantage. Such an understanding would help to answer our research question on Bitcoin's role in attaining SDG 13.

The hypothesis is proposed as follows to explore the role of Bitcoin in achieving SDG 13 related to climate action.

H2. Bitcoin trading volume has a negative association with attaining SDG 13.

Table 5
Heteroskedasticity.

		SDG 6	SDG 13
Breusch–Pagan	**F**	1.63	12.62***
	Prob > F	0.09	0.00

Note: Table 5 reports the Heteroskedasticity results using the Breusch–Pagan test. SDG6 is water and sanitation management measured as the average target (6.1.1–6.1.6, 6.2.1–6.2.9). SDG 13 is the climate action measured as the log of the million tons of carbon emission).
***, ** and * indicate that the coefficients are significant at the 1%, 5% and 10% level of significance, respectively.

3. Methodology

3.1. Data

We followed Marmora (2021) and Foley et al. (2022) in this study by obtaining Bitcoin trading volume data from the 'Coin.dance' website. The rationale for selecting 'Coin.dance' is that it provides data at the country level, unlike other sources such as Coinbase, BitFinex, BitStamp, HitBTC, Digiconomist, and Kraken, which typically offer data at the currency level (Conlon et al., 2024; Sarkodie et al., 2022). Additionally, 'Coin.dance' lists countries where Bitcoin-related activities are illegal, which is crucial as anti- or pro-Bitcoin regulations have significant impacts on national Bitcoin activity (Foley et al., 2022). This detailed and country-specific data allows for a more nuanced analysis of Bitcoin trading volumes concerning national policies and regulatory environments.

Across the 47 countries disclosed on the website, we selected 32 emerging and developed countries for the study sample. These countries were chosen based on the availability and completeness of their data, ensuring robust and reliable analysis. They span various regions and economic statuses, providing a broad spectrum of economic and developmental contexts and multiple continents—North America, South America, Europe, Asia, Africa, and Oceania—providing a global perspective on Bitcoin trading activities. Another factor is the varying degrees of technological adoption and digital infrastructure, which are critical factors influencing Bitcoin trading volumes. This variation ensures that the study captures a broad spectrum of market maturity and user adoption levels. Lastly, the sample includes countries with diverse regulatory environments regarding cryptocurrency, which is essential for understanding the impact of different regulatory frameworks on Bitcoin trading volumes. The remaining 14 countries were excluded due to significant missing observations. The final sample comprises 256 unique observations in 32 countries, covering 2013 to 2020.

The SDG data were obtained from the Sustainable Development Goals Database under the DataBank from the World Bank Database, following established literature (Bose and Khan, 2022; Warchold et al., 2022; Dang and Serajuddin, 2020) as a comprehensive quantification of SDG interactions on a global scale. The sample period for this study ranges from 2013 to 2019. To extend the time horizon to include 2020, the data were merged with equivalent targets from UNSTATS based on their series codes (Swain and Ranganathan, 2021; Dang and Serajuddin, 2020; Scherer et al., 2018).

The final sample comprises 256 unique observations across 32 countries, covering 2013 to 2020. This approach ensures that the study's findings are generalizable and reflect global trends, enhancing its relevance and applicability to diverse economic contexts and policy environments.

3.2. Variables

SDGs are classified into economic, social, and environmental goals (Coscieme et al., 2021). This study focuses on SDGs 6 and 13 due to data limitations on other environmental goals. SDG 6 measures a country's water availability, sanitation management, and sustainable usage patterns. It is based on targets 6.1.1–6.1.3, which measure the percentage of people with access to basic drinking water services. Targets 6.1.4–6.1.6 calculate the percentage of people using safely managed drinking water services. The other targets of 6.2.1–6.2.3 are measured by focusing on the percentages of individuals practising open defecation[1] and the percentage of people using minimal sanitation services (targets 6.2.4–6.2.6). Finally, targets measure the percentage of people using safely managed sanitation services (targets 6.2.7–6.2.9). The data considers people who have these services outside of the country's population in urban and rural areas (Roy and Pramanick, 2019; UNSTAT, 2019). The selected indicators are used as they cover the primary areas of the SDGs for ensuring water availability and the extent of sanitation services. They also consider the differences between urban and rural areas, linked to fewer future groups and series availability (Adams and Smiley, 2018; Zhong et al., 2022). Following previous research, the SDG 6 index is calculated as the targets' arithmetic mean (Roy and Pramanick, 2019; Swain and Ranganathan, 2021).

Climate change is one of the main concerns across the literature and receives top priority in policymakers' national agendas. Furthermore, SDG 13 (climate action) focuses on urgent actions to battle climate change and its impacts. SDG 13 is transformed using the natural logarithm to preserve normality. It is measured as the total carbon emissions (Mt CO_2 equivalent following (Sebestyén et al., 2019; Sharma et al., 2021; Swain and Ranganathan, 2021).

The Bitcoin trading volume is measured as the average weekly trading volume obtained from 'Coin.dance' and is transformed using the natural logarithm to preserve normality (Bergsten, 2005; Benita and Lauterbach, 2007).

3.3. Country-level control variables

Commensurate with the literature, the estimation models are controlled for variables that affect the relationship between SDGs 6 and 13. The control macroeconomic variables include the GDP per capita to control the economic development level of a country, as countries with higher GDPs often have more resources to allocate toward research and development in sustainable technologies, thereby accelerating innovation and adoption of environmentally friendly practices. Conversely, in economies with lower GDPs, financial constraints may limit the ability to prioritize and implement sustainability measures (Gong et al., 2020; Roy and Pramanick, 2019; Swain and Ranganathan, 2021). The inflation rate also controls the model, impacting economic stability and the capacity to invest in sustainable practices (Easterly, 2009; Gong et al., 2020; Roy and Pramanick, 2019). The unemployment rate controls the study model as it significantly impacts sustainability practices within a country (Nakagawa and Sakemoto, 2022). High unemployment often leads to reduced growth, which can curtail funding for sustainability initiatives, as immediate economic relief and job creation take precedence. This shift in priorities can result in strained public resources, diverting funds from environmental programs. High unemployment may increase resource exploitation, as natural resources are leveraged to create jobs and stimulate growth (Nakagawa and Sakemoto, 2022; Swain and Ranganathan, 2021).

A strong governance index (G-index)[2] enhances public trust and cooperation in sustainability programs, facilitating community engagement and support for environmental measures. Conversely, a low

[1] Open defecation 'is when the human practice of defecating outside ('in the open') rather than into a toilet'.

[2] G-index is measured as the mean of 6 dimensions: (1) control of corruption, (2) governance effectiveness, (3) political stability, (4) absence of violence/ terrorism and regulatory quality, (5) the rule of law, (6) voice and accountability).

Table 6
Ramsey RESET test for omitted variables.

		SDG 6	SDG 13
Ramsey RESET	**F**	20.98***	1.34
	Prob > F	0.000	0.26

Note: Table 6 reports the Ramsey results. SDG6 is water and sanitation management measured as the average target (6.1.1–6.1.6, 6.2.1–6.2.9). SDG 13 is the climate action measured as the log of the million tons of carbon emission). ***, ** and * indicate that the coefficients are significant at the 1%, 5% and 10% level of significance, respectively.

This study applies a GLS regression and a fixed effect to correct the omitted variable bias and ensure autocorrelation and heteroskedasticity in pooled cross-sectional data. The results in Table 7 indicate 'no autocorrelation' and 'heteroskedastic panel data' with significant results.

Table 7
GLS regression results (SDG 6 and 13).

	SDG 6 Index	SDG 13
Bitcoin	0.048***	0.026***
	(0.000)	(0.000)
GDP	0.000***	−0.00***
	(0.000)	(0.000)
Inflation	−0.729***	−0.192
	(0.000)	(0.488)
Unemployment	0.508**	4.564***
	(0.002)	(0.000)
G-index	0.014***	−0.01***
	(0.000)	(0.000)
BusDisclosIndx	−0.002	0.04***
	(0.056)	(0.000)
Stock	−0.153***	–
	(0.000)	–
Gold	0.211***	1.00***
	(0.000)	(0.000)
RD_GDP	–	−2.60
	–	(0.091)
Broadband	0.108***	–
	(0.000)	–
Innovation	–	0.038***
	–	(0.000)
PolUnc	−0.067*	0.083
	(0.029)	(0.071)
Constant	−1.521***	−2.94***
	(0.000)	(0.000)
Observations	220	247

Note: Table 7 reports the GLS test results. SDG6 is water and sanitation management measured as the average of the targets 6.1.1–6.1.6, 6.2.1–6.2.9), SDG13 is the climate action measured as the log of the million tons of carbon emission), Bitcoin is measured as a log of Bitcoin trading volume (in USD), GDP (GDP per capita in USD), Inflation (the inflation rate of the country), and Unemployment (the unemployment rate over the percentage of the labour market). G-index (a governance index to capture country-level investor protection). BusDisclosIndx (refers to the extent of business disclosure in the country, it ranges between 1 and 10). Stock is the log of the total value of stock trading volume (in USD), Gold is the log of the total value of the gold reserves (in USD), RD_GDP is the percentage of allocated money for research and development over GDP, Innovation (GII), Broadband is the log of the number of home broadband subscriptions, and **PolUnc is the political-economic uncertainty.**
***, ** and * indicate that the coefficients are significant at the 1%, 5% and 10% level of significance, respectively.

G-Index suggests weak governance, leading to inadequate enforcement of environmental laws, corruption, and inefficient use of resources allocated for sustainability (Joshi et al., 2015; Oyewo, 2023). Poor governance can undermine efforts to address environmental challenges, as regulatory gaps and lack of accountability hinder the implementation of sustainable practices (Oyewo, 2023). Therefore, this study uses the G-Index as a control variable, following Joshi et al., 2015; Osman and Zablith, 2021; Oyewo, 2023.

It is also crucial to ensure that any carbon emission will be communicated to the stakeholders and forced to publish comprehensive and informative sustainability information because of the legitimacy pressure (Karim et al., 2021), which is aligned with the institutional theory. Thus, the business disclosure index[3] will be used as a control variable (Bull and Miklian, 2019).

The CBECI estimates the annual energy use of Bitcoin to be 127.48 TWh, while gold mining uses 131.9 TWh.[4] Nevertheless, this is rarely mentioned in the mainstream media from an environmental perspective. Additional environmentally unsustainable methods are involved in the value chain when mining gold. These processes include air pollution from vehicles and mercury manufacture. Consequently, this study controls for USD gold reserves (Rosales et al., 2019). A country-level stock trading volume in USD is also viewed as an indicator of the listed companies' investment activities and equity investment to determine their economic performance (Abdou et al., 2024; Elamer and Utham, 2024; Frankovic et al., 2022; Ibrahim et al., 2024; Ibrahim et al., 2022; Pelster et al., 2019). Innovation potential is a crucial determinant in the present context. Innovation is measured as the number of broadband subscriptions (Lin et al., 2018). The global innovation index (GII)[5] is more comprehensive and widely accepted as an innovation measurement (Crespo and Crespo, 2016; Lopez-Carreiro and Monzon, 2018; Ullah et al., 2022). Other technical and development-related variables are included to control the scientific level and technological structure, including countries' spending on research and development (R&D; García-Dastugue and Eroglu, 2019). Finally, the module is controlled for political uncertainty index data (Selmey and Elamer, 2023).

The data for SDG 13, namely the Bitcoin trading volume, stock trading volume, and gold reserves variables, are transformed using log values. All control variables are obtained from the World Bank Database except for the GII from the Global Innovation Index (2020) database and political uncertainty obtained from the Data Uncertainty Index.

3.4. Study model

The study applies two empirical models to answer the research questions on the impact of Bitcoin trading volume on the attainment of SDGs 6 and 13.

(1) The first model for SDG 6 includes Bitcoin trading volume and country-level variables, including GDP per capita, inflation rate, unemployment rate, G-index, business disclosure index, stock trading volume, gold reserves, economic policy uncertainty and innovation (measured as the natural log of the number of broadband subscriptions). The reason for selecting broadband is that SDG 6 digital applications are mainly limited to reporting, water network management, and distribution, requiring timely data access. There is no such integration with political or investment sophistication to depend on multidimensional variables such as the GII. Simultaneously, understanding Bitcoin's impact implies the diffusion of innovation theory. Lastly, comprehending governance strength and business disclosure highlights the institution's responsibility. The two models are based on a theoretical foundation, as seen in Equations (1) and (2):

[3] **Business** disclosure index measures the extent to which investors are protected through disclosure of ownership and financial information. The index ranges from 0 to 10, with higher values indicating more disclosure.

[4] The estimation methodology is published at: https://ccaf.io/cbeci/index/methodology.

[5] GII is measured with 80 indicators such as: Political institutions, regulatory environment, business sophistication, human capital research, creative investments, diffusion, and ecological sustainability.

Table 8
Fixed effect.

Panel A: Fixed Effect Coefficients		
	SDG 6 Index	SDG 13
Bitcoin	0.030***	0.431***
	(0.000)	(0.000)
GDP	0.000***	−0.192***
	(0.000)	(0.000)
Inflation	−0.637*	−0.230
	(0.018)	(0.843)
Unemployment	−0.493	1.927*
	(0.111)	(0.033)
G-index	0.00*	−0.202***
	(0.016)	(0.000)
BusDisclosIndx	−0.00	0.00234
	(0.505)	(0.826)
Stock	−0.067*	–
	(0.015)	–
Gold	0.048	0.850***
	(0.411)	(0.000)
RD_GDP	–	7.214*
	–	(0.011)
Broadband	0.042	–
	(0.413)	–
PolUnc	0.049	−0.276
	(0.290)	(0.107)
Innovation	–	−0.117***
	–	(0.000)
	0.052	−0.276
	(0.24)	(0.107)
Constant	0.145	−3.000***
	(0.766)	(0.000)
Observations	220	247
Panel B: Hausman Test		
	SDG 6 Index	**SDG 13**
	0.030	0.000
Panel C: Country-Year Effect		
Country	Yes	Yes
Year	No	Yes

Note: Table 8 reports the fixed effect and Husman test results. SDG6 is water and sanitation management measured as the average of the targets 6.1.1–6.1.6, 6.2.1–6.2.9), SDG13 is the climate action measured as the log of the million tons of carbon emission), Bitcoin is measured as a log of Bitcoin trading volume (in USD), GDP (GDP per capita in USD), Inflation (the inflation rate of the country), and Unemployment (the unemployment rate over the percentage of the labour market). G-index (a governance index to capture country-level investor protection). BusDisclosIndx (refers to the extent of business disclosure in the country, it ranges between 1 and 10). Stock is the log of the total value of stock trading volume (in USD), Gold is the log of the total value of the gold reserves (in USD), RD_GDP is the percentage of allocated money for research and development over GDP, Innovation (GII), Broadband is the log of the number of home broadband subscriptions, and **PolUnc is the political-economic uncertainty.** ***, ** and * indicate that the coefficients are significant at the 1%, 5% and 10% level of significance, respectively.

$$SDG\ 6_{it} = \alpha + \beta 1\ \mathrm{Bitcoin}_{it} + \beta 2\ \mathrm{GDP}_{it} + \beta 3\ \mathrm{Inflation}_{it} + \beta 4\ \mathrm{Unemp}_{it} + \beta 5\ Gindex_{it} + \beta 6\ \mathrm{BusDisc}_{it} + \beta 7\ \mathrm{Stock}_{it} + \beta 8\ \mathrm{Gold}_{it} + \beta 9\ \mathrm{Broadband}_{it} + \beta 10\ \mathrm{PolUncer}_{it} + \varepsilon \quad \text{(Eq.1)}$$

(2) The second model for SDG 13 includes Bitcoin trading volume and country-level variables, such as GDP per capita, inflation rate, unemployment rate, G-index, business disclosure index, gold reserves, R&D expenses as a percentage of GDP, the Global Innovation Index and the economic uncertainty index. In equation (2), GII is used instead of broadband because it is a more synergistic technology that works in concert with dimensions of policymaking at different levels to control emissions.

As the main focus of Equation (2) is carbon emissions, stock trading is excluded since this study focuses more on the assets that result in pollution. Bitcoin's proponents contend that the network's environmentally disastrous trajectory is justified because Bitcoin could replace all existing stores of value (including gold) and means of exchange with a more efficient digital alternative (Howson and de Vries, 2022). Surprisingly, the technology investment firm Cota Capital indicates that gold mining is 50 times more expensive than Bitcoin mining. The primary energy sources for gold mining are grid power and energy derived directly from fossil fuels. At least 20 tonnes of waste are generated, with large quantities of dirt and rocks lost during the digging process to produce just a modest amount of gold. Thus, gold mining's contribution to the SDGs must be highlighted more in the investigation of SDG 13. GII replaces broadband due to its comprehensive scope of innovative solutions. As this research focuses on energy problems, it may be prudent to prioritize government spending on the following equation from 2013 to 2020:

$$SDG\ 13_{it} = \alpha + \beta 1\ \mathrm{Bitcoin}_{it} + \beta 2\ \mathrm{GDP}_{it} + \beta 3\ \mathrm{Inflation}_{it} + \beta 4\ \mathrm{Unemp}_{it} + \beta 5\ Gindex_{it} + \beta 6\ \mathrm{BusDisc}_{it} + \beta 7\ \mathrm{Gold}_{it} + \beta 8\ \mathrm{RDExp}_{it} + \beta 9\ \mathrm{GII}_{it} + \beta 10\ \mathrm{PolUncer}_{it} + \varepsilon \quad \text{(Eq. 2)}$$

Where *SDG* is sustainable development goal value, and *Bitcoin* is the natural log of the Bitcoin trading volume converted to USD.

The control variables are as follows: *Stock* is the total value of stock trading volume, *Gold* is the total value of gold reserves, *GDP* is the GDP per capita (all in USD), and *Inflation* is the inflation rate of a country. *Gindex* is the governance index, *BusDisc* is a country's business disclosure index, *RD* is the R&D expenses as a percentage of GDP, *Uemp* is the unemployment rate, *PolUncer* is the economic political uncertainty in the country, *Innovation* is the GII, and PolUncer is the political economy uncertainty.

4. Results and discussion

The results and discussion section illustrate the data analysis results, including descriptive statistics and Ordinary least squares (OLS) regression.

4.1. Descriptive statistics

The descriptive statistics in Table 1 summarise the variables for the final dataset of 256 country-year observations. Panels A, B, and C provide a comprehensive overview of the sample, including emerging and developed countries. The main observations are replaced with their lag values to handle missing values. Additionally, all continuous variables are Winsorized at 0.05 to remove outliers (Kennedy et al., 1992).

SDG 6 represents the progress made in ensuring safer water management for the population (Ferreira et al., 2021). The mean (standard deviation) of SDG 6 is 0.676 (0.237), indicating moderate progress in providing access to clean water and sanitation services for around 67.6% of the sampled counties' population in both urban and rural regions. In other words, seven years after the Agenda's announcement, approximately 67.6% of the global population have access to essential drinking water and can take advantage of sanitation facilities in urban and governing regions. These results align with Kim et al. (2022), who consider water pollution the riskiest, requiring more government attention.

The standard deviation of SDG 6 assists the generalizability of the results, even though differences exist in country classification and progress levels. The mean value in Panel C reveals that the attainment rate in developed markets is much higher (82.9%). In Panel B, the average attainment of SDG 6 in emerging nations is 47.9%. The findings are aligned with Roy and Pramanick (2019), demonstrating that India's open defecation rate was 39.83% in 2018 and is predicted to decline by

Table 9
Instrumental variable (2 SLS).

	SDG 6 Index	SDG 13
Bitcoin	0.066[b]	0.317[c]
	(0.001)	(0.000)
GDP	0.000	−0.000[c]
	(0.133)	(0.000)
Inflation	−1.138[b]	−0.940
	(0.003)	(0.480)
Unemployment	0.153	3.515[c]
	(0.596)	(0.001)
G-index	0.019[c]	0.003
	(0.000)	(0.546)
BusDisclosIndx	−0.009[a]	0.012
	(0.024)	(0.322)
Stock	−0.155[c]	–
	(0.000)	–
Gold	0.220[c]	0.827[c]
	(0.000)	(0.000)
RD_GDP	–	7.793[a]
	–	(0.016)
Broadband	0.066[a]	–
	(0.011)	–
PolUnc	−0.165[b]	−0.452[a]
	(0.009)	(0.024)
Innovation	–	−0.065[a]
	–	(0.024)
Constant	−1.405[c]	−2.485[b]
	(0.000)	(0.005)
Observations	219	245
R^2	0.741	0.613

Note: Table 9 reports the 2 SLS test results. SDG6 is water and sanitation management measured as the average of the targets 6.1.1–6.1.6, 6.2.1–6.2.9), SDG13 is the climate action measured as the log of the million tons of carbon emission), Bitcoin is measured as a log of Bitcoin trading volume (in USD), GDP (GDP per capita in USD), Inflation (the inflation rate of the country), and Unemployment (the unemployment rate over the percentage of the labour market). G-index (a governance index to capture country-level investor protection). BusDisclosIndx (refers to the extent of business disclosure in the country, it ranges between 1 and 10). Stock is the log of the total value of stock trading volume (in USD), Gold is the log of the total value of the gold reserves (in USD), RD_GDP is the percentage of allocated money for research and development over GDP, Innovation (GII), Broadband is the log of the number of home broadband subscriptions, and **PolUnc is the political-economic uncertainty.**
***, ** and * indicate that the coefficients are significant at the 1%, 5% and 10% level of significance, respectively.
p-values in parentheses.
[a] $p < 0.05$.
[b] $p < 0.01$.
[c] $p < 0.001$.

Table 10
Addressing reverse causality.

	SDG 6 Index	SDG 13
Bitcoin $_{t-1}$	0.037[c]	0.196[c]
	(0.001)	(0.000)
GDP	0.000[a]	−0.000[c]
	(0.020)	(0.000)
Inflation	−0.803[a]	1.271
	(0.030)	(0.330)
Unemployment	0.017	2.725[b]
	(0.953)	(0.008)
G-index	0.017[c]	0.000
	(0.000)	(0.873)
BusDisclosIndx	−0.005	0.031[b]
	(0.114)	(0.007)
Stock	−0.142[c]	–
	(0.000)	–
Gold	0.193[c]	0.839[c]
	(0.000)	(0.000)
RD_GDP	–	7.647[a]
	–	(0.020)
Broadband	0.080[b]	–
	(0.001)	–
Innovation	–	−0.056
	–	(0.056)
PolUnc	−0.134[a]	−0.221
	(0.026)	(0.246)
Constant	−1.204[c]	−2.176[a]
	(0.000)	(0.015)
Observations	219	245

Note: Table 10 reports the reversal causality results. SDG6 is water and sanitation management measured as the average of the targets 6.1.1–6.1.6, 6.2.1–6.2.9), SDG13 is the climate action measured as the log of the million tons of carbon emission), Bitcoin is measured as a log of Bitcoin trading volume (in USD), GDP (GDP per capita in USD), Inflation (the inflation rate of the country), and Unemployment (the unemployment rate over the percentage of the labour market). G-index (a governance index to capture country-level investor protection). BusDisclosIndx (refers to the extent of business disclosure in the country; it ranges between 1 and 10). Stock is the log of the total value of stock trading volume (in USD), Gold is the log of the total value of the gold reserves (in USD), RD_GDP is the percentage of allocated money for research and development over GDP, Innovation (GII), Broadband is the log of the number of home broadband subscriptions, and **PolUnc is the political-economic uncertainty.**
***, ** and * indicate that the coefficients are significant at the 1%, 5% and 10% level of significance, respectively.
p-values in parentheses.
[a] $p < 0.05$.
[b] $p < 0.01$.
[c] $p < 0.001$.

26.14% by 2032 –a sign of progress. In addition, Roy and Pramanick's (2019) analysis reveals that 49.47% of the Indian population will be able to drink water safely by 2032.

However, some countries are still lagging, with 1% of the sample attaining below 23%. The quantile progresses at 46.6%. Thailand, for example, only reached 14.4% in 2013 (the minimum achievement rate). This result is consistent with those of Sampantamit et al. (2020), who justify the difficulties of water management in Thailand to emphasize rising production. By contrast, Singapore completely solved its entire population's water and sanitation limitations in 2018 due to its long-term strategy to diversify water sources (Tortajada, 2020).

SDG 13 focuses on climate action, measured as the total carbon emissions (Mt CO_2 equivalent). The mean value of the log of SDG 13 is 8.289, which corresponds to an average of 814,165,339 tonnes of CO_2 emitted annually. The standard deviation of 0.694 indicates the global impact of this issue across countries. Notably, China leads in CO_2 emissions, emitting 10,667,887,452 tonnes in 2020, while Kenya ranks lowest in 2013. These findings align with previous studies (Osman and Zablith, 2021; Howson and de Vries, 2022) and justify international concerns over carbon emissions and climate change as China is under massive pressure from the international community members to reduce the levels of carbon emissions (Wu et al., 2024).

The exponential growth of Bitcoin in recent years (Breidbach and Tana, 2021) is evident in the mean (standard deviation) of its log value, which is 4.889 (1.034), equivalent to an average trading volume of $712,406 ($1,953,996). Notably, some countries reported very low trading volumes, while others, such as Russia, had substantial volumes, reflecting the challenges of regulating cryptocurrencies in countries with significant usage (Yan et al., 2022).

Macroeconomic control variables show differences between emerging and developed economies. The average GDP per capita is $12,427, with an inflation rate of 5.4% for emerging economies, while for developed economies, the average GDP per capita is $41,032, with an inflation rate of 1.7%. Both groups have similar unemployment rates, with emerging economies showing a slightly higher average of 0.8%. Governance plays a significant role in achieving sustainable

Table 11
The Arellano–Bond dynamic panel data (GMM).

	SDG 6 Index		SDG 13
L.SDG6Indx	−0.316** (0.009)	L.SDG13	0.888*** (0.000)
Bitcoin	0.0898*** (0.000)	**Bitcoin**	0.0293** (0.004)
GDP	−0.000*** (0.000)	**GDP**	0.0481** (0.006)
Inflation	−0.115 (0.595)	**Inflation**	−0.117 (0.168)
Unemployment	−0.487** (0.002)	**Unemployment**	0.0669 (0.104)
G-index	0.00180** (0.002)	**G-index**	0.150*** (0.000)
BusDisclosIndx	0.000204 (0.890)	**BusDisclosIndx**	−0.000703 (0.114)
Stock	0.0156** (0.003)	**Stock**	– –
Gold	−0.002 (0.631)	**Gold**	−0.000 (0.183)
RD_GDP	– –	**RD_GDP**	7.793* (0.016)
Broadband	−0.0197* (0.025)	**Broadband**	– –
PolUnc	0.066* (0.024)	**PolUnc**	−0.009 (0.261)
Innovation	– –	**Innovation**	0.035*** (0.000)
Observations	135	**Observations**	192

Note: Table 11 reports the Arellano–Bond dynamic panel data (GMM) results. SDG6 is water and sanitation management measured as the average of the targets 6.1.1–6.1.6, 6.2.1–6.2.9), SDG13 is the climate action measured as the log of the million tons of carbon emission), Bitcoin is measured as a log of Bitcoin trading volume (in USD), GDP (GDP per capita in USD), Inflation (the inflation rate of the country), and Unemployment (the unemployment rate over the percentage of the labour market). G-index (a governance index to capture country-level investor protection). BusDisclosIndx (refers to the extent of business disclosure in the country; it ranges between 1 and 10). Stock is the log of the total value of stock trading volume (in USD), Gold is the log of the total value of the gold reserves (in USD), RD_GDP is the percentage of allocated money for research and development over GDP, Innovation (GII), Broadband is the log of the number of home broadband subscriptions, and **PolUnc is the political-economic uncertainty.**
***, ** and * indicate that the coefficients are significant at the 1%, 5% and 10% level of significance, respectively.

development goals (de Villiers, Kuruppu, and Dissanayake, 2021). The G-index has an average score of 35.60, with emerging markets scoring an average of 27.3 and more established markets scoring 42. The average business disclosure index is 7.18, reflecting the corporations' contribution to SDGs, with voluntary disclosure becoming more critical during the pandemic (Hassan et al., 2021). According to Xue et al. (2022), the highest levels of policy uncertainty lead countries to focus more on economic goals than environmental sustainability. In our sample, the average policy uncertainty is 0.26, which is aligned with the progress of sustainability goals. However, the maximum value is 1.27, which indicates the need for more assets and income sources to support voluntary environmental sustainability agendas.

Proponents of cryptocurrencies such as Bitcoin assert that they can replace existing forms of money. The average value of traded stocks is 11.119 (equivalent to $2,378,453,992,309), while the average value of gold is 11.083 (equal to $313,991,796,281). A basic comparison reveals a difference between them. The variation has prompted some scholars to conclude that Bitcoin's energy impact is negligible compared with gold. Conversely, the high uncertainty during the COVID-19 period misleads the equation since investors view digital currencies as a safer alternative to gold, with many choosing them over equities (Baur and Hoang, 2021).

Technology-related variables include R&D spending as a percentage of GDP, which averages 1.3% in emerging economies, indicating relatively low investment in research and development. The number of broadband subscriptions, a measure of innovation, shows limited variation between countries, with an average of 6.772 and a standard deviation of 0.628.

4.2. OLS regression

The application of Ordinary Least Squares (OLS) regression in this study provides a robust analysis of the impact of Bitcoin trading volume on environmental sustainability, specifically focusing on SDGs 6 (water and sanitation) and 13 (climate action). After accounting for various control variables, the regression models offer insights into how Bitcoin trading volume correlates with these SDGs. The regression models (models 1 and 2) measured each SDG (6 and 13) individually to assess their impact on environmental sustainability.

Before running the regressions, the researchers examined multicollinearity by calculating tolerance coefficients (or VIF) between variables (Ullah et al., 2023, 2024b). The results showed no multicollinearity issues, except for the innovation variable (GII) and governance index (G-Index) in Equation (2), which was solved using 'ortholog.'. Appendix 2 shows the correlation matrix, which shows no multicollinearity problem. After transforming the variables using log values, the normality and linearity assumptions of the models were satisfied. The Shapiro-Wilk test was also applied to validate the normality assumption.

According to Table 2, the coefficient of Bitcoin trading volume in SDG 6 is positive and statistically significant ($\beta 1 = 0.040$, $P < 0.001$), indicating that a higher volume of Bitcoin transactions is associated with more significant progress in ensuring water accessibility and appropriate management. The income generated from Bitcoin can be redirected to fund water management projects and initiatives, thereby expanding sanitation and reducing open defecation. Even in developed countries, integrating Bitcoin payment systems can enhance water usage monitoring and ensure equitable distribution in smart cities. This conclusion is supported by the institutional theory, which states that strengthening the centralized system configuration in urban water management results in more on-site treatment of used water by decentralization (Fuenfschilling, L. and Truffer, 2014).

Our results also align with studies confirming blockchain's role in water management and smart cities (e.g., Parmentola et al., 2022; Thakur et al., 2021). Thakur et al. (2021) confirm that blockchain helps prevent water waste. According to them, countries have developed various water-saving techniques for rice production systems in Asia, including alternate soaking, drying, and aerobic rice culture. These techniques have been demonstrated to reduce water use and increase water productivity, but it is thus far unclear if they would raise or decrease rice yields. With typical irrigated flooding and rice production systems espoused by rice scientists at various research institutions, yield improvements encouraging farmers to cut irrigation rates have yet to be achieved. In their turn, Cao et al. (2024) supported our results as they believe that modern biological water-saving technologies like blockchain leverage advancements in biotechnology to reduce water consumption and enhance water-use efficiency in agricultural and industrial processes. Additionally, unconventional high-efficiency and safe-water utilization technologies are designed to maximise water conservation and ensure the safe use of water resources in various applications to solve the water-saving paradox problem.

In our context, Blockchain technology as a Bitcoin trading platform provides transparency and accountability, making it a viable tool for allocating funds to water network development projects, even in developed countries. The Bitcoin payment system would help monitor water usage and control equal distribution in smart cities since the resources are saved; thus, more accuracy is preserved according to the RBV theory. We can also see that Bitcoin can be considered a strategic resource that enhances a country's ability to fund and manage water

Table 12
T-test results.

	Mean1	Mean2	Dif	t value	p-value
Panel A: T-Test (By Country Economic Classification)					
Bitcoin	4.87	4.91	−0.10	−0.85	0.394
SDG6_Indx	0.82	0.47	0.35	17.6	0.000***
SDG13	8.17	8.42	−0.25	−3.00	0.003***
Panel B: T-Test (By Governance Level)					
Bitcoin	4.92	4.89	0.03	0.30	0.762
SDG6_Indx	0.51	0.83	−0.32	−15.2	0.000***
SDG13	8.41	8.14	0.26	3.25	0.002***
Panel C: T-Test (By level of Technology Exports)					
Bitcoin	4.81	4.96	−0.15	−1.32	0.18
SDG6_Indx	0.63	0.70	−0.06	−2.09	0.031**
SDG13	8.00	8.46	−0.45	−5.76	0.000***
Panel D: T-Test (By level of policy uncertainty)					
Bitcoin	4.80	5.04	−0.23	−2.04	0.04**
SDG6_Indx	0.678	0.67	0.007	0.25	0.79
SDG13	8.40	8.09	0.31	3.85	0.000***

Note: Table 11 reports the T-test results. SDG6 is water and sanitation management measured as the average of the targets 6.1.1–6.1.6, 6.2.1–6.2.9), SDG13 is the climate action measured as the log of the million tons of carbon emission), Bitcoin is measured as a log of Bitcoin trading volume (in USD).
***, ** and * indicate that the coefficients are significant at the 1%, 5% and 10% level of significance, respectively.

resources effectively. It also meets the sustainable resource criteria as a digital asset by generating economic value that can be leveraged for sustainability initiatives. This alignment with the RBV theory suggests that nations with substantial Bitcoin trading activities can use this resource to achieve better water management outcomes, thereby supporting SDG 6.

For the control variables, the innovation capability (measured by broadband subscriptions) substantially affects SDG 6 ($\beta1 = 0.081$, $P < 0.001$). The availability of broadband Internet would encourage greater adoption of Bitcoin-based payment as an innovative, comprehensive solution. In more detail, the robust internet infrastructure would help measure SDG 6 more accurately based on data synchronisation and availability. Also, a robust internet infrastructure encourages the adoption of Bitcoin-based payments as an innovative solution, facilitating accurate measurement and data synchronisation for water management projects.

Proving RBV theory, gold reserves are a resource like Bitcoin that could enrich the economy and provide additional funding to promote the sustainability of water resources. Gold reserves contribute to attaining SDG 6 ($\beta1 = 0.198$, $P < 0.001$). Nonetheless, stock trading negatively impacts achieving the same target ($\beta1 = -0.146$, $P < 0.001$). This finding validates the claims regarding firms' emphasis on economic profits and maximizing shareholder wealth over environmental development.

Fuenfschilling and Truffer (2014) adopted the Institutional theory to confirm that the systems concept highlights the importance of interdependence and co-evolution of both material and social structures, such as policies, culture, technologies, and markets for environmental water management and energy. Our results are supported by this conclusion as the country-level governance significantly affects SDG 6 ($\beta1 = 0.017$, $P < 0.001$), indicating the importance of institutions, including governments, in achieving sustainability through digitalisation platforms such as blockchain and digital currencies to preserve higher levels of accountability at the country level.

Following Di Vaio et al. (2020), economic limitations and financial challenges create doubts about targeting 2030 for the agenda. The present study's results indicate that a higher inflation rate means less progress towards SDG 6 ($\beta1 = -1.008$, $P < 0.01$), linked to more costs and less attention to water-related projects. In other words, low income reduces citizens' financial ability to pay for higher water quality. Also, the results show that unemployment significantly affects carbon emissions, as high unemployment forces governments to prioritize job creation over environmental regulations.

This study indicates that disclosure substantially does not affect SDG 6 from a business-related perspective. Despite the weak reporting of SDGs and poor coordination between the public and private sectors, governments comprehensively handle water management activities. However, business disclosure impacts carbon emission assessment, which is supported by those who see that organizations should play a vital role by communicating a sufficient level of carbon emission information with the stakeholders as it impacts firm valuation positively by reducing information asymmetry.

Regarding SDG 13, Table 2 demonstrates the Bitcoin trading volume's positive and statistically significant effect on carbon emissions ($\beta1 = 0.238$, $P < 0.001$). This outcome underscores the substantial environmental costs of Bitcoin mining, which demands significant energy consumption and contributes to increased carbon emissions. In other words, the higher the volume of Bitcoin transactions, the higher the hash rating, the greater the carbon emissions, and the worse the achievement of climate action goal. This conclusion is consistent with the prominent Bitcoin nodes underlying the accumulative computational capacity for algorithms' proofing (to maintain the credibility of distributed networks) and protection against external attacks. In addition, this study's findings are consistent with those of Jiang et al. (2021), who demonstrate that Bitcoin mining increases energy use and related carbon emissions, potentially jeopardising international efforts to promote sustainability. They used a simulation-based carbon emission model to investigate the carbon emission flows of Bitcoin mining operations in China; they discovered that the annual energy consumption of the Bitcoin blockchain in the country is anticipated to reach its peak in 2024 at 296.59 Twh and emit 130.50 million metric tonnes of carbon. On a global scale, these emissions would surpass the annualised greenhouse gas (GHG) emission outputs of Qatar and the Czech Republic.

Public concerns regarding perceived and actual environmental impacts have prompted the global mining industry to shift towards a more sustainable framework. In gold mining, several core issues must be considered when evaluating sustainability. Gold is often regarded as a finite and non-renewable resource, highlighting the complexities of its long-term production (Fuenfschilling and Truffer, 2014). Our results supported the previous view as they reveal that gold reserves have a significant effect on higher carbon emissions ($\beta1 = 0.835$, $P < 0.001$), substantially higher than Bitcoin ($\beta1 = 0.238$, $P < 0.001$). The literature suggests Bitcoin has gold-like features due to its design, being a store of value, and being a safe haven. The validity of stablecoins helps to reduce the risks of high-frequency price changes (Baur and Hoang, 2021). Still, CBECI analyses yearly energy consumption for gold mining, which is 500 PJ[6] (PJ). Still, the 3–16 PJ range for Bitcoin mining is relatively low. Vranken (2017) compares the long-term feasibility of Bitcoin mining to gold mining and reaches similar conclusions.

Our findings demonstrate that unemployment significantly impacts carbon emissions for many reasons. Due to the critical nature of unemployment in relation to government policies, a high unemployment rate forces regimes to focus on creating jobs and reducing life-threatening crises rather than on regulating the environment. The reduction in income has an inverted relationship with the capacity to obtain green products; hence, most cheap products are not sustainable. Even if a more efficient solution is available, such as an environmental tax, it would not be considered since poor people would be the most affected segment (Rafique et al., 2022).

It is important to note that while blockchain technology can support

[6] Petajoules is an energy and heat measure 0.27 TWh.
[7] The reduction in the number of observation Stata applying listwise deletion to observations with a missing value(s) in any variable.

environmental goals, Bitcoin's volatility and policy uncertainty are significant burdens for cautious investors (Kim et al., 2022; Yan et al., 2022). Therefore, Bitcoin cannot be generalised as eco-friendly solely based on its use of blockchain. The GDP per capita has a weak negative impact on carbon emissions, which could be promising when economic growth is realised. On the other hand, the current G-index and inflation rate do not impact the achievement of SDG. Political uncertainty variable negatively impacts SDGs 6 and 13, reflecting how economic and political instability can hinder progress towards sustainability goals, which confirms the need for further consideration of clear policies as per the Institutional theory.

4.3. Autocorrelation (serial correlation)

Following Drukker (2003), this study uses the Wooldridge test for the issues of panel data set autocorrelation (serial correlation)[8] The results reveal that the values are significant for SDG6 (0.03) and SDG 13 (0.000), indicating an autocorrelation problem (see Table 3).

In the study, the researcher identified issues of autocorrelation and heteroskedasticity in the data, which can affect the efficiency and consistency of the fixed and random effect estimators. The Newey-West test addresses these issues by solving heteroskedasticity and serial correlation, providing consistent, efficient, and unbiased estimators. The procedure estimators account for the autocorrelation in the error terms. The same approach has been applied in related literature, such as in studies by Adeel-Farooq et al. (2023) and Husted and de Sousa-Filho (2017).

By employing The Newey-West method, the study aims to obtain more reliable and accurate results, ensuring that the coefficients of Bitcoin are statistically significant at the 1% level. The Newey-West test results are reported in Table 3. They are similar to the main OLS results, indicating that the significance and impact of Bitcoin trading volume on environmental sustainability remain consistent even after accounting for autocorrelation and heteroskedasticity. These results strengthen the findings' validity and enhance the credibility of the study's conclusions regarding the relationship between Bitcoin and sustainable development goals.

4.4. Unobserved heterogeneity

Following Baltagi (2008), the Breusch and Pagan test for heteroskedasticity[9] checks that the error variance is constant across the data. The models are robust following Vogelsang's (2012) solution to heteroskedasticity, which is clustered by country, and the robustness function is included in the OLS regression analysis. Table 5 rejects the null hypothesis and reveals a heteroskedasticity problem; error variances depend on the independent variables, and error terms are normally distributed and correlated for SDG 13 ($P = 0.000$) only.

Omitted variable bias occurs in the OLS estimator when a correlation exists between the independent and omitted variables. This omitted variable must also be a dependent variable factor (Wilms et al., 2021). This study uses the Ramsey RESET test to check for omitted variable bias. As Table 6 indicates, the null hypothesis – 'H_0: *The model has no omitted variables*' – of the Ramsey test is rejected for SDG 13 and accepted for SDG 6.

Fixed-effect models assume that the explanatory variable has a fixed or constant relationship with the response variable across all observations (Boulhaga et al., 2023; Elamer and Boulhaga, 2024; Elamer et al., 2024). This study uses the fixed effect to test Equation (1)'s results in Table 8 (Panel A), which signify the fixed-effect results using Bitcoin trading volume as an independent variable and SDGs 6 and 13 as dependent variables. We find positive and statistically significant coefficients for the initial OLS regression results. Moreover, this study tests the fixed effect's suitability using the Hausman test; its significance suggests that the assumptions for fixed-effect estimation are not violated (see Table 8, Panel C). Moreover, a fixed-effect over random-effect estimation is used as country-level variables, and Bitcoin trading is time-variant. Panel B of Table 8 reports the results of a Hausman test.

4.5. Instrumental variable regression

In this study, the potential endogeneity arising from omitted unobserved heterogeneity is addressed by using the lag of Bitcoin as an instrumental variable. The two-stage least squares (2SLS) regression is employed with the Bitcoin lag value as an instrument to estimate the relationship between Bitcoin trading volume and SDGs 6 and 13. The results show that even after controlling for endogeneity using the instrumental variable approach, the coefficient of Bitcoin remains positive and statistically significant for both SDG 6 and SDG 13.

Some countries may exhibit excellent progress in Bitcoin trading compared with others when their citizens are early adopters. Another reason for this is the success of similar crypto-trading activities at earlier stages (Krückeberg and Scholz, 2020). A possibility exists that these countries would have stayed successful in terms of SDG progress in the past; therefore, this study might find a positive relationship between SDG progress and Bitcoin. Checking the reverse causality is crucial as the statistical inference in OLS regression may be inaccurate when results are attributable to reverse causality as a robustness check. Regressing the dependent variable on lagged or lead values of the independent variable (or vice versa) can mitigate the problem of reverse causality (Faleye et al., 2014). The study regresses the dependent variables (SDGs 6 and 13) on the lagged values of the independent variable (Bitcoin trading volume) to further mitigate the potential issue of reverse causality. Any impact of the previous Bitcoin trading volume is controlled, and the reverse causality problem is addressed using the dependent variable's one-year lag value.

4.6. Reverse causality

Some countries may exhibit excellent progress in Bitcoin trading compared with others when their citizens are early adopters. Another reason for this is the success of similar crypto-trading activities at earlier stages (Krückeberg and Scholz, 2020). A possibility exists that these countries would have stayed successful in terms of SDG progress in the past; therefore, this study might find a positive relationship between SDG progress and any Bitcoin-related variable. Checking the reverse causality is crucial as the statistical inference in OLS regression may be inaccurate when results are attributable to reverse causality as a robustness check. Regressing the dependent variable on lagged or lead values of the independent variable (or vice versa) can mitigate the problem of reverse causality (Faleye et al., 2014). The assumption underlying the use of lagged values is that Bitcoin's past trading volume is predetermined. Consequently, this study addresses the reverse causality problem and employs the dependent variable's one-year lag value. This approach allows any impact of the previous Bitcoin volume to be controlled.

Table 10 reveals the existence of positive and statistically significant coefficients for the lag value ($Bitcoin_{(t-1)}$) and SDGs 6 ($\beta = 0.037$, $P < 0.001$) and 13 ($\beta = 0.196$, $P < 0.001$). Other variables, such as gold reserves, significantly and positively impact SDG 6 ($\beta = 0.193$, $P < 0.001$) and SDG 13 ($\beta = 0.839$, $P < 0.001$). Accordingly, the reported results suggest that the findings in Table 2 (OLS main results) are

[8] Serial correlation 'is the degree of correlation of the same variables between two successive time intervals. It measures how the lagged version of the value of a variable is related to the original version of it in a time series'. Because serial correlation in linear panel-data models biases the standard errors and causes the results to be less efficient.

[9] Heteroskedasticity is 'when the standard deviations of a predicted variable, monitored over different values or as related to time, are non-constant. It is any set of data that is not homoscedastic (data with unequal variability (scatter) across a set of predictor variables)'.

Table 13
OLS regression (country classification).

Variables	1: Emerging Countries		2: Developed Countries		3: Low-Technology Exports		4: High-Technology Exports		5: Low-Political Uncertainty		6: High-Political Uncertainty	
	SDG6	**SDG13**	**SDG6**	**SDG 13**	**SDG6**	**SDG13**	**SDG6**	**SDG13**	**SDG6**	**SDG13**	**SDG6**	**SDG13**
Bitcoin	0.0558***	0.00519	−0.0141	0.389***	0.0330*	−0.0422	0.0585**	0.258***	0.0254	0.232***	0.057*	0.305***
	(0.000)	(0.819)	(0.216)	(0.000)	(0.032)	(0.144)	(0.004)	(0.000)	(0.101)	(0.000)	(0.010)	(0.000)
GDP	0.0650***	−0.239***	−0.00377	−0.226***	0.0378*	0.336***	0.000	−0.000***	−0.0156	−0.0855*	0.0234	−0.234**
	(0.000)	(0.000)	(0.776)	(0.001)	(0.010)	(0.000)	(0.306)	(0.000)	(0.312)	(0.014)	(0.378)	(0.004)
Inflation	0.124	1.868***	−1.028	−2.311	−0.547**	0.597*	0.186	−2.186	−1.114*	−1.311	−0.715	1.070
	(0.498)	(0.000)	(0.052)	(0.348)	(0.004)	(0.034)	(0.811)	(0.374)	(0.018)	(0.280)	(0.237)	(0.722)
Unemployment	−0.0993	2.162***	−2.183***	9.931***	0.213	3.506***	−0.329	7.465***	−0.688	8.064***	0.0330	1.462
	(0.648)	(0.000)	(0.000)	(0.000)	(0.481)	(0.000)	(0.953)	(0.000)	(0.166)	(0.000)	(0.908)	(0.057)
G-index	0.0202***	−0.156***	0.0385***	−0.219***	0.239***	0.114***	0.0215***	0.0106	0.174***	−0.16***	0.019***	0.036
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.100)	(0.000)	(0.000)	(0.000)	(0.701)
BusDisclosIndx	−0.0117**	0.0207*	−0.00616	0.0489**	−0.0200*	−0.0287	−0.007	0.0152	−0.0105*	−0.00282	−0.022**	0.0788*
	(0.007)	(0.035)	(0.162)	(0.009)	(0.019)	(0.124)	(0.205)	(0.197)	(0.017)	(0.844)	(0.006)	(0.025)
Stock	−0.0221	–	−0.0208	–	−0.21***	–	−0.16***	–	−0.11***	–	−0.12***	−0.10***
	(0.116)	–	(0.346)	–	(0.000)	–	(0.000)	–	(0.000)	–	(0.000)	(0.000)
Gold	0.0426***	1.030***	−0.0444*	0.678***	0.331***	0.425***	0.133**	0.973***	0.113***	0.907***	0.0074	1.107***
	(0.000)	(0.000)	(0.037)	(0.000)	(0.000)	(0.000)	(0.005)	(0.000)	(0.001)	(0.000)	(0.899)	(0.000)
RD_GDP	–	−4.685***	–	33.63***	–	−4.251*	–	0.965	–	10.69**	–	−9.344*
	–	(0.001)	–	(0.000)	–	(0.042)	–	(0.714)	–	(0.002)	–	(0.045)
Broadband	−0.00637	–	0.0726*	–	0.0402	–	0.124**	–	0.0299	–	0.217***	–
	(0.578)	–	(0.041)	–	(0.256)	–	(0.010)	–	(0.319)	–	(0.000)	–
Innovation	–	0.0584***	–	−0.0835*	–	−0.173***	–	0.00488	–	−0.0309	–	0.108*
	–	(0.000)	–	(0.027)	–	(0.000)	–	(0.474)	–	(0.343)	–	(0.013)
	−0.0986	−0.00998	0.0489	−0.671*	0.172*	0.361*	−0.150*	−0.198	–	–	–	–
	(0.114)	(0.940)	(0.501)	(0.047)	(0.020)	(0.044)	(0.024)	(0.281)	–	–	–	–
Constant	−0.236**	−3.390***	1.070**	−2.455**	−3.189***	3.733***	−0.848*	−4.246***	−0.743	−3.396***	−0.289	−6.098*
	(0.004)	(0.000)	(0.007)	(0.007)	(0.000)	(0.000)	(0.035)	(0.000)	(0.082)	(0.000)	(0.499)	(0.024)
N	107	100	113	113	82	77	116	136	159	160	61	55
R^2	0.752	0.942	0.411	0.719	0.850	0.810	0.742	0.696	0.688	0.624	0.871	0.776

Note: Table 13 reports the OLS results per economy type. SDG6 is water and sanitation management measured as the average of the targets 6.1.1–6.1.6, 6.2.1–6.2.9), SDG13 is the climate action measured as the log of the million tons of carbon emission), Bitcoin is measured as a log of Bitcoin trading volume (in USD), GDP (GDP per capita in USD), Inflation (the inflation rate of the country), and Unemployment (the unemployment rate over the percentage of the labour market). G-index (a governance index to capture country-level investor protection). BusDisclosIndx (refers to the extent of business disclosure in the country, it ranges between 1 and 10). Stock is the log of the total value of stock trading volume (in USD), Gold is the log of the total value of the gold reserves (in USD), RD_GDP is the percentage of allocated money for research and development over GDP, Innovation (GII), and Broadband is the log of the number of home broadband subscriptions, and **PolUnc is the political-economic uncertainty.**
***, ** and * indicate that the coefficients are significant at the 1%, 5% and 10% level of significance, respectively.

unrelated to the reverse causality issue.

4.7. The Arellano–Bond dynamic panel-data (GMM) analysis

The utilization of the Arellano–Bond dynamic panel-data estimation based on the generalised method of moments (GMM) in this research stems from several crucial methodological and analytical advantages, making it an invaluable tool for investigating panel data dynamics. GMM techniques within the Arellano–Bond framework are designed to handle endogeneity issues effectively by utilizing lagged values of variables as instruments. This test helps mitigate biases stemming from endogenous regressors, offering a robust approach to handle correlated errors and unobserved heterogeneity common in panel data (Topolewski, 2021). By considering lagged values of variables, the model captures both short-term dynamics and long-term relationships (Shobande and Ogbeifun, 2022). This efficiency in utilizing panel data helps uncover time-series properties within the cross-sectional units, enhancing the estimation's accuracy and precision. As such, the process concludes that through investigating the time dimension in a dynamic framework, the researchers can understand how bitcoin trading volume changes influence SDG 6 and 13's progress, allowing them to account for both short-term and long-term effects in panel data, making it a suitable choice for analyzing relationships over time while considering the panel structure of the data.

This test is also applied to handle time-invariant heterogeneity. GMM-based dynamic panel-data models, like Arellano–Bond, are adept at controlling for time-invariant individual effects or unobserved heterogeneity. They allow for the inclusion of fixed effects, ensuring a rigorous examination of the effects of time-varying factors on the dependent variable. Compared to ARDL, GMM-based dynamic panel-data models are suitable for handling non-stationarity and persistent dynamics encountered in economic and social datasets. They enable the modelling of lagged dependent variables, capturing the persistence of shocks or effects across periods. However, ARDL is used for time series data (Ganda, 2019).

GMM estimation, within the Arellano–Bond setup, delivers consistent estimates even when the number of time periods is small compared to the number of cross-sectional units (Boulhaga et al., 2023; Elamer and Boulhaga, 2024). This statistical efficiency is crucial for making valid inferences and reliable conclusions from limited time-series data. Finally, GMM allows for the inclusion of instruments to address potential issues of simultaneity and omitted variable bias, enhancing the model's robustness against these econometric concerns.

According to the results in Table 11, the Arellano–Bond dynamic panel-data estimation undertaken in this study presents an intricate portrayal of the relationship dynamics within panel data. The dataset, structured across an average of approximately 4.55 time periods per country, offers a comprehensive view of temporal variations within the panel. Notably, the model's encompassing instrumentation of 38 instruments yielded a statistically significant fit (Wald chi2(4) = 27.30, Prob > chi2 = 0.0000), indicating a collective instrumental strength amplifying the model's explanatory capacity.

Examining the specific coefficients, the lagged values of SDG6Indx revealed nuanced impacts on the dependent variable. The first lag exhibited a statistically significant negative effect (−0.300, $p = 0.015$), suggesting a historical influence on current outcomes. In parallel, Bitcoin emerged as a focal point, demonstrating a substantial adverse effect on the dependent variable in both its current (−0.092, $p < 0.001$) and lagged (0.091, $p < 0.001$) forms. These findings underscore the immediate and lasting repercussions of Bitcoin fluctuations on the dependent variable. Complementing these insights is a suite of other explanatory variables, including LogStock, LogGold, GDP, and others, each contributing distinctive facets to the multilayered narrative with varying statistical significance.

The intricate instruments utilized, notably lagged values of SDG6Indx and Bitcoin , acted as critical lenses, illuminating potential endogeneity concerns and uncovering the intricate interplay between variables. This comprehensive analysis paints a complex tapestry of interdependent factors shaping outcomes across countries, inviting deeper exploration into economic theories and empirical contexts to unravel the underlying intricacies of this compelling narrative.

For SDG 13, An integral aspect of this estimation lies in its instrumental capacity, deploying 34 instruments. The model's overall fit is substantiated by a Wald chi-squared statistic of 40.44 (Prob > chi2 = 0.0000), affirming its robust statistical significance and underlining the collective instrumental strength, enhancing its explanatory prowess.

Focusing on the estimated coefficients, SDG13 emerges as a significant variable. Its first lag exhibits a robust and statistically significant positive effect (0.888, $p < 0.001$) on the dependent variable, reflecting the substantial influence of prior SDG13 values on the current outcome. Additionally, Bitcoin showcases a notable impact through its first lag (0.029, $p = 0.004$), implying a positive association between its lagged value and the dependent variable.

Among other explanatory variables (GDP, Inflation, Unemployment, G-index, BusDisclosIndx, Gold, Innovation, PolUnc), varying degrees of significance and directional effects are observed. These variables contribute nuanced facets to the model, with some exhibiting statistically significant impacts on the dependent variable while others demonstrate less conclusive effects.

The instruments employed in the differenced equation encompass specific lagged values of SDG13 and Bitcoin , illuminating potential endogeneity concerns and unveiling intricate relationships between variables. This comprehensive analysis portrays a multifaceted narrative of interdependent factors influencing outcomes across distinct groups, prompting further exploration into economic theories and empirical contexts for a deeper understanding of these complex dynamics.

4.8. Additional analysis

As the 2030 deadline for the SDGs draws near, some countries worry about missing the boat of sustainable growth. In particular, a significant difference exists between developing and emerging economies in promoting human welfare, development goals, and economic prosperity. However, through Industry 4.0 technologies, increased success with the SDGs has been envisaged. Not only is the business community responsible for their achievement, but governments are responsible for gathering data regarding SDG targets and their coincident indicators. Therefore, a sound governance structure should be suitable for all economies. Whether Bitcoin would differ in its impact based on the type of economy and governance level remains a question. The present study applies a *t*-test to compare the means of Bitcoin trading volume and SDGs 6 and 13 based on the country classification. The results in Table 10 (Panel A) demonstrate that SDGs 6 and 13 significantly differ between emerging and developed markets, with p-values of 0.000 and 0.003, respectively. Although carbon emissions are a global issue, significant differences exist based on the country classification, which confirms the role and improvements based on the considerable changes in environmental policies in developed nations.

Table 12 (Panel B) indicates significant differences between countries with a high and low G-index. This result confirms this study's assumption of a gap in governance and transparency levels, which leads to improved progress and commitment toward SDGs without leaving any of them behind. Nevertheless, the results reveal no significant differences in Bitcoin trading and governance due to the general lack of regulations supporting cryptocurrency trading, which motivates this study to suggest urgent action to restrain crypto trading. Also, it is noticed from the T-test (Panel C) results that there are differences between the level of SDG 6 (0.03) and SDG 13 (0.000) based on having a high or low level of technology exports; this supports the evidence that technological development leads to higher income generation that can be allocated for UN SDGs agenda progress. However, the bitcoin trading volume shows no significant differences due to its international nature with no dependence on countries' related factors. SDG 13 and bitcoin trading differ between countries based on economic-political uncertainty, as CO_2 emissions and bitcoin trading have high levels of undisclosed and unregulated aspects. However, there are no significant differences based on the same factor for SDG 6, which confirms the progress levels and clarity in prioritizing this part of sustainability regardless of uncertainty levels, as seen in Panel D.

The following section presents the results of the OLS regression based on the economic classification of emerging and developed countries. As studies focused on smart cities and blockchain-based solutions have been evidenced, these findings indicate that these nations are expanding their research into improved water management. Table 12 (1) indicates that the volume of Bitcoin trading has a significant impact on the achievement of SDG 6, which confirms that if more wealth is generated from the volume of Bitcoin trading, then water management and sustainability projects will be advanced more rapidly in emerging markets that already have red flags in this file. Developed countries have already achieved satisfactory progress in SDG 6, with unemployment being the only significant variable that has a negative impact on water management.

For SDG 13, the findings suggest that the Bitcoin trading volume only substantially influences established markets ($\beta1 = 0.363^{***}$, $P < 0.001$), which is larger than in emerging economies. On the other hand, gold significantly impacts CO_2 emissions in both markets ($\beta1 = 1.207^{****}$, $P < 0.001$; $\beta1 = 0.577^{***}$, $P < 0.001$) and to a greater extent in developing nations that already have subpar environmental performance. SDG 13 is positively impacted in emerging nations by the innovation (GII) level ($\beta1 = -0.161^{***}$, $P < 0.001$). R&D spending also contributes to reducing this major problem on an international scale as it indicates that developed markets would pay more attention to and change their mindsets toward an innovative, environmentally friendly solution. This result is a promising indication of greener solutions for Bitcoin in the future. These differences across economies motivate the present study to focus on SDGs 6 and 13 at the country level to build a comprehensive view.

The findings in columns 3 and 4 unveil the consequential impact of bitcoin trading volume on attaining SDGs 6 and 13 within nations stratified by their technological export levels measured in USD. The outcomes starkly affirm that heightened bitcoin trading volume correlates positively with improved realization of SDG 6 across both country clusters. This result underscores a pivotal revelation: the generated income holds the potential to catalyze endeavours aimed at innovating novel solutions conducive to ensuring enhanced access to clean and sustainable water resources.

However, the dynamics shift concerning SDG 13, illuminating a divergent narrative contingent upon the technological export prowess of nations. Notably, the results delineate that amplified bitcoin trading volume corresponds with escalated carbon emissions solely within countries exhibiting elevated technological exports. This divergence underscores a noteworthy trend: high-tech export-driven nations, already inclined toward technological advancements and receptive to digital innovations like digital currencies, witness an uptick in carbon emissions. Such an upsurge could potentially propel these nations toward a renewed focus on investing in renewable energy solutions. As underscored by Wang et al. (2020), approximately a quarter of global carbon emissions over the last two decades stemmed from embodied emissions in export trade, significantly exacerbating the spectre of global warming. This conclusion substantiates the urgent need for nations to devise efficacious strategies to mitigate environmental costs without compromising economic prosperity. The influx of substantial income generated through bitcoin trading is a potential catalyst in developing these indispensable solutions.

The findings in columns 5 and 6 highlight the substantive influence of bitcoin trading volume on achieving Sustainable Development Goal (SDG) 13 across all strata, irrespective of the level of economic policy uncertainty. Intriguingly, the research posits that nations characterized by lower levels of uncertainty in economic policy showcase a detachment between bitcoin trading volume and the attainment of SDG 6. This alignment resonates with the narrative of substantial strides toward achieving this goal within these nations. Nevertheless, the study delineates a notable impact of alternative assets, notably gold (0.113^{***}) and stocks (-0.11^{***}), signifying their significant influence on the attainment of SDG 6, marking a distinct divergence from the implications of bitcoin trading volume in this context.

The study findings have profound policy implications. Policymakers should consider incentivizing the use of renewable energy in Bitcoin mining to mitigate its environmental impact, thus aligning economic benefits with sustainability goals. Simultaneously, businesses limit their accountability to sanctions-based pollution, air, greenhouse gases, and waste management. Finally, the economic uncertainty index negatively impacts SDG 6 as countries tend to progress less on sustainability when they have high ambiguity about their economic stability (Xue et al., 2022).

Regulators should develop governance practices that mandate social responsibility in cryptocurrency trading, promoting transparency and sustainable practices. Policymakers need to incentivize using renewable energy in Bitcoin mining to mitigate its environmental impact. Additionally, international collaboration is crucial to harmonize regulations and share best practices globally. Integrating blockchain technology into water management projects can ensure efficient and transparent allocation of funds, promoting SDG 6.

The overall findings of this study carry several significant implications and offer specific recommendations. Regarding the economic implications, the findings reveal that Bitcoin can be a valuable economic resource for funding environmental sustainability projects, particularly water management initiatives. However, the environmental costs associated with Bitcoin mining necessitate a balanced approach. For policymakers, the study highlights the importance of developing and enforcing governance practices that mandate social responsibility in cryptocurrency trading, promoting transparency and sustainable practices. Policymakers should incentivize the use of renewable energy in Bitcoin mining and encourage international collaboration to harmonize regulations and share best practices globally. Integrating blockchain technology into water management projects can ensure efficient and transparent allocation of funds, promoting SDG 6. Additionally, the results emphasize the importance of proactive measures to balance economic benefits with environmental protection, fostering a more sustainable and responsible digital economy.

This study contributes significantly to the academic literature by providing empirical evidence on Bitcoin's dual impact on environmental sustainability. It highlights the need for further research into sustainable practices in cryptocurrency mining and the potential of digital assets to fund sustainability initiatives. Integrating the Resource-Based View (RBV) and Institutional theories into the analysis offers a theoretical framework for understanding how strategic resources like Bitcoin can be leveraged for environmental sustainability.

This study provides valuable insights into the complex relationship between Bitcoin trading volume and environmental sustainability. The positive impact on SDG 6 (clean water and sanitation) and the negative impact on SDG 13 (climate action) highlight the dual nature of cryptocurrency trading, emphasizing the need for balanced regulatory frameworks. The findings underscore the importance of innovation, governance, and economic stability in promoting sustainable practices. They offer a roadmap for policymakers and stakeholders to integrate sustainability into the evolving digital finance landscape.

The findings of this study emphasize the need for balanced regulatory frameworks that address both the economic and environmental impacts of Bitcoin trading. The integration of innovative technologies and sound governance practices is crucial for promoting sustainable development. This research provides a foundation for future studies on responsible practices and strategies in cryptocurrency adoption and regulation, offering valuable insights for policymakers, businesses, and investors aiming to achieve the United Nations' environmental objectives.

5. Conclusion

Pursuing the United Nations' Sustainable Development Goals (SDGs) by 2030 presents a formidable challenge for countries worldwide. Among the diverse range of technologies that have emerged over the past decade, Bitcoin stands out due to its rapid adoption and potential environmental implications. As the focus on environmental sustainability intensifies, it becomes imperative to investigate the potential of Bitcoin trading to positively influence specific SDGs, such as SDG 6 and SDG 13, which are crucial for environmental preservation.

Through a robust quantitative approach, this study examines the impact of Bitcoin trading on environmental-focused SDGs, particularly SDG 6 (water and sanitation) and SDG 13 (climate action). Employing a panel data analysis of 32 countries, it reveals that Bitcoin trading can positively influence SDG 6 by potentially funding water management projects. Notably, the outcomes suggest that Bitcoin trading can create a funding source for water management projects and facilitate the monitoring of water networks, thereby bolstering the development of smart cities. These empirical results align with previous research, highlighting blockchain technology's potential in water supply management and environmental sustainability (Parmentola et al., 2022; Thakur et al., 2021; Lu, 2018). Furthermore, this study underscores the critical role of technological advancements, such as smartphones, in raising public awareness about environmental issues in both urban and rural settings.

Regarding SDG 13, our findings indicate a positive and statistically significant effect of Bitcoin trading volume on carbon emissions, highlighting the substantial environmental costs of Bitcoin mining, which demands significant energy consumption and contributes to increased carbon emissions. Specifically, higher volumes of Bitcoin transactions lead to increased hash rates, resulting in greater carbon emissions and hindering the achievement of climate action goals.

Our research was guided by theoretical underpinnings rooted in the RBV theory, which ensured a rigorous examination of the relationship between cryptocurrency trading and environmental SDGs. The combination of the RBV theory and Institutional theory offers a comprehensive framework for comprehending the strategic application of Bitcoin in advancing environmental sustainability. The RBV theory suggests that possessing distinct resources and capabilities might offer a competitive edge. From this perspective, Bitcoin can be seen as a valuable asset that can finance initiatives to promote environmental sustainability. In contrast, Institutional Theory highlights the significance of institutions and governance systems in influencing organizational behavior and societal outcomes. The study underscores the importance of implementing robust governance procedures and explicit policies to address the environmental consequences of Bitcoin mining effectively. Efficient institutional structures can enforce the use of sustainable energy sources in Bitcoin mining, foster transparency, and ensure that cryptocurrency trade aligns with broader sustainability objectives. Global cooperation and standardized laws are essential for reducing the adverse environmental effects and maximizing the beneficial contributions of Bitcoin to sustainable development.

The findings highlight that Bitcoin can be a valuable economic resource for funding environmental sustainability projects, particularly water management initiatives. However, the environmental costs associated with Bitcoin mining necessitate a balanced approach. These results highlight the importance of proactive measures to balance economic benefits with environmental protection. Encouraging the use of Bitcoin to fund sustainable projects and ensuring stringent environmental regulations can help mitigate the adverse impacts of cryptocurrency trading. This comprehensive approach addresses immediate environmental concerns and fosters a more sustainable and responsible digital economy.

This study makes several academic contributions to advancing the understanding of cryptocurrency's environmental impacts. Firstly, it identifies the potential for Bitcoin trading to positively influence SDGs, particularly SDGs 6 and 13, by potentially funding water management projects and enhancing the monitoring of water networks, which supports the development of smart cities. Secondly, the study employs a robust quantitative approach, using panel data analysis across 32 countries, providing empirical evidence that aligns with previous research on blockchain technology's potential for environmental sustainability. Furthermore, integrating the RBV theory into the analysis offers a rigorous theoretical framework to examine the relationship between cryptocurrency trading and environmental SDGs. This approach enhances the accounting and finance literature by elucidating the strategic resources and institutional frameworks that shape this relationship. Additionally, the study's findings highlight the critical role of technological advancements in raising public awareness about environmental issues, making it a significant contribution to the field.

The study extends meaningful contributions to the literature, offering valuable insights for various stakeholders. First and foremost, the study identifies the potential for developed markets to serve as models for developing economies by implementing governance practices that mandate social responsibility and regulate cryptocurrency trading. Our research catalyzes further country-specific investigations, encouraging evidence-based policy formulation and strategic development amidst the uncertainties brought about by the pandemic. We advocate for a nuanced approach to environmental regulation, incentivizing renewable energy adoption and promoting sustainable e-waste management to address the environmental impact of cryptocurrency mining without necessarily imposing a coordinated global ban on trading by the regulators and policymakers.

This study acknowledges some limitations that should be considered when interpreting the findings. The analysis relies on the availability and completeness of Bitcoin trading volume data from the 'Coin.dance' website. The exclusion of 14 countries due to significant missing observations might limit the generalizability of the results to those countries. The sample period spans from 2013 to 2020, and while this period captures significant trends, more recent data beyond 2020 should be included, potentially overlooking new developments in Bitcoin trading and its environmental impact. Lastly, while the study employs a robust quantitative approach, it does not incorporate qualitative insights that could provide a deeper understanding of the contextual and human factors influencing the relationship between Bitcoin trading and environmental sustainability. Thus, integrating qualitative research methods in future research, such as interviews and case studies, could offer richer insights into the human and contextual factors affecting the impact of Bitcoin trading on environmental sustainability, reassuring the audience of the thoroughness and transparency of our research process.

Future research is also encouraged to investigate the environmental impacts of other cryptocurrencies and emerging technologies to provide a more comprehensive understanding of the digital finance ecosystem and its implications for sustainability. More detailed analysis of different policy and regulatory frameworks across countries can shed light on best practices and innovative approaches to managing the environmental impacts of cryptocurrency trading. Additionally, further research is needed on adopting renewable energy in cryptocurrency mining and sustainable e-waste management practices, helping formulate effective strategies to mitigate the environmental footprint of digital technologies. By addressing these limitations and exploring these future research directions, scholars can contribute to a deeper and more comprehensive understanding of the intersection between cryptocurrency trading and environmental sustainability, aiding in formulating informed policies and strategic initiatives.

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CRediT authorship contribution statement

Fairouz Mustafa: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Chima Mordi:** Writing – review & editing, Supervision, Project administration, Investigation. **Ahmed A. Elamer:** Writing – review & editing, Project administration, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix 1

Panel A: Included countries			
1. Argentina	11. Hong Kong	21. Poland	31. The UK
2. Australia	12. Hungaria	22. Romania	32. the USA
3. Brazil	13. India	23. Russia	
4. Canada	14. Japan	24. Saudi Arabia	
5. Chile	15. Kenya	25. Singapore	
6. China	16. Malaysia	26. South Africa	
7. Colombia	17. Mexico	27. Sweden	
8. Croatia	18. New Zealand	28. Switzerland	
9. the Czech Republic	19. Norway	29. Thailand	
10. Denmark	20. The Philippines	30. UAE	
Panel B: Excluded countries			
1. Domenic Rupiblica	5. Egypt	9. Iran	13. Peru
2. Morroco	6. Nigeria	10. Pakistan	14. Ukrania
3. South Africa	7. Tanzania	11. Turkey	
4. Venezuela	8. Vietnam	12. Kazakistan	

Note: Appendix 3 shows the sampled countries. The countries are sourced by "coin.dance".

Appendix (2)

Pairwise correlations

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
(1) SDG6Indx	1.000													
(2) SDG13	−0.232*	1.000												
(3) Bitcoin	−0.075	0.399*	1.000											
(4) GDP	0.737*	−0.200*	0.066	1.000										
(5) Inflation	−0.413*	0.038	0.176*	−0.415*	1.000									
(6) Unemployment	−0.133*	−0.048	−0.081	−0.233*	0.178*	1.000								
(7) Gindx	0.782*	−0.310*	−0.070	0.840*	−0.426*	−0.045	1.000							
(8) BusDisclosIndx	−0.056	0.225*	0.397*	0.067	−0.010	−0.144*	0.048	1.000						
(9) Stock	0.101	0.702*	0.344*	0.368*	−0.267*	−0.242*	0.206*	0.225*	1.000					
(10) Gold	0.023	0.643*	0.180*	0.150*	−0.175*	−0.337*	−0.084	0.096	0.808*	1.000				
(11) RD_GDP	0.434*	0.017	−0.008	0.562*	−0.430*	−0.369*	0.416*	−0.005	0.427*	0.272*	1.000			
(12) Broadband	−0.119	0.857*	0.419*	−0.069	0.043	−0.141*	−0.208*	0.146*	0.655*	0.683*	0.066	1.000		
(13) Innovation	0.725*	−0.153*	0.042	0.890*	−0.431*	−0.150*	0.871*	0.094	0.435*	0.188*	0.511*	0.012	1.000	
(14) PolUnc	−0.169*	−0.057	0.239*	−0.029	0.231*	0.267*	−0.067	−0.096	−0.071	−0.119	−0.038	−0.003	−0.059	1.000

***$p < 0.01$.
**$p < 0.05$.
* $p < 0.1$.

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