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Governance and Financial Technologies for Climate Action: The Moderating Role of Advanced-Resource Endowments in Resource-Driven Economies

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Abstract

Climate action is an alarming issue, and the world is concerned about sustainable solutions. Governance quality, financial technology and advanced-resource endowments have a pivotal role in climate action, yet the literature lacks evidence on their linkages with carbon emissions. The present study covers this gap in the literature for the Gulf Cooperation Council countries, as they offer an ideal study setting given their extreme vulnerability to climate change, their reliance on fossil fuels, the strong efforts to address climate change issues, and their prioritization of transforming the financial sector through financial technology as a means of resolving climate issues. Results show that governance quality and financial technology curb carbon emissions. Specifically, financial technology reduces CO₂ emissions by approximately 36.4% in the FMOLS estimation, while governance quality contributes negatively and significantly to CO₂ emissions across most specifications. Further, the interaction term of financial technology and advanced-resource endowments is statistically significant with a negative coefficient, hereby providing a supportive role in reducing CO₂ emissions. Hence, advanced-resource endowments play a moderating role, transforming the effectiveness of financial technology in reducing carbon emissions. The findings are robust for quantile regressions and alternative measures of environmental degradation and have strong policy implications for the Gulf Cooperation Council countries.

Keywords: financial technology; advanced-resource endowments; governance; urbanization; GCC countries; climate change; carbon emissions

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1. Introduction

The international community has acknowledged environmental deterioration as a significant threat to human civilization and economic success [1]. Consequently, environmental sustainability has become a paramount concern for policymakers globally [1]. Climate change mitigation, i.e., the reduction of greenhouse gas emissions that contribute to

global warming, is therefore pivotal [2], and economies exhibit a genuine drive toward sustainable energy usage on the eve of global warming and with the depletion of energy resources [3].

In fact, resource depletion, biodiversity loss, and climate change represent interconnected challenges that require immediate and coordinated action across all nations [4]. To address this need, the 198 members of the Conference of the Parties (COP) to the UN Framework Convention on climate change meet annually to undertake coordinated actions, making ambitious pledges. However, there seems to be a gap between pledges and the actions needed to achieve them (see for example the speech of the UN secretary-general to the press on the final days of the COP29 meeting, <https://www.un.org/en/climatechange/cop29>, 9 April 2026). Governance quality (GQ) and financial technology (FNT) can act as means of achieving the COP's ambitious pledges and transforming them into tangible actions to control CO₂ emissions [5].

In the modern global economy, GQ has become an important variable affecting both environmental sustainability and economic performance [6]. Environmental policies function within a structural framework established by formal institutions, such as regulations, laws and constitutional policies [7]. The efficiency of institutions depends on GQ, especially the government capacity to generate, enforce and implement regulations [6]. The ability to create comprehensive environmental regulations and guarantee their uniform application across all sectors is superior in nations with more effective governments [8]. Government governance effectiveness increases the capacity to organize climate policies across various levels and sectors of a country [9]. However, the importance of GQ in CO₂ emissions management has not been sufficiently examined in the previous literature [10,11], though studies affirm that there is a connection between GQ and CO₂ emissions.

The modern global economy is undergoing significant transformation due to FNT innovation, and this is even more the case in the GCC region. This transformation primarily includes replacing the methods of financial service delivery, assessment and integration into economic systems [12]. For example, Saudi Arabia, with its Vision 2030, has established FNT as a fundamental element of economic diversification, aiming for 525 FNT enterprises by 2030, with investments surpassing \$443 million [13]. Qatar's National Vision 2030 places strategic reliance on FNT to achieve the goal of creating a diversified, knowledge-based economy. This is evident in initiatives such as the Qatar FNT Hub and FNT-related programs under the Qatar Financial Centre, among others [14]. Although the initial emergence of FNT was focused on the niches of the financial sector, it has increasingly become an integral element for economic activities as a whole.

The economic relevance of FNT clearly surpasses conventional banking services. FNT transforms payment infrastructures, changes the way credit is allocated, influences investment decisions, and redefines the ways financial risks are dealt with [15]. According to Lee and Romero [16], digital payment systems cut down transaction costs and make cash handling less burdensome and improve financial inclusion, especially through mobile-based monetary services.

In resource-rich economies, however, the interaction between FNT advancement and environmental sustainability is not one-dimensional. Proper comprehension of such a relation calls for an integrated theoretical perspective on technological capability, strategic asset deployment, and organizational competence in overcoming environmental challenges [17]. The different environmental outcomes of FNT occur not only due to FNT but also due to other complementary capabilities and resources that make it possible to utilize technological and innovative resources for sustainable environmental objectives [18]. Hence, in this study advanced-resource endowments (AREs) are taken together with FNT adaptation to elucidate how AREs interact with the relationship between FNT and CO₂ emissions.

Building on the global urgency of climate change mitigation and the recognized role of GQ and FNT in translating international pledges into tangible outcomes, it is essential to focus on regions where these interventions can have a measurable impact [19]. The GCC countries present such a unique context due to their high per capita emissions and rapid adoption of FNT-enabled financial systems, which can be leveraged to implement sustainable energy and climate policies effectively [20]. GCC nations offer an ideal setting for this research because they are faced with distinct environmental issues and at the same time, although they represent merely 0.61 of the total world's population, they account for 2.4% of global greenhouse gas emissions [20]. This is due to the fact that they have experienced significant economic expansion in recent decades, whereas considerable oil and natural gas producers have arguably harmed the environment through heightened CO₂ emissions and related ecological deterioration [21].

While prior work has addressed the role of FNT and GQ for curbing CO₂ emissions, it lacks evidence of the interactive effect of FNT and AREs for achieving carbon neutrality. This limitation is significant because AREs improve the deployment and development of FNT technological capabilities through implementation of human capital, resource rents, and infrastructure [22]. Despite increasing acknowledgement of GQ and FNT's potential environmental effects, substantial theoretical and empirical gaps exist in interpreting the role of GQ and FNT and the moderating influence of AREs in explaining their effects on CO₂ emissions in resource-abundant regions like the GCC region.

The current literature has thoroughly investigated the influence of GQ and FNT on diverse economic outcomes, such as financial stability [15], economic growth [23], and financial inclusion [24]. However, scant attention has been given to examining the effect of GQ and FNT on sustainability as a measure against climate change. Hence, firstly, this study integrates GQ and FNT within a unified framework to assess their significance in reducing CO₂ emissions.

Secondly, prior research has predominantly utilized single-indicator metrics for FNT acceptance, such as digital payment utilization or online banking penetration, which inadequately reflect the intricacies of FNT ecosystems [25]. We use a principal component analysis (PCA) technique to create a measure of FNT, including three indicators such as domestic credit to the banking sector, the number of internet users, and mobile phone subscribers. This is a comprehensive measure of FNT that encompasses all the dimensions of financial innovation.

Thirdly, despite the increased importance of FNT's proposed environmental advantages, existing research has mainly overlooked the importance of AREs as a moderating indicator of the FNT–environment relationship. Previous studies have mostly focused on the direct effects of FNT on environmental outcomes, utilizing AREs solely as a control variable, neglecting to explore their potentially beneficial moderating effects on the FNT–environment relationship. Therefore, there is a need to investigate AREs' moderating influence on the relationship between FNT adoption and environmental performance.

Furthermore, this study uses a composite measure of natural resource rent, human capital and infrastructure for AREs, significantly differing from the single-dimensional resource abundance proxies employed in the resource curse literature [26]. Our measure of AREs integrates human capital and infrastructure with resource rents to reflect the productive absorption potential of resource-driven economies, rather than simply their natural resource extractive dependence. In accordance with the conditional resource blessing hypothesis [27], we contend that economies with elevated scores on this composite index have successfully directed resource wealth towards complementary assets such as skilled labor and infrastructure which facilitate the adoption of FNT tools and the decarbonization of emissions-intensive sectors.

Fourthly, the previous research has largely focused on emerging or developed economies and has limitations of geographical scope in the proposed framework, neglecting resource-abundant regions such as GCC economies [28]. The GCC region is experiencing heightened demand for the evolution of financial systems that generate economic returns while upgrading environmental protection and social equity. Sustainable finance is crucial for attaining sustainability and climate goals and for enhancing economic resilience [29]. This geographical limitation is important to explore as resource-abundant nations may have distinct FNT–environmental dynamics compared to resource-scarce economies due to diverse resource endowments, development priorities and economic structures.

2. Theory and Hypothesis Development

2.1. Governance Quality and CO₂ Emissions

As stated by Samimi, Ahmadpour and Ghaderi [30], environmental conservation and sustainable resource management are among the important factors associated with good governance. According to North [31], good governance improves the ability of a country to deal with environmental challenges and maintain sustainable growth. Governance influences CO₂ emissions through mechanisms of institutional theory. Institutional theory states that governance is defined as the societal “rules of the game” that establish limitations on human behavior, hence deciding the scope for economic activities [32].

According to institutional theory, there are numerous indicators of GQ, such as political stability, rule of law, voice and accountability, government effectiveness and regulatory quality, each of which concentrates on a specific aspect of GQ. For instance, regulatory quality influences the sustainability of natural resources and environmental preservation [33]. Regulatory quality is a key component of the governance framework in reducing CO₂ emissions, controlling the shadow economy and corruption [34]. According to institutional theory, regulatory quality influences the execution and design of energy efficiency standards, renewable energy policies and carbon pricing [35].

It is true that government structure and institutional quality directly or indirectly impact environmental quality. By facilitating equality of power distribution and income, institutional quality contributes to environmental improvement through pollution reduction [36].

The rule of law, for example, is a factor in a governance system that can reduce the impact of market failures through effective property rights, the judicial system, and other means. Rule of law guarantees that environmental laws establish legitimate restrictions on polluting activities and offer legal stability for investments in clean technology [37]. The rule of law ensures the enforcement and application of the regulations that are necessary for environmental protection [38].

The loopholes in GQ contribute to corruption in the environmental sector, which either directly or indirectly affects environmental stress [39]. Corruption has led to regulatory deterioration where polluting sectors affect environmental policies for personal benefits instead of national gains [40]. Because corruption has a greater political cost than reducing rules targeted at CO₂ emissions, it directly affects them, which in turn contributes to pollution [41]. A structured institutional system enables governments to regulate CO₂ emissions levels because democracy and corruption-control could enhance the effectiveness of regulating environmental policies [42].

Good governance enactment through government effectiveness, rule of law, environmental standards, and quality of regulation results in control of pollution in economies [43]. Sustainable resource use and the preservation of environmental quality depend on effective environmental governance [44]. Through their influence on environmental policies, governance indicators play a significant role in reducing environmental pollution such as CO₂ emissions, which impacts the entire society. According to van Soest, Stoop

and Vyrastekova [45], governance could cause an upsurge in the level of sustainable development and reduce CO₂ emissions [46].

H1: *GQ reduces CO₂ emissions.*

2.2. Financial Technology and CO₂ Emissions

The resource-based view (RBV) posits that resources that are inimitable, non-substitutable, and rare are the key factors in achieving a sustained competitive advantage. Based on this argument of the RBV, FNT systems improve data integrity, financial transparency, risk management, and operational efficiency, establishing them as essential organizational resources [47]. From the perspective of the RBV, the implementation of FNT can be regarded as a strategic technical asset that enhances the capacities of organizations [48]. The RBV offers an inclusive mechanism for explaining the role of FNT in creating value via capability development, resource reconfigurations and strategic asset deployment [49].

According to RBV theory, a resource qualifies as a strategic asset when it satisfies the criteria of value and scarcity, rendering it difficult to replicate [50]. Long-term competitive advantages stem from resource configurations that are challenging for competitors to imitate or replace [51]. FNT displays technology resources that provide varying degrees of rarity, inimitability, value and non-substitutability to a nation in the long run [52]. According to the RBV, in contemporary digital economies, financial technologies, digital platforms, technology assets, and data analytic systems serve as strategic resources that can generate economic competitive advantage for an economy [53]. Accordingly, FNT possesses the capacity to provide a viable option for attaining green and sustainable development through cutting corporate-level carbon emissions [54].

FNT denotes financial innovation utilizing cutting-edge technology to build products, services, and business strategies for delivering financial services [55]. It integrates several technologies such as artificial intelligence, informational and communication technologies, blockchain, the Internet of Things (IoT) and wireless networks to establish a digitalized financial system [56]. FNT as a technological resource includes data analytics, software applications, algorithms and digital platforms that make it possible to deliver financial services [57]. Such technological resources add value through reduced transaction costs, improved service quality and enhanced efficiency in comparison to traditional financial systems [58].

The rarity of FNT competences occurs from the integration of infrastructure requirements, organizational capabilities and technical expertise required for its effective implementation [59]. Inimitability refers to the tacit knowledge and the complexity of technological integration [60], whereas non-substitutability shows the inimitable value of digital FNT services which could not be replicated with alternative approaches [61]. FNT platforms develop green finance operations which deliver advantages to organizations in sustainable development and environmental management [62].

Emerging technologies like cryptocurrencies and blockchain further expand the realms of financial innovation, which could enable financial arrangements that were not possible within conventional monetary frameworks. In turn, other emerging areas like decentralized finance (DeFi), smart contracts, and other related digital instruments provide a conduit for automated financial services with decreasing reliance on intermediaries and lower transaction costs, along with an increasingly broad range of financial products. Collectively, these will drive greater efficiency and, with it, increased financial inclusion and a deepening of financial markets.

The hypothetical relationship between FNT and CO₂ emissions can be explained through various mechanisms [17]. First, green finance facilitates the FNT platforms that concentrate on environmental financing and sustainable investment products [63]. FNT is

significantly contributing to the reduction of CO₂ emissions, with green finance acting as a powerful instrument to enhance environmental quality [64]. Examples include green bonds supporting substantial environmental investments, crowdfunding platforms promoting extensive involvement in renewable energy initiatives and sustainable finance applications providing access to eco-friendly financial goods [65].

The second aspect is the efficiency of finance enabled through digitalization. FNT reduces the physical infrastructure that a conventional banking system requires [66]. Through digitalization of transactions, financial institutions can avoid paper-intensive procedures, minimize energy consumption of banking branches, and reduce carbon emissions from the transportation of human and physical resources to banking centers [67]. Specifically, mobile banking and online payment solutions create a significantly lower carbon footprint than before when banking was conducted in the conventional physical banking system [68].

The third mechanism operates through improved resource allocation efficiency, where FNT enhances information processing capabilities and reduces information asymmetries in financial markets [68]. Advanced algorithms and big data analytics enable better identification of sustainable investment opportunities, more efficient capital allocation toward green projects, and improved risk assessment for environmental investments [69]. The incorporation of FNT diffuses financial resources towards sustainable choices while taking away carbon-intensive activities that reduce emissions from the system [70].

Fourth, enhanced reporting and monitoring capabilities by FNT result in improved environment management [62]. FNT tools provide carbon footprint monitoring, better environment-related decision making and real-time environmental data [71]. Hence, we propose hypothesis H2 as follows:

H2: *FNT reduces CO₂ emissions.*

2.3. Moderating Role of AREs

Firstly, resource rents empower governments to capitalize on R&D and green technology and produce knowledge on FNT solutions for environmental sustainability [72]. For example, such rents also bring about financial stability, which in turn leads to the development of long-term environmental infrastructure and technological investments [73]. Abundant natural resources drive economic diversification, create industrial upgrading and employment opportunities, support healthcare, education, and infrastructure development and enhance living standards [74], thereby supporting FNT implementation for achieving carbon neutrality. The unsustainable utilization and over-exploitation of natural resources, particularly fossil fuels, substantially contribute to environmental degradation [28].

The advancement of nations is predominantly contingent upon the exploitation of natural resources, leading to increases in the rents generated from oil, natural gas and forests [75]. However, transitioning to energy sources such as wind, hydroelectric, solar and nuclear power may mitigate the strain on finite natural resources and reduce the adverse impacts of greenhouse gas emissions [76]. Sustainable development depends on responsible resource management, as reckless extraction leads to environmental degradation [77].

According to Barney [49], resource rents are a tangible strategic resource that can be reinvested in FNT ecosystems and green technologies. This provides resource complementarity, making natural resources and FNT more environmentally beneficial when combined. Without resource rent reinvestment, FNT cannot access the regulatory, infrastructural, and financial ecosystems required to achieve CO₂ reductions. For example, Okere et al. [78] stated that although oil-rich economies' dependence on natural resources

can lead to carbon emissions, the interaction with FNT has the potential to be a transformative effect, improving energy and carbon intensities, but this transformative effect depends on how resource revenues under fiscal policy are reinvested.

Secondly, building human capital as a valuable advanced resource enhances FNT not only because of organizational research but also due to a competent workforce and a knowledge network that fosters environmentally sustainable technological innovation [79]. In the GCC countries, significant educational investments increase the development and expansion of FNT solutions [80]. A shared body of know-how from various disciplines among financial experts, technology experts, and environmental experts facilitates the use of FNT solutions to achieve environmental sustainability [81].

Human capital is an inimitable and intangible resource according to the RBV [82,83]. The RBV has greatly influenced research on strategic human capital and scholars agree that human capital creates value and becomes more effective when it is combined with technology. For instance, Imtiaz, Awan and Fatima [84] stated that human capital increases development of sustainable innovations, which can help achieve sustainability.

Thirdly, physical and information infrastructure establishes the technological foundation for the development of FNT and environmental surveillance [85]. According to Du and Fang [86], the quality and scale of the labor force are crucial moderators in the relationship between FNT development and regional economic growth. Hence, nations with elevated educational levels derive enhanced growth advantages from FNT adoption [86]. The development of human capital is essential for expediting financial progress and improving quality of life [54]. Digital and physical infrastructure is the enabling platform for FNT to unlock its full CO₂-reducing potential. In areas with strong infrastructure, FNT adoption reaches a wider population, facilitating comprehensive green credit allocation, carbon-efficient resource management and carbon monitoring [87].

The GCC countries have invested significantly in telecommunications infrastructure such as fiber optic and 5G technology, thus allowing faster adoption of FNT and immediate environmental surveillance [88]. On the other hand, financial market infrastructure such as online trading systems and payment systems makes green finance and institutional financial services easier [89]. Additionally, energy infrastructure such as smart grids and renewable energy infrastructure improves environmental sustainability with stable energy power for all financial activities [90].

Further, Davradakis and Santos [91] emphasized that robust information technology infrastructure is essential for effectively utilizing FNT to enhance competitiveness, particularly regarding blockchain technology. Romanova et al. [92] posited that organizations with sophisticated infrastructure are more adept at leveraging FNT prospects.

The combined effect of these sophisticated resources and FNT is creating collective effects beyond their individual implications for environmental sustainability. The moderating role of advanced resources emphasizes how these resources and FNT together can work in tandem to provide more favorable outcomes for environmental sustainability [93]. The existence of AREs boosts the FNT capabilities by offering technological resources for their effective scaling and deployment [94]. In turn, this enables improved environmental monitoring, enhanced regulatory compliance and more efficient resource utilization [95]. This interaction's multiplicative effect implies that AREs and FNT have a greater influence on environmental consequences together than would be predicted from their separate effects alone.

FNT's environmental effect requires thorough investigation, especially in the presence of abundant resources, diverse human capital, and infrastructure variability [49]. Hence, we hypothesized H3 as follows:

H3: *AREs negatively moderate the FNT and CO₂ emissions relationship.*

3. Data and Methodology

This study examines the determinants of consumption-based CO₂ emissions in six Gulf Cooperation Council countries the UAE, Saudi Arabia, Bahrain, Qatar, Kuwait, and Oman, from 2010 to 2023. More specifically, this study explains how GQ, FNT, and the interaction of FNT with AREs determine carbon dioxide emissions, measured in metric tons per capita [96,97], while controlling for population size (POP), income (I), and urbanization (U). Table 1 outlines the variable symbolization, measurements, and data sources. This section outlines the model construction, theoretical background, and estimation strategy employed in the study. Further, the justification for using principal component analysis (PCA) for GQ, FNT, and AREs is explained as follows:

Instead of focusing on particular FNT products, the FNT index is intended to capture the ecosystem that facilitates FNT diffusion. The technological and financial underpinnings of digital financial services are represented by internet prevalence, mobile connectivity, and financial depth, which makes them suitable proxies for FNT development in the GCC. PCA was employed to attain composite indices for FINT, GQ, and AREs to reduce dimensionality and minimize multicollinearity among highly correlated indicators. The selected FNT indicators capture key dimensions of internet users, mobile phone subscribers, and domestic credit to the private sector. Similarly, the ARE index combines human capital, infrastructure, and natural resource rents to reflect the strategic resource capabilities emphasized in the RBV framework. GQ is measured using the six Worldwide Governance Indicators to comprehensively capture institutional effectiveness and regulatory capacity. Tables A1–A3 (see Appendix A) report the PCA factor loadings, eigenvalues, and cumulative variance, for transparency.

This study's FNT index uses a proxy-based methodology to capture the environment that fosters FNT growth. According to recent research, domestic credit reflects the breadth and accessibility of the financial system in which FNT innovation functions, while internet penetration and mobile connectivity represent the technological infrastructure required for the adoption and diffusion of digital financial services. For instance, Zheng et al. [98] used PCA techniques to combine financial-access variables with internet and mobile technology indicators to create a FNT-related composite index. In a similar vein, recent data from the World Bank and IMF emphasize financial access, mobile technology usage, and digital connection as essential elements of FNT ecosystems. The PCA-based composite measure offers a theoretically sound and empirically verified proxy for FNT progress given the scarcity of harmonized FNT-specific variables across GCC nations throughout the study period.

Table 1. Variable details.

	Variables	Measurements	Data Sources
Carbon Dioxide Emissions	CO ₂	Carbon dioxide emissions.	Carbon Atlas Data
Financial Technology	FNT	Financial technologies, measured by a PCA of domestic credit to the bank sector, and the number of internet users and mobile phone subscribers.	World Bank
Advanced-Resource Endowments	ARE	Advanced-resource endowment is measured by PCA of natural resource rents, human capital, and infrastructure.	World Bank
Population Size	POP	Population size is measured by the total population.	World Bank
Income	I	Income level is measured by GDP per capita.	World Bank

Governance Quality	GQ	Governance quality is measured by PCA of six factors: political stability, voice and accountability, rule of law, government effectiveness, absence of violence, and control of corruption and regulatory quality.	WGI
Urbanization	U	Urbanization is measured by the percentage of the total population in urban areas.	World Bank

3.1. Model Construction and Theoretical Background

This study's empirical model is based on three key theoretical frameworks: Endogenous Growth Theory (EGT), Treadmill Production Theory (TPT) and Ecological Modernization Theory (EMT).

From the perspective of the TPT, the destruction of the environment is an intrinsic byproduct of infinite economic expansion and the intense utilization of natural resources [99]. In contrast, EGT focuses primarily on the potential of technology, particularly disruptive innovations in the realm of FNT, to foster sustainable development while concurrently upgrading the quality of the environment [100,101]. Similarly, EMT asserts that financial innovations can positively contribute to the improvement of the environment with proper institutional frameworks being in place [102,103]. In essence, all the aforementioned approaches form the background for investigating the complex relationships between the advancement of technology, economic development, and sustainable development of the environment, particularly the issue of CO₂ emissions.

The suggested approach makes the assumption that advanced-resource endowments, FNT development, and governance quality all affect carbon emissions through linked mechanisms rather than separate ones. The institutional basis for environmental regulation, policy enforcement, and sustainable resource management is provided by high-quality governance. In this context, FNT functions as a technology tool that encourages green investment, increases financial inclusion, and improves resource allocation efficiency. However, the availability of complementary resources determines how effective FNT is in terms of the environment. Based on the resource-based view, advanced-resource endowments, such as infrastructure, human capital, and resource rents, improve economies' capacity to embrace, execute, and expand FNT-enabled sustainability solutions. As a result, FNT offers the technological capacity for environmental development, improved governance enhances the institutional framework for climate action, and advanced-resource endowments increase the efficacy of these capacities.

Although FNT has technological capabilities that can support environmental sustainability, its efficacy is unlikely to be consistent across nations. According to the RBV, complementing strategic assets help technology resources produce better results. AREs, including as human capital, infrastructure quality, and resource rents, are crucial enabling resources that impact the ability of GCC economies to successfully implement FNT solutions. The technical know-how and expertise needed for the uptake and application of digital FNT are provided by human capital. While resource rents supply the funding required for investments in innovation, environmental monitoring, and sustainable technological development, infrastructure facilitates the spread of FNT through digital connectivity and technological preparedness. Therefore, it is anticipated that countries with superior resource capacities will gain more from FNT in terms of the environment. According to this viewpoint, AREs enhance the efficacy of FNT in promoting climate action and lowering carbon emissions in addition to acting as independent determinants of environmental performance.

Based on the empirical methodology developed by Feng, Zhou and Hussain [96], the model developed in this research will test the relationship between the emission of CO₂ and the variables and factors considered. A closer analysis of the moderating impacts of

the development of FNT on the relationship between the factors of resource endowment will also be provided, to determine the impacts of technological innovations in such economies [90].

$$C_{i,t} = f(GQ_{i,t}, FNT_{i,t}, ARE_{i,t}, FNT \times ARE_{i,t}, POP_{i,t}, I_{i,t}, U_{i,t}) \quad (1)$$

Here, GQ, FNT, ARE, FNT $\times$ ARE, POP, I, and U refer to governance quality, financial technology, advanced-resource endowments, the interaction term of advanced-resource endowments and financial technology, population size, income, and urbanization, respectively. This study incorporates elements of EGT [104], suggesting that FNT can improve resource efficiency and mitigate environmental harm. Based on the objectives, economic model, and theoretical underpinning, the following panel econometric model is established, where the variables are as described already and $\varepsilon_{i,t}$ is a random disturbance term with a mean of zero and variance of σ^2 :

$$C_{i,t} = \beta_0 + \beta_1 GQ_{i,t} + \beta_2 FNT_{i,t} + \beta_3 ARE_{i,t} + \beta_4 ARE_{i,t} \times FNT_{i,t} + \beta_5 POP_{i,t} + \beta_6 I_{i,t} + \beta_7 U_{i,t} + \varepsilon_{i,t} \quad (2)$$

To address issues of data non-uniformity, non-normality, and skewness, the paper uses natural logarithmic transformations for all variables, as in [96]. The log-linear regression yields more robust and efficient outcomes compared to the standard linear model [105]:

$$C_{i,t} = \beta_0 + \beta_1 GQ_{i,t} + \beta_2 FNT_{i,t} + \beta_3 ARE_{i,t} + \beta_4 ARE_{i,t} \times FNT_{i,t} + \beta_5 POP_{i,t} + \beta_6 I_{i,t} + \beta_7 U_{i,t} + \varepsilon_{i,t} \quad (3)$$

In this context, I represent the nation (where $i = 1, 2, \dots, 6$), and t denotes the time period (2010–2023). Each of the coefficients, $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6$ and β_7 , captures the effects of the independent variables on the dependent variable holding other variables constant. Further, the error term is $\varepsilon_{i,t}$, which is the portion of the dependent variable not explained by the independent variables.

3.2. Estimation Strategy

The empirical analysis involves several steps to ensure robust and reliable results, such as (i) panel unit root tests, including ADF, PPC, LLC, and IPS tests; (ii) Pedroni cointegration tests; (iii) long-run estimations utilizing FMOLS and DOLS methods; (iv) robustness checks through static panel estimations and the Panel ARDL-PMG approach; (v) panel data diagnostics; and (vi) panel quantile regression. The econometric analysis was conducted using Stata 15.

3.2.1. Panel Unit Root Test

To ensure that the regression results are reliable, we always conduct a check for unit roots. In case there is a unit root in a variable, it has to undergo transformation into a stationary process to maintain stability in regression. Other studies indicate that one has to ascertain the order of integration prior to cointegration analysis. Liang, Liu and Geng [106] warn that using only one test on unit roots can be very risky because tests exhibit different performances under different sample sizes.

This study, therefore, applies a battery of tests for autoregressive unit roots: Augmented Dickey–Fuller (ADF), Phillips–Perron (PP), Levin–Lin–Chu (LLC), and Im–Pesaran–Shin (IPS). We apply the ADF test following the Dickey–Fuller framework; we also apply the DF–GLS approach in line with Dagar et al. [107] and the Phillips–Perron test from Westerlund, Hosseinkouchack and Solberger [108]. These tests are necessary to ascertain that no variable exceeds the necessary order of integration and all meet stationarity criteria before applying the dynamic ordinary least squares method.

3.2.2. Pedroni Cointegration Test

The second step of the analysis focuses on checking long-run equilibrium relationships among the selected variables. For this purpose, three panel cointegration methods are estimated: Pedroni, Kao, and Fisher. According to Abumunshar, Aga and Samour [109], these methods are suitable for the variables integrated at a first-difference level. Of the various techniques described above, the Pedroni cointegration test represents the most suitable approach for the present study as it allows multiple explanatory variables within a panel framework.

3.2.3. Long-Run Estimation by FMOLS and DOLS

With evidence of long-run cointegration, the study estimates the long-run relationships among the variables using the fully modified ordinary least squares and dynamic ordinary least squares techniques. These estimators are applicable only when robust cointegration has been established, hence allowing for reliable long-run inference. Zhang et al. [110] explain that both FMOLS and DOLS are appropriate in panel data analysis since they efficiently resolve common econometric problems such as endogeneity, serial correlation, and cross-sectional dependence for regressors and error terms.

The specific functional forms of the panel FMOLS and DOLS models used in this study are given below. For the FMOLS estimation,

$$\beta_{FMOLS} = \left[\frac{1}{N} \sum_{i=1}^N (\sum_{t=1}^T A_{i,t} - \bar{A}_i)^2 \right]^{-1} \times [\sum_{t=1}^T (A_{i,t} - \bar{A}_i)^2] \times \bar{Y}_{i,t} - \bar{T}_{\Delta\epsilon\mu} \quad (4)$$

For the DOLS estimation,

$$\beta_{DOLS} = \left[\frac{1}{N} \sum_{i=1}^N (\sum_{t=1}^T A_{i,t} A'_{i,t})^2 \right]^{-1} \times \sum_{t=1}^T (A_{i,t} A'_{i,t}) \quad (5)$$

3.2.4. Robustness Check

The association between mean-differentiated independent variables and the white noise term can introduce bias into panel data models with individual effects. This bias makes ARDL estimation methods ineffective in addressing the issue. To resolve this issue, the ARDL model and the PMG estimator are combined [111], allowing for the correction of this bias. Therefore, the PMG-ARDL approach, as suggested by the relevant literature, is employed in this study.

Further, this study estimates panel quantile regression to identify the roles of different drivers of CO₂ levels at varying points in their distribution, with the usual focus of mean regression methods (as employed in many analyses across related fields, as mentioned by Syed et al. [112]) proving potentially misleading or even causing bias in certain distributional assumptions [113].

4. Results

4.1. Descriptive, Correlation, Unit Root, Cointegration, and Longrun Statistics

The basic descriptive statistics of the data set are presented in Table 2, including mean, standard deviation, skewness, and kurtosis values for each variable. Descriptive statistics can be used to detect any anomalies and irregularities in the pattern, as shown in Table 2, which could help in identifying anomalies and irregularities in patterns [90]. The output has shown distinct economic and social characteristics in the variables. The POP has recorded the highest mean value of 15.3925, which reflects the size of the region's population. The mean value of CO₂ is relatively similar, at 4.77, while the mean value of FNT is lower.

The ranges indicate considerable variation in dispersion, more so in CO₂, which varies between 3.36 and 6.43. The bulk of the variables, CO₂ and POP among them, are positively skewed. This is an indication that these distributions are largely right-skewed,

meaning they have tails on the sides where larger observations are sought. On the contrary, FNT is negatively skewed; this is an indication of concentration in smaller figures. The negative kurtosis in general reveals more flat distributions that are less extreme. Overall, from the descriptive statistics, it appears there is moderate variation among GCC states, using size as an indicator.

Table 2. Descriptive statistics.

Statistics	CO ₂	GQ	FNT	AREs	POP	I	U
Mean	4.7895	4.1907	4.0179	3.2770	15.3925	10.4623	4.4970
Standard Error	0.0964	0.0219	0.0228	0.0465	0.1088	0.0511	0.0088
Median	4.6098	4.1841	4.0612	3.2960	15.2633	10.2938	4.4832
St. Deviation	0.8831	0.2006	0.2091	0.4262	0.9969	0.4686	0.0808
Variance	0.7798	0.0402	0.0437	0.1816	0.9938	0.2196	0.0065
Kurtosis	−0.4688	−0.8531	0.2045	−0.4646	−0.5850	−0.3545	−1.1277
Skewness	0.4252	−0.1164	−0.7737	−0.2880	0.6175	0.6964	0.1171
Minimum	3.3616	3.7799	3.5193	2.2668	13.9937	9.7282	4.3196
Maximum	6.4344	4.5569	4.3970	4.0787	17.3200	11.5942	4.6052
Count	84	84	84	84	84	84	84

A correlation matrix gives a first impression of how the variables move together, indicating the direction and strength of their linear ties, and flags possible multicollinearity before running regressions (see Table 3). Because multicollinearity can lead to biased coefficient estimates and obscure inferences, checking for pairwise correlations is an indispensable early step. Several notable connections are emphasized by the findings for the study variables. CO₂ has a positive relationship ($r = 0.9944$, $p < 0.01$) with the size of the population (POP) ($r = 0.9513$, $p < 0.01$), which means that higher export activity and larger population would go along with higher emissions.

FNT also tends to move in the opposite direction of emissions, showing significant negative associations with CO₂ ($r = -0.2948$, $p < 0.01$). The connection of AREs to CO₂ is negligible ($r = -0.1966$ and $r = -0.1881$, at $p < 0.10$), hence indicating a modest inverse link with emissions. U is positively related to CO₂ as well as to POP, therefore suggesting that more urbanized economies usually present higher emissions and larger populations. GQ expresses a negative link to AREs ($r = -0.462$, $p < 0.01$), which reveals a correlation between better governance and low dependency on resources.

Table 3. Correlation matrix.

Variables	CO ₂	GQ	FNT	AREs	POP	I	U
CO ₂	1						
GQ	0.071	1					
FNT	−0.294 ***	0.032	1				
AREs	−0.196 *	−0.462 ***	0.127	1			
POP	0.951 ***	−0.050	0.229 **	0.168	1		
I	0.07	0.553 ***	0.151	0.121	−0.202 *	1	
U	0.264 **	−0.096	0.288 ***	0.183 *	0.457 ***	0.592 ***	1

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

The panel unit root test results indicate that most variables become stationary after the first difference in Table 4. In the level form, variables such as CO₂, FNT, AREs, POP, I, GQ, and U do not exhibit stationarity. Their test statistics are not significant at the $p < 0.05$ level. However, when the first difference (Δ) is considered, many variables achieve stationarity. For instance, CO₂ and FNT show significant results at the $p < 0.01$ level in all

panel unit root tests (ADF, PP, LLC, IPS). Similarly, AREs, POP, I, GQ, and U also become stationary after differencing, with p -values indicating significance at the $p < 0.01$ or $p < 0.05$ level. These results suggest that the variables are non-stationary in their levels but stationary after first differencing, making them suitable for further panel data analysis.

Table 4. Unit root test.

Variables	ADF		PP		LLC		IPS	
	Level	Δ	Level	Δ	Level	Δ	Level	Δ
CO ₂	−3.827	−4.195 ***	−3.827	−4.195 ***	−1.674	−2.861 ***	−1.835	−2.943 ***
FNT	0.466	−2.800 ***	0.466	−2.800 ***	−6.519	−3.255 ***	0.403	−2.009 **
AREs	0.371	−3.818 ***	0.371	−3.818 ***	−3.778	−5.685 ***	−0.148	−2.855 **
POP	−1.839	−1.936 **	−1.83	−1.936 **	−2.748	−4.048 ***	−1.218	−1.727 *
I	−1.839	−4.684 ***	−0.6606	−4.684 ***	−3.277	−6.190 ***	−0.948	−3.290 ***
GQ	−0.264	−6.128 ***	−0.264	−6.128 ***	−1.680	−2.065 **	−0.3504	−3.436 ***
U	−1.144	−13.39 ***	−1.144	−13.39 ***	−1.856	−6.185 ***	−1.980	−2.380 **

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

In Table 5, the Pedroni panel cointegration indicates significant evidence of cointegration between the variables. The rho and t statistics are significant at the $p < 0.01$ level for both the panel and group tests, while the adf statistics are significant at the $p < 0.05$ level, suggesting long-term relationships among the variables.

In Table 6, the long-run relationships between variables are estimated using the fully modified ordinary least squares (FMOLS) and dynamic ordinary least squares (DOLS) methods. FNT has a significant negative effect on the FMOLS model (−0.364, $p < 0.01$). However, its impact is considerably smaller in the DOLS model (−0.00115, $p < 0.01$). AREs also show a negative effect in both models. In the FMOLS model, the effect is −0.268 ($p < 0.01$). In the DOLS model, the effect is −0.116 ($p < 0.05$). This indicates a stronger effect in FMOLS. The interaction term FNT * AREs is negative and statistically significant in both models. In the FMOLS model, the effect is −0.298 ($p < 0.01$). In the DOLS model, the effect is −0.215 ($p < 0.01$). This suggests that the combined effect of FNT and AREs is negative in the long run. POP shows a positive relationship in both models. The coefficient values of POP reveal positive and significant results in both models. For the coefficient in the FMOLS, it is located at 0.401, which increases to 0.913 in the DOLS ($p < 0.01$). Income (I) has a positive long-run relationship, with coefficients of 0.618 in the FMOLS and 0.607 in the DOLS ($p < 0.01$). The coefficient for GQ is negative in both methods, with a stronger impact measured in the DOLS, which is −0.351 ($p < 0.05$). Urbanization (U) is positively related, primarily in the FMOLS, where the coefficient is set at 1.141 ($p < 0.01$). There is a high explanatory fit in the FMOLS, evident from its R-squared value of 0.991.

Table 5. Cointegration test.

Stats.	Panel	Group
V	−1.551 *	−
rho	2.953 ***	3.997 ***
T	−4.673 ***	−5.687 **
adf	2.308 **	2.867 **

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

The moderating effect's practical significance is further illuminated by the interaction plot. Figure 1 illustrates how the degree of AREs affects the relationship between CO₂ and FNT development. FNT has a comparatively smaller environmental impact at lower AREs levels. However, the advantages of FNT for the environment get significantly larger as

AREs levels rise. According to this research, FNT might not be enough to produce significant environmental improvements on its own. Instead, the availability of complementary resources like competent human capital, high-quality infrastructure, and sufficient investment capacity determines how effective it is.

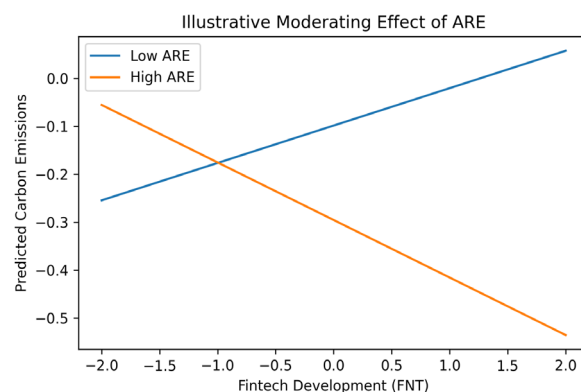


Figure 1. Moderation Effect.

Table 6. Long-run estimation of FMOLS and DOLS tests.

VARIABLES	FMOLS	DOLS
GQ	−0.052 *** (0.000)	−0.351 ** (0.000)
FNT	−0.364 *** (0.000)	−0.001 *** (0.000)
AREs	−0.268 *** (0.000)	−0.116 ** (0.048)
FNT × AREs	−0.298 *** (0.006)	−0.215 *** (0.007)
POP	0.401 *** (0.001)	0.913 *** (0.018)
I	0.618 *** (0.000)	0.607 *** (0.000)
U	1.141 *** (0.005)	0.198 *** (0.000)
Constant	−15.34 *** (1.468)	−14.63 *** (1.586)
R-squared	0.991	-
F-statistics	246.096	-
Prob (F-statistics)	0.000	-

Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$.

The diagnostic test outcomes leave no ambiguity in how the panel should be designed (see Table 7). It can be seen that there is no cross-sectional dependence; the cross-section test gives $p = 0.2119$, and hence there are no concerns regarding the correlation between the cross-sectional units. Heteroskedasticity is detected because the modified Wald test gives $p = 0.0001$, and there is evidence of the presence of the serial correlation problem in the panel data as revealed by the Wooldridge test ($p = 0.0009$). The indication from both tests is adequate to prefer the GLS-based methods that are robust to those disturbances. The residuals from the test satisfy the normality test, as the Jarque–Bera test gives $p = 0.5584$. The Hausman test provides strong support to the fixed-effects model as compared to the random effects model ($p = 0.0000$).

Table 7. Diagnostic tests .

Test	Statistic	<i>p</i> -Value	Decision
Cross-sectional dependence	1.248	0.211	No cross-sectional dependence
Modified Wald test for groupwise heteroskedasticity	28.98	0.000	Heteroskedasticity is present in panels
Wooldridge test for autocorrelation in panel data	48.876	0.000	Serial correlation exists in panel data
Jarque–Bera test for normality	1.17	0.558	Residuals are normally distributed
Hausman specification test	89.87	0.000	Fixed-effects model is appropriate

4.2. Robustness Tests

In Table 8, robustness tests fixed effects, GLS, and OLS maintain similarity in results. FNT and AREs register negative and significant effects in each specification, the largest being in fixed effects (-0.161 , $p < 0.01$) and GLS (-0.115 , $p < 0.01$). The interaction variable FNT $\times$ AREs remains negative in each specification, although the largest result is in the OLS test (-0.105 , $p < 0.01$). POP maintains a strong and significant positively influencing role in GLS and OLS (0.913 , $p < 0.01$). The OLS test has high explanatory value, registering an R-squared value of 0.982. Therefore, the overall results in each specification are significant at the 1% level.

Table 8. Robustness tests.

Variables	Robust Estimates		
	Fixed Effect	GLS	OLS
GQ	−0.009 (0.086)	−0.351 ** (0.145)	−0.351 ** (0.145)
FNT	−0.161 *** (0.091)	−0.115 *** (0.076)	−0.115 *** (0.061)
AREs	−0.185 *** (0.021)	−0.116 ** (0.046)	−0.116 *** (0.040)
FNT $\times$ AREs	−0.110 * (0.078)	−0.105 * (0.087)	−0.105 *** (0.050)
POP	0.642 *** (0.132)	0.913 *** (0.017)	0.913 *** (0.015)
I	0.116 * (0.054)	0.607 *** (0.068)	0.607 *** (0.055)
U	0.864 * (0.405)	0.198 (0.343)	0.198 (0.300)
Constant	−10.16 *** (1.659)	−14.63 *** (1.518)	−14.63 *** (1.445)
Observations	84	84	84
Number of groups	6	6	−
R-squared	0.840	−	0.982
F-statistics	63.0	4592.68	1007.08
Prob (F-statistics)	0.000	0.000	0.000

Robust standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.3. Robustness Check Using Alternative Estimation Techniques

The extended results from the ARDL-PMG analysis show clear relationships among the main variables (see Table 9). FNT and AREs both bear negative and statistically significant relationships across all models, with stronger impacts in the fixed-effects specification—about -0.161 , $p < 0.01$ —and GLS—about -0.115 , $p < 0.01$. The interaction term $FNT \times AREs$ is significant—around -0.201 , $p < 0.01$ —indicating that together, FNT and AREs push the long-run outcomes in a favorable direction. FNT's negative coefficient indicates that by increasing financial efficiency, enabling green investments, and lowering transaction-related environmental costs, digital financial innovation helps reduce carbon emissions. The potential of FNT as a policy instrument to achieve climate-transition goals in GCC economies is highlighted by this research. Stronger institutional quality, effective regulations, and environmental enforcement systems all contribute to lower emissions, according to the negative governance coefficient. This result suggests that in order to achieve climate targets, technology solutions can be supplemented by governance improvements. POP, I, and U all exert positive and significant long-run effects, with U carrying the largest coefficient—about 3.889 , $p < 0.01$.

In the short run, the error-correction term has a negative and significant value—for instance, -0.721 , $p < 0.05$ —indicating that convergence is achieved towards the long-run equilibrium. The estimated value of $\Delta LAREs$ is -0.173 , where $p = 0.051$, whereas for ΔFNT , it is insignificant. Their interaction in the short run— $FNT \times AREs$ —is captured negatively and found to be very significant, with a value of approximately -0.718 , $p < 0.01$. Other short-run relevant variables, like ΔPOP , ΔI , and ΔG , are significant. The Hausman test, conducted without systematic differences between fixed and random effects estimators— $p = 1.000$ —confirmed that fixed-effects methods are appropriate.

Table 9. ARDL-PMG test.

Long-Run Estimates	Coef.	SE.	t-Value	p-Value
GQ	−0.021	0.032	−0.671	0.504
FNT	−0.211 ***	0.0288	−7.33	0.000
AREs	−0.390 ***	0.025	−15.13	0.000
$FNT \times AREs$	−0.200 ***	0.022	8.97	0.000
POP	0.653 ***	0.073	8.82	0.000
I	0.974 ***	0.065	14.96	0.000
U	3.888 ***	0.310	12.52	0.000
Short-Run Estimates				
ECT	−0.720 **	0.293	−2.46	0.014
ΔGQ	−0.167 *	0.093	−1.80	0.073
ΔFNT	−1.824	1.860	−0.98	0.327
$\Delta AREs$	−0.172 *	0.088	−1.96	0.051
$FNT \times AREs$	−0.717 ***	0.280	2.56	0.000
ΔPOP	0.462 *	0.268	1.72	0.061
ΔI	0.381 *	0.206	1.85	0.065
ΔU	97.342	112.230	0.87	0.386
Constant	−15.692 **	6.563	−2.39	0.017
Hausman Test	0.000(1.000)		1.576 (0.5934)	

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

4.4. Panel Quantile Regression

In Table 10, from the 40th quantile onward, the impact of FNT becomes more favorable and statistically significant. At Q0.40, the coefficient is 0.139; at Q0.90, it is 0.387. This implies that FNT growth is linked to increased emissions in environments with comparatively high emissions. It means development of FNT first boosts economic activity, the growth of digital infrastructure, financial deepening, and consumption, all of which raise the demand for energy. Short-term benefits in environmental efficiency may be dominated by the scale impacts of digitalization in carbon-intensive economies. Similar claims that technology advancement first raises resource consumption before long-term environmental benefits materialize have been covered in research on rebound effects and digital transformation.

AREs have a negative and significant effect on all quantiles, ranging from 0.40 (−0.167, $p < 0.01$) to −0.37 in the 0.90 quantile ($p < 0.01$), indicating that their adverse effect is greater in the higher quantiles. The interaction term FNT × AREs remains negative and significant at the higher quantiles, with coefficients of −0.139 (0.40), −0.198 (0.50), −0.278 (0.60), −0.310 (0.70), −0.389 (0.80), and −0.354 (0.90), all $p < 0.01$. It appears that the cumulative weight of FNT and resource endowment rises as we progress further into the upper tail. The quantile analysis's key conclusion is that FNT's effects on the environment differ depending on CO₂ levels. The quantile results show a positive and substantial effect at higher CO₂ quantiles, despite the FMOLS, DOLS, and PMG calculations suggesting that FNT reduces CO₂ on average. The diverse nature of the link between FNT and the environment is reflected in this apparent disparity. FNT growth may initially boost economic activity, the development of digital infrastructure, the need for data processing, and electricity use in very carbon-intensive settings, which would raise emissions. The improvements in environmental efficiency linked to digital financial innovation may be overshadowed by this scale and rebound impacts. The long-term advantages, however, become more apparent as FNT ecosystems develop and incorporate greener technologies and sustainable investment strategies. This is demonstrated by the panel assessments' negative average effects. Consequently, rather than being contradictory, the quantile results should be seen as proof of transitional heterogeneity.

The variable related to POP maintains a strong and significant impact at every quantile, albeit less so at the stronger quantiles. The variable representing U maintains a significant and strong impact at every quantile, with the impact being stronger at the stronger quantiles. All other variables, including I and the GQ, manifest varying levels of significance at the quantiles.

Table 10. Panel Quantile Regression.

Variables	Quantiles								
	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
GQ	−0.115 (0.141)	−0.070 (0.097)	−0.046 (0.082)	−0.016 (0.065)	−0.004 (0.062)	−0.022 (0.064)	0.037 (0.071)	−0.053 (0.082)	0.067 (0.103)
FNT	−0.015 (0.134)	−0.019 (0.094)	0.050 (0.077)	0.139 ** (0.061)	0.177 ** (0.059)	0.253 *** (0.062)	0.298 *** (0.069)	0.347 *** (0.080)	0.387 *** (0.091)
AREs	0.0068 (0.055)	−0.003 (0.039)	−0.094 ** (0.032)	−0.167 *** (0.025)	−0.197 *** (0.024)	−0.26 *** (0.025)	−0.30 *** (0.028)	−0.34 *** (0.033)	−0.37 *** (0.038)
FNT × AREs	−0.013 (0.102)	−0.021 (0.099)	−0.068 ** (0.032)	−0.139 *** (0.052)	−0.198 *** (0.065)	−0.278 *** (0.051)	−0.310 *** (0.060)	−0.389 *** (0.078)	−0.354 *** (0.093)
POP	0.801 *** (0.153)	0.734 *** (0.104)	0.699 *** (0.090)	0.653 *** (0.071)	0.635 *** (0.068)	0.595 *** (0.069)	0.572 *** (0.075)	0.548 *** (0.087)	0.527 *** (0.119)
I	0.150 (0.111)	0.136 * (0.078)	0.128 ** (0.063)	0.118** (0.051)	0.114 ** (0.048)	0.105 ** (0.051)	0.100* (0.057)	0.0949 (0.066)	0.0905 (0.075)

U	0.513 (0.560)	0.660 * (0.392)	0.739 ** (0.326)	0.839*** (0.260)	0.881 *** (0.249)	0.967 *** (0.259)	1.018 *** (0.285)	1.073 *** (0.329)	1.118 *** (0.400)
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Standard errors in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

4.5. Robustness Check Using an Alternative Proxy of the Dependent Variable (Consumption-Based Carbon Emissions)

The robustness check results while uses consumption-based carbon emissions as an alternative proxy for the dependent variable is shown in Table 11. Results are consistent across estimation techniques, including fixed effects, GLS, and OLS. FNT has a significant negative effect on the OLS and GLS models (-0.306 , $p < 0.01$). AREs have a negative effect on all models, with the strongest impact on OLS and GLS (-0.0455 , $p < 0.01$). The interaction term FNT $\times$ AREs shows a significant negative effect in both GLS and OLS models (-0.298 , $p < 0.01$); i.e., their combined effect is supportive. POP and I show strong positive relationships in all models, particularly in GLS and OLS (0.938 , $p < 0.01$). GQ and U show weaker effects across models. The R-squared value for OLS is 0.987, indicating a very good model fit.

Table 11. Robust Estimates with Consumption-Based Carbon Emissions.

Variables	Robust Estimates		
	Fixed Effect	GLS	OLS
GQ	−0.118 (0.113)	−0.185 (0.132)	−0.185 (0.139)
FNT	−0.0232 (0.076)	−0.306 *** (0.070)	−0.306 *** (0.054)
AREs	−0.003 (0.047)	−0.045 (0.042)	−0.045 (0.033)
FNT $\times$ AREs	−0.010 (0.056)	−0.298 *** (0.056)	−0.299 *** (0.050)
POP	0.503 ** (0.131)	0.938 *** (0.016)	0.938 *** (0.013)
I	0.0917 (0.127)	0.581 *** (0.0627)	0.581 *** (0.0600)
U	0.658 (0.384)	0.194 (0.314)	0.194 (0.314)
Constant	−7.468 *** (1.172)	−15.19 *** (1.389)	−15.19 *** (1.418)
Observations	84	84	84
Number of Groups	6	6	−
R-Squared	0.644	−	0.987
R-Squared	0.991	−	−
F-Statistics	246.096	6278.0	1601.27
Prob (F-Statistics)	0.000	0.000	0.000

Robust standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$.

5. Discussion

Based on comprehensive econometric estimations, it is essential to discuss the meaning of the results. The major contribution of FNT is found to be substantially significant, hereby indicating a signal for the GCC economies. The results offer significant proof of how GQ, FNT and AREs assist environmental sustainability in GCC economies. The findings indicate that the interplay between financial technological innovation and advanced-

resource availability has a significant impact on climatic outcomes, even though the GCC nations have similar institutional and economic traits.

The inverse relationship between GQ and CO₂ emissions emphasizes the significance of strong institutions in tackling environmental issues. Similarly, Baloch and Wang [44] applied the Environmental Kuznets Curve hypothesis on panel data of BRICS countries from 1996 to 2017 and found that governance exerts negative and statistically significant effects on CO₂ emissions. They found that governance systems have an impact on the adoption and enforcement of climate-related policies as well as environmental regulation in resource-dependent economies. Increased accountability, efficient public administration, and robust regulatory frameworks can enhance adherence to environmental regulations and promote investments in greener technologies [114]. This result is in line with the findings of Hassan et al. [36], who contend that by improving policy efficacy and environmental oversight, institutional quality plays a critical role in reducing environmental deterioration. To achieve long-term sustainability goals, governance reforms may be especially crucial for GCC nations, whose economic progress has historically been associated with petroleum dependence.

Hence, GCC economies should reconsider the role of GQ to limit the harmful impacts of environmental degradation in these regions and around the globe. The GCC governments ought to allocate resources towards establishing specialized climate governance departments inside their finance and planning ministries, employing experts in carbon accounting, green finance and climate risk evaluation. GCC states ought to institutionalize transparent and accountable environmental governance by creating independent national climate authorities tasked with establishing, monitoring, and publicly reporting on binding emission reduction objectives. Transparency in environmental governance diminishes knowledge asymmetries among regulators, companies, and the public, fostering accountability constraints that encourage adherence to emission norms [115]. The inadequate enforcement of environmental restrictions, despite their legal existence, has been recognized as a principal factor contributing to the sustained high emission levels in resource-abundant economies [116]. GCC officials should consequently enhance the capabilities of regulatory inspectorates, environmental courts and digital compliance monitoring systems to bridge the divide between policy formulation and execution.

The findings also show that FNT helps lower CO₂ emissions. Udeagha and Muchapondwa [117] find similar results, such as energy innovation and FNT enhancement of environmental sustainability. For example, Wen and Liu [118] applied the panel data technique to FNT, society, economy and environment in China to examine the influence of FNT on regional pollution management and carbon emission reduction. They found that FNT not only markedly decreases pollutant and carbon dioxide emissions but also substantially enhances the synergy between pollution control and carbon reduction. One explanation for this negative relationship could be that FNT increases access to eco-friendly investment possibilities and enhances financial efficiency. Green finance, better resource allocation, and a decrease in the operational inefficiencies of traditional financial services are all made possible by digital financial platforms. Additionally, the growth in digital transactions lowers transaction costs and lessens reliance on paper-based systems. Arner et al. [25] have revealed similar findings, suggesting that FNT can promote sustainable development through technical innovation, financial inclusion, and green investment mobilization [119].

The findings have policy implications for FNT. GCC economies could focus on enhancing investments in FNT products to boost the reduction of carbon emissions, ascertaining sustainable solutions. The GCC policymakers and governments must vigorously enhance digital banking and sustainable financial management initiatives to ensure envi-

ronmental integrity, foster the development of innovative credit intermediaries to promote green finance and FNT, and potentially mitigate moral hazard in FNT, particularly within the investment banking and financial services sector. Further, the GCC countries' governments can encourage academia to conduct research and development on future FNT products and services through initiating funded projects that combine academia and industry collaboratively. This will enhance the pace of FNT invention. GCC national authorities can implement "green finance" resources to support and enhance the FNT sector. Further, political leaders and governments ought to endorse and formulate explicit regulations for the advancement of FNT, particularly within the banking sector, since it enhances sustainability performance [117].

Furthermore, the function of AREs is one particularly significant discovery. The negative coefficient indicates that nations with better infrastructure, more strategic resource capacity, and higher human capital are better able to lessen environmental constraints. Similarly, Hanif, Arshed and Aziz [3] found that development in human capital negatively influences CO₂ emissions, hence improving environmental performance [3]. The RBV contends that useful and complementary resources improve performance outcomes by enhancing the efficacy of organizational and technology capabilities, which is compatible with this finding. Environmental progress in the GCC seems to be facilitated by investments in digital infrastructure, education, and technology readiness. More significantly, across all specifications, the relationship between the interaction term of (FNT × AREs) and CO₂ emissions continues to be negative and significant. FNT does not function in a vacuum, according to this conclusion. Instead, the availability of complementary resources that enable its efficient deployment is crucial to its environmental benefits.

The investment in AREs by GCC countries can also help to reduce harmful emissions in this region. In doing so, the investment in natural resources, human resources, and infrastructure offers a novel opportunity for sustainable regional development. Consequently, sustainable regional development is expected to reduce carbon emissions. First, regarding the investment in natural resources, GCC policymakers need to divert some of their hydrocarbon revenue into renewable and clean energy transitions. This is consistent with the broader conditional hypothesis of "resource blessing", in which resource wealth results in better environmental outcomes when strategically reinvested in sustainable and productive assets [120]. This logic is evident in Saudi Arabia's Vision 2030 and the UAE's Net Zero by 2050 Strategic Initiative, which have committed billions in sovereign wealth fund capital to solar, hydrogen, and wind energy infrastructure [121]. Investing resource rents in green energy projects diversifies the economic base and directly reduces the carbon intensity of the energy mix, and therefore economy-wide emissions, in line with GCC commitments under the Paris Agreement [122].

The literature repeatedly indicates that the environmental advantages of technological innovation depend on the presence of trained labor proficient in assimilating and disseminating these innovations [123]. Therefore, investment in human capital is essential for the effective design, deployment, and regulation of FNT-driven environmental solutions in GCC economies. The GCC states should consequently enhance green finance educational initiatives, STEM curricula focused on clean technology, and targeted training in environmental FNT applications, including carbon credit platforms, ESG reporting systems, and AI-driven energy management tools.

Further, the modernization of infrastructure serves as the critical physical foundation that enables financial techniques to yield quantifiable reductions in emissions. Digital infrastructure, comprising smart grid systems, Internet of Things (IoT)-enabled energy monitoring networks, and high-speed broadband, facilitates real-time tracking and management of carbon emissions across the transportation, industrial, and residential sectors [124]. GCC economies must expedite investments in smart city infrastructure, exemplified

by projects like NEOM in Saudi Arabia and Masdar City in Abu Dhabi, which combine digital connection with zero-carbon urban planning [125].

The study is not exempted from limitations that may lead future studies to re-explore the phenomenon to bring new insights into the creation of knowledge. Firstly, due to the limited data availability of FNT proxies, the study is unable to explore the desired time series analysis of the individual GCC economies. Therefore, further investigations into individual country-based cases may bring more interesting results in the future. Secondly, the study only considers a specific region for the investigation based on natural resource abundance; further investigation in countries with fewer natural resources may bring different outcomes. Thirdly, the prospect of reverse causality between GQ, FNT, and environmental performance cannot be completely ruled out, even though FMOLS and DOLS aid in reducing endogeneity related to cointegration linkages. To improve causal identification, future studies might use quasi-experimental or instrumental-variable methods.

6. Conclusions

The objectives of this study were to find a framework which can decrease the level of CO₂ emissions in GCC countries. To highlight such a framework, this study identified GQ, FNT and AREs as important indicators for reduction in CO₂ emissions. The study investigated the role of governance and FNT in curbing carbon CO₂ emissions, with AREs acting as a moderator alongside FNT. The findings of this study revealed an inverse relationship between governance quality and carbon emissions, highlighting the need for strong institutions in addressing environmental challenges. Baloch and Wang [48] tested the Environmental Kuznets Curve hypothesis on panel data from BRICS nations from 1996 to 2017 and showed that governance has a considerable negative impact on CO₂ emissions. Second, the outcomes of this study demonstrate that FNT has a negative impact on carbon emissions in GCC countries. Furthermore, this study found that AREs negatively moderate the association between FNT and carbon emissions. The negative coefficient suggests that countries with superior infrastructure, greater strategic resource capacity, and higher human capital are better able to reduce environmental limitations.

The findings of this study make three distinct contributions. First, GQ is inversely related to CO₂ emissions, underscoring the pivotal role of strong institutions in addressing environmental challenges. Second, FNT development significantly reduces CO₂ emissions in GCC countries, highlighting digital finance as a viable pathway toward environmental sustainability. Third, and most notably, AREs—encompassing infrastructure, strategic resource capacity, and human capital—negatively moderate the FNT–carbon emissions nexus, amplifying the environmental benefits of FNT in resource-rich economies. Collectively, these findings offer actionable policy insights for leveraging institutional quality and digital innovation to achieve sustainable development goals.

Even if the empirical results are strong, there are a few things to be aware of. First, the research is limited to the six GCC member states between 2010 and 2023, which may limit the estimations' statistical strength and their applicability to other economies that rely on natural resources. Second, the relatively small panel structure calls for caution when interpreting parameter stability, even though several estimators and robustness tests were used. To further evaluate the results and improve external validity, future studies might expand the analysis to a wider range of nations and longer time periods.

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Appendix A

Table A1. PCA of governance indicators of GCC countries.

Principal_Component	Eigen_Value	Explained_Variance_Ratio	Cumulative_Variance
PC1 (ARE index)	4.000757143	0.658854847	0.658854847
PC2	1.33872701	0.220464964	0.879319811
PC3	0.358023598	0.058960235	0.938280046
PC4	0.210953938	0.03474043	0.973020477
PC5	0.10461679	0.017228559	0.990249035
PC6	0.059210677	0.009750965	1

Table A2. PCA of FNT of GCC countries.

Component	Eigenvalue	% of Variance Explained	Cumulative % of Variance
PC1 (FNT Index)	1.7734	58.41%	58.41%
PC2	1.0116	33.32%	91.73%
PC3	0.2511	8.27%	100.00%

Table A3. PCA of AREs of GCC countries.

Component	Eigenvalue	% of Variance Explained	Cumulative % of Variance
PC1 (Endowment Index)	1.9671	65.57%	65.57%
PC2	0.8143	27.14%	92.71%
PC3	0.2186	7.29%	100.00%

References

1. Murshed, M.; Khan, I.; Loganathan, N.; Sultana, T.; Mubarak, S. The nexus between environmental regulations, economic growth, and environmental sustainability: Linking environmental patents to ecological footprint reduction in South Asia. *Environ. Sci. Pollut. Res.* **2021**, *28*, 49967–49988.
2. Bello, S.A.; Oyedele, L.O.; Akinade, O.O.; Bilal, M.; Delgado, J.M.D.; Akanbi, L.A.; Ajayi, A.O.; Owolabi, H.A. Cloud computing in construction industry: Use cases, benefits and challenges. *Autom. Constr.* **2021**, *122*, 103441.
3. Hanif, N.; Arshed, N.; Aziz, O. On interaction of the energy: Human capital Kuznets curve? A case for technology innovation. *Environ. Dev. Sustain.* **2020**, *22*, 7559–7586.
4. Calvin, K.; Dasgupta, D.; Krinner, G.; Mukherji, A.; Thorne, P.W.; Trisos, C.; Romero, J.; Aldunce, P.; Barrett, K.; Blanco, G.; et al. IPCC, 2023: *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; IPCC: Geneva, Switzerland, 2023.
5. Jia, Z.; Mehta, A.M.; Qamruzzaman, M.; Ali, M. Relationship between natural resources, economic growth, and carbon emissions: The role of fintech, information technology and corruption to achieve the targets of COP-27. *Resour. Policy* **2024**, *90*, 104751.
6. Kaufmann, D.; Kraay, A.; Mastruzzi, M. The worldwide governance indicators: Methodology and analytical issues. *Hague J. Rule Law* **2011**, *3*, 220–246.
7. Robinson, J.A.; Acemoglu, D. *Why Nations Fail: The Origins of Power, Prosperity and Poverty*; Profile Books: London, UK, 2012.

8. Bättig, M.B.; Bernauer, T. National institutions and global public goods: Are democracies more cooperative in climate change policy? *Int. Organ.* **2009**, *63*, 281–308.
9. Jordan, A.; Huitema, D. Policy innovation in a changing climate: Sources, patterns and effects. *Glob. Environ. Change* **2014**, *29*, 387–394.
10. Halkos, G.E.; Tzeremes, N.G. Carbon dioxide emissions and governance: A nonparametric analysis for the G-20. *Energy Econ.* **2013**, *40*, 110–118.
11. Zhang, Y.-J.; Jin, Y.-L.; Chevallier, J.; Shen, B. The effect of corruption on carbon dioxide emissions in APEC countries: A panel quantile regression analysis. *Technol. Forecast. Soc. Change* **2016**, *112*, 220–227.
12. Gomber, P.; Kauffman, R.J.; Parker, C.; Weber, B.W. On the fintech revolution: Interpreting the forces of innovation, disruption, and transformation in financial services. *J. Manag. Inf. Syst.* **2018**, *35*, 220–265.
13. Setup in Saudi. Saudi Vision 2030: Progress in Fintech. 2024. Available online: <https://www.setupinsaudi.com/en/saudi-vision-2030-progress-in-fintech> (accessed on 1 January 2024).
14. Qatar FinTech Hub. *From Qatar to the World: A Report on the State of FinTech in Qatar (2021)*; Qatar FinTech Hub: Doha, Qatar, 2021.
15. Buchak, G.; Matvos, G.; Piskorski, T.; Seru, A. Fintech, regulatory arbitrage, and the rise of shadow banks. *J. Financ. Econ.* **2018**, *130*, 453–483.
16. Lee, H.; Romero, J. (Eds.) *IPCC, 2023: Climate Change 2023: Synthesis Report, Summary for Policymakers. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; IPCC: Geneva, Switzerland, 2023.
17. Hart, S.L. A natural-resource-based view of the firm. *Acad. Manag. Rev.* **1995**, *20*, 986–1014.
18. Teece, D.J.; Pisano, G.; Shuen, A. Dynamic capabilities and strategic management. *Strateg. Manag. J.* **1997**, *18*, 509–533.
19. Sachs, J.D.; Schmidt-Traub, G.; Mazzucato, M.; Messner, D.; Nakicenovic, N.; Rockström, J. Six transformations to achieve the sustainable development goals. *Nat. Sustain.* **2019**, *2*, 805–814.
20. Bekhet, H.A.; Matar, A.; Yasmin, T. CO₂ emissions, energy consumption, economic growth, and financial development in GCC countries: Dynamic simultaneous equation models. *Renew. Sustain. Energy Rev.* **2017**, *70*, 117–132.
21. Jarallah, S.; Faisal, F.; Tursoy, T.; Pervaiz, A. Examining the impact of ecological deficit on life expectancy in GCC countries: A nonlinear panel data investigation. *Environ. Dev. Sustain.* **2024**, *28*, 1–37. <https://doi.org/10.1007/s10668-024-05265-2>.
22. Bentaleb, D. Digital transformation and ESG performance in emerging-market banks: Asymmetric effects across environmental, social and governance pillars. *Compet. Rev. Int. Bus. J.* **2026**, 1–24. <https://doi.org/10.1108/CR-06-2025-0189>.
23. Philippon, T. *The Fintech Opportunity*; National Bureau of Economic Research: Cambridge, MA, USA, 2016.
24. Demircug-Kunt, A.; Klapper, L.; Singer, D.; Ansar, S.; Hess, J. *The Global Findex Database 2017: Measuring Financial Inclusion and the Fintech Revolution*; World Bank Publications: Washington, DC, USA, 2018.
25. Arner, D.W.; Buckley, R.P.; Zetsche, D.A.; Veidt, R. Sustainability, FinTech and financial inclusion. *Eur. Bus. Organ. Law Rev.* **2020**, *21*, 7–35.
26. Asiaei, K.; Bontis, N.; Alizadeh, R.; Yaghoubi, M. Green intellectual capital and environmental management accounting: Natural resource orchestration in favor of environmental performance. *Bus. Strategy Environ.* **2022**, *31*, 76–93.
27. Liu, L.; Huang, C.; Yu, F.; Failler, P. Exploring resource blessing hypothesis within the coffin of technological innovation and economic risk: Evidence from wavelet quantile regression. *Energy Econ.* **2024**, *137*, 107802.
28. Ahmad, M.; Pata, U.K.; Ahmed, Z.; Zhao, R. Fintech, natural resources management, green energy transition, and ecological footprint: Empirical insights from EU countries. *Resour. Policy* **2024**, *92*, 104972.
29. Khan, A.J.; Fatima, H.; Saleem, M.; Nawaz, K. Greening for greater good: Investigating the critical factors for customer satisfaction with sustainable e-banking. *Environ. Sci. Pollut. Res.* **2024**, *31*, 46255–46265.
30. Samimi, A.J.; Ahmadpour, M.; Ghaderi, S. Governance and environmental degradation in MENA region. *Procedia Soc. Behav. Sci.* **2012**, *62*, 503–507.
31. North, D.C. *Institutions, Institutional Change and Economic Performance*; Cambridge University Press: Cambridge, UK, 1990.
32. Marošević, K.; Jurković, Z. Impact of informal institutions on economic growth and development. *Interdiscip. Manag. Res.* **2013**, *9*, 701.
33. Abdala, M.A. Governance of competitive transmission investment in weak institutional systems. *Energy Econ.* **2008**, *30*, 1306–1320.
34. Goel, R.K.; Herrala, R.; Mazhar, U. Institutional quality and environmental pollution: MENA countries versus the rest of the world. *Econ. Syst.* **2013**, *37*, 508–521.
35. Ang, G.; Marchal, V. *Mobilising Private Investment in Sustainable Transport*; OECD: Paris, France, 2013.

36. Hassan, S.T.; Khan, S.U.-D.; Xia, E.; Fatima, H. Role of institutions in correcting environmental pollution: An empirical investigation. *Sustain. Cities Soc.* **2020**, *53*, 101901.
37. Fredriksson, P.G.; Neumayer, E. Corruption and climate change policies: Do the bad old days matter? *Environ. Resour. Econ.* **2016**, *63*, 451–469.
38. La Porta, R.; Lopez-de-Silanes, F.; Shleifer, A. The economic consequences of legal origins. *J. Econ. Lit.* **2008**, *46*, 285–332.
39. Leita, A. Corruption and the environment. *J. Socialomics* **2016**, *5*, 1000173.
40. Fredriksson, P.G.; Neumayer, E. Democracy and climate change policies: Is history important? *Ecol. Econ.* **2013**, *95*, 11–19.
41. Wang, Z.; Zhang, B.; Wang, B. The moderating role of corruption between economic growth and CO₂ emissions: Evidence from BRICS economies. *Energy* **2018**, *148*, 506–513.
42. Hosseini, H.M.; Kaneko, S. Can environmental quality spread through institutions? *Energy Policy* **2013**, *56*, 312–321.
43. Ferrero-Ferrero, I.; Fernández-Izquierdo, M.Á.; Muñoz-Torres, M.J. The effect of environmental, social and governance consistency on economic results. *Sustainability* **2016**, *8*, 1005.
44. Baloch, M.A.; Wang, B. Analyzing the role of governance in CO₂ emissions mitigation: The BRICS experience. *Struct. Change Econ. Dyn.* **2019**, *51*, 119–125.
45. van Soest, D.; Stoop, J.; Vyrastekova, J. Toward a delineation of the circumstances in which cooperation can be sustained in environmental and resource problems. *J. Environ. Econ. Manag.* **2016**, *77*, 1–13.
46. Güney, T. Solar energy, governance and CO₂ emissions. *Renew. Energy* **2022**, *184*, 791–798.
47. Yu, G.; Qi, Y.; Ren, Y. FinTech adoption and farmers' wealth distribution: Evidence from a large micro-data in China. *Finance Res. Lett.* **2025**, *72*, 106621.
48. Tanveer, M. FinTech-enabled digital transformation for sustainable performance: The strategic role of dynamic capabilities. *Front. Hum. Dyn.* **2026**, *8*, 1747642.
49. Barney, J. Firm resources and sustained competitive advantage. *J. Manag.* **1991**, *17*, 99–120.
50. Kornelius, H.; Supratikno, H.; Bernarto, I.; Widjaja, A.W. Strategic planning and firm performance: The mediating role of strategic maneuverability. *J. Asian Finance Econ. Bus.* **2021**, *8*, 479–486.
51. Wernerfelt, B. A resource-based view of the firm. *Strateg. Manag. J.* **1984**, *5*, 171–180.
52. Peteraf, M.A. The cornerstones of competitive advantage: A resource-based view. *Strateg. Manag. J.* **1993**, *14*, 179–191.
53. Zhou, F.; Chen, Y.; Wen, H. FinTech and innovation: The path to upgrading regional carbon-intensive industries in China. *Emerg. Mark. Financ. Trade* **2025**, *61*, 4808–4825.
54. Wang, J.; Zhu, G.; Chang, T.-C. Unveiling the relationship between institutional quality, fintech, financial inclusion, human capital development and mineral resource abundance: An Asian perspective. *Resour. Policy* **2024**, *89*, 104521.
55. Shan, H.; Khan, Y.; Ullah, A.; Khattak, S.I.; Ahmad, M. Fintech innovation for sustainable environment: Understanding the role of natural resources and human capital in BRICS using MMQR. *Resour. Policy* **2024**, *88*, 104468.
56. Bibri, S.E. The IoT for smart sustainable cities of the future: An analytical framework for sensor-based big data applications for environmental sustainability. *Sustain. Cities Soc.* **2018**, *38*, 230–253.
57. Wade, M.; Hulland, J. The resource-based view and information systems research: Review, extension, and suggestions for future research. *MIS Q.* **2004**, *28*, 107–142.
58. Brynjolfsson, E.; Hitt, L.M. Beyond computation: Information technology, organizational transformation and business performance. *J. Econ. Perspect.* **2000**, *14*, 23–48.
59. Bharadwaj, A.S. A resource-based perspective on information technology capability and firm performance: An empirical investigation. *MIS Q.* **2000**, *24*, 169–196.
60. Mata, F.J.; Fuerst, W.L.; Barney, J.B. Information technology and sustained competitive advantage: A resource-based analysis. *MIS Q.* **1995**, *19*, 487–505.
61. Powell, T.C.; Dent-Micallef, A. Information technology as competitive advantage: The role of human, business, and technology resources. *Strateg. Manag. J.* **1997**, *18*, 375–405.
62. Christmann, P. Effects of “best practices” of environmental management on cost advantage: The role of complementary assets. *Acad. Manag. J.* **2000**, *43*, 663–680.
63. Flammer, C. Corporate green bonds. *J. Financ. Econ.* **2021**, *142*, 499–516.
64. Meo, M.S.; Ademokoya, A.A.; Abubakar, A.B. Energy-related uncertainty, financial regulations, and environmental sustainability in the United States. *Clean Technol. Environ. Policy* **2025**, *27*, 2269–2288.
65. Cumming, D.J.; Leboeuf, G.; Schwienbacher, A. Crowdfunding models: Keep-it-all vs. all-or-nothing. *Financ. Manag.* **2020**, *49*, 331–360.

66. Berger, A.N. The economic effects of technological progress: Evidence from the banking industry. *J. Money Credit Bank.* **2003**, *35*, 141–176.
67. King, B. *Bank 3.0: Why Banking Is No Longer Somewhere You Go but Something You Do*; John Wiley & Sons: Hoboken, NJ, USA, 2012.
68. Malhotra, P.; Singh, B. The impact of internet banking on bank performance and risk: The Indian experience. *Eurasian J. Bus. Econ.* **2009**, *2*, 43–62.
69. Goldstein, I.; Jiang, W.; Karolyi, G.A. To FinTech and beyond. *Rev. Financ. Stud.* **2019**, *32*, 1647–1661.
70. Levine, R. Finance and growth: Theory and evidence. In *Handbook of Economic Growth*; Aghion, P., Durlauf, S., Eds.; Elsevier: Amsterdam, The Netherlands, 2005; pp. 865–934.
71. Delmas, M.; Blass, V.D. Measuring corporate environmental performance: The trade-offs of sustainability ratings. *Bus. Strategy Environ.* **2010**, *19*, 245–260.
72. Gelb, A.H. *Oil Windfalls: Blessing or Curse?* Oxford University Press: Oxford, UK, 1988.
73. Sachs, J.D.; Warner, A. *Natural Resource Abundance and Economic Growth*; National Bureau of Economic Research: Cambridge, MA, USA, 1995.
74. Tadadjeu, S.; Ningaye, P.; Njangang, H. Are natural resources also bad for infrastructure quality? *J. Int. Dev.* **2023**, *35*, 1053–1079.
75. Zafar, M.W.; Zaidi, S.A.H.; Khan, N.R.; Mirza, F.M.; Hou, F.; Kirmani, S.A.A. The impact of natural resources, human capital, and foreign direct investment on the ecological footprint: The case of the United States. *Resour. Policy* **2019**, *63*, 101428.
76. Ahmadov, A.K.; Van Der Borg, C. Do natural resources impede renewable energy production in the EU? A mixed-methods analysis. *Energy Policy* **2019**, *126*, 361–369.
77. Luthra, S.; Mangla, S.K.; Sarkis, J.; Tseng, M.-L. Resources melioration and the circular economy: Sustainability potentials for mineral, mining and extraction sector in emerging economies. *Resour. Policy* **2022**, *77*, 102652.
78. Okere, K.I.; Dimnwobi, S.K.; Fasanya, I.O.; Umeajaghaku, O.L. Advancing environmental sustainability through fintech, structural transformation, and resource diversification in emerging economies. *Environ. Sci. Eur.* **2025**, *37*, 197.
79. Lucas, R.E. On the mechanics of economic development. *J. Monet. Econ.* **1988**, *22*, 3–42.
80. Barro, R.J. Human capital and growth. *Am. Econ. Rev.* **2001**, *91*, 12–17.
81. Romer, P.M. Endogenous technological change. *J. Polit. Econ.* **1990**, *98*, S71–S102.
82. Barney, J.B. Resource-based theories of competitive advantage: A ten-year retrospective on the resource-based view. *J. Manag.* **2001**, *27*, 643–650.
83. Wright, P.M.; McMahan, G.C. Theoretical perspectives for strategic human resource management. *J. Manag.* **1992**, *18*, 295–320.
84. Imtiaz, M.; Awan, M.E.A.; Fatima, N. Innovation and human capital as drivers of global FinTech development: Evidence from 217 countries using system GMM. *Soc. Sci. Rev. Arch.* **2025**, *3*, 1924–1941.
85. Aschauer, D.A. Public investment and productivity growth in the Group of Seven. *Econ. Perspect.* **1989**, *13*, 17–25.
86. Du, X.; Fang, S. Smart finance, skilled workers: The role of labor force in FinTech-driven economic growth. *Financ. Res. Lett.* **2025**, *88*, 109103.
87. Dai, L.; Li, X.; Ullah, S.; Ahmad, M. The integration of green finance and logistics: Implications for green industry transformation. *Front. Environ. Sci.* **2025**, *13*, 1556580.
88. Röller, L.-H.; Waverman, L. Telecommunications infrastructure and economic development: A simultaneous approach. *Am. Econ. Rev.* **2001**, *91*, 909–923.
89. Levine, R. Financial development and economic growth: Views and agenda. *J. Econ. Lit.* **1997**, *35*, 688–726.
90. Worighi, I.; Maach, A.; Hafid, A.; Kotb, M.; Eltoum, M.A. Integrating renewable energy in smart grid system: Architecture, virtualization and analysis. *Sustain. Energy Grids Netw.* **2019**, *18*, 100226.
91. Davradakis, E.; Santos, R. *Blockchain, FinTechs and Their Relevance for International Financial Institutions*; EIB Working Papers; European Investment Bank: Luxembourg, 2019.
92. Romanova, I.; Grima, S.; Spiteri, J.; Kudinska, M. The payment services Directive II and competitiveness: The perspective of European fintech companies. *Eur. Res. Stud.* **2018**, *21*, 3–22.
93. Milgrom, P.; Roberts, J. Complementarities and fit strategy, structure, and organizational change in manufacturing. *J. Account. Econ.* **1995**, *19*, 179–208.
94. Teece, D.J. Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy. *Res. Policy* **1986**, *15*, 285–305.
95. Christensen, C.M. *The Innovator's Dilemma*; Harvard Business School Press: Boston, MA, USA, 1997.

96. Feng, X.; Zhou, D.; Hussain, T. An investigation of fintech governance, natural resources and government stability on sustainability: Policy suggestions under the SDGs theme. *Resour. Policy* **2024**, *96*, 105184.
97. Wang, H.; Li, Y.; Han, B.; Liang, Y. Application of feed-splitting in extractive distillation in the separation of the CO₂-C₂H₆ azeotrope for recovering light hydrocarbon. *Energy Sources Part A Recover. Util. Environ. Eff.* **2024**, *46*, 14687–14698.
98. Zheng, C.; Rahman, M.A.; Hossain, S.; Siddik, M.N.A. Construction of a composite fintech index to measure financial inclusion for developing countries. *Appl. Econ.* **2024**, *56*, 6498–6515.
99. Lewis, T.L. Globalizing the treadmill of production: A solutions-oriented application to Ecuador. *Environ. Sociol.* **2019**, *5*, 219–231.
100. Nassani, A.A.; Aldakhil, A.M.; Qazi Abro, M.M.; Islam, T.; Zaman, K. Financial integration and economic growth: Impact of renewable energy investments, technology transfer, and climate change on Europe and central Asian economies. *Financ. Innov.* **2025**, *11*, 41.
101. Yuan, F.; Zhang, P. Are natural resources, sustainable growth and entrepreneurship matter endogenous growth theory? The strategic role of technical progress. *Resour. Policy* **2024**, *96*, 105189.
102. Abbas, J.; Najam, H. Role of environmental decentralization, green human capital, and digital finance in firm green technological innovation for a sustainable society. *Environ. Dev. Sustain.* **2025**, *27*, 19763–19777.
103. Siddik, A.B.; Rahman, M.N.; Yong, L. Do fintech adoption and financial literacy improve corporate sustainability performance? The mediating role of access to finance. *J. Clean. Prod.* **2023**, *421*, 137658.
104. Chandra, R. Paul Romer and modern endogenous growth theory. In *Endogenous Growth in Historical Perspective: From Adam Smith to Paul Romer*; Springer: Berlin/Heidelberg, Germany, 2021; pp. 251–281.
105. Ortega-Ruiz, G.; Mena-Nieto, A.; García-Ramos, J.E. Is India on the right pathway to reduce CO₂ emissions? Decomposing an enlarged Kaya identity using the LMDI method for the period 1990–2016. *Sci. Total Environ.* **2020**, *737*, 139638.
106. Liang, C.; Liu, Z.; Geng, Z. Assessing e-commerce impacts on China's CO₂ emissions: Testing the CKC hypothesis. *Environ. Sci. Pollut. Res.* **2021**, *28*, 56966–56983.
107. Dagar, V.; Khan, M.K.; Liaqat, I.; Shah, S.Q.A.; Rizvi, S.K.A.; Alam, M.S.; Bhutta, M.S.; Oláh, J. Testing the pollution haven hypothesis with the role of foreign direct investments and total energy consumption. *Energies* **2022**, *15*, 4046.
108. Westerlund, J.; Hosseinkouchack, M.; Solberger, M. The local power of the CADF and CIPS panel unit root tests. *Econom. Rev.* **2016**, *35*, 845–870.
109. Abumunshar, M.; Aga, M.; Samour, A. Oil price, energy consumption, and CO₂ emissions in Turkey: New evidence from a Bootstrap ARDL test. *Energies* **2020**, *13*, 5588.
110. Zhang, S.; Anser, M.K.; Peng, M.Y.-P.; Chen, C. Visualizing the sustainable development goals and natural resource utilization for green economic recovery after COVID-19 pandemic. *Resour. Policy* **2023**, *80*, 103182.
111. Alamgir, F.; Amin, S.B. The nexus between oil price and stock market: Evidence from South Asia. *Energy Rep.* **2021**, *7*, 693–703.
112. Syed, Q.R.; Bouri, E.; Zafar, R.F.; Adekoya, O.B. Does geopolitical risk mitigate inbound tourism? Evidence from panel quantile regression. *J. Public Aff.* **2022**, *22*, e2784.
113. Musibau, H.O.; Adedoyin, F.F.; Shittu, W.O. A quantile analysis of energy efficiency, green investment, and energy innovation in most industrialized nations. *Environ. Sci. Pollut. Res.* **2021**, *28*, 19473–19484.
114. Shan, C.; Ji, X. Environmental regulation and green technology innovation: An analysis of the government subsidy policy's role in driving corporate green transformation. *Ind. Eng. Innov. Manag.* **2024**, *7*, 39–46.
115. Cole, M.A. Corruption, income and the environment: An empirical analysis. *Ecol. Econ.* **2007**, *62*, 637–647.
116. Pellegrini, L.; Gerlagh, R. Corruption, democracy, and environmental policy: An empirical contribution to the debate. *J. Environ. Dev.* **2006**, *15*, 332–354.
117. Udeagha, M.C.; Muchapondwa, E. Green finance, fintech, and environmental sustainability: Fresh policy insights from the BRICS nations. *Int. J. Sustain. Dev. World Ecol.* **2023**, *30*, 633–649.
118. Wen, H.; Liu, Y. Can fintech lead to the collaborative reduction in pollution discharges and carbon emissions? *Sustainability* **2023**, *15*, 11627.
119. Ozili, P.K. Financial inclusion and Fintech during COVID-19 crisis: Policy solutions. *Co. Lawyer J.* **2020**, *8*. <https://doi.org/10.2139/ssrn.3585662>.
120. Mehlum, H.; Moene, K.; Torvik, R. Institutions and the resource curse. *Econ. J.* **2006**, *116*, 1–20.
121. Al-Sarihi, A.; Mansouri, N. Renewable energy development in the Gulf cooperation council countries: Status, barriers, and policy options. *Energies* **2022**, *15*, 1923.

122. UNFCCC. The Paris Agreement. In Proceedings of the 21st Conference of the Parties, Paris, France, 30 November–12 December 2015; United Nations Framework Convention on Climate Change: Bonn, Germany, 2015.
123. Acemoglu, D.; Aghion, P.; Bursztyn, L.; Hémous, D. The environment and directed technical change. *Am. Econ. Rev.* **2012**, *102*, 131–166.
124. Wojtaszek, H. Energy transition 2024–2025: New demand vectors, technology oversupply, and shrinking net-zero 2050 premium. *Energies* **2025**, *18*, 4441.
125. Sumra, K.B.; Siddique, H.; Afzal, S.; Qazi, A. Sustainable smart cities: Promotion of circular economy in urban GCC regions. *J. Sci. Technol. Policy Manag.* **2026**, *17*, 60–99.

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