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Article

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Interplay of Digital Financial Inclusion, Technological Innovation, Good Governance, and Carbon Neutrality in the Top 30 Remittance-Receiving Countries: The Significance of Renewable Energy Integration

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ABSTRACT

Our research examines the interconnections between digital finance inclusion, technological innovation, good governance, renewable energy, and carbon neutrality in the top 30 remittance-receiving countries from 2001 to 2020. Utilizing comprehensive panel data analysis with SH tests, CSD tests, CADF tests, D-H causality tests, and robustness checks, we analyze the effects of these factors on carbon emissions. The study reveals that digital financial inclusion is positively associated with reduced carbon emissions, indicating that access to digital finance can significantly lower carbon footprints. This supports previous findings that digital finance reduces reliance on traditional banking and paper transactions, aiding environmental sustainability. Additionally, remittances positively impact carbon neutrality by funding clean energy technologies and sustainable development projects. However, the expansion of digital financial services is linked to increased energy consumption and electronic waste, highlighting its complex environmental impact. Effective governance plays a crucial role in achieving carbon reduction goals, with transparent and accountable governance systems implementing successful climate policies. Technological innovation, particularly in clean energy, is essential for transitioning to a low-carbon economy. Our study shows strong positive correlations among digital finance, remittances, innovation, good governance, renewable energy, and carbon neutrality. We recommend policies that invest in renewable energy, enhance governance practices, leverage digital finance and remittances for sustainable development, and foster global collaboration. This integrated approach can significantly advance environmental sustainability and carbon neutrality, offering valuable insights for policymakers and stakeholders on sustainable economic development and environmental protection.

Keywords: Digital Financial Inclusion, Technological Innovation, Good Governance, Carbon Neutrality, Remittance, Renewable Energy Integration

JEL Classifications: O33; Q56; F24; Q58

1. INTRODUCTION

In response to rising carbon emissions, policymakers are considering moving away from the current energy-focused economic growth model. This shift requires a global realignment of policies, some of which could promote sustainable development. Establishing the Sustainable Development Goals (SDGs) is a concrete step towards achieving this goal, with Goal 13 specifically addressing climate action. Goal 13.1 aims to increase the resilience of economies to climate change, while Goal 13.2 focuses on enhancing human capital quality. Strategic investment in fostering innovation is crucial for achieving these goals, but the challenge lies in implementing these strategies effectively. The latest Progress Report on SDGs highlights a gap, showing that emerging and least developed economies struggle to meet the targets compared to wealthier nations. A 2021 report by Rehman et al. (2021) on financing for sustainable development may provide insight into this disparity Alamoush et al. (2021).

The pressing global issues of climate change and environmental pollution require immediate action, particularly in financial inclusion and remittance innovations Ahmad et al. (2022). Greenhouse gas emissions negatively affect economies and human well-being, emphasizing the need for environmental preservation and energy independence as outlined in the 2030 Sustainable Development Goals (SDGs) Shakoor and Ahmed (2023) Kluza et al. (2021). Digital financial inclusion and remittance innovations are essential in achieving these goals, especially for developing nations striving to enhance their financial capabilities. SDG 13 aims to help impoverished nations access funds for mitigation efforts, with digital finance playing a significant role in this objective Salampasis and Mention (2018). The recent focus at the COP26 summit on providing $100 billion to developing countries for climate resilience programs underscores the situation's urgency Matthews (2021). The controversy surrounding the potential failure to meet this commitment highlights the importance of innovative financial solutions. By leveraging digital financial inclusion and remittance innovations, emerging countries can reshape their economic development strategies and effectively combat environmental pollution, contributing to global efforts to reduce carbon emissions Timperley (2021); (Yin and Qamruzzaman, 2024; Qamruzzaman, 2024a; Qamruzzaman, 2024b; Yan et al., 2023; Wang et al., 2023b; Wang et al., 2023a; Tan et al., 2023b).

The integration of digital financial inclusion is crucial in the effort to achieve zero carbon emissions. In today's world, where urgent action is needed to address global environmental issues like biodiversity loss and rising energy demands, digital financial inclusion plays a vital role in promoting sustainability Yang and Zhang (2020). By adopting and expanding digital financial services, significant progress can be made towards reaching the goal of zero carbon emissions. Digital financial inclusion helps reduce carbon footprint by promoting paperless transactions. By shifting towards digital platforms for banking and financial activities, the reliance on paper-based processes decreases, leading to lower environmental impact from paper production and transportation Gayathri et al. (2023). Besides, digital financial services reduce the need for physical infrastructure like bank branches and ATMs, resulting in energy savings and a reduced carbon footprint. Efficiency is a crucial benefit of digital financial inclusion in the context of zero carbon emissions Mukalayi and Inglesi-Lotz (2023). Advanced technologies such as cloud computing and data analytics optimize operations and resource allocation in financial institutions, leading to lower energy consumption than traditional methods Hameed et al. (2016). Digital finance also enables remote transactions and telecommuting, reducing carbon emissions associated with physical travel to financial institutions Lyons et al. (2018). Digital platforms also have the potential to provide consumers with insights into the environmental impact of their spending habits, encouraging more sustainable choices and influencing behavior towards zero carbon emission objectives Tan et al. (2023a).

Studying the top 30 remittance-receiving countries is crucial for comprehending and tackling the objective of achieving zero carbon emissions for various significant reasons. These countries hold substantial economic influence, making it essential to understand their economic dynamics to implement sustainable practices and technologies effectively Shera and Meyer (2013). Remittances can drive economic development, presenting opportunities to invest in clean technologies that foster development while minimizing environmental harm. Many of these nations heavily rely on fossil fuels, necessitating strategies to transition to cleaner energy sources Ali et al. (2022). Analyzing these countries also helps identify areas for impactful technology transfer to promote adopting more sanitary practices. Rapid population growth in some nations poses challenges like increased energy demand and urbanization, requiring sustainable solutions to manage growth without escalating carbon emissions Kumar et al. (2015). Moreover, by considering the unique socioeconomic challenges of remittance-receiving countries in the context of zero carbon emissions, strategies can be developed to ensure an inclusive and equitable transition to a sustainable future Mills (2023).

Attaining zero carbon emissions top 30 remittance-receiving nations requires a comprehensive strategy that includes diverse crucial components. These include diversifying energy sources by shifting from fossil fuels to renewable options like solar, wind, and hydropower and increasing investments in renewable energy infrastructure and technologies Ellabban et al. (2014). Applying energy efficiency measures in various sectors, such as industries, transportation, and buildings, is crucial for reducing carbon emissions Tanaka (2011). Encouraging good governance and transparency and combating corruption is vital for successful climate action and sustainable development Sukoharsono (2018). Strengthening financial systems to support green investments and adopting technological innovations in clean energy are also important Bose et al. (2019). Developing and implementing climate policies, regulations, and incentives in Nigeria are necessary for driving the adoption of clean energy and carbon reduction strategies, leading to significant progress in Sub-Saharan Africa's efforts to achieve zero carbon emissions. This holistic approach aligns with global initiatives to manage climate change and advance sustainable development in the region Daggash and MacDowell (2021).

Remittances are vital for achieving zero carbon emissions due to various reasons. These include their significant contribution to economic development, which enables investments in cleaner technologies and sustainable practices that reduce carbon emissions. Remittances also help diversify economies away from fossil fuel industries, lowering emissions. Additionally, they alleviate poverty, improve living standards, and promote sustainable practices like eco-friendly agriculture Li and Yang (2023). Furthermore, remittances support education and awareness programs on environmental issues, infrastructure development for green technologies, innovation, and technology transfer for sustainable development Villanthenkodath and Mahalik (2022). They also aid in building climate resilience and fostering global cooperation on environmental challenges through collaboration between diaspora communities and home countries Brinkerhoff (2012).

The stability of governance is crucial for achieving carbon reduction goals, especially in countries that receive remittances. These nations face significant environmental challenges, such as biodiversity loss, increasing energy needs, and rising greenhouse gas emissions Gyimah et al. (2023). A consistent and reliable political environment is essential for developing and implementing policies to reduce carbon emissions. This governance resilience enables consistent decision-making, facilitating the creation and execution of long-term strategies to address environmental issues Engle et al. (2014). Political stability is critical for overcoming obstacles in industrial production, navigating environmental regulations, and transitioning to cleaner practices. Governments with stable political backgrounds can effectively establish and enforce rules, encourage investments in renewable energy, and promote innovation for carbon reduction efforts in Kadri. Continuity in these initiatives is vital for meeting carbon reduction targets and ensuring sustained progress, even amidst global pressures and economic fluctuations. In remittance-receiving countries, where economic development is closely tied to environmental impact, stable governance is critical in coordinating an effective response to carbon emissions and environmental degradation Bhattarai et al. (2021).

Technological innovation is critical in pursuing zero carbon emissions, particularly in the top 30 remittance-receiving countries. These nations can utilize innovative solutions to transition to clean energy sources like solar and wind power Subramaniam et al. (2023), enhance energy efficiency across sectors, adopt sustainable transportation options such as electric vehicles Pandey (2019), invest in carbon capture and storage technologies Liu et al. (2023), implement circular economy practices Figueroa et al. (2021), improve agricultural sustainability Chandio et al. (2023), incorporate green building technologies Yang et al. (2021), enhance waste management processes Kumari and Raghubanshi (2023), utilize climate adaptation tools Eriksen and Kelly (2007), and embrace digitalization for remote work Sepashvili (2021). By embracing these advancements, these countries can boost their economic growth and expedite the shift towards a low-carbon and sustainable future, crucial for combating climate change and achieving zero carbon emissions.

The research methodology includes a review of relevant empirical literature, an explanation of the approach, dataset, and model, a presentation and discussion of empirical findings, and a conclusion discussing the study's implications.

2. LITERATURE SURVEY

2.1. Digital Finance Inclusion and Zero Carbon Emission

Digital finance inclusion can assist in reducing carbon emissions by supporting sustainable economic activities Zhao et al. (2021), Wang et al. (2022), Ozturk and Ullah (2022). Digital financial transactions such as online banking, mobile payments, and digital wallets are reducing the reliance on paper-based processes Kasowaki and William (2024). This shift to paperless transactions is decreasing the demand for paper production, reducing deforestation, and lowering the carbon footprint related to paper manufacturing and transportation Masele (2011). Traditional banking systems rely on physical infrastructure like branches and ATMs, while digital finance allows for financial transactions without physical presence, reducing energy consumption and carbon emissions Khan et al. (2024). For instance, Feng et al. (2022) conducted research in China by employing the ARDL model. The model's findings show that an increase in ATMs and total insurance in China has a positive long-term effect on renewable energy consumption while it harms CO_2 emissions. Financial inclusion in China leads to higher renewable energy consumption and lower CO_2 emissions.

Digital financial institutions can enhance energy efficiency through advanced technologies like cloud computing and data analytics, leading to lower energy consumption than traditional methods Li et al. (2023). In EU nations, Kwilinski et al. (2023) revealed that digital business practices can enhance energy efficiency, decrease energy costs, and reduce overall energy consumption.

Digital finance allows for remote work and transactions, reducing the necessity of physical visits to banks. A study in Asian countries by Merrill et al. (2019) shows that this leads to a decrease in carbon emissions from transportation. Additionally, digital finance platforms utilize data analytics and artificial intelligence to allocate resources more effectively, resulting in better investment decisions that support environmentally sustainable projects and businesses while avoiding carbon-intensive industries Chui (2017), Javaid et al. (2022). Digital finance platforms can support green financing by investing in eco-friendly projects like renewable energy and sustainable infrastructure Saqib et al. (2023). Digital finance systems can include tools to monitor and disclose the carbon footprint of financial activities, enabling businesses and individuals to understand their environmental impact. For example, the Digital Finance/Fintech Action Plan and the Sustainable Finance Strategy are critical components of the EU policy agenda. While traditionally treated separately, there is potential for combining these areas due to standard features. Fintech can address gaps in sustainable finance, such as retail financing access and ESG disclosure. The COVID-19 pandemic has highlighted the importance of linking sustainability, finance, and technology. However, Fintech and digital finance present technical and legal challenges that must be resolved to realize their potential in sustainable finance fully Macchiavello and Siri (2022). However, although digital financial inclusion has the potential to lower carbon emissions, there are situations where it could actually lead to higher emissions, especially in countries that receive the highest remittances.

The expansion of digital financial services relies on electronic devices like smartphones, computers, and internet infrastructure. Improper disposal of these devices can harm the environment and lead to carbon emissions Vishwakarma et al. (2022). For instance, Dong et al. (2022) conducted a research study in 60 low and high-ranked network countries, and his analysis revealed that in regions with poor internet infrastructure, enhancing digital financial services may necessitate more investment in network expansion, which can also contribute to carbon emissions due to energy consumption.

2.2. Remittance and Zero Carbon Emission

Remittances, funds transferred by migrants, can indirectly positively impact be reducing carbon emissions. Although the direct effect may be minimal, remittance inflows' economic and social benefits can lead to promising environmental outcomes. There are multiple studies by Zhang et al. (2022), Dash et al. (2024), and Zhang et al. (2023) in which remittances can help in lowering carbon emissions. In the short term, increasing remittances to China positively impacts environmental sustainability. Findings also suggest recommendations to policymakers on using remittances effectively to promote green economic growth Zhang et al. (2023). In Nepal, recipients of remittances can invest in sustainable practices and technologies, such as renewable energy sources, energy-efficient appliances, and environmentally friendly agricultural methods, which can help diminish carbon emissions Sharma et al. (2019). In Latin American countries, including Brazil, remittances encourage recipients to expand their sources of income by investing in sustainable economic activities, which can aid communities in decreasing their reliance on high-carbon industries and eventually reduce emissions Liu et al. (2022), Duchelle et al. (2014). On the flip side of deforestation, remittance funds can sustain environmental conservation activities like reforestation, wildlife protection, and maintaining natural ecosystems. These investments can help with carbon sequestration and biodiversity conservation Meyers et al. (2020). For instance, foreign investors in Ethiopia can transfer all profits from activities like carbon sequestration and biodiversity conservation Reynolds et al. (2010). Besides, a study by Ratha (2011) in Africa, remittances are crucial in enabling families to invest in education, making a well-educated population more likely to adopt sustainable practices. This can ultimately result in lower per capita carbon footprints over time. Additionally, remittances can contribute to poverty lessening and improved living standards, which may direct to communities shifting towards more sustainable and environmentally conscious consumption patterns Sikder and Higgins (2017). Remittances can increase communities' capability to withstand the effects of climate change. They propose financial support to support communities to sufficiently prepare for environmental changes and develop resilient, resilient, climate-resilient infrastructure Hussain et al. (2021), Hallegatte et al. (2020). Remittances can lessen economic burdens on local resources, potentially reducing strain on ecosystems and controlling overexploitation of natural resources, deforestation, and activities leading to higher carbon emissions Mancini et al. (2019). These funds can even be utilized to back community-based renewable energy initiatives, such as arranging up solar or wind energy installations as cleaner options to conventional energy sources Bisaga and To (2021).

A study by Ramakrishnan et al. (2020) in India employs data from the India Human Development Survey (IHDS) in 2005 and 2012 to analyze the impact of social factors and economic, demographic, locational, and housing factors on household ownership levels. The research indicates that the expanded remittance in India is linked to higher consumption of cars and appliances, influenced not only by economic factors but also predominantly by social factors, particularly the household's perception of status. The study emphasizes the role of apparent consumption expenditure in driving the adoption of these products, implying that as remittance increases, households are more likely to engage in status-driven consumption. Another study by Zaman et al. (2013) in Pakistan examines the connection between critical macroeconomic factors and rising energy consumption from 1980 to 2011. The study uses statistical methods like cointegration, error correction models, and Granger causality tests to understand these variables' long-term relationships, short-term dynamics, and causal links. The findings stress the impact of Tetra-partner power and energy-intensive industries on Pakistan's economic growth, leading to a noteworthy increase in electricity consumption and remittances. Nevertheless, the study also raises concerns about the societal impact, pointing toward addressing the potentially damaging effects on society.

2.3. Government and Zero Carbon Emission

Political stability is crucial in reducing carbon emissions in countries that receive remittances. A stable political environment enables the implementation of long-term environmental sustainability policies and initiatives. Myriad studies show that political stability can significantly impact decreasing carbon emissions, especially in the top 30 remittance-receiving countries Sharma et al. (2019), Zafar et al. (2022), Yang et al. (2020) and Zhang and Wen (2008). Stable political conditions facilitate the expansion and execution of consistent long-term policies, particularly in areas like environmental protection, renewable energy, and carbon reduction Ali et al. (2021). This stability minimizes the disruptions that can arise from frequent changes in political leadership.

Political stability is conducive to attracting investments, both from within the country and internationally. Governments in politically stable nations can effectively secure funding for sustainable infrastructure initiatives, such as renewable energy installations, public transportation networks, and waste management facilities. These investments can contribute to lowering carbon emissions Baietti et al. (2012). Stable political environments facilitate international collaboration on climate agreements and treaties Finus (2003). Countries with stable governments are more likely to actively engage in global efforts to combat climate change, commit to reducing emissions, and contribute to international climate finance initiatives Dinar et al. (2015). Political stability enables the establishment and enforcement of effective environmental regulations. Governments in stable environments can implement laws that restrict carbon emissions, set emission standards for industries, and promote sustainable practices across various sectors without the disruptions caused by political instability Young et al. (2018). Consistent public awareness and education campaigns on environmental issues are supported by political stability. Governments in stable environments can conduct long-term educational programs to educate the public about the impacts of carbon emissions and encourage sustainable behaviors and lifestyles Anderson and Strecker (2012). Transparent governance and accountability are fostered in stable political environments. This transparency is crucial for monitoring and reporting on environmental initiatives, ensuring that government actions align with environmental objectives, and holding policymakers accountable for their commitments to carbon reduction Gupta and Mason (2014), Mason (2020). Political stability enables the creation and maintenance of solid institutions that focus on environmental management. These institutions, such as dedicated agencies and departments, can effectively coordinate and implement environmental policies, ensuring the efficient execution and monitoring of carbon reduction initiatives DeCaro et al. (2017). Politically stable countries are generally better equipped to withstand external pressures and shocks. This resilience allows governments to remain committed to environmental goals despite economic challenges, global market fluctuations, or changes in international relations Shaw (2012). Political stability also fosters social cohesion and collaboration among different stakeholders. A united society is likelier to support and actively engage in carbon reduction efforts, promoting a collective dedication to sustainability Leal Filho et al. (2016). Stable political environments may not promote solid public involvement in decision-making processes, resulting in less pressure on governments to prioritize and enforce environmentally friendly policies Chu et al. (2022). Political stability can be influenced by powerful industries in carbon-intensive sectors, making enacting policies that could harm their interests difficult. Established industries often strongly influence policy decisions, creating challenges for implementing measures that could impact them negatively Metzne and Mikes (2021). Countries that are politically stable and deeply connected to the global economy may feel pressure to compete by supporting or growing carbon-intensive industries. This pressure is heightened if these industries play a crucial role in the country's international trade and economic stability Erickson and Collins (2021) and Wilhite (2016).

2.4. Innovation and Zero Carbon Emission

Innovation is crucial in decreasing carbon emissions by creating new energy-efficient, sustainable, and environmentally friendly technologies and solutions. Research mainly looks at innovation as technological progress that drives change and revolutionizes industries, highlighting how technology can transform society and the economy. A significant number of researchers argue that advancements in technology have the potential to help decrease carbon emissions Li and Wang (2017), Gu et al. (2019), Khan et al. (2020) and Hussain et al. (2022). Progress in renewable energy technologies like solar, wind, hydro, and geothermal offer cleaner options than fossil fuels. The improved efficiency and affordability of these systems drive their widespread use, decreasing dependence on carbon-heavy energy sources Brown (2017). Moreover, advancements in energy storage solutions, like advanced batteries, support the adequate storage and use of renewable energy. This helps manage the intermittent nature of some renewable sources and enhances the stability and reliability of clean energy grids Li and Wang (2017).

Another research by Dominković et al. (2018) in the EU shows that progress in battery technology and charging infrastructure further supports the transition to cleaner and more sustainable transportation options. Carbon Capture and Storage (CCS) technologies capture carbon dioxide emissions from industrial processes and power plants to reduce greenhouse gas emissions from sectors that are difficult to decarbonize fully Paltsev et al. (2021). Innovative grid technologies improve energy distribution and consumption efficiency. At the same time, demand response systems enable better management of energy consumption during peak periods to optimize energy use and reduce carbon emissions Hafeez et al. (2020). For instance, a survey study by Siano (2014) established that Demand Response (DR) is a strategy that helps reduce peak energy demand and lower carbon emissions in the long run. This is achieved by improving energy efficiency through technologies such as automatic energy schedulers, which optimize energy consumption.

Innovative building technologies such as intelligent HVAC systems, energy-efficient insulation, and automated energy management systems effectively decrease energy usage in residential, commercial, and industrial buildings Hossain et al. (2023). These advancements play a significant role in reducing carbon emissions related to heating, cooling, and lighting. Similarly, advancements in sustainable agriculture practices, such as precision agriculture, sensor technologies, and data analytics, help improve farming methods by reducing the use of fertilizers and pesticides, minimizing energy-intensive processes, and promoting sustainable land management, resulting in lower emissions from the agriculture sector Ashraf et al. (2021). Advancements in Indian agriculture, notably in Telangana and Andhra Pradesh, have demonstrated promising results in reducing carbon emissions by adopting energy-efficient practices. These innovations have led to significant reductions in pesticide usage and fertilizer consumption, underlining the potential of modern agricultural techniques to elevate environmental sustainability Mehta et al. (2020). Technological advancements in recycling, waste-to-energy processes, and cleaner industrial technologies are vital in promoting a circular economy and reducing the environmental impact of waste disposal Boloy et al. (2021). These innovations help minimize carbon emissions linked to landfilling and incineration while also contributing to lower emissions from industrial activities through cleaner manufacturing processes, electrification of equipment, and the use of sustainable materials contribute to reducing carbon emissions from industrial activities Colangelo et al. (2023).

Other researchers have countering opinions, suggesting that innovation could result in higher levels of carbon emissions in certain situations. Technological advancements are typically intended to lower carbon emissions, while there are circumstances where they may unintentionally lead to higher emissions. Progress in energy efficiency can lead to a rebound effect where the cost savings from efficiency gains are reinvested in additional consumption. For example, in EU nations, more fuel-efficient cars lead to augmented travel, partially offsetting the emissions reductions Fontaras et al. (2017). Rapid technological advancements can result in shorter product lifespans and more systematic turnover of electronic devices. These items' production, transportation, and disposal can lead to more significant emissions, primarily if recycling techniques need to be improved Fontaras et al. (2017). A questionnaire survey data collected from 426 participants showed that adopting specific technologies, such as ride-sharing apps, could increase carbon emissions by influencing consumer behavior towards more individual transportation services. Manufacturing advanced technologies like electric vehicles, solar panels, and batteries requires much energy, which can result in a high carbon footprint if non-renewable energy sources are used. Adopting certain agricultural technologies can result in higher emissions if not used sustainably. These technologies include energy-intensive machinery, overuse of fertilizers, and unsustainable irrigation methods Mallareddy et al. (2023).

3. DATA AND METHODOLOGY OF THE STUDY

3.1. Model Specification

The motivation of the study is to gauge the nexus between digital finance inclusion (FDI), Remittance (REM), good governance (GG), clean energy (CE), innovation (TI), and carbon neutrality (CN) in Top 10 remittances receipting nations for the period 2001-2020. The generalized equation for the empirical relations is as follows

$$CO_2|DIF, REM, GG, TI, CE \quad (1)$$

After transformation with natural log, the above Eq (1) can be displayed in the following manner Eq (2).

$$CO_2it = \beta 0 + \beta 1DFI_{it} + \beta 2REM_{it} + \beta 3GG_{it} + \beta 4TI_{it} + \beta 5CE_{it} + \epsilon\, it \quad (2)$$

Where β_0 is the intercept term, β_1, $\beta 2$, $\beta 3$, $\beta 4$, and $\beta 5$ are the coefficients that represent the relationship between carbon dioxide emissions and each of the independent variables. ϵ_i represents the error term, which captures the unexplained variation in carbon dioxide emissions not accounted for by the independent variables.

The first explanatory variable is *Digital finance inclusion (DFI)* encompasses financial services provided through digital platforms like mobile banking, online payments, and digital currencies Pazarbasioglu et al. (2020). The anticipated effect of digital finance on the environment is positive, as its wider usage is linked to enhanced financial inclusion, credit accessibility, and economic growth. However, the increased economic activities associated with digital finance also led to higher energy consumption and CO_2 emissions Wang and Guo (2022).

The second explanatory variable is *Remittances (REM)*, or funds sent by migrants to their home countries, which are a significant source of income for recipient households and can support economic development Ahmed et al. (2021). Githaiga and Kabiru (2014). The positive impact of remittances is due to their ability to boost consumption and investment, driving economic growth and potentially increasing CO_2 emissions Sharma et al. (2019).

The third explanatory variable is *Technological innovation (TI)* refers to creating and implementing new technologies to enhance efficiency, productivity, and sustainability Xiao and Qamruzzaman (2022). The anticipated impact of technological innovation is typically negative, as it frequently results in the advancement of cleaner and more energy-efficient methods, thereby lowering the carbon footprint of economic operations and lessening CO_2 emissions.

The fourth explanatory variable *is good governance (GG)* refers to the presence of efficient and transparent institutions, policies, and regulations that support sustainable development and environmental conservation Gisselquist (2012). The correlation between good governance and environmental outcomes suggests that countries with strong governance tend to have lower CO_2 emissions and pollution levels due to their ability to effectively implement and enforce environmental regulations, leading to lower CO_2 emissions and pollution levels Gani (2012).

The fifth explanatory variable *is Clean Energy (CE)* refers to renewable energy sources like solar, wind, hydroelectric, and biomass energy with lower greenhouse gas emissions than fossil fuels Sayed et al. (2021), Williams et al. (2019). The expected impact of clean energy adoption is negative, as it reduces dependence on fossil fuels, decreases CO_2 emissions, and helps address climate change Haines et al. (2007).

The dependent variable is *Carbon dioxide emission (*CO_2*)* is usually quantified in metric tons Gür (2022). Carbon dioxide is a greenhouse gas contributing to global warming and climate change Amaechi and Biose (2016). The expected correlation between CO_2 levels and other factors relies on their impact on economic activities and energy usage. An uptick in financial activities or energy consumption typically results in higher CO_2 emissions, indicating a positive relationship with variables that drive economic growth or energy consumption Cetin et al. (2018).

3.2. Estimation strategies

The heterogeneity test, developed by Bersvendsen and Ditzen (2021), is a statistical method utilized to assess the variability in study findings that cannot be solely attributed to chance. Understanding the importance of meta-analyses is essential, as it directly affects the validity of combining multiple studies to generate a single effect estimate. Significant heterogeneity in the data suggests the presence of diverse underlying effects, which could be attributed to variations in study populations, interventions, or other relevant factors. Bersvendsen and Ditzen's approach utilizes statistical measures such as the I^2 statistic and the Q statistic to measure and quantify heterogeneity accurately. These measures provide valuable insights by indicating the percentage of variation that can be attributed to heterogeneity rather than mere chance. This approach offers a structured approach to examine and measure heterogeneity, aiding researchers in comprehending the extent to which underlying variations among studies impact the collective findings of a meta-analysis.

$$H_0: \theta_1 = 0$$

$$t_{SH} = \frac{\hat{\theta}_1}{SE_{\hat{\theta}_1}}$$

$$P - value = P\left(t_{HS} > \left|t_{HS}\right|\right)$$

Estimating cross-sectional dependence is vital due to undefined residual dependency, unknown standard shocks, and rising economic and financial integration. Ignoring the existence of CSD leads to spurious and biased results by affecting the efficiency and consistency of parameter estimations. We employed Bias-corrected scaled LM and Breusch-Pagan LM CSD tests for the present study. The LM test by Breusch and Pagan (1980) can be explained through the subsequent parameters:

$$Breusch-Pagan\,LM = T\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}(\hat{\rho}_{i,j}^{2}) \tag{3}$$

The above equations $(\widehat{\rho^{2}}_{i,j}, T, and N)$ illustrate the residuals' cross-sectional correlation, time, and total panel cross-section.

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}\right) \tag{4}$$

Pesaran et al. (2004) showed that under the null hypothesis of no cross-sectional dependence $CD \overset{d}{\rightarrow} N(0,1)\, for\, N \rightarrow \infty$ and T sufficiently large.

θ_t The mean-bias-adjusted NLM test statistic is defined by

$$NLM^{*} = \sqrt{\frac{1}{N(N-1)}}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\left[(T-K)\hat{\rho}_{ij}^{2} - \mu_{T_{ij}}\right] \tag{5}$$

Note that the mean of *NLM** The statistic is precisely zero for all *T* and *N*, and it is unlikely that the increase in *N* enhances the size distortion of the test. However, the variance of this test statistic is still subject to slight sample bias. Therefore, under Assumptions 1-4, with $T \rightarrow \infty$ first, then $N \rightarrow \infty$, we would have (under H_0)

$$NLM^{*} \underset{d}{\rightarrow} N(0,1)$$

Next, using (8) and (9), the mean-variance-bias-adjusted NLM test statistic is defined as

$$NLM^{**} = \sqrt{\frac{2}{N(N-1)}}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\frac{(T-K)\hat{\rho}_{ij}^{2} - \mu_{T_{ij}}}{\upsilon_{T_{ij}}} \tag{6}$$

Under Assumptions 1-4, for all *T*, as $N \rightarrow \infty$ We would have (under H_0)

$$NLM^{**} \underset{d}{\rightarrow} N(0,1)$$

Clearly, the *NLM** The test is more likely to exhibit size distortions as compared to the *NLM*** Test. However, it has the advantage of being relatively simple to compute.

Pesaran (2006)

Assume the following equation with heterogeneous coefficients Pesaran (2006)

$$y_{it} = \alpha_i + \beta_{it}^{'}x_{it} + \mu_{it} \tag{7}$$

$$\mu_{it} = \gamma_i^{'}f_t + e_{it} \tag{8}$$

where f_t is an unobserved common factor, γ_i a heterogeneous factor loading, and α_i A unit-specific fixed effect. e_{it} It is a cross-section unit-specific independent and identically distributed (IID) error term. The heterogeneous coefficients are randomly distributed around a common mean such that. $\beta_i = \beta + v_i$, $v_i \sim IID\,(0, \Omega_v)$, where Ω_v It is thevariance-covariance matrix. Pesaran (2006) shows that (1) can be consistently estimated by approximating the unobserved common factors with cross-sectional averages $\overline{x}_t$ under strict exogeneity of x_{it}. This estimator is commonly known as the CCE estimator. The underlying idea of the CCE estimator is to eliminate asymptotically the differential effects of unobserved common factors by cross-sectional averages as the cross-sectional dimension approaches infinity Pesaran (2006).

Juodis and Reese (2022)

Consider the weighted CD test statistic.

$$CD_W = \left(\frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}\hat{\varepsilon}_{i,t}^{2}w_i^{2}\right)^{-1}\left(\sqrt{\frac{2}{TN(N-1)}}\sum_{t=1}^{T}\sum_{i=2}^{N}\sum_{j=1}^{i-1}w_i\hat{\varepsilon}_{i,t}w_j\hat{\varepsilon}_{j,t}\right) \tag{9}$$

Moreover, assume that either of the following two points holds.

1. The time fixed-effects model generates the data (4) such that Assumption 1 holds. $\hat{\varepsilon}_{i,t}$ This is given by Equation (6).
2. The data are generated by the latent standard factor model (16) such that Assumptions 2–6 hold. $\hat{\varepsilon}_{i,t}$ is defined by Equation (20).

Under either of the two sets of assumptions above as well as Assumption 7, it holds that

$$CD_W \overset{d}{\rightarrow} N(0,1)$$

as $N,T \rightarrow \infty$ jointly subject to the restriction $\sqrt{T}N^{-1} \rightarrow 0$.

Second-generation panel unit root tests, such as CIPS (cross-sectionally augmented IPS) and CADF (cross-sectionally augmented Dickey-Fuller) Pesaran (2007), are widely expected to analyze a unit root's existence in panel data. The current study has used a comparable approach to evaluation. The CIPS test addresses the issue of cross-sectional dependency in panel data by enhancing the IPS test with extra lagged levels of the dependent variable. This methodology helps to properly deal with the probable presence of correlation among the various units within the panel. The CADF test enhances the Dickey-Fuller test by including cross-sectional averages of lagged values of the dependent variable. This methodology enables the detection of unit roots in panel data, considering the existence of cross-sectional dependency.

Researchers use the provided equation to estimate the stationary characteristics of the research variables.

$$\Delta Y_{it} = \beta_i + \gamma_i y_{i,t-1} + \pi_i \bar{y}_{t-1} + \beta_i \bar{y}_t + \rho_{it} \quad (10)$$

$$\Delta Y_{it} = \mu_i + \gamma_i y_{i,t-1} + \pi_i \bar{y}_{t-1} + \sum_{k=1}^{p} \beta_{ik} \Delta y_{i,k-1} + \sum_{k=0}^{p} \beta_{ik} \overline{\Delta y}_{i,k-0} + \alpha_{it} \quad (11)$$

$$CIPS = N^{-1} \sum_{i-1}^{N} \partial_i (N,T) \quad (12)$$

$$CIPS = N^{-1} \sum_{i-1}^{N} CADF \quad (13)$$

Integration (or unit-root) test of Herwartz and Siedenburg (2008)

$$H_0{:}\delta=0$$

$$t_{SH} = \frac{\hat{\delta}_1}{SE_{\hat{\delta}_1}}$$

$$\text{P}-value = P\left(t_{HS} > \left|t_{HS}\right|\right)$$

The research utilized a panel cointegration test to investigate the association between variables over an extended period. Westerlund's error correction-based cointegration test was another method they used in their experiments. With the help of two different sets of test statistics, the research endeavored to test the null hypothesis that there was no cointegration.

$$\Delta Z_{it} = \partial_i d_i + \varnothing_i \left(Z_{i,t-1} - \delta_i W'_{i,t-1} \right) + \sum_{r=1}^{p} \varnothing_{i,r} \Delta Z_{i,t-r} + \sum_{r=0}^{p} \gamma_{i,j} \Delta W_{i,t-r} + \varepsilon_{i,t} \quad (14)$$

$$G_T = \frac{1}{N} \sum_{i-1}^{N} \frac{\varphi_i}{SE\varphi_i}$$

$$G_T = \frac{1}{N} \sum_{i-1}^{N} \frac{T\varphi_i}{\varphi_i(1)}$$

$$P_T = \frac{\varphi_i}{SE\varphi_i}$$

$$P_a = T\varphi_i$$

Pedroni (2004) develops residual-based cointegration test statistics for heterogeneous dynamic panels. The Author discussed asymptotic properties, conducted finite sample analysis, and explored relevance to the Purchasing Power Parity hypothesis. Besides, Kao (1999) explores the asymptotic properties of the least-squares dummy variable (LSDV) estimator and other standard statistics in spurious panel data regressions. Utilizing residual-based cointegration tests such as Dickey-Fuller (DF) and modified DF tests, the study employs asymptotic distributions and Monte Carlo experiments to evaluate finite sample quality and comprehend spurious regression in the panel.

Westerlund (2005); (2007) utilized a panel cointegration test to investigate the association among variables over an extended period. Westerlund's error correction-based cointegration test was another method they used in their experiments. With the help of two different sets of test statistics, the research endeavored to test the null hypothesis that there was no cointegration.

$$\Delta Z_{it} = \partial_i d_i + \varnothing_i \left(Z_{i,t-1} - \delta_i W'_{i,t-1} \right) + \sum_{r=1}^{p} \varnothing_{i,r} \Delta Z_{i,t-r} + \sum_{r=0}^{p} \gamma_{i,j} \Delta W_{i,t-r} + \varepsilon_{i,t} \quad (15)$$

$$G_T = \frac{1}{N} \sum_{i-1}^{N} \frac{\varphi_i}{SE\varphi_i}$$

$$G_T = \frac{1}{N} \sum_{i-1}^{N} \frac{T\varphi_i}{\varphi_i(1)}$$

$$P_T = \frac{\varphi_i}{SE\varphi_i}$$

$$P_a = T\varphi_i$$

The DCE model of the economy described above is given by the following equations:

$$c_t / \left(1-n_t\right) = \frac{\mu_1}{\mu_2}\left(1-\tau_t^l\right) w_t$$

$$U_{c_t} = \beta U_{c_t+1}\left[\left(1-\tau_{t+1}^k\right) r_{t+1} + 1 - \delta^k\right]$$

$$Q_{t+1} = \left(1-\delta^q\right)\overline{Q_t} + \delta^q Q_t - \phi A k_t^\alpha n_t^{1-\alpha} + vgt$$

$$c_t + k_{t+1} = A k_t^\alpha n_t^{1-\alpha} - gt + \left(1-\delta^q\right) k_t$$

DCE model is based on primary provisions for the variables of K_0 and Q_0 with first-order conditions of the sample firm problem, with endogenous variables A and ϕ with the given policy (τ^k, τ^l) which has resulted in $r_t = a_t n_t$ and $w_t = (1-\text{a}) A_t^a D_t^{-a}$. Then, we have a system containing five equations as $\left\{c_t, n_t, k_{t+1}, Q_{t+1}, g_t\right\}_{t=0}^{\infty}$. If we discard the subscript t, we can also get a long-term DCE.

The Dumitrescu-Hurlin (DH) panel causality model is articulated as:

$$y_{i,t} = \alpha_i + \sum_{k=1}^{K} \gamma_{ik} y_{i,t-k} + \sum_{k=1}^{K} \beta_{ik} x_{i,t-k} + \varepsilon_{i,t}$$
$$with\, i = 1,\ldots,N \; and \; t = 1,\ldots,T \quad (16)$$

In equation (2), $x_{i,t}$ and $y_{i,t}$ represent the observations of two stationary variables for individual *i* in period *t*. The coefficients are allowed to vary across the individual sample while remaining time-invariant, and the lag order *K* is assumed to be uniform across the panel. It is further assumed that the panel is balanced. The null hypothesis is stated as:

$H_0{:}\beta_{i1} = \ldots = \beta_{ik} = 0 \quad \forall_i = 1, \ldots, N$

The model implies the absence of a specific direction of causality for all individuals in the panel. The DH test also assumes that there can be a causal link between some variables and not necessarily all. Therefore, the alternative hypothesis is formulated as:

$H_1{:}\beta_{i1}=...=\beta_{ik}=0 \quad \forall_i=1,\ldots,N_1$

$\beta_{i1}\neq 0$ or…or $\beta_{ik}\neq 0 \quad \forall_i=N_1+1,\ldots,N$

Where $N_1 \in [0,N\text{-}1]$ is unknown. If N_1 is equal to 0, there is a causal link among the individual variables in the panel, and N_1 must be strictly greater than N.

AMG estimator introduced by Eberhardt and Bond (2009) and Eberhardt and Teal (2010) is highly robust regardless of cross-sectional dependence and slope heterogeneity. AMG estimator captures the unobservable common factors f t specified in equation (16) by the standard dynamic effect parameter. To describe the AMG estimator, consider this first difference OLS equation:

$$\Delta y_{it} = \alpha_i + \beta_i \Delta x_{it} + \sum_{t=1}^{T} \theta_t D_t + \varphi_i f_t + \varepsilon_{it} \tag{17}$$

Δ denotes the first-difference operator, β_i indicates the country-specific coefficients and θ_t Describes the coefficients of the time dummies.

The AMG estimator is then obtained from the across-panel averaged group-specific parameters:

$$AMG = \frac{1}{N}\sum_{i=1}^{N}\tilde{\beta}_i$$

In this equation, $\tilde{\beta}_i$ Are the estimates of β_i In other equations. As the performance of the AMG method in Monte Carlo simulation is unbiased and efficient for different N (number of observations) and T (time) settings Bond and Eberhardt (2013), this study employs the AMG method to evaluate the long-run parameters.

None of the above estimators allows for heterogeneity in the slopes. Pesaran and Smith (1995) propose a MG approach that does so by estimating individual (OLS) equation.

$$y_{it} = \alpha_i + \beta_i x_{it} + e_{it},\ e_{it} \sim iid\left(0,\sigma_i^2\right), \tag{18}$$

And define the estimator $\hat{\beta}^{MG} = N^{-1}\sum_{i=1}^{N}\hat{\beta}_i$ with variance

$$V\left(\hat{\beta}^{MG}\right) = \frac{1}{N(N-1)}\sum_{i=1}^{N}\left(\hat{\beta}_i - \overline{\beta}\right)^2$$

Pesaran (2004) reviews this and other RCM estimators. If the variables are $I(1)$ and cointegrated, then $\hat{\beta}_i$ is super consistent (rate T) for the long-run coefficient β_i. However, the estimates $\hat{\beta}_i$ will be spurious if e_{it} i s $I(1)$. But again, as with POLS and FE, averaging over the units will attenuate the noise, allowing a consistent estimator of β for large N. The response surface estimates in Fuertes et al. (2001) suggest that the dispersion of $\hat{\beta}^{MG}$ falls at rate $\sqrt{N}$ in the $I(1)$ error case; just like that of POLS and FE.

Regarding the results of CDST and SHT, the present study intends to adopt efficient and robust techniques for elasticity documentation and, most significantly, produce unbiased estimation in the presence of cross-sectional dependency and heterogenetic attributes in the research units. The present study has executed the target model following the framework familiarized by Chudik and Pesaran (2015), commonly known as CSARDL.

The Nonlinear Autoregressive Distributed Lag (NARDL) model can be suitable for our research investigating the relationship between digital finance inclusion, technological Innovation, remittance, good governance, and carbon emission. The NARDL model allows for capturing both short-run and long-run dynamics, which is paramount for understanding the potential impact of tourism on environmental sustainability through green energy and innovation.

$$\begin{aligned}\ln CO2_{it} &= \alpha_0 + \sum_{j=1}^{q^1 j}\gamma_{ij}\ln CO2_{i(t-j)} + \sum_{j=0}^{q}\gamma_{1j}\ln DFI_{i(t-j)} \\ &+ \sum_{j=0}^{q}\gamma_{2j}\ln TI_{it-j} + \sum_{j=0}^{q}\gamma_{3j}\ln REM_{it-j} + \sum_{j=0}^{q}\gamma_{4j}\ln GG_{it-j} \\ &+ \sum_{j=1}^{q^1 j}\theta_{ij}\ln\overline{CO2}_{i(t-j)} + \sum_{j=0}^{q}\theta_{1j}\overline{inDFI}_{i(t-j)} + \sum_{j=0}^{q}\theta_{2j}\, lnTI_{it-j} \\ &+ \sum_{j=0}^{q}\theta_{3j}\overline{lnREM}_{it-j} + \sum_{j=0}^{q}\theta_{4j}\overline{lnGG}_{it-j} + \varepsilon_{it-j}\end{aligned} \tag{19}$$

4. ESTIMATION AND INTERPRETATION

The Table 1 delivers the results of the SH test conducted by Bersvendsen and Ditzen (2021) to evaluate the validity of instruments used in an econometric model. The Delta Statistic, the test statistic, is reported as 3.2968, with three asterisks (***) indicating statistical significance. An Adjusted Delta Statistic is also provided, documented as 5.9833 with the exact significance level. These statistics reveal the strength of evidence against the null hypothesis of over-identifying restrictions. The "SH exits" column exhibits whether the null hypothesis is rejected, with a "Yes" indicating rejection, suggesting that the instruments used in the model are valid.

The results of cross-sectioal dependency test displayed in Table 2, In the Breusch and Pagan (1980) test, the regression analysis reveals significant relationships between variables and carbon dioxide (CO_2) emissions. The coefficient estimates indicate strong positive associations with CO_2 emissions for different factors. CO_2

Table 1: SH test of Bersvendsen and Ditzen (2021)

	Delta Statistic	Adjusted delta statistic	SH exits
Model	3.2968***	5.9833***	Yes

Table 2: Results of cross-sectional dependency test

	(Breusch and Pagan 1980)	Pesaran (2004)	Pesaran, Ullah et al. (2008)	Pesaran (2006)	Juodis and Reese (2022)
CO_2	413.09***	45.016***	173.15***	28.592***	6.1066***
DFI	207.463***	36.064***	102.303***	7.815***	−0.3903***
REM	396.291***	32.435***	213.568***	52.481***	−3.8954***
TI	369.576***	16.77***	111.91***	18.097***	4.6731***
GG	290.215***	19.047***	147.162***	14.341***	2.1472***
CE	264.608***	23.171***	109.583***	55.925***	−1.936***

Table 3: Results of panel unit root tests

Variables	CADF test statistic		CIPS test statistic		Herwartz and Siedenburg -2008	
	Level	First difference	Level	First difference	Level	First difference
CO_2	−2.775	−5.008***	−2.747	−3.869***	1.2107	7.8053***
DFI	−1.969	−4.429***	−2.925	−3.921***	0.8598	−0.3915***
REM	−1.77	−7.82***	−2.031	−6.037***	1.0385	−6.3244***
TI	−1.332	−5.339***	−2.653	−5.443***	1.8063	2.8382***
GG	−1.331	−3.198***	−1.685	−5.262***	−0.4217	7.2329***
CE	−1.383	−6.937***	−1.813	−2.099***	1.1055	6.1581***

Table 4: Panel cointegration test

Model	DFI--->CN	TI--->CN	CE--->CN	REM--->CN	GG--->CN
Gt	−11.441***	−10.177***	−13.212***	−9.507***	−13.848***
Ga	−12.228***	−14.295***	−8.675***	−7.319***	−9.011***
Pt	−13.492***	−10.09***	−5.666***	−15.012***	−9.366***
Pa	−13.243***	−14.718***	−7.104***	−14.501***	−15.277***
KRCPT					
MDF	11.132***	5.63***	10.987***	3.287***	−0.271***
DF	21.617***	−1.092***	2.408***	−8.74***	8.445***
ADF	16.569***	5.492***	18.977***	−0.474***	−0.479***
UMDF	−4.503***	12.851***	−7.47***	−2.442***	17.085***
UDF	−4.554***	13.518***	5.545***	7.753***	0.531***
PCT					
MDF	−8.499***	6.416***	13.72***	10.066***	0.841***
PP	3.288***	0.678***	15.222***	2.549***	−1.629***
ADF	11.792***	10.28***	8.332***	8.97***	9.397***

Panel B: Cointegration test of Westerlund and Edgerton (2008)						
	no shift		mean shift		regime shift	
	LMr stat.	LMΦ stat.	LMr stat.	LMΦ stat.	LMr stat.	LMΦ stat.
Model 1	−3.949***	−4.7635***	−4.9816***	−2.5166***	−2.2002***	−3.3095***

has a coefficient estimate of 413.09, showing a robust positive relationship with its emissions. Foreign direct investment (DFI) has a substantial coefficient estimate of 207.463, indicating a strong positive correlation with CO_2 emissions. Remittances (REM) and technology innovation (TI) also exhibit similar patterns, with coefficient estimates of 396.291 and 369.576, respectively, suggesting significant positive relationships with CO_2 emissions. Good governance (GG) and clean energy (CE) also show significant positive associations with CO_2 emissions, with coefficient estimates of 290.215 and 264.608, respectively. Throughout the various tests Pesaran et al. (2004), Pesaran et al. (2008), Pesaran (2006), and Juodis and Reese (2022) conducted, the coefficients of the independent variables (DFI, REM, TI, GG, CE) consistently show significance, albeit with different levels of t-statistics. This consistency indicates solid and reliable relationships between these independent variables and carbon dioxide emissions (CO_2) over different methodologies and timeframes.

The CADF test results demonstrate in, Table 3, the stationarity of each variable. CO_2 exhibits stationarity, with a test statistic of −2.775 at the level and −5.008 after differencing, both highly significant at the 1% level. DFI also shows stationarity, with a test statistic of −1.969 at the level and −4.429 after differencing, both highly significant. REM indicates stationarity, with a test statistic of −1.77 at the level and −7.82 after differencing, both highly significant. TI indicates stationarity, with a test statistic of −1.332 at the level and −5.339 after differencing, both highly significant. GG shows stationarity, with a test statistic of −1.331 at the level and −3.198 after differencing, both highly significant. CE shows stationarity, with a test statistic of −1.383 at the level and −6.937 after differencing, both highly significant. All variables show strong evidence of stationarity, particularly in the first differences, making them appropriate for further econometric analysis.

The CIPS test statistics suggest the presence of stationarity for each variable. For CO_2, the test statistic is −2.747 at the level and increases to −5.008 after differencing, with highly significant t-statistics of −3.869*** in both cases, indicating strong evidence of stationarity. Similarly, DFI exhibits stationarity, with test statistics of −2.925 at the level and −4.429 after differencing, both supported by highly significant t-statistics of −3.921***. REM shows stationarity with test statistics of −2.031 at the level and −7.82 after differencing, accompanied by highly significant t-statistics of −6.037***. TI displays stationarity, with test statistics of −2.653 at the level and −5.339 after differencing, both supported by highly significant t-statistics of −5.443***. GG indicates some evidence of stationarity at the level, with a test statistic of −1.685, and becomes more evident after differencing, with a test statistic of −3.198, both supported by highly significant t-statistics of −5.262*** and −5.443***, respectively. CE also exhibits evidence of stationarity, with test statistics of −1.813 at the level and −6.937 after differencing, both supported by highly significant t-statistics of −2.099. The results suggest that all variables are likely stationary in both levels and first differences, making them suitable for econometric analysis.

The Herwartz and Siedenburg (2008) statistics for variables such as CO_2, DFI, REM, TI, GG, and CE. The statistics show values for both levels and first differences, with significance at the 1% level. The statistics indicate stationarity after differencing for CO_2 and significant results for the other variables in both levels and first differences.

The panel cointegration test results in Table 4, indicate the presence of cointegration among the variables in the specified models. For the model FDI--->EC, the test statistics (Gt) are all highly significant, with values of −11.441***, −12.228***, −13.492***, and −13.243*** for the different specifications. Likewise, the test statistics are highly significant for the FDI--->GG model, ranging from −10.177*** to −14.718***. For the FDI--->ED model, the test statistics range from −5.666*** to −7.47*** and are all highly significant. For the FDI--->ER model, the test statistics range from −9.507*** to −15.277*** and are also highly significant. Additionally, the panel cointegration test of Westerlund and Edgerton (2008) further supports the presence of cointegration across the models, with LMr statistics ranging from −3.949*** to −2.2002*** and LMΦ statistics ranging from −4.7635*** to −3.3095***, all of which are highly significant. These results imply the existence of long-run relationships among the variables in the specified models, implying their mutual dependence and the presence of cointegration effects.

In the following, the empirical equation is executed with DCE and DCE−IV, and their results are displayed in Table 5. CN (−1) presence of a negative coefficient indicates that endeavors to achieve carbon neutrality in the preceding era are linked to a reduction in CO_2 emissions. The substantial t-statistic confirms that this association is statistically significant. The presence of a positive coefficient indicates that greater levels of digital financial inclusion are linked to a rise in CO_2 emissions, maybe owing to an upsurge in economic activity and energy use. The t-statistic's significance confirms the existence of this link.

Like DFI, remittances have a positive correlation with CO_2 emissions, suggesting that more significant inflows of remittances may result in heightened consumption and perhaps higher emissions.

Technological Innovation (TI) incidence of a negative coefficient suggests that technological innovation is linked to a decrease in CO_2 emissions, most likely due to enhancements in efficiency and the adoption of cleaner technology. This variable has a high level of statistical significance. CE (Clean Energy) unexpectedly, the coefficient is negative, indicating that while it is clean energy, the variables in the model may include factors where an increase in this variable is linked to a slight rise in emissions, maybe owing to the early establishment of infrastructure. The presence of a positive association in the alternative specification indicates that context plays a significant role. The negative coefficient in the context of Good Governance (GG) indicates that improved governance is linked to reduced CO_2 emissions, perhaps owing to more stringent environmental rules and policies.

The test statistics present evidence of Granger causality, see Table 6, from other variables to CO_2. For instance, the value (5.7598) for DFI indicates strong evidence of Granger causality from DFI to CO_2, as it exceeds the critical value. Contrariwise, the value (4.0648) for CO_2 under the DFI column suggests evidence of Granger causality from CO_2 to DFI. These results imply a bi-directional causality between CO_2 and DFI. Besides, significant test statistics under other variables' columns indicate Granger causality from those variables to CO_2, presenting a multi-directional relationship between CO_2 and the different variables. The values in square brackets represent the corresponding critical values at the 1% significance level. The test statistics indicate evidence of Granger causality from DFI to other variables like CO_2, REM, TI, GG, and CE, as indicated by their respective values exceeding the critical values. However, there is no significant evidence of Granger causality from other variables to DFI, as the corresponding test statistics do not exceed the critical values. These findings suggest that DFI may play a causal role in influencing other variables but is not influenced by them in return.

Table 5: Results of DCE and DCE-VI estimation

	Coefficient	SE	t-Statistic	Coefficient	SE	t-Statistic
		DCE			DCE-IV	
CN(-1)	−0.15184	0.024	−6.3266	−0.14	0.0416	−3.3653
DFI	0.14766	0.0318	4.6433	0.12311	0.0172	7.1575
REM	0.14621	0.0421	3.4729	0.12731	0.0444	2.8673
TI	−0.08487	0.0335	−2.5334	−0.12548	0.0187	−6.7101
CE	−0.08684	0.0319	−2.7222	0.13172	0.0265	4.9705
GG	−0.12427	0.0353	−3.5203	−0.13147	0.0177	−7.4276
c	−16.29	0.24013	−67.8382	−12.124	0.24013	−50.4893
R2	0.9035			0.8906		
Adj R^2	0.9224			0.9357		

The test statistics propose evidence of Granger causality from REM to TI and GG, as their values exceed the critical values. However, there is no significant evidence of Granger causality from other variables to REM, as their corresponding test statistics do not surpass the critical values. These results indicate a unidirectional causality from REM to TI and GG, indicating that remittances may influence technological innovation and good governance. The test statistics reveal evidence of Granger causality, see Table 6, from TI to CO_2, REM, and GG, as their values surpass the critical values. Conversely, there is no significant evidence of Granger causality from other variables to TI, as their corresponding test statistics do not exceed the critical values. These findings suggest a causal relationship between technological innovation and CO_2 emissions, remittances, and good governance, highlighting the importance of innovation in shaping various aspects of the economy. The test statistics indicate evidence of Granger causality from GG to CO_2, DFI, REM, and CE, as their values exceed the critical values. However, there is no significant evidence of Granger causality from other variables to GG, as their corresponding test statistics do not surpass the critical values. These results imply a causal relationship between good governance and CO_2 emissions, foreign direct investment, remittances, and clean energy, underscoring the role of governance in influencing various economic factors. The test statistics suggest evidence of Granger causality from CE to DFI and REM, as their values surpass the critical values. Nevertheless, there is no significant evidence of Granger causality from other variables to CE, as their corresponding test statistics do not exceed the critical values. These findings imply a causal relationship between clean energy and foreign direct investment and remittances, suggesting the potential of clean energy initiatives to impact these economic variables.

Following the study, different techniques were used to assess the earlier estimation robustness and efficiency. Table 7 displays the results of MG, MG, and CS-ARDL. Referring to the sign of the independent variables, it is found that the association with carbon neutrality supports the earlier model estimating with DCE and DCE-IV.

Table 8 displayed the results of the endogeneity issue and exposed the constructed empirical equation out of the endogeneity issue, thus revealing the robustness of the empirical estimation.

5. DISCUSSION OF STUDY FINDINGS

Our research reveals a positive correlation between including digital financial services and decreasing carbon emissions. It suggests that improved access to digital finance can lead to lower carbon emissions. This discovery is consistent with previous studies by Zhao et al. (2021), Wang et al. (2022), Ozturk and Ullah (2022), and Kasowaki and William (2024), which also linked increased digital financial inclusion to reduced carbon emissions by reducing the need for traditional banking methods and paper transactions. The findings emphasize the significance of implementing supportive policies to promote digital financial inclusion to achieve environmental sustainability objectives Gazzola et al. (2017). Oláh et al. (2018). Nations that focus on enhancing digital finance accessibility through mobile banking and electronic payments could see advantages in financial inclusion and reducing carbon emissions linked to conventional banking methods Li et al. (2023), Kwilinski et al. (2023). While our study confirms a link between the inclusion of digital finance and reduced carbon emissions,

Table 6: Results of the D-H causality test

	CO_2	DFI	REM	TI	GG	CE
CO_2		(5.7598)***	(4.0648)**	(3.3453)**	(3.3761)**	(2.9404)**
		(6.0708)	(4.2843)	(3.526)	(3.5585)	(3.0992)
DFI	(4.8012)***		(2.8257)*	1.5409	(3.8831)**	(5.2667)***
	(5.0605)		(2.9783)	(1.6241)	(4.0927)	(5.5511)
REM	0.8639	(3.4909)**		(4.4962)**	(4.3294)**	(2.8437)*
	(0.9106)	(3.6794)		(4.739)	(4.5632)	(2.9973)
TI	(6.086)***	1.4133	(3.3039)**		(4.8746)***	(6.0371)***
	(6.4147)	(1.4897)	(3.4823)		(5.1378)	(6.3632)
GG	(3.2571)**	(5.356)***	(3.5132)**	1.8841		(4.7098)**
	(3.433)	(5.6452)	(3.703)	(1.9859)		(4.9642)
CE	(2.2826)*	(6.0063)***	(4.0541)**	1.3081	(4.1498)**	
	(2.4059)	(6.3307)	(4.2731)	(1.3788)	(4.3739)	

Table 7: Robustness test with different techniques

	MG			AMG			CS-ARDL		
	Coeff	t-stat	std. error	Coeffi	t-stat	std. error	Coeff	t-stat	std. error
DFI	0.1768	0.0046	38.4347	0.1649	0.0021	78.5238	0.0817	0.0091	8.978
REM	−0.0279	0.0071	−3.9295	−0.1179	0.0028	−42.1071	−0.1513	0.006	−25.2166
TI	−0.0865	0.0064	−13.5156	−0.0988	0.0032	−30.875	−0.1683	0.0054	−31.1666
CE	−0.1019	0.0097	10.5051	−0.0187	0.005	−3.7465	−0.1437	0.0089	−16.146
GG	−0.0566	0.0119	−4.7563	−0.0398	0.0053	−7.5094	−0.0309	0.0044	−7.0227
c	6.8345	1.1078	6.1694	8.7038	1.1612	7.4955	1.4809	0.445	3.3278
CD test		0.0322			0.0234			0.0329	
Wooldridge Test for auto		0.0293			0.0321			0.0244	
Normality test		0.0271			0.0312			0.0247	
Remsey RESET test		0.0232			0.0289			0.0298	

Table 8: Endogeneity issue assessment-IV estimation

Robustness check	Coefficient	t-stat	SE
DFI	0.145	(0.0365)	(−3.9726)
REM	0.1317	(0.0195)	(−6.7538)
TI	−0.156	(0.0413)	(3.7772)
CE	−0.1624	(0.036)	(4.5111)
GG	−0.134	(0.0399)	(3.3583)
Anderson canon. Corr. LM statistics		12.1558	
Cragg-Donald Wald F statistics		1875.641	
Stock-Yogo weak ID test critical values		18.2305	

other studies have reported contrasting results. For instance, Zheng and Li (2022), Shen et al. (2023), and Mensah and Abdul-Mumuni (2023) discovered that the growth of digital financial services resulted in higher energy usage and electronic waste production, counteracting possible environmental advantages. The discrepancies in results may stem from variations in research methods, data used, and contextual elements like the state of digital infrastructure and regulatory frameworks across countries. It is essential to consider the surrounding circumstances that could affect the connection between the inclusion of digital finance and carbon emissions. For example, areas with restricted access to renewable energy and inadequate digital infrastructure may experience little environmental advantages from digital finance. Moreover, regulatory measures that promote sustainability and discourage harmful environmental practices can play a crucial role in shaping the link between digital finance and carbon emissions.

Our results support existing research showing that remittances can positively impact efforts to reach zero carbon emissions. Previous studies, i.e., by Zhang et al. (2022), Dash et al. (2024), and Zhang et al. (2023), have shown a link between remittances and investments in clean energy technologies, infrastructure, and sustainable development projects. Households receiving remittances may use some money for eco-friendly practices and renewable energy, leading to decreased carbon emissions Ratha (2011), Sikder and Higgins (2017). It is crucial to recognize conflicting research findings on the impact of remittances on clean energy investments Liu et al. (2023), Ramakrishnan et al. (2020). These discrepancies may be attributed to variations in how remittance funds are distributed among regions and households. Some studies show a strong positive link between remittances and clean energy investments. In contrast, others find little to no effect due to differences in socioeconomic conditions, governance systems, and policy frameworks Hamouri (2020), Yuyang (2024). The connection between remittances and environmental sustainability, specifically in decreasing carbon emissions, is well-recognized. Remittance money boosts the economic power of receiving households, allowing them to invest in clean energy technologies and eco-friendly practices Yang et al. (2021). Moreover, these funds often back local projects promoting environmental conservation and climate resilience Mills (2023). Both policy backing and research findings confirm this beneficial link, underlining how remittances can contribute to positive environmental outcomes in recipient communities Sikder and Higgins (2017).

Research results on the correlation between effective governance and achieving zero carbon emissions provide essential information on how governance strategies can influence environmental sustainability. Multiple studies support these findings, emphasizing the significant contribution of governance in encouraging eco-friendly behaviors and reducing carbon emissions Sharma et al. (2019), Zafar et al. (2022), Yang et al. (2020) and Zhang and Wen (2008). Research conducted by Ali et al. (2021) Osei-Kyei and Chan (2017) revealed that nations with elevated levels of transparency, accountability, and efficient governance systems are inclined to implement more ambitious climate policies and experience more significant success in decreasing carbon emissions. Likewise, a study by Leal Filho et al. (2016) demonstrated a direct relationship between indicators of good governance, like political stability and regulatory quality, and the execution of clean energy projects, resulting in reduced carbon emissionsCountries with strong governance structures may excel in environmental protection efforts. At the same time, those facing issues like corruption, inefficiency, or lack of political commitment may need help to address carbon emissions effectively Chu et al. (2022). Good governance is essential for reducing carbon emissions by creating an environment that supports sustainable practices and effective climate policies. Transparent and accountable governance structures help policymakers develop and enforce regulations that encourage industries to adopt low-carbon technologies. By setting clear rules, governments can incentivize businesses to invest in renewable energy sources and green infrastructure, thus reducing their carbon footprint. Additionally, good governance improves regulatory enforcement, ensuring compliance with environmental laws and promoting responsible corporate behavior. Participatory decision-making processes facilitated by effective governance allow diverse perspectives and interests to be included in climate policymaking, leading to more comprehensive solutions. Strong governance frameworks can also mobilize resources and facilitate cooperation among stakeholders at different levels to address environmental challenges collaboratively.

Similar findings to our study can be observed in research by, Gu et al. (2019), Khan et al. (2020), Hussain et al. (2022), who found a positive correlation between innovation efforts and the transition to zero carbon emissions. They emphasized the impact of technological innovation on clean energy adoption and carbon emission reduction, as well as stressed the significance of innovation in advancing renewable energy technologies. These studies align with our research, highlighting the essential role of innovation in transitioning to a low-carbon economy. Various factors can lead to different research findings, such as varying technological readiness levels and infrastructure investment in renewable energy technologies across regions or countries. Studies by Mohideen et al. (2023) showed that the impact of innovation on reducing carbon emissions varied based on the level of technological advancement and policy support in different regions. Regions with vital innovation ecosystems and supportive policies experienced more significant transitions to zero carbon emissions than regions with limited technological capabilities. Our study's thorough analysis, which includes various econometric tests and factors, provides a strong understanding of the connection between innovation, zero carbon emissions, and sustainability. The results offer necessary guidance for policymakers and stakeholders working towards creating effective strategies for a low-carbon economy.

6. CONCLUSION AND POLICY SUGGESTION

The research examined the connections between digital finance, remittances, good governance, clean energy, innovation, and carbon neutrality in the top 10 countries receiving remittances from 2001 to 2020. The study used panel data analysis and different statistical methods such as SH tests, CSD tests, CADF tests, D-H causality tests, and robustness checks; we analyzed the relationships between these variables. The research shows strong positive connections between carbon dioxide emissions and digital finance, remittances, technology innovation, good governance, and clean energy. These factors are found to impact carbon emissions in countries that receive remittances significantly. Furthermore, the analysis indicates that the variables exhibit stationary behavior, especially after undergoing differencing. The research suggests several policy recommendations to support sustainability and decrease carbon emissions. These include investing in renewable energy and technological advancements to encourage cleaner and more sustainable economic development. It is also advised that governance practices, such as transparency and accountability, be improved to help enforce successful environmental policies. Additionally, advocating for digital financial services and utilizing remittances for sustainable development efforts can direct financial support towards environmentally friendly projects. Moreover, encouraging collaboration and sharing of information globally can speed up the journey towards achieving carbon neutrality, particularly in developing countries heavily reliant on remittances. The study provides essential insights into how digital finance, remittances, governance, innovation, clean energy, and carbon emissions are interconnected. By adopting the recommended policies and promoting cooperation among different parties, we can work towards a more sustainable and environmentally friendly future.

Building upon our findings, there are some essential policies listed below. Firstly, policy initiatives should focus on investing in clean energy infrastructure, precisely renewable sources like solar and wind power. This investment can help countries decrease reliance on fossil fuels and lower carbon emissions. Encouraging the use of clean energy through subsidies and tax incentives can motivate businesses and individuals to switch to sustainable energy options. Secondly, governments should encourage the advancement of green technologies through incentives like research grants and partnerships between academia and industry. By supporting initiatives such as green tech incubators and promoting international collaboration, countries can speed up developing and implementing innovative solutions to reduce carbon emissions. Thirdly, implementing carbon pricing mechanisms like carbon taxes or cap-and-trade systems can motivate businesses to decrease carbon emissions by attaching a financial cost to them. This helps companies understand the impact of their emissions and encourages them to adopt strategies to lower their carbon footprint. Additionally, the funds generated from carbon pricing can support sustainable development projects, facilitating the shift towards a more environmentally friendly economy. Next, improving regulations and standards by setting strict emission targets can help businesses prioritize sustainability and invest in eco-friendly technologies. Regular monitoring and reporting can track carbon neutrality progress and ensure environmental performance accountability. Fifth, to decrease emissions, governments are encouraged to support sustainable transportation options like electric vehicles and public transit. Incentives like subsidies for EV purchases and charging infrastructure development can speed up the shift to cleaner transportation. Investing in public transit and promoting walking and cycling can also help reduce carbon emissions and enhance city air quality. Finally, it is recommended that policymakers focus on public education and awareness initiatives to promote sustainable behaviors and reduce carbon emissions. By educating citizens about the environmental impact of their actions and the benefits of sustainable living, governments can empower individuals to make informed decisions that support efforts to reduce carbon emissions. Additionally, integrating environmental education into school curriculums can instill a culture of sustainability in younger generations, leading to a lasting commitment to carbon neutrality.

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