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FinTech Adoption and Its Influence on Sustainable Mineral Resource Management in the United States

Asif Raihan [1], Syed Masiur Rahman [1,2,3], Mohammad Ridwan [4] and Tapan Sarker [5,*]

[1] Applied Research Center for Environment and Marine Studies, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia; asif.raihan@kfupm.edu.sa (A.R.); smrahman@kfupm.edu.sa (S.M.R.)
[2] Department of Civil and Environmental Engineering, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia
[3] Interdisciplinary Research Center for Construction and Building Materials, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia
[4] Department of Economics, Noakhali Science and Technology University, Noakhali 3814, Bangladesh; m.ridwan.econ@gmail.com
[5] School of Business, University of Southern Queensland, Toowoomba, QLD 4300, Australia
* Correspondence: tapan.sarker@unisq.edu.au; Tel.: +61-7-3470-4406

Abstract: Sustainable mineral resource management is critical amid escalating environmental concerns and growing demand for minerals in digital and clean energy technologies. While financial technology (FinTech) has been widely recognized for enhancing financial inclusion and economic efficiency, its role in environmental governance—particularly in the mining sector—remains underexplored, especially within developed economies like the United States. This study addresses this gap by examining how FinTech adoption influences mineral sustainability, using time series data from 1998 to 2023. Four FinTech proxies—mobile cellular subscriptions, Internet usage, fixed broadband access, and financial inclusion—were analyzed alongside environmental compliance and investment in sustainable mining technologies. Using the Autoregressive Distributed Lag (ARDL) model and Frequency Domain Causality (FDC) analysis, the results show that greater FinTech adoption significantly reduces mineral depletion rates, indicating improved sustainability. Internet and broadband access exhibit strong long-term impacts, while mobile connectivity and credit access show notable short- and medium-term effects. Investment in sustainable mining technologies further enhances these outcomes. Our findings suggest that FinTech serves as a multidimensional enabler of sustainability through digital inclusion, transparency, and access to green financing. This study provides empirical evidence to guide policymakers in integrating digital financial infrastructure into strategies for sustainable mineral resource governance.

Keywords: resources; mineral management; FinTech; environment; sustainability; USA

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1. Introduction

The sustainable management of natural resources has emerged as a pressing concern for policymakers, researchers, and industry stakeholders globally [1,2]. In resource-intensive economies, mineral resources play a pivotal role in supporting industrial growth, technological innovation, and national security [3]. However, their unsustainable extraction and depletion pose serious environmental and economic challenges [4]. With rising demand for minerals—especially those critical to clean energy technologies and digital infrastructure—ensuring sustainable practices in resource utilization has become increasingly important [5]. In this context, emerging digital innovations, particularly in financial services, present new opportunities to drive sustainability in the extractive sectors [6]. Financial technology, commonly known as FinTech, refers to the use of innovative digital tools and platforms to deliver financial services more efficiently, inclusively, and affordably [7]. FinTech encompasses a wide array of services ranging from mobile payments to digital banking, peer-to-peer lending, and blockchain applications [8].

The drivers of FinTech adoption can play a transformative role in promoting sustainable mineral resource management [9]. Enhanced digital connectivity facilitates real-time monitoring, data sharing, and transparent reporting across mining operations [10]. For instance, mobile and broadband technologies can enable stakeholders to access environmental data, compliance reports, and community feedback mechanisms [11]. Similarly, improved access to domestic credit through formal banking systems can incentivize investments in clean technologies and environmentally compliant practices in mining [12]. As such, FinTech drivers can contribute to an integrated ecosystem where financial inclusion, environmental compliance, and digital innovation converge to promote sustainable resource governance [13].

The United States holds an abundance of diverse mineral resources, including rare earth elements, copper, lithium, and iron ore, which are essential for the production of high-tech devices, renewable energy systems, and military technologies [14]. However, the environmental implications of mining—such as land degradation, water pollution, and greenhouse gas emissions—necessitate a shift toward more sustainable practices [15]. FinTech can be an enabler in this transition by unlocking new financing models for sustainable mining projects, supporting regulatory enforcement through data transparency, and improving resource allocation through digital financial solutions [16]. Therefore, the potential role of FinTech in driving sustainable mineral development in the U.S. is both timely and vital.

Despite the promising linkages between FinTech adoption and sustainable resource management, the relationship remains underexplored in empirical literature—especially in the context of the U.S. mineral sector. The problem this study seeks to address is the lack of comprehensive analysis of how FinTech adoption factors influence sustainable mineral resource management. Understanding these dynamics is essential for developing strategies that align financial innovation with environmental sustainability, particularly in a resource-intensive economy like the United States. The existing literature has examined FinTech's role in enhancing financial inclusion, supporting small and medium enterprises (SMEs), and promoting green investments [17–20]. However, few studies have systematically linked FinTech adoption with natural resource management [21–23], and even fewer have focused specifically on mineral resource sustainability in developed economies [6]. Most existing research tends to be fragmented or focuses on developing countries [9,13], often neglecting the advanced financial and digital infrastructure present in the U.S. Thus, a significant research gap exists in assessing the interplay between FinTech drivers and sustainable mineral depletion metrics in this national context.

To address the existing research gap, this study examines how the adoption of FinTech can influence and potentially enhance sustainable mineral resource management in the United States. This study focuses on four key proxies of FinTech adoption including mobile cellular subscriptions, Internet usage, fixed broadband subscriptions, and financial inclusion, along with environmental compliance and investment in sustainable mining technologies as essential control variables. The study employs annual time series data from 1998 to 2023 and uses the ARDL and FDC approaches for its ability to capture both short-term and long-term relationships among variables. The expected outcome reveals how specific FinTech-related factors influence mineral sustainability trends, providing empirical evidence for policy and investment decisions.

This research contributes to the intersection of digital finance and environmental sustainability by offering novel insights into how FinTech adoption can influence natural resource governance. Its novelty lies in linking FinTech indicators with environmental outcomes in the mineral sector, using a robust econometric framework and long-term national data. The study provides empirical evidence for policymakers, mining firms, environmental advocates, and financial institutions on how digital and financial inclusion can drive resource sustainability. Furthermore, it underscores the importance of integrating FinTech infrastructure development with environmental policy to foster a more resilient, efficient, and transparent mining sector in the United States. These findings are particularly relevant in an era where digital transformation and green transition must go hand in hand to meet the challenges of sustainable development.

2. Literature Review

The evolution of FinTech has significantly altered the landscape of global finance, with widespread implications across multiple economic sectors [24]. The literature documents how FinTech innovations—ranging from mobile banking to digital lending platforms—have expanded access to financial services, reduced transaction costs, and fostered greater economic inclusion [25–27]. Studies [19,27,28] highlighted FinTech's disruptive potential and its role in democratizing finance by breaking down traditional institutional barriers. These developments have catalyzed changes not only in banking but also in sectors like healthcare, energy, and increasingly, environmental governance.

Research on FinTech adoption often focuses on specific drivers such as mobile cellular subscriptions, Internet penetration, and fixed broadband infrastructure, which collectively reflect the digital maturity of a society [29,30]. Such infrastructural indicators are strong predictors of FinTech engagement, particularly in enabling digital payment systems and facilitating online credit platforms [30,31]. Previous studies [32–34] have underscored that financial and digital inclusion are closely linked, as higher connectivity often correlates with increased access to formal financial services. However, a few studies [35–37] extend this link to sustainability outcomes, especially in sectors like natural resource management.

Some scholars have begun exploring how FinTech might indirectly influence environmental sustainability [38–40]. Studies [41–45] have suggested that digital financial inclusion can support sustainable development by reducing poverty and encouraging investment in environmentally friendly technologies. Similarly, other studies [46–49] have reported that FinTech platforms improve access to green finance, thereby facilitating investments in renewable energy and eco-friendly projects. Nonetheless, much of this work remains general and does not delve into sector-specific applications such as sustainable mining or mineral resource governance.

In the realm of natural resource management, sustainability is often evaluated through the lens of depletion, environmental degradation, and investment in sustainable practices [50–52]. The literature on sustainable mining [15,53,54] identifies key enablers such as regulatory compliance, stakeholder transparency, and technological innovation. Previous studies [55–57] have focused more on institutional and environmental reforms than on financial mechanisms like FinTech. As a result, the role of digital finance in advancing sustainable practices in mineral extraction remains an underexplored dimension in the resource economics literature.

Despite the increasing attention being paid to ESG (Environmental, Social, and Governance) principles in mining, few studies [58,59] have explicitly examined how FinTech adoption may contribute to these outcomes. Prior studies [60–63] noted that blockchain and digital traceability systems can improve accountability in extractive industries. Yet even these analyses tend to be conceptual, lacking empirical testing or quantification, especially in national contexts such as the United States, where the digital infrastructure is mature and the mineral dependence is substantial.

From a sustainability perspective, FinTech has the potential to address multiple Sustainable Development Goals (SDGs). For example, SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) are all indirectly supported through FinTech-enabled investments and environmental transparency tools. Moreover, FinTech intersects with sustainability through economic (e.g., access to credit), environmental (e.g., funding for green technologies), and social (e.g., digital inclusion) dimensions. This multi-dimensional potential is illustrated in Table 1 below.

Table 1. FinTech's contributions to sustainability dimensions and SDGs.

Sustainability Dimension	FinTech Contribution	Aligned SDGs
Economic	Digital credit access, mobile banking, investment platforms	SDG 1, SDG 8, SDG 9
Environmental	Financing green technologies, traceability, carbon tracking	SDG 12, SDG 13, SDG 15
Social	Financial inclusion, digital literacy, reduced inequality	SDG 5, SDG 10, SDG 16

Another emerging area of research focuses on how FinTech enhances environmental compliance and investment in sustainable innovations [64,65]. Digital finance platforms are enabling new forms of crowdfunding and green bonds targeted at sustainable infrastructure, including eco-mining practices [66,67]. However, the previous studies tend to cluster in broader discussions of green finance, with limited insight into how general FinTech adoption indicators like broadband or credit access actually relate to environmental resource metrics such as mineral depletion.

The United States presents a unique case where both FinTech infrastructure and mineral resource dependency are pronounced. Existing literature often treats the U.S. as a benchmark for digital innovation [68] but neglects to explore how these technologies could align with national strategies for resource sustainability. Moreover, previous empirical research examining mineral depletion trends often focuses on macroeconomic or environmental policy variables [69,70], overlooking the influence of technological and financial enablers. This highlights a clear disconnect between digital finance research and sustainable resource governance studies.

In summary, the major research gap lies in the absence of empirical studies that link FinTech adoption factors—such as mobile connectivity, Internet usage, broadband access, and domestic credit—to sustainable mineral resource management, specifically within the U.S. context. While many studies emphasize either FinTech development or resource sustainability independently, very few integrate these domains into a unified analytical framework. Additionally, no comprehensive model has evaluated this relationship using long-term time series data and a rigorous econometric technique such as the ARDL and FDC approaches.

This study addresses this gap by developing an integrated model that assesses the impact of FinTech adoption drivers on sustainable mineral resource management in the United States. By using mineral depletion as the dependent variable and incorporating digital connectivity, financial access, environmental compliance, and green investment as explanatory factors, the study offers a holistic and data-driven contribution. It not only tests theoretical assumptions from existing literature but also provides actionable insights for policymakers aiming to align digital finance strategies with sustainable resource use.

3. Methodology

3.1. Data

The research draws its variables from the World Development Indicators (WDI) [71]. The research period spans from 1998 to 2023. The dataset is limited within this period due to the unavailability of data on fixed broadband subscriptions in the United States before 1998. Table 2 shows all examined variables, which provide their signs together with measurement units in the study. Figure 1 illustrates the yearly trends of the variables, while the dataset is provided in Table A1 in Appendix A.

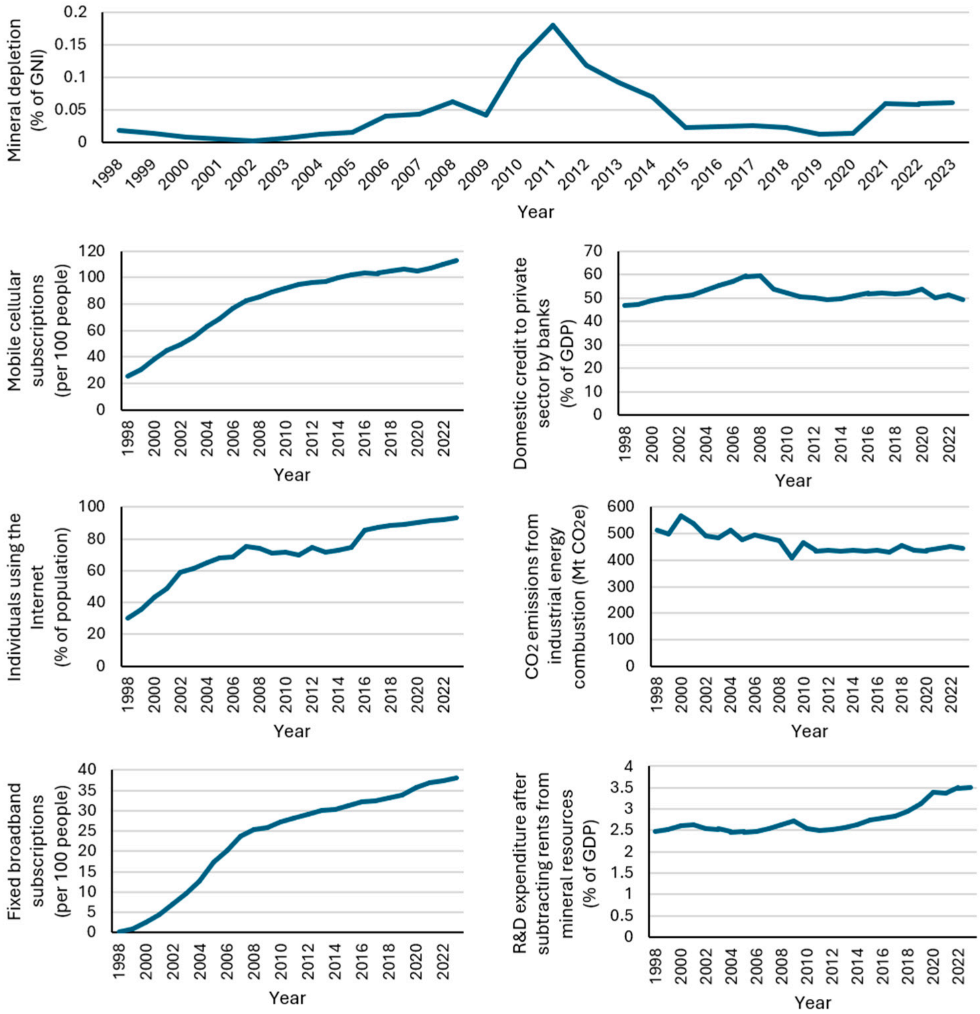

Figure 1. Annual trends of the variables.

Table 2. Variables with their sign and measurement unit.

Variables	Sign	Measurement Unit
Mineral management	MM	Mineral depletion rate (% of GNI)
Mobile cellular	MC	Mobile cellular subscriptions (per 100 people)
Internet	I	Individuals using the Internet (% of the population)
Broadband	B	Fixed broadband subscriptions (per 100 people)
Financial inclusion	FI	Domestic credit to the private sector by banks (% of GDP)
Environmental compliance	EC	CO_2 emissions from industrial energy combustion (Mt CO_2e)
Investment in sustainable mining technologies	IN	R&D expenditure after subtracting rents from mineral resources (% of GDP)

This study employed sustainable mineral resource management as an outcome factor, which denotes the responsible and effective oversight of mineral wealth to guarantee that their extraction and use are in accordance with principles of social, economic, and environmental sustainability. This approach encompasses methods that reduce adverse environmental effects, aid local communities, and foster sustainable economic growth while effectively managing mineral resources. The mineral depletion rate is a widely recognized and meaningful indicator of sustainable mineral resource management [6,9] because it reflects the economic cost associated with the extraction and use of non-renewable mineral resources. Specifically, it measures the decline in the value of a country's mineral assets due to extraction, expressed as a percentage of its Gross National Income (GNI). A higher mineral depletion rate suggests unsustainable exploitation, where resource extraction may be contributing to short-term income at the expense of long-term environmental and economic stability. By quantifying resource loss relative to national income, this indicator captures the trade-off between economic growth and environmental sustainability. GNI refers to the total domestic and foreign income earned by a country's residents and businesses, including income from abroad. It provides a comprehensive measure of national economic performance and well-being. Using mineral depletion as a share of GNI thus allows for evaluating how much of a nation's income is effectively being "spent" or eroded through the irreversible extraction of mineral resources—making it a powerful proxy for assessing the sustainability of mineral resource management policies.

The adoption of FinTech pertains to the degree to which people and companies embrace these innovations to make them available and handle their financial activities. FinTech includes a variety of technological advancements designed to enhance and simplify financial operations, such as electronic payments, digital banking, peer-to-peer financing, robot consultants, and blockchain systems. This study focuses on four key proxies of FinTech adoption: mobile cellular subscriptions (per 100 people), individuals using the Internet (% of the population), fixed broadband subscriptions (per 100 people), and domestic credit to the private sector by banks (% of GDP). These indicators collectively capture both digital connectivity and financial service accessibility, two crucial enablers of modern FinTech ecosystems. Mobile cellular subscriptions reflect the penetration of mobile devices, a critical platform for mobile banking and digital payment services, particularly in remote or underserved areas. Individuals using the Internet measure the proportion of the population with access to online services, which enables participation in a wide range of FinTech applications such as digital wallets, peer-to-peer lending, and online investment platforms. Fixed broadband subscriptions indicate the availability of high-speed, stable internet connections necessary for more data-intensive financial services, including fintech-driven analytics and cloud-based platforms. Lastly, domestic credit to the private sector by banks (% of GDP) serves as a proxy for financial system inclusiveness and the degree to which businesses and individuals can access formal credit, a cornerstone for enabling digital lending, microfinancing, and broader FinTech-driven credit innovations. Together, these four indicators provide a multidimensional view of a country's readiness and engagement in FinTech adoption. Analyzing these variables provides insights into the diffusion and impact of FinTech on broader sectors beyond traditional finance, specifically across the mining as well as the natural resources industry in the USA.

Furthermore, this study considered environmental compliance and investment in sustainable mining technologies as essential control variables. Investment in sustainable mining techniques encompasses the overall funding and financial resources allocated to the development, implementation, and utilization of sustainable mining technologies within the USA. This may encompass funding for clean energy sources for mining activities, the reuse of water infrastructure, waste management innovations, and various environmentally sustainable practices. The investigation separates the number of economic sources that mining enterprises are spending on particular R&D for mining technologies by deducting the mineral resource rents from overall R&D spending. Furthermore, adherence to ecological regulations assesses how well mining companies adhere to environmental laws and guidelines. This variable indicates the sector's dedication to sustainable and eco-friendly practices. The analysis utilized CO_2 emissions from industries such as manufacturing and construction to evaluate the environmental effects of the mining sector and its adherence to emissions standards. A lower value indicates that the mining sector is successfully managing and mitigating its carbon emissions associated with production and building operations, reflecting a more environmentally conscious strategy. On the other hand, an increased value could suggest elevated emissions and possibly reduced adherence to emissions regulations.

3.2. Econometric Model and Estimation Strategies

The current paper established an econometric framework to gain insights into the relationship between FinTech adoption and sustainable exploration for minerals in the USA at the time "t."

$$MM_t = \beta_0 + \beta_1 MC_t + \beta_2 I_t + \beta_3 B_t + \beta_4 FI_t + \beta_5 EC_t + \beta_6 IN_t + \varepsilon_t \quad (1)$$

The pertaining logarithmic presentation is outlined below:

$$LMM_t = \beta_0 + \beta_1 LMC_t + \beta_2 LI_t + \beta_3 LB_t + \beta_4 LFI_t + \beta_5 LEC_t + \beta_6 LIN_t + \varepsilon_t \quad (2)$$

The solution to unreliable regression outcomes demands the use of unit root tests as a first step. Testing variable stationarity in regression requires both different methods and stationary processes to create the relevant equation. Existing empirical research shows that to investigate cointegration potential among variables, researchers need to detect integration patterns and apply diverse unit root testing approaches to determine the integration level of individual time series [72,73]. The diversity in unit root test effectiveness exists because sample size determines how well a unit root test performs. As part of the analysis, the researchers employed three statistical tests, including the Augmented Dickey–Fuller (ADF) test [74] and the Dickey–Fuller generalized least squares (DF-GLS) test [75], followed by the Phillips–Perron (P-P) test [76]. The investigation uses the unit root test to check whether each variable surpassed its integrating threshold. The findings validate how the ARDL methodology surpasses conventional cointegration methods based on its implementation.

The research used Pesaran et al.'s [77] bounds test of ARDL to determine cointegration among the examined variables. Several key advantages exist for using the ARDL bounds test to evaluate cointegration in comparison to other single-equation methodologies. When time series data contains integration orders that differ from each other, the ARDL bounds test serves as a practical analysis method. This test brings multiple benefits because it lacks compulsory requirements for assumptions and ensures the systematic inclusion of every variable during analysis. Moreover, it demonstrates greater reliability, especially when dealing with a limited range of observations [78]. Additionally, it provides a detailed assessment of the overall framework over an extended period. Consequently, this testing technique functions effectively for any integration order present in the essential ARDL framework that could be order 2. Furthermore, the cointegration order operates within two distinct classifications: either I(0) or I(1). The mathematical model for the ARDL bounds test appears in Equation (3) below:

$$\begin{aligned}\Delta LMM_t = \beta_0 + \beta_1 LMM_{t-1} + \beta_2 LMC_{t-1} + \beta_3 LI_{t-1} + \beta_4 LB_{t-1} + \beta_5 LFI_{t-1} + \beta_6 LEC_{t-1} \\ + \beta_7 LIN_{t-1} + \sum_{i=1}^{q} \alpha_1 \Delta LMM_{t-i} + \sum_{i=1}^{q} \alpha_2 \Delta LMC_{t-i} + \sum_{i=1}^{q} \alpha_3 \Delta LI_{t-i} \\ + \sum_{i=1}^{q} \alpha_4 \Delta LB_{t-i} + \sum_{i=1}^{q} \alpha_5 \Delta LFI_{t-i} + \sum_{i=1}^{q} \alpha_6 \Delta LEC_{t-i} + \sum_{i=1}^{q} \alpha_7 \Delta LIN_{t-i} + \varepsilon_t\end{aligned} \quad (3)$$

where Δ and q are the first difference operators and optimal lag length.

The ARDL bounds test employs critical values of the F-distribution for its calculations. The assessment technique starts with Equation (3) while employing OLS to conduct an F-test for evaluating the cumulative value of coefficients from lagged variables. The main objective of this method is to determine whether two variables will sustain an enduring connection over time. The test examines whether regressors in the system have any cointegrating relationships through the null hypothesis (H_0). F-statistics require a comparison with the critical thresholds at both ends of their specified boundaries [77]. The existence of a long-term connection between analyzed variables can be confirmed when F-statistics surpass the set upper critical values. A test outcome with F-statistics lower than the lower critical limit supports the retention of the null hypothesis. A test result becomes unreliable when the F-statistics fall between the established lower and upper critical levels.

After confirming variable cointegration, the analysis proceeds to use Equation (3) within an ARDL framework to estimate long-run coefficients. Once this study verifies the existence of long-term interactions, it will proceed to analyze the error correction term (ECT). Therefore, this approach helps evaluate short-term variables while determining their equilibrium convergence rate over time. The ECT in an ARDL framework serves to achieve this objective as presented in Equation (4).

$$\begin{aligned}\Delta LMM_t = \beta_0 + \beta_1 LMM_{t-1} + \beta_2 LMC_{t-1} + \beta_3 LI_{t-1} + \beta_4 LB_{t-1} + \beta_5 LFI_{t-1} + \beta_6 LEC_{t-1} \\ + \beta_7 LIN_{t-1} + \sum_{i=1}^{q} \alpha_1 \Delta LMM_{t-i} + \sum_{i=1}^{q} \alpha_2 \Delta LMC_{t-i} + \sum_{i=1}^{q} \alpha_3 \Delta LI_{t-i} \\ + \sum_{i=1}^{q} \alpha_4 \Delta LB_{t-i} + \sum_{i=1}^{q} \alpha_5 \Delta LFI_{t-i} + \sum_{i=1}^{q} \alpha_6 \Delta LEC_{t-i} + \sum_{i=1}^{q} \alpha_7 \Delta LIN_{t-i} \\ + \theta ECT_{t-1} + \varepsilon_t\end{aligned} \quad (4)$$

The integer θ, known as the speed of adjustment, defines the pace at which adjustments occur. The first lag of the error term, denoted as ECT_{t-1}, functions as a key indicator within the error correction model. The typical value of ECT generally exists between 0 and 1. When the ECT is incorporated into the model, important findings emerge revealing that variables might exhibit level non-stationarity, yet their variations fail to match random walk characteristics. Moreover, the long-term equilibrium interaction established through ECT integrates all these variables. The potential to decrease uncertainty emerges when ECT proves significant and shows negative results.

To ensure the robustness of the model, this study utilized the Frequency Domain Causality (FDC) test [79] to explore the causal relationships among the variables. Unlike the traditional Granger causality test, the FDC approach enables the detection of causality at specific time frequencies, making it possible to identify historical patterns and temporal dynamics where policy interventions may be most effective [80–82]. This frequency-based analysis offers a more nuanced understanding of how variables interact over different time horizons. However, a notable limitation of the method is that it operates within a finite time scale, making it unsuitable for capturing effects over an infinite forecast horizon. The FDC test is represented by the following equation:

$$x_t = \alpha_1 X_{t-1} + \ldots + \alpha_p X_{t\text{-}p} + \beta_1 Y_{t-1} + \ldots + \beta_p Y_{t\text{-}p} + \varepsilon_t \quad (5)$$

The linear constraint aligns with the H_0 hypothesis. Nonetheless, α and β are the evaluated parameters at time t, lag p, and an error term ε_t.

4. Results

Table 3 sheds light on the breakdown and characteristics of the selected components in the USA from 1998 to 2023 through descriptive statistics. The kurtosis values falling below 3 suggest that the dataset exhibits lighter tails compared to a normal distribution. Furthermore, the skewness values are near zero, suggesting a normal distribution of the data series.

Table 3. Descriptive statistics.

Variables	LMM	LMC	LI	LB	LFI	LEC	LIN
Mean	−3.55	4.34	4.23	2.77	3.95	6.14	1.00
Median	−3.65	4.53	4.28	3.32	3.94	6.11	0.96
Kurtosis	0.56	1.02	2.11	2.47	0.73	0.11	0.23
Skewness	−0.18	−0.38	−0.50	−0.61	0.29	0.47	0.28
Minimum	−5.69	3.22	3.40	−1.36	3.86	6.01	0.90
Maximum	−1.72	4.73	4.53	3.64	4.09	6.34	1.26

Table 4 displays the results of the correlation analysis among the variables. The findings indicate a positive correlation between mineral resource management and the factors influencing FinTech adoption, including mobile cellular subscriptions, Internet usage, fixed broadband subscriptions, and financial inclusion. Nonetheless, environmental compliance exhibits a negative correlation with all other factors. Moreover, whereas investment in sustainable mining demonstrates a positive correlation with mineral resource management, mobile cellular subscriptions, Internet usage, and fixed broadband subscriptions, it exhibits a negative correlation with financial inclusion and environmental compliance.

Table 4. Correlation analysis.

Variables	LMM	LMC	LI	LB	LFI	LEC	LIN
LMM	1.00						
LMC	0.58	1.00					
LI	0.41	0.97	1.00				
LB	0.50	0.97	0.97	1.00			
LFI	0.11	0.34	0.41	0.44	1.00		
LEC	−0.56	−0.80	−0.71	−0.72	−0.06	1.00	
LIN	0.09	0.54	0.61	0.44	−0.09	−0.42	1.00

The current examination seeks to explore the establishment of a continuous connection within each series being analyzed. Estimating the unit root test is important for evaluating the integration characteristics of the factors, which is necessary for implementing methods aimed at establishing long-term relationships. Consequently, ADF, DF-GLS, and P-P assessments are utilized to conduct a unit root analysis to determine whether the data are stationary at levels I(0) or at the first difference I(1). Table 5 presents the unit root projections, illustrating the stationary characteristics of the parameters. The findings demonstrate that all variables exhibit stationarity at I(1), confirming the absence of unit roots.

Table 5. Results of unit root tests.

Variables	ADF		DF-GLS		P-P	
	I(0)	**I(1)**	**I(0)**	**I(1)**	**I(0)**	**I(1)**
LMM	−1.35	−4.01 ***	−1.35	−4.03 ***	−1.49	−4.01 ***
LMC	−0.18	−3.84 ***	−0.19	−3.88 ***	0.17	−3.38 **
LI	−6.01 ***	−3.13 **	−1.18	−3.96 ***	−5.52 ***	−3.04 **
LB	−33.84 ***	−5.49 ***	1.04	−3.19 **	−26.09 ***	−15.10 ***
LFI	−2.58	−3.48 **	−1.48	−3.55 ***	−2.01	−3.53 **
LEC	−1.40	−7.80 ***	−1.16	−7.80 ***	−1.95	−11.81 ***
LIN	1.00	−3.47 **	0.90	−3.54 **	0.78	−3.45 **

*** $p < 0.01$, ** $p < 0.05$.

After confirming the stationarity of the data, this study aims to estimate cointegration among the factors adopting the ARDL framework. The outcomes of the ARDL bounds test, which evaluates the presence of cointegration, are illustrated in Table 6. The data presented confirms a consistent relationship between the parameters, contingent upon the evaluated F-test value exceeding both the lower and upper limits. The null hypothesis is rejected due to the observed F-statistic value of 9.17, which exceeds the critical thresholds for significance at the 10%, 5%, 2.5%, and 1% levels for both the I(0) and I(1). The conclusion indicates a reliable correlation between the selected factors.

Table 6. Results of ARDL bounds test.

Test Statistic	Estimate	Significance Levels	I(0)	I(1)
F-statistic	9.17	10%	1.99	2.94
K	6	5%	2.27	3.28
		2.5%	2.55	3.61
		1%	2.88	3.99

Table 7 presents the estimations for both the short and long-term use of the ARDL approach. The findings indicate a notable and beneficial effect of FinTech adoption on sustainable mineral resource management in the USA. The outcomes imply that a 1% rise in mobile cellular subscriptions, Internet use, fixed broadband subscriptions, and financial inclusion would improve the sustainability of mineral resource management by reducing mineral depletion by 0.13%, 0.21%, 0.19%, and 0.17% in the short term and 0.32%, 0.54%, 0.48%, and 0.57% in the long term, respectively. Furthermore, the results indicate a positive association between environmental compliance and mineral management, indicating that a 1% increase in CO_2 emissions from industrial energy combustion is linked to an increase in mineral depletion by 0.30% in the short run and 0.71% in the long run. Finally, the results reveal that a 1% increase in investment in sustainable mining technologies would lead to sustainable management of mineral resources by reducing mineral depletion by 0.48% in the short term and 0.85% in the long term. The coefficients of all the variables are found significant at different levels both in the short and long term.

Furthermore, the short-term simulation using the ARDL model demonstrates persistent stability between all long-term coefficient values. The result shows that ECT has a negative value, with significant statistical evidence at the 1% level, indicating that yearly modifications occur approximately 57% of the time when dealing with short-term deviations from the long-term balance. The long-term approximation produces R^2 and adjusted R^2 equaling 0.95 and 0.91. Consequently, this analysis demonstrates that regression modeling properly captures the existing data patterns. The statistical data suggest that a considerable portion of the fluctuations in the regressor could be accounted for by the regressors, reaching more than 90%.

Table 7. ARDL long- and short-term outcomes.

Variables	Long-Run			Short-Run		
	Coefficient	*t*-Statistic	*p*-Value	Coefficient	*t*-Statistic	*p*-Value
LMC	−0.32 **	−2.79	0.02	−0.13 **	−2.32	0.03
LI	−0.54 ***	−4.96	0.00	−0.21 ***	−4.17	0.00
LB	−0.48 ***	−3.77	0.00	−0.19 ***	−3.79	0.00
LFI	−0.57 *	−1.91	0.06	−0.17 **	−2.05	0.04
LEC	0.71 ***	3.12	0.00	0.30 ***	3.99	0.00
LIN	−0.85 *	−1.86	0.07	−0.48 *	−1.94	0.05
C	28.39	1.09	0.18	-	-	-
ECT (−1)	-	-	-	−0.57 ***	−4.84	0.000
R^2	0.95					
Adjusted R^2	0.91					

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

Additionally, the study assessed the precision of the ARDL findings through various diagnostic evaluations. Table 8 presents the calculations for the diagnostic tests related to the ARDL estimation. The model functioned without any issues. The Jarque–Bera normality test served to determine whether the series followed a normal distribution. Statistics from the Jarque–Bera test reveal that the residuals follow a normal distribution pattern according to the reported statistics and *p*-value values. Results from the Breusch–Godfrey LM test confirm both series are free from serial correlation. The Breusch–Pagan–Godfrey test results show heteroskedasticity does not appear in the dataset. The suitability of the regression model is confirmed through the application of the Ramsey RESET test. This study involved the application of CUSUM and CUSUM square scrutiny to assess the stability of the model. Figure 2 shows the CUSUM and CUSUM square charts, which were tested at a 5% significance level. The blue lines show the residuals, whereas the red outlines represent confidence ranges. The analysis confirms that variables maintain their residuals inside the confidence level limits at a 5% significance threshold, thus proving the model's reliability. Furthermore, all diagnostic assessments performed on the ARDL simulation reveal meaningful concordance results.

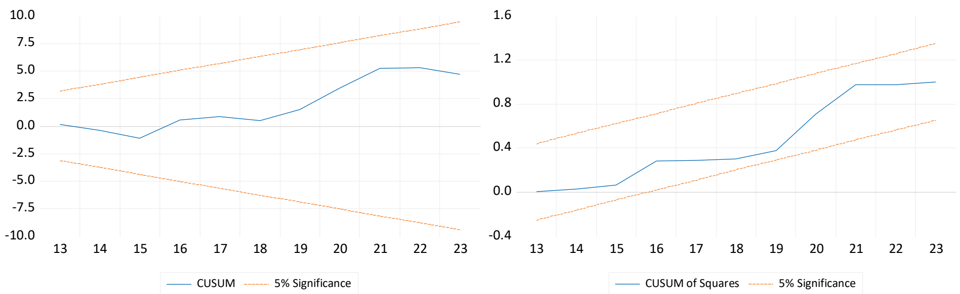

Figure 2. Results of CUSUM and CUSUM square tests.

Table 8. Results of diagnostic tests.

Tests	Coefficient	*p*-Value	Verdict
Jarque-Bera	0.98	0.61	Normal distribution of residuals
Breusch-Godfrey LM	1.40	0.30	No serial correlation
Breusch-Pagan-Godfrey	0.65	0.77	No heteroscedasticity
Ramsey RESET	0.63	0.54	Properly described model

Following the computation of short- and long-term ARDL estimations, the investigation proceeds with the Frequency Domain Causality test to explore the causal link between the variables. The results of the short-, medium-, and long-term outcomes are displayed in Table 9. The results reveal a strong frequency-dependent causal relationship between LMM and the explanatory variables. Specifically, LEC exhibits statistically significant causality across all three frequency bands—long-term (ω = 0.05), medium-term (ω = 1.50), and short-term (ω = 2.50)—indicating its robust and sustained influence on LMM. LMC and LB demonstrate highly significant causality in the medium and short term, while LI shows significant effects in the long and medium term but not in the short term. LFI displays only medium-term significance, suggesting its influence is less persistent across other time horizons. LIN shows a strong causal impact in the medium term but is not significant in the long or short term. These findings suggest that the determinants of sustainable mineral management are time-scale sensitive, with digital connectivity, financial access, and environmental regulation contributing variably depending on the frequency of impact.

Table 9. Results of frequency domain causality analysis.

Direction of Causality	Long-Term		Medium-Term		Short-Term	
	Wald Stats (ω_i = 0.05)	*p*-Value	Wald Stats (ω_i = 1.50)	*p*-Value	Wald Stats (ω_i = 2.50)	*p*-Value
LMC → LMM	0.55	0.76	9.19 ***	0.00	11.27 ***	0.00
LI → LMM	6.05 **	0.04	12.55 ***	0.00	1.14	0.56
LB → LMM	0.00	0.99	14.46 ***	0.00	9.64 ***	0.00
LFI → LMM	2.95	0.23	13.97 ***	0.00	0.09	0.96
LEC → LMM	16.11 ***	0.00	16.81 ***	0.00	7.25 **	0.03
LIN → LMM	1.18	0.55	8.45 ***	0.00	0.76	0.68

*** $p < 0.01$, ** $p < 0.05$.

5. Discussion

The ARDL estimation results provide compelling empirical evidence of a statistically significant and economically meaningful long-term relationship between key FinTech indicators and sustainable mineral resource management in the United States. The findings reveal that increasing mobile cellular subscriptions, internet usage, fixed broadband subscriptions, and financial inclusion substantially reduce the mineral depletion rate. These results underscore the transformative role of digital connectivity and financial accessibility in reshaping environmentally intensive sectors like mining toward more sustainable trajectories. The present study's findings are supported by previous studies [6,9,13,83–86], which reported that FinTech promotes sustainable mineral management.

Among the four FinTech indicators analyzed, Internet usage emerges as a particularly potent driver of sustainability in the long run. This highlights the role of online platforms in fostering transparency, improving access to environmental data, and supporting platforms for digital governance in the mining sector. In practical terms, increased Internet penetration enables real-time tracking of mining activities, facilitates e-reporting for regulatory compliance, and empowers civil society through accessible information on environmental impacts [87].

Fixed broadband subscriptions, another measure of digital infrastructure maturity, show similarly strong negative effects on mineral depletion both in the short and long term. The results reveal that faster, more stable Internet connections enable more complex, data-intensive FinTech applications that enhance sustainability. These include cloud-based analytics for resource monitoring, blockchain systems for supply chain verification, and AI-driven tools for predictive maintenance in mining equipment [88]. Together, these technologies reduce waste, improve efficiency, and lower the ecological footprint of mineral extraction [88–90].

Mobile cellular subscriptions also exert a significant influence, particularly in short- and medium-term dynamics. The proliferation of mobile devices expands the reach of mobile banking, mobile reporting platforms, and SMS-based environmental alert systems. In remote or rural mining areas, where fixed broadband may be sparse, mobile networks play a critical role in enabling miners and communities to access financial services, engage in compliance reporting, or communicate environmental hazards.

The variable of financial inclusion, measured by domestic credit to the private sector, stands out for its strategic role in enabling long-term sustainable practices. The result suggests that improved access to credit helps mining enterprises, especially small and medium-sized operators, to invest in cleaner technologies and adopt practices that minimize environmental harm. Financial inclusion, therefore, serves as both an economic and environmental enabler, bridging gaps in capital access while promoting green innovation [91].

In contrast, environmental compliance, proxied by CO_2 emissions from industrial combustion, was positively associated with mineral depletion in both the short and long term. This somewhat counterintuitive finding suggests that despite formal regulations, enforcement may be weak or lagging, leading to a scenario where higher emissions accompany increased extraction activity. This interpretation aligns with previous studies [6,9] that caution that without rigorous enforcement, regulatory frameworks may be insufficient to curb environmental harm, even in advanced economies like the USA [84].

Investment in sustainable mining technologies was found to significantly reduce mineral depletion, confirming its critical role in driving long-term sustainability. This supports prior literature [6,9] that emphasized the importance of innovation in tailings management, waste reduction, and cleaner production. The relatively stronger long-term effect of these investments compared to their short-term impact underscores the time-lagged nature of R&D implementation and the compounding benefits of sustained innovation in eco-mining.

Complementing the ARDL results, the FDC analysis reveals a more nuanced view of the temporal patterns underlying FinTech's influence. Specifically, Internet usage shows a significant causal influence in the long and medium terms, emphasizing the enduring nature of digital literacy and the integration of online platforms in governance mechanisms. Conversely, mobile cellular subscriptions and broadband access exhibit strong effects primarily in the short and medium term, suggesting their roles are more immediate and operational—optimizing efficiency, enhancing communication, and facilitating compliance in real time. Interestingly, financial inclusion shows significant causality only in the medium term, implying that the benefits of improved credit access may take time to manifest in measurable sustainability outcomes. This delay could reflect the gestation period required for capital investments in green mining technologies to be implemented and yield results. Nonetheless, the strong ARDL coefficient reaffirms that, once established, these impacts are substantial and persistent.

The empirical findings also highlight the multifaceted nature of FinTech as a sustainability enabler. Rather than acting solely through financial channels, FinTech indicators influence sustainability by integrating digital infrastructure, information flows, and capital mobilization [19,42]. The Internet facilitates knowledge diffusion and stakeholder engagement, mobile platforms offer inclusive tools for marginalized communities, broadband enables high-resolution analytics, and financial credit empowers green entrepreneurship. This holistic interaction supports the idea that FinTech is a multi-dimensional enabler of sustainable development.

Environmental compliance, though not a FinTech indicator, plays a critical role in shaping the context in which FinTech operates. Its positive association with mineral depletion in both time domains suggests that regulations alone may not be sufficient, especially when enforcement mechanisms lag behind technological advancements. Thus, while FinTech tools can enhance compliance by increasing transparency and reporting, institutional capacity and regulatory coherence are essential complements to technology-driven solutions. In addition, investment in sustainable mining technologies, which also showed strong negative effects on mineral depletion, reinforces the view that FinTech's influence is most effective when coupled with innovation-led approaches. Credit enabled by financial inclusion and supported by digital platforms can serve as a funding mechanism for R&D in clean mining techniques. As such, FinTech can be positioned as a conduit—not a substitute—for sustainable industrial innovation.

In a nutshell, the results affirm that FinTech adoption—via mobile cellular subscriptions, Internet usage, fixed broadband access, and financial inclusion—holds transformative potential for sustainable mineral resource management in the United States. These indicators operate through distinct yet interlinked pathways to reduce resource depletion, promote accountability, and stimulate green innovation. The findings offer both validation for existing theoretical models and actionable guidance for policymakers, regulators, and industry stakeholders seeking to align digital transformation with SDGs.

6. Conclusions and Policy Implications

6.1. Conclusions

This study provides robust empirical evidence that FinTech adoption—measured through mobile cellular subscriptions, Internet usage, fixed broadband subscriptions, and financial inclusion—plays a significant role in promoting sustainable mineral resource management in the United States. By employing the ARDL modeling framework and FDC analysis on the time series data, the study reveals that enhanced digital connectivity and greater access to formal financial services are strongly associated with reduced mineral depletion rates, indicating improved sustainability outcomes. The findings underscore the transformative potential of FinTech not only as a financial innovation but as a multidimensional tool that fosters environmental accountability, operational efficiency, and green investment in the mining sector. As environmental degradation and resource scarcity become increasingly pressing global challenges, the study highlights the critical importance of integrating digital and financial infrastructures into national sustainability strategies. These insights offer valuable direction for policymakers, industry stakeholders, and environmental advocates seeking to align technological advancement with responsible resource governance.

6.2. Policy Implications

The empirical evidence presented in this study underscores the strategic role of FinTech adoption in enhancing sustainable mineral resource management in the United States. The findings offer important guidance for policymakers aiming to integrate digital innovation with environmental sustainability in the extractive sectors. Given the statistically significant long-term relationships between FinTech indicators and reduced mineral depletion rates, policies must prioritize expanding digital and financial infrastructure as a pathway to achieving SDGs.

One of the most immediate implications is the need to enhance access to high-speed and reliable broadband services in mining-intensive regions. Fixed broadband access emerged as a critical driver of sustainability, supporting data-intensive applications like blockchain traceability, real-time emissions monitoring, and geospatial resource mapping. National and subnational governments should invest in broadband expansion projects, particularly in rural and resource-rich areas where infrastructure gaps hinder technological adoption. Ensuring equitable broadband access would not only improve digital connectivity but also provide the technological backbone for modern sustainability monitoring tools.

Similarly, the strong role of Internet penetration in reducing mineral depletion points to the necessity of fostering digital literacy and online accessibility. Policymakers should develop programs that promote digital skills across mining communities, industry workers, and regulatory bodies. This includes expanding public-private partnerships aimed at disseminating digital tools that support environmental compliance, such as mobile apps for community reporting or cloud platforms for environmental impact disclosures. Such initiatives can democratize access to environmental data, enhance community oversight, and improve government transparency in resource governance.

The significant influence of mobile cellular subscriptions on sustainable mineral management highlights the need to harness mobile technology in environmental monitoring and financial inclusion efforts. Policymakers can encourage the development of mobile-based platforms that allow miners, inspectors, and community members to report violations, submit compliance documents, or access micro-loans for sustainable practices. Mobile-based environmental reporting systems have the potential to address enforcement gaps by enabling real-time feedback loops between stakeholders and regulators, especially in geographically dispersed mining zones.

Financial inclusion, as reflected in the strong effects of credit access, necessitates targeted financial sector reforms to support environmentally responsible investment. Policymakers should work with banks, credit unions, and FinTech startups to design financial products tailored to the needs of sustainable mining operations. This could include low-interest green loans, impact bonds, or FinTech-enabled crowdfunding platforms focused on environmental innovation. Regulatory incentives, such as tax breaks or credit guarantees for investments in sustainable technologies, can further mobilize capital toward low-impact mining practices.

The role of investment in sustainable mining technologies further reinforces the need for long-term public support for research and development. While the private sector plays a role in financing innovation, the study findings indicate that public investment remains essential for creating foundational technologies that reduce resource depletion. As such, public policy should allocate funding toward eco-mining R&D, including water recycling systems, energy-efficient extraction techniques, and waste reduction technologies. These investments should be integrated with digital financing mechanisms to ensure effective deployment and scale.

Moreover, the nuanced findings from the FDC analysis emphasize the importance of time-sensitive policy interventions. For example, while broadband and mobile connectivity yield immediate benefits, Internet usage and financial inclusion demonstrate more sustained, long-term impacts. Policymakers should therefore adopt phased approaches, combining short-term interventions like digital infrastructure expansion with long-term capacity building in digital governance and financial access.

Environmental compliance, which showed a counterintuitive positive relationship with mineral depletion, suggests that current regulatory frameworks may be inadequate or poorly enforced. This implies an urgent need to modernize environmental regulations to align with digital capabilities. Governments can leverage FinTech tools to enhance compliance monitoring, such as through automated audit trails, blockchain-secured reporting, and AI-powered risk assessments. Strengthening regulatory institutions and ensuring that digital tools are effectively integrated into compliance processes will be vital to translating policy into measurable environmental outcomes.

In conclusion, this study highlights the necessity for an integrated policy framework that views FinTech not merely as a financial innovation but as a cross-sectoral enabler of sustainability. National strategies should align FinTech expansion with sustainability goals, particularly in sectors like mining where environmental risks are high. A coordinated approach involving infrastructure development, financial sector reform, regulatory modernization, and digital literacy promotion will be crucial for harnessing the full potential of FinTech in sustainable mineral resource governance. Ultimately, this policy shift represents a timely and necessary response to the twin imperatives of digital transformation and environmental stewardship.

6.3. Limitations and Future Research

Despite offering valuable insights, this study has several limitations that warrant consideration and open avenues for future research. First, the analysis relies on national-level aggregate data, which may mask regional disparities in FinTech infrastructure, environmental performance, and mining practices across different states or localities within the United States. Second, while the selected proxies for FinTech adoption effectively capture digital and financial inclusion, they do not account for the qualitative dimensions of usage, such as user behavior, trust in technology, or the functionality of specific FinTech platforms. Additionally, the study uses CO_2 emissions as a proxy for environmental compliance, which, although practical, may not fully capture the broader regulatory dynamics or environmental impact nuances specific to the mining sector. Future research should consider disaggregated or firm-level data to explore heterogeneity in outcomes and incorporate qualitative assessments through surveys or case studies to understand user engagement and institutional effectiveness. Expanding the analytical framework to include emerging technologies like blockchain, artificial intelligence, and climate FinTech could also yield deeper insights into the evolving landscape of digital sustainability governance.

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Abbreviations

The following abbreviations are used in this manuscript:

ADF	Augmented Dickey–Fuller
ARDL	Autoregressive Distributed Lag
B	Broadband
CO_2	Carbon dioxide
CUSUM	Cumulative sum
DF-GLS	Dickey–Fuller generalized least squares
EC	Environmental compliance
ECT	Error correction term
ESG	Environmental, Social, and Governance
FDC	Frequency Domain Causality
FI	Financial inclusion

FinTech	Financial technology
GDP	Gross domestic product
GHG	Greenhouse gas
GNI	Gross national income
H_0	Null hypothesis
I	Internet
IN	Investment in sustainable mining technologies
LM	Lagrange Multiplier
MC	Mobile cellular
MM	Mineral management
P-P	Phillips–Perron
R&D	Research and development
RESET	Regression equation specification error test
SDGs	Sustainable Development Goals
SMEs	Small and medium enterprises
SMS	Short Message Service
WDI	World Development Indicators
USA	United States of America

Appendix A

Table A1. Annual time series dataset of the study variables.

Year	Mineral Depletion (% of GNI)	Mobile Cellular Subscriptions (Per 100 People)	Individuals Using the Internet (% of Population)	Fixed Broadband Subscriptions (Per 100 People)	Domestic Credit to Private Sector by Banks (% of GDP)	CO_2 Emissions from Industrial Energy Combustion (Mt CO_2e)	R&D Expenditure After Subtracting Rents from Mineral Resources (% of GDP)
1998	0.018468	25.09084	30.1	0.255914	47.25185	512.7422	2.471183
1999	0.014701	30.82116	35.8	0.986557	47.30557	499.3623	2.522945
2000	0.008964	38.76721	43.1	2.51164	48.97489	567.1249	2.60639
2001	0.005093	45.01341	49.1	4.50008	50.15256	540.0108	2.629399
2002	0.003378	49.17631	58.8	6.92533	50.31227	490.816	2.542282
2003	0.007748	55.18089	61.7	9.57005	51.46307	485.416	2.539748
2004	0.012909	62.87475	64.8	12.7576	53.33389	511.6738	2.467796
2005	0.016466	68.62221	68	17.2991	55.2583	477.3253	2.476325
2006	0.04154	76.59637	68.9	20.1646	57.15217	495.8157	2.481704
2007	0.043988	82.34696	75	23.7553	59.37752	486.0106	2.545144
2008	0.062557	85.47738	74	25.291	59.54707	474.7671	2.634314
2009	0.04271	88.90512	71	25.9695	53.90014	407.5382	2.717953
2010	0.127401	91.62395	71.7	27.172	52.27172	466.3256	2.547544
2011	0.179611	94.75188	69.7	28.117	50.62595	435.6929	2.499033
2012	0.119271	96.2693	74.7	29.1736	49.8985	438.5726	2.509315
2013	0.091823	97.28308	71.4	29.9996	49.08048	434.8862	2.575563
2014	0.070988	100.1748	73	30.2709	49.56806	437.2563	2.620763
2015	0.023353	102.3084	74.6	31.3412	50.83802	433.8849	2.73703
2016	0.025055	103.3703	85.5	32.1144	52.01192	439.0239	2.798758
2017	0.026698	103.1298	87.3	32.5703	52.05487	429.4054	2.842302
2018	0.022796	104.8479	88.5	33.0559	51.78332	454.0616	2.955205
2019	0.012759	106.414	89.4	33.8352	52.20557	439.0522	3.12829
2020	0.014477	104.9354	90.3	35.7157	53.76515	437.4557	3.40328
2021	0.060605	107.3195	91.3	37.0074	50.21477	445.7564	3.38113
2022	0.05981	110.1665	92.2	37.4914	51.13658	451.4372	3.499854
2023	0.060984	112.7049	93.1	38.0508	49.15056	444.5117	3.517508

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