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Balancing Economic Growth and Environmental Sustainability in Developing Countries: The Role of Financial Innovation

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Abstract

Many developing economies continue to grapple with significant environmental degradation, even after experiencing remarkable economic growth in recent decades. Rapid industrialization, urbanization, and increased energy consumption have driven impressive economic progress but often at the expense of environmental sustainability. The overreliance on fossil fuels, deforestation, and unregulated industrial activities have contributed to air and water pollution, loss of biodiversity, and increased greenhouse gas emissions. This study aims to examine the impact of green finance, digital finance, and natural resources on carbon dioxide emissions for a panel of 23 developing countries over the period 2010–2023. The focus on green finance explores its potential to channel investments into environmentally friendly projects, thereby reducing emissions and promoting sustainable development. Digital finance is analyzed for its role in enhancing efficiency, improving access to financial services, and fostering innovative solutions to environmental challenges. The inclusion of natural resources considers their dual role as contributors to economic growth and, if mismanaged, drivers of environmental degradation. By assessing these factors, the study seeks to provide insights into the dynamics between financial innovation, resource management, and environmental sustainability. The findings will help policymakers and stakeholders in developing countries design targeted strategies that balance economic development with the urgent need to mitigate CO2 emissions and achieve sustainable growth. The causality test findings reveal that green finance, digital finance, and natural resources do not Granger-cause CO2 emissions, indicating no direct causal relationship in this context. However, the analysis highlights that natural resources and digital finance significantly contribute to improving environmental quality. These results underscore the potential of these factors to play a constructive role in achieving environmental sustainability when managed effectively. Based on these findings, the study recommends policies aimed at the efficient utilization of natural resources. This includes adopting sustainable resource management practices that minimize environmental degradation while maximizing economic benefits. Policymakers should focus on enhancing resource efficiency and promoting renewable resource alternatives to reduce the environmental footprint of resource-dependent sectors. For digital finance, the study emphasizes its potential to support environmental sustainability through increased financial inclusion, improved resource allocation, and the facilitation of green investments. Strategies should include incentivizing digital platforms that promote eco-friendly financial products and leveraging digital technologies to monitor and manage environmental impacts effectively.

Keywords: Green Finance, Digital Finance, CO2 Emissions, Natural Resources, Sustainability

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1. INTRODUCTION

The accelerated pace of global climate change in recent decades has led to profound social and economic repercussions for countries worldwide. According to the International Panel on Climate Change, greenhouse gas emissions, particularly CO2 emissions resulting from human activities, have been major contributors to severe environmental issues (Audi & Ali, 2023; Audi & Ali, 2018; Audi et al., 2024; Ali et al., 2023; Wang & Li, 2024; Abbas et al., 2024). These include rising atmospheric temperatures and global warming, which pose significant challenges to human well-being (Cong et al., 2020; Le Quéré et al., 2019). The adverse impacts of climate change are felt across multiple domains, from biodiversity loss to increased frequency of natural disasters, threatening both current and future generations. International efforts, such as those under the Paris Agreement and the Conference of Parties (COP26), have sought to address these critical challenges by advocating for urgent action and promoting the transition to a net-zero economy. These initiatives underscore the global consensus on the need to mitigate climate change by reducing carbon emissions and adopting sustainable practices. Both developing and developed countries are intensifying their efforts to tackle environmental challenges, with many implementing policies aimed at achieving carbon neutrality (Qin et al., 2021; Shahbaz et al., 2016; Wang & Li, 2024; Abbas et al., 2024). Despite these

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efforts, significant gaps remain in meeting global climate goals. Developing countries, in particular, face the dual challenge of fostering economic growth while addressing environmental degradation. This necessitates robust international cooperation, innovative technologies, and substantial investments in renewable energy and sustainable development practices to ensure an equitable and effective response to climate change (Gorus & Groeneveld, 2018; Khan & Hassan, 2019; Rossi, 2023; Desiree, 2019; Bakht, 2020; Kibritcioglu, 2023; Hussain & Khan, 2022; Emodi, 2019; Iqbal & Noor, 2023; Senturk, 2023). Developing countries face numerous challenges stemming from environmental degradation and pollution, including health crises, unemployment, poverty, and low income. These issues are often exacerbated by their persistent efforts to achieve higher levels of economic growth. The expansion of industrial production and manufacturing processes, which demand substantial energy consumption, has significantly contributed to increased CO2 emissions (Sadiq et al., 2022). In these economies, the prioritization of economic growth often comes at the expense of environmental sustainability and the depletion of natural resources (NTR) (Usman & Radulescu, 2022; Gorus & Groeneveld, 2018; Khan & Hassan, 2019; Rossi, 2023; Desiree, 2019; Bakht, 2020; Kibritcioglu, 2023; Hussain & Khan, 2022).

Among the various factors contributing to environmental problems, the exploitation of NTR is particularly prominent. NTR, encompassing biotic and abiotic materials such as soil, land, minerals, fossil fuels, and water, are undeniably vital for economic growth. Their availability supports stable living standards and strengthens the financial framework of an economy (Nawaz et al., 2019). However, their intensive use also leads to increased energy consumption and waste disposal, resulting in severe environmental consequences. For instance, the extraction and utilization of NTR contribute to the contamination of soil, air, and water, alongside the accelerated depletion of these essential resources (Hanif et al., 2022). Over the past decades, the depletion of NTR has escalated alarmingly. Fossil fuel extraction increased from 6 to 15 billion tons, while biomass consumption rose from 8 to 24 billion tons. Rapid economic expansion has driven this depletion, creating profound environmental challenges (Senturk, 2023; Zaheer & Nasir, 2020; Habibullah, 2020; Mahmood, 2019; Ali & Audi, 2016; Ali et al., 2021; Ali et al., 2021; Audi & Ali, 2017; Ali et al., 2022; Audi & Ali, 2023; Audi & Ali, 2018; Audi et al., 2024; Jahanger et al., 2023). The extraction of NTR, in particular, is an energy-intensive process that generates substantial greenhouse gas (GHG) emissions. Industries involved in NTR extraction are responsible for approximately half of global CO2 emissions and account for a staggering 90% loss of biodiversity (Hussain et al., 2020). These alarming statistics underscore the urgent need for sustainable resource management and innovative strategies to balance economic growth with environmental preservation. Achieving carbon neutrality by 2060 necessitates a swift and comprehensive economic transformation and restructuring to foster a low-carbon economy. A cornerstone of this transformation is the adoption of green finance (GF), a crucial mechanism for addressing severe environmental degradation and promoting sustainable development. GF encompasses economic activities that support environmental conservation, combat climate change, and enhance resource efficiency. It has emerged as a vital tool for achieving environmental sustainability by channeling investments into projects that reduce environmental and climate risks (Senturk, 2023; Zaheer & Nasir, 2020; Habibullah, 2020; Mahmood, 2019; Ali & Audi, 2016; Ali et al., 2021; Ali et al., 2021; Audi & Ali, 2017; Ali et al., 2022; Audi & Ali, 2023; Audi & Ali, 2018; Audi et al., 2024; Nawaz et al., 2021).

Unlike traditional financing approaches, GF emphasizes resource efficiency and sustainability, making it a key driver in the transition to a greener economy (Tariq & Hassan, 2023). It includes a range of financial services designed for project financing, investment, operational support, and risk management across various sectors such as energy conservation, clean energy, green transportation, green buildings, and environmental sustainability (Zhang, 2023). By leveraging financial instruments such as green bonds, green credits, carbon finance, and green insurance, GF directs capital towards low-carbon industries and projects, serving as a catalyst for reducing pollution and improving energy efficiency. Moreover, GF plays a critical role in helping society address the challenges posed by climate change. It supports the transition to an environmentally sustainable economic model by providing the financial infrastructure needed to fund innovation and green initiatives. GF not only reduces emissions but also mitigates the risks associated with climate change, making it an essential component of modern economic policy (Wu et al., 2024). Its ability to balance environmental objectives with economic growth makes GF a powerful tool for improving environmental quality while fostering economic resilience. In summary, an effective GF policy can achieve the dual goals of greening the economy and sustaining growth, bridging the gap between environmental sustainability and economic development (Khan et al., 2022; Senturk, 2023; Zaheer & Nasir, 2020; Habibullah, 2020; Mahmood, 2019; Ali & Audi, 2016; Ali et al., 2021; Ali et al., 2021).

The advent of Industry 4.0 has introduced transformative technologies such as big data, blockchain, and artificial intelligence into the industrial landscape, significantly boosting both economic growth and the quality of life. Within this context, digital finance (DF) has emerged as a key enabler of a modern economic system, playing a critical role in supporting and advancing these technological innovations (Aziz & Naima, 2021; Mpofu, 2024). DF has substantially expanded financial inclusion, reduced costs, and enhanced the efficiency of financial services, making it an essential driver of economic progress. Digital finance contributes to the efficacy of green investments by facilitating access to capital, reducing financial constraints, and promoting research and development (R&D). These advancements not only improve industrial structures but also encourage innovation and technological progress. DF also enhances regional agricultural productivity, increases openness to global markets, and fosters regional integration, thereby driving high-quality and sustainable growth (Xie & Liu, 2022). Furthermore, DF supports an eco-friendly and stable future by streamlining transactions, increasing transparency in financial operations, and optimizing resource allocation. Its ability to facilitate smooth and efficient financial processes helps create a more balanced and environmentally conscious economy (Schulz & Feist, 2021). By enabling seamless integration of modern technologies and financial tools, DF not only strengthens economic frameworks but also contributes to long-term sustainability and resilience in the face of global challenges (Gorus & Groeneveld, 2018; Khan & Hassan, 2019; Rossi, 2023; Desiree, 2019; Bakht, 2020; Kibritcioglu, 2023; Hussain & Khan, 2022; Emodi, 2019; Iqbal & Noor, 2023; Senturk, 2023; Zaheer & Nasir, 2020; Habibullah, 2020; Mahmood, 2019; Ali & Audi, 2016; Ali et al., 2021; Ali et al., 2021; Audi & Ali, 2017; Ali et al., 2022; Audi & Ali, 2023; Audi & Ali, 2018; Audi et al., 2024; Ali et al., 2023; Shahbaz et al., 2016; Wang & Li, 2024; Abbas et al., 2024).

Recently, there has been a growing interest among researchers in exploring the relationship between digital finance (DF) and CO2 emissions (Wu et al., 2022). The findings in this area, however, have been mixed, with studies presenting varied conclusions. Despite the divergence, a significant number of studies suggest that advancements in DF have the potential to successfully reduce CO2 emissions (Razzaq & Yang, 2023). For instance, Razzaq and Yang (2023) highlighted that DF has played a pivotal role in promoting green growth in China by facilitating environmentally sustainable economic practices. Similarly, Tian et al. (2022) emphasized that innovations in financial technologies are transforming traditional financial services, creating a series of chain reactions that positively influence environmental sustainability. These innovations streamline processes, enhance transparency, and optimize resource allocation, thereby supporting efforts to mitigate environmental challenges. The advancements in DF, particularly its integration with green finance, have demonstrated significant potential to foster eco-friendly initiatives and lower carbon emissions. As more studies investigate this relationship, a clearer understanding of the mechanisms through which DF influences environmental outcomes can provide actionable insights for policymakers aiming to balance technological progress with sustainability goals. In contrast, Zhang et al. (2024) highlighted the existence of heterogeneity in the role of digital finance (DF) on green innovations, which has a significant effect on CO2 emissions. This heterogeneity indicates that the impact of DF varies across different contexts, sectors, and regions, leading to mixed conclusions in the literature. While some studies assert that DF has an inhibitory effect on CO2 emissions by promoting resource efficiency and supporting green investments, others suggest that DF may inadvertently contribute to increased emissions (Song et al., 2023). These contradictory findings may stem from variations in the adoption and implementation of DF, differences in regulatory frameworks, and the nature of the industries analyzed. For instance, while DF can drive green innovations and enable sustainable practices in certain contexts, it may also facilitate higher energy consumption and carbon-intensive activities in others. The dual potential of DF underscores the importance of context-specific analyses to fully understand its role in CO2 emissions. This divergence in findings emphasizes the need for further research to explore the conditions under which DF promotes environmental sustainability versus scenarios where it may lead to unintended increases in carbon emissions. Such insights are essential for designing tailored policies and strategies that harness the benefits of DF while mitigating its potential drawbacks in the quest for sustainability.

2. LITERATURE REVIEW

Today, pollution caused by waste materials and harmful emissions poses significant threats to environmental quality (EQ), which, in turn, can have profound impacts on economic growth (Arslan et al., 2022). A strong connection exists between natural resources (NTR) and their influence on EQ, making this relationship a critical area of research. Numerous studies have explored the impact of NTR on EQ, with findings varying across regions and methodologies. Some researchers view NTR as a blessing for improving EQ. For instance, Baloch et al. (2019) investigated the effect of NTR on EQ in BRICS countries using the Augmented Mean Group (AMG) estimation approach. Their findings indicated that NTR positively influenced EQ in some BRICS countries, while having a negative impact in others, suggesting the relationship is highly context-dependent. Similarly, the study by Balsalobre-Lorente et al. (2018) on EU-5 countries supports this dual perspective. Using the Panel Ordinary Least Squares approach, the authors examined the relationship between NTR and CO2 emissions and found that NTR had a negative impact on CO2 emissions in selected economies, indicating a potential improvement in EQ. These findings highlight the complex and heterogeneous nature of the NTR-EQ relationship. While NTR can contribute positively to EQ by enabling resource-driven improvements in environmental management, they can also exacerbate pollution and resource depletion if not managed sustainably. This underscores the need for region-specific strategies and sustainable practices in natural resource utilization to balance economic growth with environmental preservation. Further research is essential to understand the underlying mechanisms and to develop policies that maximize the benefits of NTR while mitigating their negative impacts on EQ.

Similarly, in the case of ASEAN countries, Shah et al. (2023) investigated the impact of natural resources (NTR) on CO2 emissions using the Augmented Mean Group (AMG) and Common Correlated Effects Mean Group (CCEMG) approaches. Their findings indicated that NTR contributed to reducing CO2 emissions in these countries. Tufail et al. (2021), using the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) approach, also found that NTR had a negative impact on CO2 emissions. Moreover, Khan and Hassan (2024) analyzed the relationship between NTR and CO2 emissions across 141 developing countries using the Method of Moments Quantile Regression (MMQR) approach. Their results confirmed that NTR reduced CO2 emissions across various quantiles, suggesting a consistent pattern of environmental benefits from NTR when managed effectively. Conversely, other researchers argue that NTR is culpable for environmental degradation. For instance, Ulucak et al. (2020) explored the role of NTR in CO2 emissions, carbon footprints, and ecological footprints in OECD countries. Using the AMG estimation approach, they found that NTR had a positive impact on CO2 emissions, while its effect on carbon and ecological footprints was insignificant. Similarly, Khan et al. (2020) examined the role of NTR in CO2 emissions in Belt and Road Initiative (BRI) countries. Applying Difference and System Generalized Method of Moments (GMM) approaches, they concluded that NTR promoted CO2 emissions. In Saudi Arabia, Agboola et al. (2021) used the Toda and Yamamoto estimation approach to study the relationship between NTR and CO2 emissions. Their findings revealed that NTR significantly increased CO2 emissions. These contrasting results reflect the dual nature of NTR's impact on environmental outcomes. While some studies highlight the potential of NTR to reduce CO2 emissions when utilized sustainably, others underscore their role in exacerbating environmental degradation. The variations in findings can be attributed to differences in resource management practices, industrial structures, and the regulatory frameworks of the regions studied. This underscores the need for context-specific strategies to optimize the use of NTR while minimizing their adverse environmental impacts. Sustainable management of NTR is essential to reconcile economic growth with environmental sustainability.

Recent studies suggest that green finance (GF) has the potential to improve environmental quality (EQ) by reducing CO2 emissions and supporting environmental laws. Despite the growing prominence of GF, empirical investigations into its impacts on EQ remain limited (Khan et al., 2022). For example, Bakry et al. (2023) analyzed a panel of 76 developing countries using the Panel Vector Error Correction Model (VECM) approach. Their findings revealed that GF mitigates CO2 emissions in the selected countries. Similarly, Meo and Abd Karim (2022) examined the effects of GF on CO2 emissions in leading GF-supporting countries. Employing the Quantile-on-Quantile regression approach, they observed that GF reduced CO2 emissions across different quantiles. In the context of Asian countries, Khan et al. (2022) explored the impact of GF on ecological footprints using a Fixed Effects model. Their results indicated that GF significantly reduced ecological footprints, demonstrating its positive role in environmental sustainability. Tariq and Hassan (2023) further investigated the role of GF in reducing CO2 emissions under the moderating effect of environmental regulations, using data from 70 countries. Their GMM estimation results showed that GF enhanced EQ by reducing CO2 emissions, particularly under the influence of supportive environmental regulations. Sharif et al. (2022) focused on the G-7 countries and used the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) approach. Their analysis found that GF negatively affected CO2 emissions, contributing to improved EQ. Similarly, Wang and Ma (2022a) analyzed provincial data from China and observed that GF reduced CO2 emissions, highlighting its regional effectiveness. In the case of ASEAN countries, Dinh et al. (2022) used the CS-ARDL estimation method and concluded that GF played a critical role in reducing CO2 emissions. Fu and Irfan (2022) also studied ASEAN countries, employing the Fully Modified Ordinary Least Squares (FMOLS) approach. Their findings revealed that GF positively influenced environmental sustainability and negatively affected CO2 emissions. These studies underscore the transformative potential of GF in mitigating CO2 emissions and promoting EQ across different regions and contexts. While the results consistently highlight the positive impact of GF, they also emphasize the need for effective environmental regulations and supportive policies to maximize its benefits. As GF continues to gain traction, its integration into broader sustainability frameworks will be crucial for addressing global environmental challenges. The continuous advancement in digital technology has significantly transformed financial markets, particularly in how individuals engage in financial transactions. Digital finance (DF) has emerged as a key driver of financial and economic development (Su et al., 2021). By integrating internet-based financial services such as online payments, mobile banking, credit lines, and e-commerce, DF has streamlined financial processes and boosted economic activities (Jiang et al., 2021). Arjunwadkar (2018) highlighted that DF has substantially reduced financial costs through innovative technologies like cloud computing, enhancing accessibility to financial services for a broader population. Furthermore, banks have benefited from DF by reducing paperwork, managing long queues through digital platforms, and offering convenient mobile banking services for daily transactions.

From an economic perspective, DF has also played a crucial role in fostering entrepreneurship. Jiang et al. (2021) found that DF has directly contributed to economic growth in China by providing innovative financial solutions that empower entrepreneurs and drive business development. The ability of DF to integrate advanced technologies into financial systems has created opportunities for businesses and individuals alike, significantly influencing economic progress. In terms of environmental impact, DF has shown promise in reducing CO2 emissions. Zhou (2022) examined the effects of DF on CO2 emissions in Chinese cities using the Fixed Effects Model and found that DF contributed to lower emissions. Similarly, Khan et al. (2023) analyzed the role of DF on CO2 emissions in emerging countries, observing its positive environmental impact. Mo and Ke (2023) explored the nonlinear relationship between DF and CO2 emissions in China using the ARDL approach and concluded that DF mitigated emissions. Wang et al. (2024), in a recent study, investigated the inclusion of DF in 284 Chinese cities using a conditional heteroskedastic error approach, revealing that DF inclusion significantly reduced CO2 emissions. These findings demonstrate the multifaceted benefits of DF, not only in driving economic growth but also in promoting environmental sustainability. By leveraging digital technologies to enhance financial services and reduce emissions, DF presents a dual opportunity for economic and environmental progress, particularly in rapidly developing and emerging economies.

3. METHODOLOGY

The present study aims to empirically assess environmental quality (EQ) in a panel of developing countries, including Afghanistan, Armenia, Bangladesh, Bolivia, Chile, China, Costa Rica, Cuba, Morocco, Malaysia, Nepal, Turkey, Ecuador, Ethiopia, Egypt, Indonesia, Ghana, Kenya, Malawi, Mali, Laos, Pakistan, and Mozambique. Specifically, the study examines the effects of natural resources (NTR), green finance (GF), and digital finance (DF) on EQ. The model is developed under the STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) framework, as proposed by Dietz and Rosa (1997). The STIRPAT framework provides a robust theoretical basis for understanding the determinants of environmental quality. It assumes that environmental impacts result from the interaction of three key factors: population (P), affluence (A), and technology (T). This framework enables researchers to quantitatively analyze how these factors contribute to environmental changes, offering insights into the complex dynamics that shape EQ.

Following this framework (Gorus & Groeneveld, 2018; Khan & Hassan, 2019; Rossi, 2023; Desiree, 2019; Bakht, 2020; Kibritcioglu, 2023; Hussain & Khan, 2022; Emodi, 2019; Iqbal & Noor, 2023; Senturk, 2023; Zaheer & Nasir, 2020; Habibullah, 2020; Mahmood, 2019; Shahbaz et al., 2016; Wang & Li, 2024; Abbas et al., 2024), the study specifies the following model:

$$CO2_{it} = \beta_0 + \beta_1 NTR_{it} + \beta_2 DF_{it} + \beta_3 GF_{it} + \beta_4 POP_{it} + \beta_5\ GDP_{it} + \beta_6\ GDP_{it}^2 + \mu_{it}$$

This model incorporates the effects of NTR, GF, and DF alongside the core components of the STIRPAT framework (population, affluence, and technology), allowing a comprehensive analysis of the factors influencing environmental quality in the selected developing countries. The results of this analysis aim to provide actionable insights for policymakers to balance economic growth with environmental sustainability effectively. This table outlines the variables used in the study, their respective measurements, and the data sources, providing a clear framework for the analysis. Each variable reflects a specific aspect of the research, focusing on environmental quality, finance, natural resources, economic growth, and population dynamics. Environmental quality is measured using CO_2 emissions in metric tons per capita, sourced from the World Development Indicators (WDI). This indicator provides a direct measure of the environmental impact of a population, particularly in terms of carbon emissions, and serves as a proxy for assessing sustainability challenges.

Green finance is quantified by international financial flows to developing economies aimed at supporting clean energy research and development as well as the production of renewable energy, including hybrid systems. Measured in constant US dollars (millions), this data is sourced from *Our World in Data*, highlighting the financial commitment toward combating climate change and promoting renewable energy adoption. Digital finance is represented by the number of ATMs per 100,000 adults, sourced from WDI. This metric reflects the accessibility of digital financial services and indicates the level of technological integration in financial systems, which can play a crucial role in economic inclusivity and modernization. Natural resources are assessed through total natural resource rents as a percentage of GDP, also sourced from WDI. This metric captures the economic reliance on natural resources, which can have significant implications for both economic resilience and environmental sustainability. Economic growth is measured using Gross Domestic Product (GDP) in constant US dollars, sourced from WDI. This serves as a traditional indicator of economic performance, adjusted for inflation to provide a consistent measure of growth over time. Population is simply represented by the total population, sourced from WDI, serving as a fundamental variable that impacts environmental quality, resource demand, and economic dynamics. Overall, these variables collectively provide a comprehensive view of the interplay between environmental, financial, and economic factors, forming the basis for understanding sustainable development trends and challenges.

Table 1: Measurements of Variables

Variables	Measurement
Environmental Quality (CO_2 emissions)	CO_2 emissions (metric ton per capita)
Green finance	International financial flows to developing economies to support clean energy R&D and production of renewable energy, including in hybrid systems (constant US dollars millions)
Digital Finance	ATMs (per 100,000 adults)
Natural Resources	Total Natural Resource Rents (% of GDP)
Economic growth	Gross Domestic Product (Constant US$)
Population	Total population

4. RESULTS AND DISCUSSION

This table 2 provides descriptive statistics for the variables used in the analysis, offering insights into their central tendencies and variability. The statistics include the mean, standard deviation (SD), minimum, and maximum values for each variable, illustrating the range and dispersion of the data. The CO_2 emissions variable has a mean of 1.9338 metric tons per capita, with a standard deviation of 2.0804. The minimum value is 0.0634, while the maximum is 7.7561, showing significant variation in environmental quality across observations. This suggests that some regions experience very high per capita emissions compared to others. GDP, measured in constant US dollars, has a mean value of 6.4811 and a standard deviation of 2.3112, indicating moderate variability in economic growth. The range is from 1.4613 to 7.530, reflecting diverse economic conditions among the observations. Green finance, represented by international financial flows, has a mean of 2.580 and a standard deviation of 4.550. The minimum value is −9.770, indicating negative financial flows in some instances, possibly due to repayment obligations or disinvestment, while the maximum is 3.3909. The industrialization index (IND) has a mean value of 126, with a standard deviation of 73.172. The minimum value is 1, and the maximum is 252, showing significant variability in industrial development levels across observations.

Natural resource rents (NR), expressed as a percentage of GDP, have a mean of 5.1911 and a standard deviation of 4.555. The values range from 0.221 to 18.051, highlighting differences in economic reliance on natural resources. Digital finance (DF), measured by ATMs per 100,000 adults, shows a mean of 106.296 and a standard deviation of 71.137. The range spans from 1.00 to 230, indicating substantial variation in financial infrastructure across regions or countries. The population variable has a mean of 1.1408 (likely in millions), with a high standard deviation of 2.7808. The minimum population is 28,056, and the maximum reaches 1,410,000, reflecting vast disparities in population sizes among the observations. These summary statistics illustrate the heterogeneity of the dataset, with variables such as CO_2 emissions, green finance, industrialization, and digital finance showing wide ranges. Such variability underscores the diverse contexts within the dataset and highlights the importance of tailoring policies to specific economic, environmental, and demographic conditions.

Table 2: Descriptive or summary statistics

Variables	Mean	SD	Min	Max
CO_2	1.9338	2.0804	0.0634	7.7561
GDP	6.4811	2.3112	7.530	1.4613
GF	2.580	4.550	−9.770	3.3909
IND	126.00	73.172	1.000	252
NR	5.1911	4.555	0.221	18.051
DF	106.296	71.137	1.00	230
POP	1.1408	2.7808	28056	1410000

This table 3 presents the results of unit root tests conducted on the dataset variables, using the CIPS and CADF methods. These tests evaluate the stationarity of each variable at both the level and first-difference stages, with statistical significance denoted at the 1, 5, and 10 percent levels by three, two, and one asterisks respectively. Stationarity is essential for time-series data to ensure valid econometric analysis. For CO2 emissions, the CIPS test at the level is significant at the 10 percent level with a statistic of −2.138, indicating marginal evidence of stationarity. The CADF test confirms strong stationarity at the level, significant at the 1 percent level with a statistic of −4.616. GDP does not show stationarity at the level under either test. However, after differencing, GDP becomes stationary in the CIPS test at the 10 percent level and in the CADF test at the 5 percent level, suggesting it is an integrated variable of order one. Green finance demonstrates stationarity at the level under the CIPS test, significant at the 1 percent level, but it does not achieve stationarity in the CADF test until the first difference, where it is significant at the 5 percent level. This mixed result highlights the variable's partial adherence to stationarity criteria.

Table 3: Findings of unit root tests

Variables	CIPS		CADF	
	Level	First Difference	Level	First Difference
CO_2	−2.138*	---------	−4.616***	---------
GDP	−1.305	−2.217*	−0.896	−1.710**
GF	−3.260***	---------	0.932	−2.251**
IND	−1.819	−3.120 ***	−2.528***	---------
NR	−1.775	−2.567***	−2.943***	---------
POP	−0.309	−2.624***	−1.611	−1.632**
DF	−2.019	−2.613***	0.286	−3.303***

***, ** & * represent significance at a 1, 5 and 10 percent respectively.

Industrialization shows stationarity only at the first difference in the CIPS test, significant at the 1 percent level. Conversely, the CADF test confirms stationarity at the level, significant at the 1 percent level. This suggests variability in test outcomes for this variable. Natural resource rents show a similar pattern to industrialization, with the CIPS test indicating stationarity at the first difference, significant at the 1 percent level, and the CADF test confirming stationarity at the level, also significant at the 1 percent level. Population is non-stationary at the level stage under both tests. After first differencing, it becomes stationary, with the CIPS test significant at the 1 percent level and the CADF test at the 5 percent level. This finding underscores the presence of trends in population data. Digital finance exhibits stationarity in the CIPS test only after first differencing, with significance at the 1 percent level. The CADF test shows it is non-stationary at the level but achieves stationarity at the first difference, significant at the 1 percent level. Overall, the findings reveal that most variables are non-stationary at the level stage but achieve stationarity upon first differencing, confirming their integration of order one. Exceptions include CO2 and green finance, which show evidence of stationarity at the level in at least one test. These results underscore the importance of unit root testing to address potential non-stationarity issues in time-series data, ensuring that econometric models are robust and reliable.

This table 4 presents the results of the panel causality test, which examines the directional causal relationships between the variables in the dataset. The null hypotheses test whether one variable does not homogeneously cause another across the panel. The test statistics and corresponding p-values are reported, with significance levels marked at 1, 5, and 10 percent by three, two, and one asterisks respectively. The results show that digital finance does not homogenously cause CO2 emissions, with a statistic of 0.255 and a p-value of 0.774, indicating no evidence of causality. However, CO2 emissions appear to homogenously cause digital finance at a significance level of 10 percent, with a statistic of 2.609 and a p-value of 0.076. This suggests that changes in CO2 emissions might influence digital finance adoption. Green finance does not homogenously cause CO2 emissions, as evidenced by a statistic of 0.177 and a p-value of 0.837. On the other hand, CO2 emissions significantly cause green finance at the 5 percent level, with a statistic of 5.073 and a p-value of 0.007. This indicates that CO2 emissions might drive financial flows toward green initiatives. Natural resource rents do not exhibit causality with CO2 emissions in either direction, with statistics of 0.283 and 1.418 and p-values of 0.753 and 0.244, respectively. This suggests no clear interdependence between natural resource rents and CO2 emissions.

Table 4: Panel Causality Test

Null hypothesis	Statistics	P-value
DF doesn't homogenously cause CO_2	0.255	0.774
CO_2 doesn't homogenously cause DF	2.609*	0.076
GF doesn't homogenously cause CO_2	0.177	0.837
CO_2 doesn't homogenously cause GF	5.073**	0.007
NTR doesn't homogenously cause CO_2	0.283	0.753
CO_2 doesn't homogenously cause NTR	1.418	0.244
GDP doesn't homogenously cause CO_2	0.748	0.474
CO_2 doesn't homogenously cause GDP	1.246	0.289
GDP^2 doesn't homogenously cause CO_2	0.792	0.453
CO_2 doesn't homogenously cause GDP^2	3.118**	0.046
IND doesn't homogenously cause CO_2	0.592	0.554
CO_2 doesn't homogenously cause IND	0.017	0.982
POP doesn't homogenously cause CO_2	1.300	0.274
CO_2 doesn't homogenously cause POP	6.168**	0.002

Economic growth (GDP) does not homogenously cause CO2 emissions, with a statistic of 0.748 and a p-value of 0.474. Similarly, CO2 emissions do not significantly cause GDP, as indicated by a statistic of 1.246 and a p-value of 0.289. However, squared GDP (GDP2) shows a different pattern, as CO2 emissions significantly cause GDP2 at the 5 percent level, with a statistic of 3.118 and a p-value of 0.046, implying a potential nonlinear relationship. Industrialization does not show causality with CO2 emissions in either direction. The statistics of 0.592 and 0.017 and p-values of 0.554 and 0.982 provide no evidence of interaction between these variables. Population does not significantly cause CO2 emissions, with a statistic of 1.300 and a p-value of 0.274. However, CO2 emissions significantly cause population at the 5 percent level, with a statistic of 6.168 and a p-value of 0.002, suggesting a unidirectional causal relationship where environmental quality impacts population dynamics. In sum, the panel causality test reveals unidirectional relationships where CO2 emissions significantly cause digital finance, green finance, GDP2, and population. These findings highlight the influence of environmental quality on various economic and demographic factors, suggesting that CO2 emissions play a critical role in shaping related dynamics across the panel.

5. CONCLUSIONS

This study aims to empirically estimate the impact of natural resources (NTR), digital finance (DF), and green finance (GF) on environmental quality (EQ). To achieve this objective, the analysis utilizes a comprehensive dataset encompassing 23 developing countries over the period from 2010 to 2023. This timeframe allows for an in-depth examination of the trends and relationships between these variables in the context of rapidly evolving economic, financial, and environmental dynamics. The inclusion of natural resources highlights their dual role in economic development and environmental sustainability, considering their contribution to both growth and ecological challenges. Digital finance is analyzed for its transformative potential in improving financial inclusion and efficiency, which can indirectly influence environmental outcomes. Green finance is examined for its direct role in promoting investments aimed at reducing environmental degradation and fostering sustainability. The study leverages a robust empirical framework to explore these relationships, accounting for both linear and non-linear effects. By focusing on developing countries, the research provides valuable

insights into the unique challenges and opportunities faced by these nations in balancing economic development with environmental preservation.
The findings aim to inform policymakers and stakeholders about effective strategies for leveraging natural and financial resources to enhance environmental quality in the face of global sustainability challenges. The findings of the study reveal that digital finance (DF) and natural resources (NTR) play a positive role in promoting environmental quality (EQ) in the selected developing countries. DF enhances EQ by facilitating efficient financial transactions, supporting green initiatives, and promoting resource optimization. Similarly, the sustainable use of NTR contributes positively by enabling resource-driven development with minimal environmental trade-offs. However, contrary to expectations, green finance (GF) is found to have a detrimental impact on EQ, potentially due to challenges in its implementation, such as inadequate regulation, misallocation of funds, or greenwashing practices that fail to yield the intended environmental benefits. Regarding the control variables, economic growth and industrialization are observed to negatively affect EQ, likely due to increased energy consumption, emissions, and resource exploitation associated with these processes. On the other hand, population growth and the square of economic growth (capturing non-linear effects) are found to enhance EQ. This suggests that as income levels rise beyond a certain threshold, environmental awareness and investments in sustainability measures improve, aligning with the Environmental Kuznets Curve (EKC) hypothesis. These findings provide valuable insights into the complex interplay between economic, financial, and demographic factors affecting EQ in developing countries. They highlight the need for tailored policies to maximize the positive impacts of DF and NTR while addressing the challenges associated with GF. Additionally, the study underscores the importance of sustainable industrialization and targeted economic policies to balance growth with environmental sustainability. These insights can guide policymakers and stakeholders in crafting effective strategies to improve EQ and achieve long-term sustainability goals. In conclusion, the current study provided a comprehensive understanding of the relationship between the selected regressors—natural resources, digital finance, and green finance—and environmental quality. The findings confirmed the hypothesis that natural resources positively influence environmental quality, emphasizing that the sustainable management of resource rents plays a crucial role in preserving the natural environment. This highlights the importance of adopting resource utilization strategies that prioritize ecological conservation alongside economic benefits. Surprisingly, the study denied the widely held notion that green finance has a significant positive effect on environmental quality. This unexpected result raises questions about the effectiveness of green finance and calls for further investigation into how it can be better aligned with ecological goals.
The findings underline the need to explore the mechanisms through which financial instruments, including green finance, impact environmental outcomes and to identify strategies for optimizing their effectiveness. The results also demonstrated that digital finance adoption has contributed to improving environmental quality in developing countries. By embedding digital finance into conservation strategies, nations have been able to reconcile ecological sustainability with economic growth. This integration facilitates efficient resource allocation, promotes green initiatives, and supports broader financial inclusion, making it a powerful tool for advancing sustainability goals. Overall, the study emphasizes the critical need for deeper research into the complex interactions between financial tools, natural resource management, and environmental quality. These insights are essential for policymakers and stakeholders seeking to leverage financial and technological innovations to achieve sustainable development in the context of growing environmental challenges. The theoretical contributions of this study offer valuable insights into the complex dynamics between economic activities and environmental quality, particularly in the context of climate resilience in developing countries. By emphasizing the sustainable management of natural resources and their confirmed positive impact on environmental quality, the findings reinforce key principles of environmental economics. This highlights the critical importance of integrating environmental considerations into resource extraction policies and processes, promoting ecological conservation as an essential element of sustainable resource management. The study also challenges the assumed effectiveness of financial instruments in achieving sustainability goals. By rejecting the hypothesis that green finance significantly impacts environmental quality, it calls into question the foundational premises of current approaches to green finance. This finding underscores the need for a more nuanced understanding of the relationship between ecological outcomes and financial flows. It suggests that existing models may require re-evaluation to better align financial instruments with environmental objectives, potentially reshaping how green finance is conceptualized and implemented. Additionally, the study contributes to the growing body of literature on digital finance by confirming its role in improving environmental quality. This finding expands theoretical perspectives on the intersection of digitalization and sustainable development, highlighting the transformative potential of financial technology in balancing environmental management with economic growth. By facilitating efficient resource allocation, reducing costs, and promoting green initiatives, digital finance emerges as a powerful tool for fostering sustainability. Overall, these contributions deepen our understanding of the interplay between economic mechanisms and environmental outcomes. They call for more integrated and innovative approaches to policy and practice, encouraging the development of frameworks that more effectively address the dual goals of ecological preservation and economic resilience in developing countries.

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