JREE: Vol. 12, No. 2, (Spring 2025) 85-95

Journal of Renewable Energy and Environment

Journal Homepage: www.jree.ir

Materials and Energy Research Center

MERC

Research Article

Green Finance, Technological Innovation and Financial Globalization: Assessing Environmental Quality in MINT Economies

Emmanuel Samuel Udo[a], Johnson Ifeanyi Okoh[b]*, Okuji Obinna Oreh[b], Ewere Success Obieze[c], David Jerry Oziegbe[d], Olufolakemi Afrogha[e]

[a]Department of Banking and Finance, University of Akwa Ibom State, Obio Akpa Campus, Nigeria.
[b]Department of Financial Studies, National Open University of Nigeria, Abuja, Nigeria.
[c]Department of Business Administration, University of Delta, Agbor, Nigeria.
[d]Department of Accounting, University of Benson Idahosa, Benin, Nigeria.
[e]Department of Financial Studies, National Open University of Nigeria, Lagos, Nigeria.

PAPER INFO

Paper history:
Received: 28 October 2024
Revised: 12 February 2025
Accepted: 07 April 2025

Keywords:
Green Energy Financing,
Environmental Quality,
Financial Globalization,
Technological Innovation

ABSTRACT

Balancing economic growth and environmental quality (ENQ) remains a critical challenge for emerging economies, particularly in MINT countries (Mexico, Indonesia, Nigeria, and Turkey), where rapid industrialization, urbanization, and globalization impact ENQ. While green finance (GEFIN), technological innovation (TEIN), and globalization (GLOB) are key drivers of sustainability, their interactive effects on ENQ remain underexplored. This study investigates the interactive effects of GEFIN, TEIN, GLOB, and non-renewable energy (NREN) on ENQ, proxied by CO_2 and N_2O emissions from 1990 to 2023. Using Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS), we ensure robust long-run estimations while addressing issues like heterogeneity, serial correlation, and endogeneity. Panel cointegration tests confirm a long-run relationship. Data were sourced from the World Bank and the International Energy Agency (IEA). The results reveal that while GEFIN and TEIN initially increase emissions, GLOB mitigates these effects. Specifically, GEFIN increased CO_2 by 69.7% (FMOLS), 53.8% (DOLS), and N2O by 73.1% (FMOLS) and 2.6% (DOLS). TEIN increased CO2 by 10.8% (FMOLS), 4.2% (DOLS), and N_2O by 83.3% (FMOLS) and 14.9% (DOLS). On the other hand, GLOB reduced CO_2 by 33.3% (FMOLS), 26.7% (DOLS), and N_2O by 9.4% (FMOLS) and 10.2% (DOLS). NREN significantly worsens ENQ by increasing emissions. This study supports the Environmental Kuznets Curve hypothesis, revealing an inverted U-shaped relationship between economic growth and ENQ. The interaction terms indicate that GLOB helps mitigate the negative environmental effects of GEFIN and TEIN. We recommend strengthening GEFIN strategies, accelerating the adoption of renewable energy, and leveraging GLOB to enhance ENQ in MINT countries.

https://doi.org/10.30501/jree.2025.484493.2130

1. INTRODUCTION

The MINT countries (Mexico, Indonesia, Nigeria, and Turkey) represent a dynamic bloc of emerging economies characterized by rapid industrial growth, urbanization (URB), and increasing globalization (GLOB). These advancements have significantly spurred inclusive economic growth (PGDPC), but have also intensified environmental challenges, such as air and water pollution, habitat degradation, and climate change. These environmental issues pose a substantial threat to the achievement of the United Nations 2030 Sustainable Development Goals (UN-SDGs), particularly those related to environmental sustainability (ENQ), public health, and climate resilience. The urgency to address these challenges is heightened by the dominance of fossil fuels in MINT's energy mix, which accounts for 75–85% of global greenhouse gas (GHG) emissions. In 2023 alone, MINT countries collectively emitted around 1,587 million metric tons of CO_2 approximately 3% of global emissions underscoring the immediate need to transition to cleaner energy sources (Samuel et al., 2021; Udo et al., 2024).

Distinct from Brazil, Russia, India, China, and South Africa (BRICS) where China and India lead in green technology adoption, the MINT bloc lacks a unified ENQ governance framework for ENQ. Despite the increasing awareness of these challenges, the interactive effects of green finance (GEFIN), technological innovation (TEIN), globalization (GLOB), and non-renewable energy (NREN) on ENQ remain underexplored in the MINT bloc. Understanding these interactions is critical, as a fragmented approach could lead to piecemeal policy responses that may inadvertently worsen environmental challenges. Studies by Udo et al. (2024); Prince et al (2023) Udoh et al. (2024); Inim et al. (2024) while assessing these key factors in isolation, neglect their interactive and cumulative effects on ENQ.

This study addresses this gap by investigating how these four key drivers collectively influence ENQ. ENQ is proxied by greenhouse gas emissions (carbon dioxide (CO_2) and nitrous

*Corresponding Author's Email: jokoh@noun.edu.ng (J. I. Okoh)
URL: https://www.jree.ir/article_218406.html

Please cite this article as: Udo, E. S., Okoh, J. I., Oreh, O. O., Obieze, S. S., Oziegbe, D. J., Afrogha, O. (2025). Green Finance, Technological Innovation and Financial Globalization: Assessing Environmental Quality in MINT Economies, *Journal of Renewable Energy and Environment (JREE)*, 12(2), 85-95. https://doi.org/10.30501/jree.2025.484493.2130

oxide (N_2O)) given their significant contributions to climate change and public health risks. CO_2 the predominantly linked to fossil fuel combustion, deforestation, and industrial activities, whereas N_2O originates from agricultural, industrial, and organic combustion processes. These indicators provide a multidimensional assessment of the effect of PGDP activities on ENQ in the MINT bloc. These assessments align with the emergence of GFIN, TEIN, and GLOB as crucial tools for promoting sustainable development, energy efficiency, and industrial transformation to improve ENQ globally (Udo et al., 2024).

GFIN mitigate ENQ degradation through investment in renewable energy (REN) projects and sustainable technologies (Inim, 2024; Udo et al 2023). Unlike prior studies proxying GFI using the Environmental, Social, and Governance (ESG) index, this study adopts a more direct approach measuring GFIN based on funds allocated for REN projects, thereby offering policy-relevant insights into the role of the GFI in improving ENQ. TEIN also improves ENQ through energy efficiency and industrial transformation (Udo et al., 2024), but deplete ENQ if not managed properly. TEI presents a dual impact on the ENQ through scale, composition, and technique effects. Similarly, GLOB degrades ENQ through expansion in PGDP activities, it also improves ENQ by facilitating the transfer of cleaner technologies and promoting stringent ENQ standards in emerging markets. The scale effect of GLOB reveals that increased trade and investment inflows increase energy consumption (EC) and emissions, whereas the technique effect reveals that exposure to global markets encourages the adoption of green technologies. The direction and magnitude to which these factors interact to shape ENQ in the MINT bloc remains underexplored, with existing studies reporting mixed results on whether GLOB improves or degrades ENQ. Given MINT bloc's strategic roles in global trade and investment flows. Assessing the GLOB, GFI, and TEI interactive nexus on ENQ is vital for shaping MINT environmental economic policies.

Theoretical the EKC hypothesis underpinning this study, is an extension of Simon Kuznets' 1955 study on income inequality and inclusive economic growth (PGDP). Kuznets proposed that as economies evolve, income inequality initially rises and then falls, forming an inverted U-shaped curve (Figure 1). This concept was later adapted to environmental studies by environmental economists in the early 1990s, linking PGDP with ENQ impact (Inim et al., 2024; Enemuo et al. (2025). Environmental economists posit that ENQ initially decreases in the early stages of PGDP expansion and then improves as economies evolve, to adopt cleaner technologies at higher income levels, and prioritize environmental protection. While previous studies by Udoh et al. (2024) and Inim et al., (2024) have validated this hypothesis in BRICS and economic blocs, its application to MINT countries, with a specific focus on GEFIN, TEIN, and GLOB interactions, remains underexplored. (Figure 1) (Inim et al., 2024).

The urgency of addressing environmental quality (ENQ) challenges is heightened by global climate-related crises such as the COVID-19 pandemic (2020) and the Ebola outbreak (2014–2016), which underscored the interdependence between public health, ENQ, and economic resilience (Samuel et al., 2020;Pabon et al. 2015). Climate change poses significant threats to global livability, with temperatures projected to increase from 2.6°C to 4.8°C by 2100, exacerbating heat-related deaths, which reached 356,000 in 2019, food insecurity, and economic losses estimated to reach $23 trillion annually by 2050 (Samuel et al., 2020; Udo et al 2024).

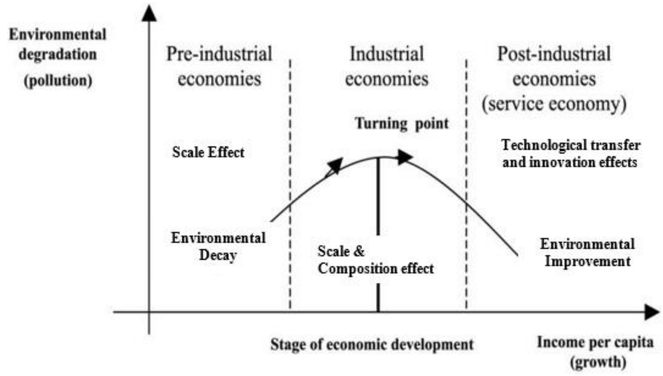

Figure 1. Environmental Kuznets Curve (EKC)

MINT countries contribute substantially to emissions, with CO_2 levels surpassing 420 ppm, a 50% increase from the pre-industrial era, while N_2O concentrations have risen from 20 to 40 µg/m³. Specifically, Mexico contributes 476 million metric tons of CO_2; Indonesia, 633 million metric tons of CO_2; Nigeria, 94 million metric tons of CO_2; and Turkey, 384 million metric tons of CO_2. According to the World Health Organization (WHO), poor ENQ contributed to approximately nine million premature deaths in 2023, with climate-induced food insecurity projected to increase global food demand by 50% by 2050. The dual challenge of meeting rising energy demands while reducing fossil fuel dependence underscores the need for sustainable energy transitions and technological innovations in MINT countries.

This study explores how TEIN, GEFIN, and GLOB interact to influence CO_2 and N_2O emissions, offering insights into their collective role in improving ENQ and fostering sustainable development in the bloc. This study expands existing literature by integrating the roles of GEFIN, TEIN, GLOB, and non-renewable energy (NREN) in shaping ENQ within the MINT bloc.

The key research contributions are:

1. Analysing the individual and combined effects of GEFIN, TEIN, GLOB, NREN, and per capita GDP squared ($PGDPC^2$) on ENQ.
2. Investigating the interactive effects of GEFIN, TEIN, and GLOB on CO_2 and N_2O emissions.
3. Testing the validity of the EKC hypothesis within the MINT context, incorporating the role of GLOB in mitigating environmental degradation.
4. Providing policy recommendations to balance PGDPC with ENQ.

To achieve these objectives, we employ Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) models, which address endogeneity, heteroskedasticity, and serial correlation challenges common to time-series analysis. Panel cointegration tests (Pedroni & Kao) ensure robust long-run relationships, while variance inflation factor (VIF) tests assess multicollinearity. This study provides critical policy insights for MINT economies to balance economic growth with ENQ. By integrating GEFIN, TEIN, and GLOB, the study underscores the need for targeted investments in GEFIN and TEIN, policies to accelerate renewable energy adoption, and leveraging GLOB for TEIN, along with robust climate governance and emissions regulation. By bridging existing gaps and offering a comprehensive policy framework, this study contributes to the sustainable development discourse in emerging economies.

2. LITERATURE REVIEW

The nexus between GEFIN, TEIN, PGDPC, GLOB, NREN, and environmental degradation has been extensively examined. This study aims to address three core areas: (1) the GEFIN and TEIN nexus and their influence on environmental quality, (2) the impact of GLOB on environmental sustainability, and (3) the energy-environment quality nexus within the Environmental Kuznets Curve (EKC) framework. Table 1 summarizes the relevant empirical studies that have applied the EKC framework.

2.1. Research Gap and Objectives

Despite substantial studies on the Environmental Kuznets Curve (EKC) framework and the role of green finance (GEFIN), technological innovation (TEIN), and globalization (GLOB) in environmental quality (ENQ), several critical gaps still persist. Notably, while significant attention has been paid to economic blocs such as BRICS and the EU, studies on MINT countries are sparse. The MINT bloc is characterized by unique socio-economic and environmental challenges, thus requiring a tailored investigation. Few studies have comprehensively examined the combined influence of GEFIN, TEIN, and GLOB on ENQ, particularly within heterogeneous and emerging economies such as the BRICS and EU blocs. However, the differential effects of renewable (REN) and non-renewable energy (NREN) consumption on environmental sustainability in the MINT context remain largely unexplored.

2.2. GEFIN, TEIN, and Environmental Quality Nexus

GEFIN and TEIN have been recognized as pivotal drivers of environmental quality (ENQ) improvement. Using a linear approach, Udo et al (2024) Samuel et al, (2023) confirmed the positive influence of TEIN on MINT countries. Similarly, Chen and Lee (2020) confirmed the synergistic impact of globalization (GLOB) and TEIN in driving ENQ across 96 countries. By employing a fixed-effects model for 96 countries from 1970 to 2016, Chen and Lee (2020) confirmed the synergistic impact of GLOB and TEIN on environmental sustainability across countries. However, contrasting findings by Costantini et al. (2017) and Dogan et al. (2020) in the BRICS bloc suggest that the effectiveness of TEIN depends on regional and institutional contexts. Focusing on MINT nations, this study investigates how these variables interact in underexplored regions with diverse socio-economic profiles. Based on this literature, hypotheses H_1 and H_2 are proposed: H_1: GEFIN significantly influences environmental sustainability in MINT countries. H_2: TEIN significantly influences environmental sustainability in MINT countries.

2.3. GLOB and Environmental Nexus

Previous studies have assessed the significant yet complex effects of globalization (GLOB) on environmental quality (ENQ) through scale, composition, and technique effects. Although GLOB drives industrialization (IND) and increases emissions through scale effects, it also facilitates the adoption of cleaner technologies for production through composition and technique effects (Usman et al. 2022; Enemuo et al. 2025;Yang et al. 2020). However, Umar et al. (2020) and (Inim et al., 2024) argue that GLOB exacerbates environmental degradation by enabling the relocation of carbon-intensive multinational corporations (MNCs) to developing nations, such as those in the MINT bloc, with lax environmental regulatory frameworks. By contrast, Jahanger et al. (2022), using quantile regression analysis in 73 developing countries, observed that GLOB enhances environmental quality in regions such as Africa and Latin America by facilitating technological transfer. The quantile regression models applied by Usman et al. (2021) and Jahanger et al. (2022), offer valuable insights into how GLOB affects environmental quality at diverse levels of development. However, this method ignores the complex nonlinear dynamics that more sophisticated models, such as ARDL or DOLS, address. Abner et al. (2021), revealed the non-linear effects of GLOB, providing a more nuanced understanding, particularly for MINT countries where GLOB intersects with unique developmental challenges. Therefore, based on the literature, H_3 is proposed as follows: GLOB significantly influences environmental quality in MINT countries.

2.4. Energy- Environmental Nexus and the EKC Framework

Energy consumption, both renewable (REN) and nonrenewable (NREN), plays a dual role in economic growth and environmental sustainability. Anwar et al. (2021), using ARDL and panel data methodologies, revealed that REN consumption reduces environmental degradation, whereas NREN exacerbates it. Salem et al. (2021) confirmed the Environmental Kuznets Curve (EKC) hypothesis, revealing an inverted U-shaped relationship.

Table 1. Summary of Empirical Studies and EKC Framework

Authors	Year	Scope	Methodology	Findings
Udo et al (2024)	1990-2023	MINT countries	linear ARDL	(∅) = Varied results
Usman et al (2021)	1990–2016	93 countries.	Quantile regression	(n) = N-shaped nexus
Samuel et al (2021); Ndubuaku et al (2021)	2000Q1-2018Q4	Nigeria	Linear ARDL	
Enemuo et al. (2025)	1999 to 2023		DARDL	
Arshad Ansari et al. (2020)	1991–2016	5 ASIA countries	FMOLS and DOLS	(∅) = Mixed results
Danish et al (2019)	1992–2016	BRICS countries		(∪) = U-shaped nexus
Dogan et al. (2020)	1980–2014		FMOLS, AMG, and DOLS	(×) = No nexus
Pata et al., (2020)	1965–2016	6 countries	Fourier-bootstrap autoregressive distributed lag	(×) = No nexus
Altıntaş et al (2020)	1990–2014	14 EU countries	Heterogenous estimation	(n) = N-shaped nexus
Destek et al (2020)	1980–2014	24 countries	Second-generation method	(×) = No nexus

Source: Author (2024)

However, the lack of focus on the REN-NREN interplay in the MINT bloc leaves a critical gap that this study addresses. Based on this literature, hypotheses H_4 and H_5 are proposed as follows: H_4: An increase in NREN consumption depletes environmental quality in MINT nations. H_5: The EKC hypothesis applies to MINT countries.

To address this methodological gap, this study employed Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) to provide a more robust methodological approach for estimating the long-term nexus between variables, offering corrections for endogeneity, serial correlation, and cross-sectional dependence. These models are superior in handling nonstationary data, making them particularly suitable for analyzing complex relationships in economic and environmental studies, where long-term effects and dynamics are essential. By employing FMOLS and DOLS, this study fills the methodological gaps left by previous models and ensures more accurate and unbiased results.

3. METHODOLOGY

3.1. Method, Data, and Analysis

The symmetric effects of GEFIN, TEIN, and GLOB on ENQ in MINT countries were assessed from 1990 to 2023. The selected timeframe encompasses a period of significant structural transformations, industrialization, and urbanization, all of which directly influence energy consumption and ENQ. The annualized dataset was extracted and collated from the World Development Indicators (WDI) and the International Renewable Energy Agency (Table 2). Prior studies assessing the economic-ENQ nexus have ignored the role of TEIN and GLOB in mitigating environmental degradation in MINT economies. This study fills this gap by incorporating the interactive effects of GEFIN and TEIN with GLOB to provide a comprehensive understanding of their environmental implications.

3.2. Model Specification

Fully Modified Ordinary Least Squares estimator (FMOLS) and Dynamic Ordinary Least Squares estimator (DOLS)

To capture the long-run elasticity of the ENQ determinants in MINT countries, we employ the FMOLS and DOLS models. These models are particularly suitable for analyzing panel data with non-stationary variables, a common characteristic in macroeconomic and environmental studies. Both FMOLS and DOLS are designed to address the econometric challenges that arise in such contexts, ensuring robust and unbiased estimates. The FMOLS corrects for endogeneity and serial correlation by incorporating non-parametric corrections, without altering the data structure. This makes it particularly effective in heterogeneous panels such as MINT blocs, which exhibit cross-sectional dependence due to shared economic shocks, trade linkages, and environmental spillovers. The model's ability to account for these dynamics while providing reliable long-run estimates aligns well with the study's objective of understanding the complex interactions among GEFIN, GLOB, and TEIN. The DOLS model, by incorporating lead and lag differences in explanatory variables, addresses autocorrelation and simultaneity issues, also mitigating small-sample bias and enhancing precision in finite samples by correcting for omitted variable bias. This is particularly important in the MINT context, in which the interplay between GLOB, TEIN, and ENQ involves time-lagged effects. The FMOLS and DOLS models are as follows:

The FMOLS model:

$$\emptyset^{\alpha} = \begin{pmatrix} \alpha \\ \beta \end{pmatrix} = \left(\sum_{t=2}^{T} Z_t Z_t^T\right) - 1\left(\sum_{t=2}^{T} Z_t\, T_t^{+}\right) - T\begin{pmatrix} \theta_{12}^{A+} \\ 0 \end{pmatrix} \quad (1)$$

DOLS Model:

$$y^{y} = X_t^{!}a + D_t^{!}\beta_1 + \sum_{j=-q}^{r} \Delta X_{t+j}\, Q + V_{1t} \quad (2)$$

In comparison with alternative models, such as the Autoregressive Distributed Lag (ARDL) adopted by Samuel et al. (2021); Samuel et al, (2023) and Udoh et al. (2024) to capture both short- and long-term dynamics in ENQ studies, the ARDL fails to adequately capture cross-sectional dependence in panel data, which is a critical factor in this study. While the Common Correlated Effects Mean Group (CCEMG), adopted by Kirikkaleli et al. (2022) and Destek et al (2020) effectively handles cross-sectional dependence something ignored by the ARDL model—it emphasizes group averages and fails to provide detailed long-run elasticity estimates, limiting its applicability to studies focused on individual country-level dynamics.

Table 2. Variable Descriptions and Source of Data

Variables	Nomenclature	Measurement	Source
Environmental quality (ENQ) (Proxied by CO_2 and N_2O emissions)	Carbon dioxide Emissions (CO_2)	CO2 emissions per capita (kt)	WDI (2023)
	Nitrous oxide (N_2O	kt of CO_2 equivalent	
Research and development expenditure	REDE	R&D expenditure (% of GDP)	
Technological innovation	TEIN	Number of patent applications	
Inclusive growth	PGDPC	GDP per capita (constant 2015 US$)	
Non-renewable energy	NREN	Fossil fuel energy consumption (% of total)	
Globalization index	GLOB	Globalization index (scale: 0–100)	(KOF 2023).
Green finance	GEFIN	Renewable energy projects investment (million $ at 2019 prices)	International Renewable Energy Agency (IRENA 2023)
Interactive Variables	GLOB*TEIN	Interaction between GLOB and TEIN	
	GLOB*GEFIN	Interaction between GLOB and GEFIN	

Source: Author (2024)

While the CCEMG is also suitable for addressing shared shocks, it does not capture the nuanced, long-term interactions between variables such as GEFIN, TEIN, and GLOB, which are central to this study. Using FMOLS and DOLS, this study achieves methodological rigor and ensures reliable estimates of the long-run integration nexus between GEFIN, GLOB, TEIN, and ENQ in the MINT bloc. This methodological approach enhances the study's ability to draw actionable policy insights for sustainable development.

The Baseline Model Equation:

Following Udo et al (2024) and Udoh et al. (2024), we specify the functional forms of CO_2 and N_2O emissions as proxies for ENQ:

$$CO_{2it} = f(GEFIN_{it}, TEIN_{it}, PGDPC_{it}, NREN_{it}, GLOB_{it}, REDE_{it}) \quad (3)$$

$$N_2O_{it} = f(GEFIN_{it}, TEIN_{it}, PGDPC_{it}, NREN_{it}, GLOB_{it}, REDE_{it}) \quad (4)$$

To address autocorrelation and heteroscedasticity, the equations are transformed into a natural logarithmic form:

$$CO2_{2it} = \gamma_0 + \gamma_1 In(GEFIN_{it} + \gamma_2 InTEIN_{it} + \gamma_3 InPGDPC_{it} + \gamma_4 InNREN_{it} + \gamma_5 InGLOB_{it} + \gamma_6 InREDE_{it} + \mu_{it} \quad (5)$$

$$N_2O_{it} = \mathfrak{Q}_0 + \mathfrak{Q}_1 In(GEFIN_{it} + \mathfrak{Q}_2 InTEIN_{it} + \mathfrak{Q}_3 InPGDPC_{it} + \mathfrak{Q}_4 InNREN_{it} + \mathfrak{Q}_5 InGLOB_{it} + \mathfrak{Q}_6 InREDE_{it} + \mu_{it} \quad (6)$$

i = cross-section of MINT countries; t = time period; Ω_0 *and* $Л_0 =$ intercept. The coefficients ($\Omega_1 - \Omega_6$ *and* $Л_1 - Л_2$) the elasticity of GEFIN, TEIN, PGDPC, NREN, GLOB, and REDE, with μ_{it} = error term.

Interactive Models

To examine how GLOB interacts with GEFIN and TEIN, we extend our baseline model: $GLOB * GEFIN$ *and* $GLOB * TEIN$

$$CO_{2it} = \Omega_0 + \Omega_1 In(GEFIN_{it}) + \Omega_2 In(TEIN_{it}) + \Omega_3 In(PGDPC_{it}) + \Omega_4 In(NREN_{it}) + \Omega_5 In(GLOB_{it}) + \Omega_6 In(REDE_{it}) + \Omega_7 In(GLOB * GEFIN_{it}) + \Omega_8 In(GLOB * TEIN_{it} + \mu_{it} \quad (7)$$

$$N_2O_{it} = Л_0 + Л_1 In(GEFIN_{it}) + Л_2 In(TEIN_{it}) + Л_3 In(PGDPC_{it)} + Л_4 In(NREN_{it}) + Л_5 In(GLOB_{it}) + Л_6 In(REDE_{it}) + Л_7 In(GLOB * GEFIN_{it}) + Л_8 In(GLOB * TEIN_{it}) + \mu_{it} \quad (8)$$

This specification allows assessing whether GLOB amplifies or mitigates the environmental impact of financial and technological advancements. Furthermore, to test the EKC hypothesis, we augment the baseline model by incorporating the squared term of GDP per capita ($PGDPC^2$):

$$CO_{2it} = \varkappa_0 + \varkappa_1 InGEFIN_{it} + \varkappa_2 InTEIN_{it} + \varkappa_3 InPGDPC_{it} + \varkappa_4 InPGDPC^2{}_{it} + \varkappa_5 InNREN_{it} + \varkappa_6 InGLOB_{it} + \varkappa_7 InREDE_{it} + \mu_{it} \quad (9)$$

$$N_2O_{it} = Л_0 + Л_1 In(GEFIN_{it} + Л_2 InTEIN_{it} + Л_3 InPGDPC_{it} + Л_4 InPGDPC^2{}_{it} + Л_5 InNREN_{it} + Л_6 InGLOB_{it} + Л_7 InREDE_{it} + \mu_{it} \quad (10)$$

EKC Interpretation:

To test the EKC hypothesis (inverted U-shaped), the model is extended by including the PGDPC terms:

$$ENQ_{it} = \beta_0 + \beta_1 InPGDPC_{\,it} + \beta_2 InPGDPC^{\,2}_{\,it} + X + \varepsilon \quad (11)$$

$\beta_1 > 0$ = PGDPC initially degrades ENQ. $\beta_2 < 0$ = Improves ENQ at higher income levels (quadratic effect, "turning point").
X = Control variables that may influence ENQ.
The turning point (PGDPC *) is calculated as

$$PGPD^* = -\frac{\beta 1}{2\beta 2} \quad (12)$$

This allows us to estimate the income threshold at which the quality of the environment begins to improve.

Cross-sectional Dependency (CD) and Panel Unit Root Test

Given the interconnectedness of MINT economies, cross-sectional dependence (CD) test was conducted using Breusch-Pagan Lagrange Multiplier (BP-LM) test, Pesaran's scaled LM test, and Pesaran's Cross-sectional Dependence (CD) test. Stationarity properties of the series were tested using the cross-sectional augmented IPS (CIPS) and cross-sectional augmented Dickey-Fuller (CADF) tests. These tests account for common shocks and heterogeneous dynamics in panel datasets.
The CIPS test equation:

$$\Delta S_{i,t} = \phi_i + \phi_i S_{i,t-1} + \sum_{I=0}^{p} \phi_i^{\,I} S_{t-1} + \mu_{it} \quad (13)$$

Panel Cointegration Tests

To assess the presence of long-run relationships among variables, we employ Pedroni (1999) residual cointegration test and Kao (1999) cointegration test. Both tests consider cross-sectional heterogeneity and serial correlation.

4. RESULTS AND DISCUSSION

The descriptive statistics in Table 3 highlight the significant variability of the environmental and economic indicators across MINT countries. Mexico (13.71 kt) had the highest mean N_2O emissions, followed by Nigeria (6.21 kt), Turkey (6.24 kt), and Indonesia (4.83 kt). In terms of CO_2 emissions, Indonesia (4.06 kt) recorded the highest average, followed by Mexico (3.83 kt) and Turkey (3.63 kt), while Nigeria (0.68 kt) had the lowest emissions.

Table 3. Descriptive Summary of the Study Variables

Panel	CO_2 (Kt)	N_2O (kt)	REDE (%)	TEIN	PGDPC ($)	NREN (%)	GEFIN ($)	GLOB
Mean	2.41	7.70	4.28	7.73	4582.88	4.44	2.19	7.97
Median	2.43	7.22	2.48	7.32	3399.60	3.72	2.17	5.49
Std. Dev.	1.42	5.28	7.95	3.99	3644.86	1.83	1.82	6.65
Skewness	0.06	0.64	5.93	0.07	0.60	1.20	0.492	0.36
Kurtosis	1.45	3.60	55.32	1.56	1.944	3.57	1.90	1.54
Turkey								
Mean	3.63	6.24	4.74	1.31	7020.58	2.86	4.70	8.54
Median	3.39	6.50	2.74	1.38	7686.44	2.92	4.69	7.11
Std. Dev.	0.76	4.04	9.40	0.84	3552.94	0.23	0.75	6.63
Skewness	0.25	-0.37	6.31	0.11	0.014	0.05	0.67	0.05
Kurtosis	1.82	1.89	53.30	1.89	1.366	1.713	3.21	1.52

Indonesia								
Mean	4.06	4.83	3.68	7.24	2063.77	4.16	0.677	10.29
Median	3.06	4.50	1.99	7.45	1411.09	4.26	0.664	11.44
Std. Dev.	0.38	2.66	6.24	1.47	1366.14	0.83	0.132	5.04
Skewness	0.02	-0.02	2.75	-0.36	0.36	0.11	0.098	-1.07
Kurtosis	2.25	2.71	15.59	2.33	1.42	1.52	2.468	2.81
Mexico								
Mean	3.83	13.71	4.46	2.64	7812.12	3.57	2.89	13.20
Median	3.86	13.50	3.05	1.32	8213.38	3.68	2.86	15.38
Std. Dev.	0.27	3.81	6.78	3.69	2322.55	0.31	0.36	6.77
Skewness	-0.26	0.77	5.62	3.00	-0.46	-0.45	-0.27	-1.25
Kurtosis	2.00	5.248	46.64	14.79	1.99	1.82	2.49	3.04
Nigeria								
Mean	0.68	6.215	4.06	6.81	1435.05	7.28	0.36	2.90
Median	0.70	6.55	3.06	1.788	1451.28	6.84	0.35	4.23
Std. Dev.	0.12	5.10	2.52	29.94	929.68	1.17	0.05	2.68
Skewness	0.21	1.28	0.83	10.99	0.229	1.11	0.17	-0.06
Kurtosis	1.78	6.23	2.34	140.69	1.591	3.16	1.92	1.23

Source: Author (2024)

The high level of CO_2 and N_2O emissions in Indonesia and Mexico can be attributed to reliance on fossil fuels and industrial inefficiencies. While Nigeria's emissions remain lower, they are compounded by high non-renewable energy use (7.28%) and minimal R&D investment (0.36%). Globalization plays a crucial role in mitigating environmental degradation, with Mexico (13.20) and Indonesia (10.29) demonstrating robust integration into global markets and benefiting from greater trade openness and technology transfer. In contrast, Nigeria's (2.90) globalization score indicates limited global integration, which constrains its sustainability efforts. This aligns with the Pollution Halo Hypothesis (Emmanuel et al., 2023), which argues that globalization facilitates technology transfer and cleaner industrial practices. Thus, increasing trade openness and foreign direct investment (FDI) in green sectors can enhance sustainability outcomes. These findings underscore the need for targeted policies, including accelerated renewable energy adoption, increased foreign investment in green industries, enhanced R&D spending, stricter industrial and agricultural regulations, and the promotion of circular economy practices. By implementing these measures, MINT countries can achieve a balanced approach to economic growth and environmental sustainability, aligning with global climate goals.

4.1. Unit Root

The unit root results in Panel A of Table 4 reveal that the study variables are stationary at mixed orders (I(0) and I(1)). The presence of I(1) variables, particularly CO_2 and N_2O emissions, supports the adoption of the FMOLS and DOLS models for cointegration analysis to examine the long-term environmental interactions. Both models are suitable for handling mixed integration levels. The CD results in Panel B show significant CD statistics across all variables, implying that ENQ and its determinants are interdependent across MINT countries. This underscores the necessity of employing panel econometric techniques that account for cross-country spillover effects, such as FMOLS and DOLS. Ignoring cross-sectional dependence could lead to biased estimates and misleading policy conclusions.

4.2 Panel Cointegration Test Model

The results in Table 5 (Panel A) reject the null hypothesis (H_0) of no cointegration across multiple tests (Pedroni, Kao). This confirms the presence of a long-run equilibrium relationship between ENQ, GEFIN, TEIN, GLOB, and NREN. This result justifies the use of FMOLS and DOLS to analyze the long-run and stable nexus between the study variables over time. Diagnostic tests (Panel B) confirmed the robustness of the model. Heteroskedasticity (0.619) indicates that the residuals have constant variance, ensuring the reliability of our results. Serial Correlation (0.325) indicates the absence of serial correlation, meaning past errors do not systematically affect future values. Normality (0.778) confirms that the residuals follow a Gaussian distribution, further validating the statistical reliability of the model. These results confirm that GEFIN, GLOB, and TEIN interact with ENQ in a stable long-run equilibrium. Policymakers should focus on sustainable financial strategies and technology-driven environmental solutions that yield long-term benefits across MINT economies.

Long-Run Elasticity Estimations

Model 1: GEFIN -Environmental Quality Nexus

Across the models, GEFIN significantly increases emissions, supporting the idea that GEFIN initially leads to higher emissions due to upfront costs and inefficiencies in fund allocation. In the CO_2 model, GEFIN increased emissions by 69.7% (FMOLS) and 53.8% (DOLS), while also increasing N_2O by 73.1% (FMOLS) and 2.6% (DOLS). These results imply that while GEFIN aims to support sustainability, its initial impact is detrimental due to carbon-intensive industrial projects and regulatory inefficiencies.

As economies evolve and financial institutions allocate resources more effectively to renewable energy (REN) projects, ENQ improves while emissions decline. This aligns with the EKC hypothesis, where emissions rise at early development stages before declining. This result aligns with the findings of Ndubuaku et al (2021) Sadorsky (2010); Emmanuel et al (2023); Udo et al (2024); Udoh et al (2024) the long-run contribution of GEFIN towards ENQ sustainability. These studies revealed that stringent policy frameworks and incentives reduce short-term emissions incurred due to industrial activities and lax regulations.

Le et al (2020) and Inim et al., 2024) also revealed that the positive impacts of GEFIN on emissions reduction are conditional on the maturity of the financial sector and its ability to channel funds effectively into green projects.

Table 4. Unit Root Test and Cross-Sectional Dependence Result

Panel A: Unit Root					Panel B: (CD)			
Variables	CIPS		CADF		Breusch–Pagan LM	Pesaran scaled LM	Bias-corrected scaled LM	Pesaran CD
	I (0)	I(1)	I (0)	I(1)				
CO_2	-3.013	-8.677**	-2.11	-6.628**	197.400**	55.252**	55.190**	14.049**
N_2O	-2.509	-8.912**	-2.06	-5.719**	162.891**	45.290**	45.226**	12.758**
REDE	-3.017	-7.421**	-1.351	-8.566**	49.656**	12.602**	12.540**	6.531**
TEIN	-4.011*	-6.761**	-3.014*	-6.335**	75.981**	12.891**	12.701**	7.708**
PGDPC	-5.865**	-2.107*	-2.139*	-8.491**	79.042**	21.085**	21.020**	8.322**
NREN	-2.290	-6.216**	-3.373*	-6.286**	37.775**	9.172**	9.110**	7.6024**
GEFIN	-2.349*	-8.013**	-4.416*	-6.052**	67.374**	17.717**	17.654**	7.499**
GLOB	-3.810*	-7.382**	-3.152*	-6.597**	70.071**	18.495**	14.433**	8.113**

N/B * significant at 1% and ** 5%. Source: Author (2024)

Table 5. Cointegration Test and Diagnostics Test Results

Panel A: Cointegration Test Results			Panel B: Diagnostics Tests Results	
Statistics	Value	Prob…	Tests	Prob…
Pedroni Test			Heteroskedasticity	0.619
H_0: No cointegration; H_1: Cointegration			Serial correlation	0.325
Modified Phillips-Perron regression	6.010	0.001**	Normality	0.778
Phillips-Perron regression	(4.419)	0.000**	The prob-values of the diagnostics test results are non-significant, implying the absence of heteroskedasticity and serial correlation, and that the series is normally distributed.	
Augmented Dickey-Fuller regression	(6.118)	0.000**		
Kao Test				
H_0: No cointegration; H_1: Cointegration				
Modified Dickey-Fuller t	-5.222	0.000**		
Dickey-Fuller t	-6.375	0.000**		
Augmented Dickey-Fuller t	-6.501	0.000**		
Unadjusted modified Dickey-Fuller t	-7.020	0.000**		
Unadjusted Dickey-Fuller t	-6.060	0.000**		
Note: *** (significance at 1%)				

Source: Authors (2024)

Table 6. Long-Run Estimations

DP = CO_2	**H_1**		**H_2 GEFIN* GLOB**		**H_3 EKC Hypothesis**		**H_4 TEIN* GLOB**	
	FMOLS	**DOLS**	**FMOLS**	**DOLS**	**FMOLS**	**DOLS**	**FMOLS**	**DOLS**
GEFIN	0.697** (2.20)	0.538* (1.49)	0.634** (5.56)	0.166* (2.69)	0.083* (1.50)	0.022* (0.40)	0.014* (1.01)	0.045** (2.72)
TEIN	0.108* (2.55)	0.042** (3.21)	0.063** (5.30)	0.052* (1.91)	0.036* (2.21)	0.052* (1.91)	0.038* (2.21)	0.054* (1.86)
PGDPC	0.674** (30.51)	0.773** (21.86)	0.934* (2.76)	0.735** (18.42)	0.993* (3.22)	0.356** (5.26)	0.494* (3.51)	0.490** (15.74)
$PGDPC^2$					-0.467** (-5.13)	-0.54** (-3.71)		
NREN	0.719** (3.18)	0.530** (5.89)	0.620** (9.55)	0.187* (2.77)	0.993** (3.22)	0.016** (3.807)	0.243** (7.04)	-0.095* (-0.30)
REDE	-0.819* (-0.21)	-0.381* (-1.78)	-0.315* (-2.46)	-0.203** (-3.36)	-0.166* (-2.69)	-0.012* (-0.61)	-0.765** (-5.66)	-0.233** (-4.851)
GLOB	-0.333* (-2.84)	-0.267* (-4.77)	-0.080* (-0.091)	-0.062* (-0.84)	-0.365** (-3.65)	-0.304** (-3.80)	-1.563** (-5.95)	-2.072** (-2.89)
GEFIN* GLOB			-0.689** (-19.24)	-0.507** (-8.28)				
TEIN* GLOB							-0.410** (-5.60)	-0.739** (-6.25)
DP = N_2O	H_1		H_2		H_3		H_4	
	FMOLS	DOLS	FMOLS	DOLS	FMOLS	DOLS	FMOLS	DOLS
GEFIN	0.731** (3.86)	0.026* (0.93)	0.022* (2.54)	0.264* (3.07)	0.269** (11.93)	0.530* (1.79)	0.134* (0.66)	0.352* (2.22)

TEIN	0.833** (6.46)	0.149** (9.30)	0.154** (8.24)	0.535** (7.45)	0.502* (3.98)	0.045** (24.09)	0.451** (4.10)	0.7817 (5.51)
$PGDPC^1$	0.018** (2.77)	0.036** (6.24)	0.081 (0.33)	0.470** (2.98)	0.815* (3.07)	0.055** (7.78)	0.475** (4.09)	0.706** (7.66)
PGDPC2					-0.246** (-16.56)	-0.62** (-3.45)		
NREN	0.017* (1.032)	0.198** (7.24)	0.058** (6.76)	0.030* (0.71)	0.035** (5.87)	0.246** (16.56)	0.133** (6.37)	0.706** (7.96)
REDE	-0.764** (-9.29)	0.013 (13.69)	0.099 (4.27)	0.2804** (3.96)	0.950** (5.28)	0.114** (3.44)	0.860** (11.06)	0.084** (5.39)
GLOB	-0.094** (-5.84)	-0.102** (-6.36)	-0.165 (-9.70)	-0.017** (-10.85)	-0.106* (-0.12)	-0.614** (-9.92)	-0.074* (-0.59)	-0.486** (-8.717)
GEFIN* GLOB			0.351** (5.52)	0.614** (9.92)				
TEIN* GLOB							0.641** (6.24)	0.417** (7.87)

Source: Author (2024)

Model 2: TEIN -ENQ Nexus: TEIN has a positive and significant effect on emissions, revealing the dependence of MINT countries on non-renewable energy (NREN) for industrial innovation. A 1% increase in TEIN consumption driven by fossil fuels depletes ENQ through CO_2 emissions by 10.8% (FMOLS) and 4.2% (DOLS), and N_2O by 83.3% (FMOLS) and 14.9% (DOLS). This indicates that TEIN in MINT countries is energy-intensive and heavily dependent on NREN energy sources. These results reveal that the transition to eco-friendly R&D and clean energy-based innovation is slow due to a lack of policy incentives and green technology diffusion. This finding shows that MINT countries are still in the early stages of green technological adoption, where initial technological adoption increases pollution, thus supporting the EKC hypothesis, which states that innovation initially exacerbates environmental degradation before sustainability benefits emerge. To address the slow transition, triggered by a lack of effective knowledge sharing, there is a dire need for innovation hubs, public-private partnerships, and international cooperation for sustainable technology exchanges.

GLOB - Environmental Nexus: GLOB improves ENQ, reinforcing the role of global technology spillovers in sustainability. The negative coefficient of GLOB shows that a 1% increase in GLOB decreases CO_2 emissions by 33.3% (FMOLS) and 26.7% (DOLS), and N_2O by 9.4% (FMOLS) and 10.2% (DOLS), respectively. These results reveal that MINT countries can benefit from globalization through knowledge and technology transfer that promotes clean energy adoption and sustainable business and economic practices, reducing emissions over time. These results validate the theoretical argument that GLOB promotes sustainability through technological spillovers and resource exchange. It also aligns with the argument that foreign investments and trade openness facilitate sustainability, reducing environmental degradation. This result is consistent with those reported by Yang et al. (2020), Udo et al (2024), and Udoh et al (2024). The study recommends that policymakers should leverage GLOB to attract sustainable investments and enhance technology exchange among MINT countries.

NREN- ENQ Nexus: NREN positively and significantly increases emissions, highlighting continued dependence on fossil fuels for industrialization in the MINT bloc. As such, NREN degrades ENQ through CO_2 by 71.9% (FMOLS) and 53.0% (DOLS), and N_2O by 1.7% (FMOLS) and 19.8% (DOLS). Heavy reliance on fossil fuels for industrialization is a key driver of environmental degradation in MINT economies. This result reinforces the urgent need for REN investment, infrastructure, and carbon taxation policies to enhance the adoption of REN and improve ENQ.

Model 3: The positive PGDPC coefficient for CO_2 (0.674 FMOLS, 0.773 DOLS) and N_2O (0.018 FMOLS, 0.036 DOLS) indicates that economic growth initially increases emissions. The negative $PGDPC^2$ coefficient for CO_2 (-0.467 FMOLS, -0.540 DOLS) and N_2O (-0.246 FMOLS, -0.620 DOLS) confirms the EKC hypothesis, showing that emissions decline as income rises. The Turning Point (TP) is estimated to be around $12,000 per capita GDP in the CO_2 model and around $10,000–$12,000 GDP per capita in the N_2O model (Figure 2). According to the World Bank Index (2023), the GDP per capita of Mexico ($10,500), Turkey ($11,000), Indonesia ($4,300), and Nigeria ($2,200) are below the estimated $10,000–$12,000 GDP per capita turning point. According to the EKC, the economic growth of these countries is associated with increasing emissions due to industrial expansion, lax environmental regulations, and reliance on fossil fuel-based energy. However, Mexico and Turkey are approaching the pollution peaks, while Indonesia and Nigeria are still in the emission-growth phase. The actual emission trends are determined by factors like industrial composition, energy consumption sources, and regulatory effectiveness.

Model 4: Interactive Effects: (GEFIN*GLOB) and (TEIN*GLOB) on Environmental Quality: The interactive terms (GEFIN * GLOB) and (TEIN * GLOB) significantly reduce emissions. This suggests that GLOB enhances the sustainability of technological innovation and the efficiency of green finance. The GEFIN * GLOB term has coefficients of -0.689 (FMOLS) and -0.507 (DOLS), while the TEIN * GLOB term has coefficients of -0.410 (FMOLS) and -0.739 (DOLS). These results confirm theoretical predictions that global partnerships, foreign investments, and policy harmonization can drive sustainability in emerging economies. The findings are consistent with those reported by (Inim et al., 2024; Samuel et al, 2023;Samuel et al 2021; Enemuo et al. (2025) This gradual shift aligns with the EKC hypothesis. The study recommends that governments foster international collaboration to maximize synergies between GLOB, GEFIN, and TEIN. Figure 2 illustrates the residual, actual, and fitted terms of environmental quality depletion caused by CO_2 and N_2O emissions in MINT countries over the long term.

Residual, Actual, and Fitted Terms of Environmental Degradation: The blue line in the residuals in Figure 3 represents the variance between actual and fitted values over time. Figure 3 highlights the predictive power of GEFIN, GLOB, and TEIN on environmental quality in MINT countries. The close alignment between the "Actual" and "Fitted" lines emphasizes their significant influence, although periods of divergence suggest varying impacts. This study recommends that policymakers focus on high-residual periods and countries to identify additional factors influencing environmental quality. Increasing investments in green finance and technology, alongside supportive globalization policies, is essential for improving environmental outcomes.

The findings of this study support the EKC hypothesis and underscore the significance of focused strategies involving GEFIN, GLOB, and TEIN to achieve environmental sustainability. Key recommendations include prioritizing the development of REN infrastructure, incentivizing green R&D, fostering innovation hubs, leveraging GLOB to attract sustainable investments, and enhancing technological spillovers. These strategies align with the EKC framework and will support MINT countries in transitioning towards sustainable development while mitigating the environmental costs associated with industrialization and innovation.

5. CONCLUSIONS

This study evaluates the impact of GLOB, GEFIN, NREN, and TEIN on environmental quality in MINT countries within the EKC framework from 1990 to 2023, using FMOLS and DOLS models to address key econometric challenges such as endogeneity, serial correlation, and heteroscedasticity. The results reveal significant long-term relationships among the variables, with differentiated effects on environmental quality (ENQ), proxied by GHGs (CO_2 and N_2O emissions). GEFIN increased CO_2 emissions by 69.7% (FMOLS) and 53.8% (DOLS), and GHG emissions by 73.1% (FMOLS) and 2.6% (DOLS). These results suggest that, in MINT countries, the early phase of financial inclusion in green investments is linked to increased emissions due to infrastructure expansion and transitional costs. Inim et al., (2024) reported similar trends, noting that GEFIN results in short-term emissions trade-offs as infrastructure adapts but yields long-term benefits as financing mechanisms mature.

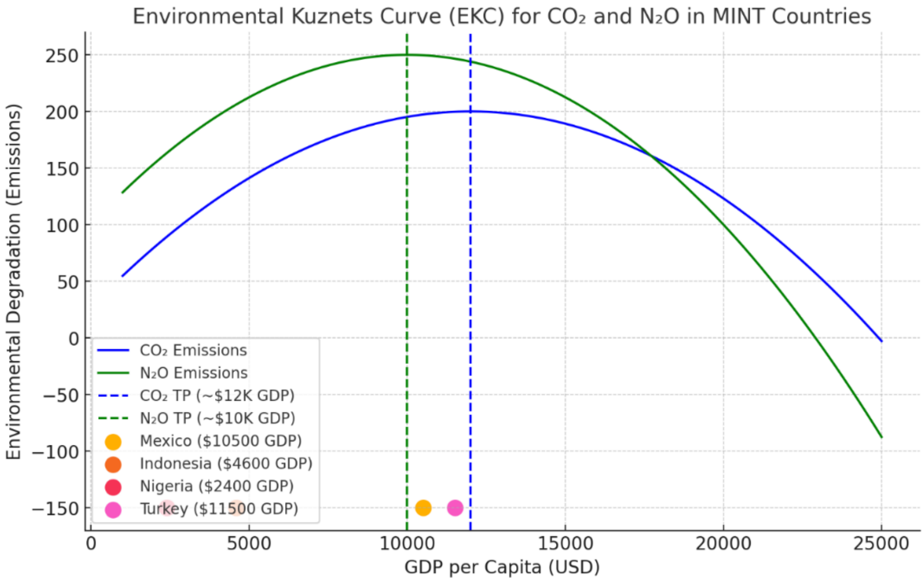

Figure 2. Environmental Kuznets Curve (EKC) for CO_2 and N_2O emissions in MINT

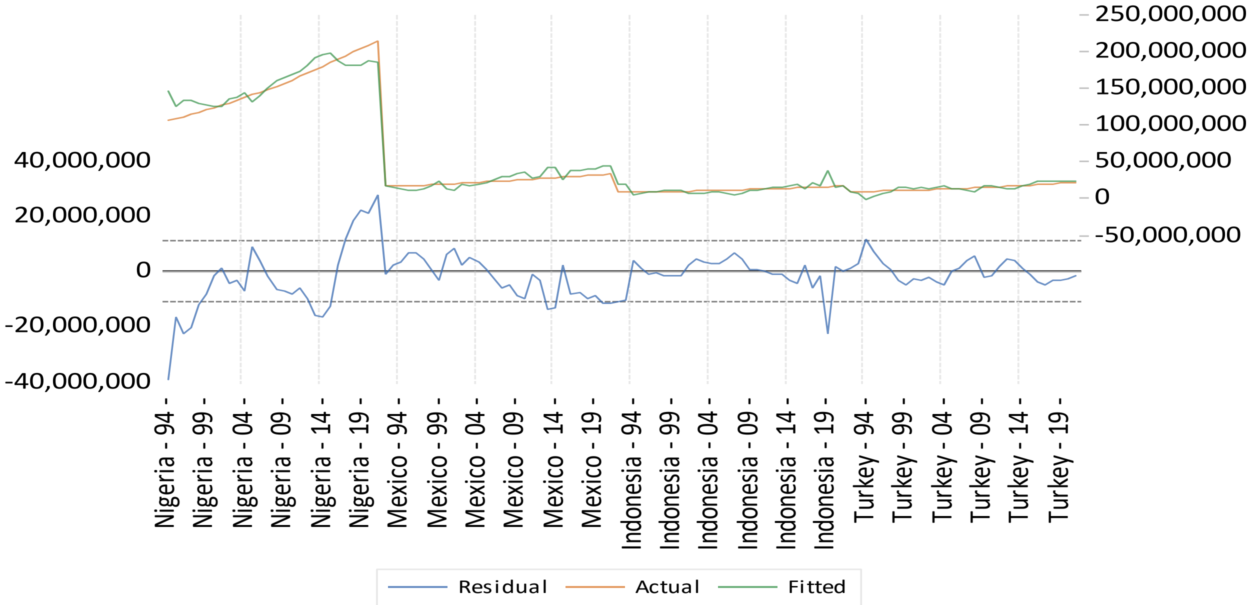

Figure 3. Residual, Actual, and Fitted Terms of Environmental Quality Depletion. Source: Author (2024)

A 1% change in TEIN resulted in a 10.8% (FMOLS) and 4.2% (DOLS) increase in CO2 emissions, and an 83.3% (FMOLS) and 14.9% (DOLS) increase in N2O emissions. This indicates that TEIN development in MINT countries is energy-intensive, relying heavily on fossil energy (Inim et al., 2024); Udo et al 2024). However, when driven by artificial intelligence (AI), TEIN has the potential to transform renewable energy (REN) systems, improve grid efficiency, and reduce emissions and transmission losses by up to 25% (Udo et al 2024).

NREN increased CO_2 emissions by 71.9% (FMOLS) and 53.0% (DOLS), and GHG emissions by 1.7% (FMOLS) and 19.8% (DOLS). These results highlight the urgent need for a transition to REN in MINT economies. A study by Wilson et al. (2023) in emerging economies found a 40% reduction in emissions following large-scale investments in solar and wind energy, further emphasizing the need for policy-driven REN adoption.

GLOB reduced CO_2 emissions by 33.3% (FMOLS) and 26.7% (DOLS), and GHG emissions by 9.4% (FMOLS) and 10.2% (DOLS). These results underscore GLOB's role in the transfer of TEIN and fostering sustainable practices. Rahman et al. (2023) reported similar findings, emphasizing the positive environmental impact of GLOB, particularly through multinational collaborations on REN projects and emissions reduction targets.

The study confirms a U-shaped EKC pattern for MINT countries, where economic growth initially leads to higher emissions ($PGDPC^2$ coefficients of -0.467 for CO2 and -0.246 for GHG). However, as these economies evolve and invest in green energy, ENQ improves. The findings indicate that MINT countries must reach turning points (TP) for CO2 (≈ $12,000) and N2O (≈ $10,000 GDP per capita) before emission reductions occur through economic transformation and sustainability investments. Mexico ($10,500 GDP per capita) and Turkey ($11,500 GDP per capita) are approaching these turning points, suggesting that their emissions may soon stabilize or decline. In contrast, Indonesia ($4,600 GDP per capita) and Nigeria ($2,400 GDP per capita) remain in the emissions-rising phase, requiring proactive green policy interventions.

The interaction terms (GEFIN * GLOB and TEIN * GLOB) significantly reduced emissions. Specifically, GEFIN * GLOB reduced emissions by 68.9% (FMOLS) and 50.7% (DOLS), while TEIN * GLOB reduced emissions by 41.0% (FMOLS) and 73.9% (DOLS). These results highlight the synergy between TEIN and GLOB in promoting sustainability.

The integration of AI into REN development optimizes energy storage, predicts demand patterns, and enhances the efficiency of REN grids. Udo et al. (2024); Prince et al (2023) found that integrating AI into REN systems reduced operational costs by 30% and increased system reliability in developing countries. Based on these results, the following policy recommendations are proposed to improve environmental sustainability in MINT countries:

1. **International Collaboration:** MINT countries should strengthen partnerships with advanced economies, such as China, the United States, and the European Union, to facilitate knowledge transfer and increase investments in REN technologies.
2. **AI in REN Systems**: International cooperation should accelerate the adoption of green innovations, leveraging AI to optimize REN systems, improve grid efficiency, and reduce energy wastage.
3. **Regional Energy Markets**: Establishing regional energy markets and facilitating technology exchange within the MINT bloc can help expedite the transition to sustainable energy systems.

This study aligns with global trends showing that, while challenges persist, technological advancements and globalization offer substantial opportunities for improving environmental quality through renewable energy developments.

6. ACKNOWLEDGMENT

We are grateful to the anonymous referees of the journal for their amazing and useful suggestions to improve the quality of the article. Usual disclaimers apply.

REFERENCES

1. Abner Ishaku Prince, Inim, I. O., Eneoli Obinna Callistus, & Udo, E. S. (2021). Energy Consumption Effect on Economic Growth in Nigeria: Multivariate Framework. *International Journal of Economics, Management and Accounting*, 29(2), 519–542. https://journals.iium.edu.my/enmjournal/index.php/enmj/article/view/932

2. Altıntaş, H., and Kassouri, Y. (2020) Is the Environmental Kuznets Curve in Europe Related to the Per Capita Ecological Footprint or CO2 Emissions? Ecol. Indicators 113, 106187. https://doi.org/10.1016/j.ecolind.2020.106187

3. Anwar, A., Sinha, A., Sharif, A., Siddique, M., Irshad, S., Anwar, W., et al. (2021b). The Nexus Between Urbanization, Renewable Energy Consumption, Financial Development, and CO2 Emissions: Evidence from Selected Asian Countries. Environ. Dev. Sustain., 1–21. https://doi.org/10.1007/s10668-021-01716-2

4. Arshad Ansari, M., Haider, S., and Khan, N. A. (2020). Environmental Kuznets Curve Revisited: An Analysis Using Ecological and Material Footprint. *Ecol. Indicators* 115, 106416. https://doi.org/10.1016/j.ecolind.2020.106416

5. Chen, Y., and Lee, C.-C. (2020). Does Technological Innovation Reduce CO2 emissions? Cross - Country Evidence. J. Clean. Prod. 263, 121550. https://doi.org/10.1016/j.jclepro.2020.121550

6. Costantini, V., Crespi, F., Marin, G., and Paglialunga, E. (2017). Eco-innovation, Sustainable Supply Chains and Environmental Performance in European Industries 1 1We Gratefully Acknowledge the Support by the European Union's Horizon 2020 Research and Innovation Programme under grant Agreement No. 649186 - ISIGrowth. The Comments and Suggestions by Three Anonymous Referees Are Also Acknowledged. The Usual Disclaimers Apply. J. Clean. Prod. 155, 141–154. https://doi.org/10.1016/j.jclepro.2016.09.038

7. Danish, Baloch, M.A., Mahmood, N., Zhang, J.W., (2019). Effect of natural resources, renewable energy and economic development on CO2 emissions in BRICS countries. Sci. Total Environ. 678, 632–638. https://doi.org/10.1016/j.scitotenv.2019.05.028

8. Destek, M. A., and Sinha, A. (2020). Renewable, Non-renewable Energy Consumption, Economic Growth, Trade Openness and Ecological Footprint: Evidence from Organization for Economic Co-operation and Development Countries. *Journal of clean production*. 242, 118537. https://doi.org/10.1016/j.jclepro.2019.118537

9. Dogan, E., Ulucak, R., Kocak, E., and Isik, C. (2020). The Use of Ecological Footprint in Estimating the Environmental Kuznets Curve Hypothesis for BRICST by Considering Cross-Section Dependence and Heterogeneity. *Sci. Total Environ.* 723, 138063. https://doi.org/10.1016/j.scitotenv.2020.138063

10. Emmanuel, N., Prince, A., Inim, V., Chuke, N., James, S., & Samuel, U. (2023). Financial Development, Foreign Direct Investment, and CO2 Emissions Nexus: Evidence from Sub-Saharan Africa. *Journal of Hunan University Natural Sciences*, *50*(6). https://doi.org/10.55463/issn.1674-2974.50.6.12

11. Enemuo, J. I., Idamoyibo, H. R., Ogbeta-Ogwu, E. M., & Udo, E. S. (2025). Exploring the N-shaped nexus between financial inclusion and environmental management in Nigeria: Evidence from the STIRPAT and DARDL framework. *FWU Journal of Social Sciences*, *19*(1), 102–112. https://doi.org/10.51709/19951272/Spring2025/9

12. Inim, V. E., Udo, E. S., Akpan, E. J., & Abner, I. P., (2024) Green Finance and Sustainable Development Nexus in Sub-Saharan Africa. (2024). *FWU Journal of Social Sciences*, 78–90. https://www.researchgate.net/publication/382128386

13. International Renewable Energy Agency (IRENA, 2023) Renewable Energy Generation in Emerging Economies. *International Renewable Energy Agency Report*. Available at: https://www.irena.org/statistics (June October 18, 2024)

14. Jahanger, A., Usman, M., Murshed, M., Mahmood, H., and Balsalobre-Lorente, D. (2022). The Linkages between Natural Resources, Human Capital, Globalization, Economic Growth, Financial Development, and Ecological Footprint: The Moderating Role of Technological Innovations. Resour. Pol. 76, 102569. https://doi.org/10.1016/j.resourpol.2022.102569

15. Kao, C. (1999). Spurious Regression and Residual-Based Tests for Cointegration in Panel Data. *Journal of Economics*. 90 (1), 1–44. https://doi.org/10.1016/S0304-4076(98)00023-2

16. Kirikkaleli, D., Güngör, H., and Adebayo, T. S. (2022). Consumption-based Carbon Emissions, Renewable Energy Consumption, Financial Development and Economic Growth in Chile. *Business Strategy and the Environment* 31 (3), 1123–1137. https://doi.org/10.1002/bse.2945

17. KOF (2023). *Globalization index*. Available at: https://kof.ethz.ch/en/forecasts-and-indicators/indicators/kof-globalisation-index.html.(Accessed September, 4, 2024).

18. Le, T. H., Nguyen, C. P., & Park, D. (2020). Financing renewable energy development: Insights from 55 countries. *Energy Research & Social Science*, 68, 101537. https://doi.org/10.1016/j.erss.2020.101537

19. Ndubuaku, V., Inim, V., Samuel, U. E., Rosemary, I. H., & Prince, A. I. (2021). Financial Development on Employment Rate in Nigeria. *Research in World Economy*, *12*(1), 267. https://doi.org/10.5430/rwe.v12n1p267

20. Pabon, B. G. , Udoms, B. E. , & Atakpa, O. E. (2024, April 15). Post-Covid 19 Nigeria and the 2023 General Elections. *AKSU Journal of Administration and Corporate Governance (AKSUJACOG).* https://doi.org/10.61090/aksujacog.2024.013

21. Pata, U. K., and Aydin, M. (2020). Testing the EKC hypothesis for the top six hydropower energy-consuming countries: Evidence from Fourier Bootstrap ARDL procedure. *Journal of Cleaner Production* 264, 121699. https://doi.org/10.1016/j.jclepro.2020.121699

22. Pedroni, P. (1999). Critical Values for Cointegration Tests in Heterogeneous Panels With Multiple Regressors. Oxford Bull. *Econ. Stats* 61 (S1), 653–670. https://onlinelibrary.wiley.com/doi/abs/10.1111/1468-0084.0610s1653

23. Prince, A. I., Edet, I. V., Akpan, B. L., Udo, E. S., & Akpan, E. E. (2023). Energy Efficiency, Renewable Energy and Economic Growth Nexus on CO2 Emission: Evidence from MINT Countries. *Seybold Report Journal*, *18*(10), 253-273. https://seybold-report.com/wp-content/uploads/2023/12/Udo30.pdf

24. Sadorsky, P. (2010). The impact of financial development on energy consumption in emerging economies. *Energy Policy*, 38(5), 2528-2535. https://doi.org/10.1016/j.enpol.2009.12.048

25. Salem, S., Arshed, N., Anwar, A., Iqbal, M., and Sattar, N. (2021). Renewable Energy Consumption and Carbon Emissions-Testing Nonlinearity for Highly Carbon Emitting Countries. *Sustainability* 13 (21), 11930. https://doi.org/10.3390/su132111930

26. Samuel, U, E., Abner, I, P., Inim, V., Ededem, J. A., (2020) SARS-CoV-2 Pandemic on the Nigerian Educational System (November 28, 2020). International Journal of Management, 11(10), 2020, pp. 626-635. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3738925

27. Samuel, U. E., Rosemary, I. H., Inim, V., Ededem, A. J., & Ndubuaku, V. (2021). Energy Consumption and Sectorial Value Addition on Economic Growth in Nigeria. *Universal Journal of Accounting and Finance*, 9(1), 74–85. https://doi.org/10.13189/ujaf.2021.090108

28. Samuel,U. E., Prince, A. I., Ndubuaku, V., Udoh, B. E., & Okoh, J. I. (2023). Effect of FinTech on cash holding: Quarterly evidence from Nigeria. *The Economics and Finance Letters*, *10*(2), 172–183. https://doi.org/10.18488/29.v10i2.3407

29. Udo, E. S., Jack, A. E., Edet, I. V., Agama, E. J., Ugar, O. A. & Olusegun, J. S. (2024) Unveiling the Transformative Nexus of Energy Efficiency, Renewable Energy, and Economic Growth on CO2 Emission in MINT Countries, *Journal of Renewable Energy and Environment* (JREE), 11(2), 89- 101. https://doi.org/10.30501/jree.2024.430213.1770

30. Udo, E., Victor, I., Abner, I., & Ogbodo, I. (2022). Effect of financial technology on economic growth in Nigeria. *Journal of Xi'an Shiyou University, Natural Science Edition*, *18*(3), 390-401. https://www.xisdxjxsu.asia/V18I03-38.pdf

31. Udo, E.S, Prince, A. I., Edet, I. V., Manasseh, C. O., Daniel, C. O., Okanya, O. C., Mgbobi, I. C., & Onwumere, J. U. J. (2023). Financial Technology and Economic Growth Nexus: Quarterly Evidence from Nigeria. *Seybold Report Journal*, *18*(07), 106- 129. https://www.researchgate.net/publication/374240709

32. Udoh, B. E., Enemuo, J. I., Samuel, U. E., Jack, A. E., Ugar, O. A., & Caroline, N. N. (2024). Effects of Industrialization on Business and Economic Climate in Nigeria: Evidence from Sectoral Analysis. Global Business Review, 0(0). https://doi.org/10.1177/09721509241261859

33. Umar, M., Ji, X., Kirikkaleli, D., Shahbaz, M., and Zhou, X. (2020). Environmental Cost of Natural Resources Utilization and Economic Growth: Can China Shift Some Burdens Through Globalization for Sustainable Development? *Sustainable Development*. 28 (6), 1678–1688. https://doi.org/10.1002/sd.2116

34. Usman, M., and Balsalobre-Lorente, D. (2022). Environmental Concerns in the Era of Industrialization: Can Financial Development, Renewable Energy And Natural Resources Alleviate Some Load? *Energy Policy* 162, 112780. https://doi.org/10.1016/j.enpol.2022.112780

35. Usman, M., Anwar, S., Yaseen, M. R., Makhdum, M. S. A., Kousar, R., and Jahanger, A. (2021d). Unveiling the Dynamic Relationship between Agriculture Value Addition, Energy Utilization, Tourism and Environmental Degradation in South *Asia. J. Public Aff.,* e2712. https://doi.org/10.1002/pa.2712

36. World Development Indicators (2023). World Bank. Available at: https://databank.worldbank.org/indicator/NY.GDP.PCAP.CD/1ff4a498/Popular-Indicators (Accessed June 30, 2024).

37. Yang, B., Jahanger, A., and Khan, M. A. (2020). Does the Inflow of Remittances and Energy Consumption Increase CO2 Emissions in the Era of Globalization? A Global Perspective. Air Qual. *Atmos. Health* 13 (11), 1313–1328. https://doi.org/10.1007/s11869-020-00885-9