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RESEARCH ARTICLE

Unlocking Environmental Sustainability through Financial Inclusion: Evidence from Developing Economies

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Abstract: This study examines the correlation among financial inclusion, technological innovation, and greenhouse gas emissions in developing nations. The analysis utilizes a sample of 50 developing countries spanning the years 2004 to 2020 to identify trends. Principal component analysis is utilized to develop composite indicators for financial inclusion and technological innovation, derived from normalized variables. This study investigates the effects of financial inclusion and technological innovation on greenhouse gas emissions by employing the Driskoll-Kraay standard errors and Feasible Generalized Least Squares methodologies. The estimation results reveal that both financial inclusion and technological innovation are associated with higher GHG emissions when considered separately. However, in terms of moderation, an increase in technological innovation significantly reduces greenhouse gas emissions while simultaneously enhancing financial inclusion. Countries characterized by inclusive financial systems and advanced technologies are likely to exhibit reduced carbon footprints, as a result of more efficient resource allocation and the implementation of cleaner technologies. Policymakers are encouraged to formulate strategies that foster an inclusive financial framework and ensure fair access to technological innovations, with the aim of reducing greenhouse gas emissions.

Keywords: Financial Inclusion, Technology Innovation, Greenhouse Gas Emission, Principal Component Analysis, Developing Countries

Introduction

Financial development (FD) is an important and inextricable part of the development process (Le, Chuc, & Taghizadeh-Hesary, 2019). Developing nations are currently facing the noteworthy challenges of promoting sustainable development (SD) while considering the effects of climate change. The challenge of reducing greenhouse gas (GHG) emissions on a global level demands innovative and diverse strategies. One such strategy is financial inclusion (FI), which holds significant potential to influence GHG emissions positively by increasing access to financial resources. Improved access enables both individuals and industries to capitalize in sustainable technologies and practices. Nevertheless, the relationship between FI and GHG emissions is complicated, as enhanced access to financial services may lead to increased consumption and production activities, possibly resulting in increased GHG emissions. The relationship between technology and climate change is made more complex by the influence of technological innovation (TI). This study aims to clarify these intricate dynamics, offering understanding into how the integration of FI and TI can play a significant role in reducing GHG and advancing global climate goals. Our study seeks to explain the intricate relationships that form the infrastructure of global sustainability initiatives. Our research seeks to clarify the intricate

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relationships that underpin global sustainability initiatives It is crucial for policy makers must pay more attention to promoting sustainable economic development (SED) to understand how FI and TI influence greenhouse (GHG) emission. Affordable financing motivates both governments and businesses to embrace environmentally friendly technologies, leading to a decrease in carbon emissions and enhanced sustainability The relationship between the FI, GHG emission and TI can be comprehend through the insight of DOI According to diffusion of innovation theory (DOI), financial inclusion (FI) encouraging the technological innovation (TI) that contributes to lower greenhouse gas (GHG) emission.

The interplay between financial inclusion, CO_2 emissions, and technological innovation can be understood through the lens of the Diffusion of Innovation Theory (DOI). This theory suggests that financial inclusion is crucial in fostering the adoption of technological solutions that contribute to the reduction of CO_2 emissions. Financially inclusive environments can enhance the spread and scalability of technological innovations by providing networks, market access, and platforms for knowledge exchange. By connecting innovators with prospective users, investors, and collaborators, inclusive financial systems can accelerate the adoption of environmentally friendly technologies across diverse sectors and geographical areas(Daud & Ahmad, 2023).

Financial inclusion primarily seeks to ensure that financial services, including transactions, loans, savings, and insurance, are available to both individuals and businesses. This accessibility allows them to conduct their financial operations with greater efficiency and security(Group & China, 2018; Liu, Hong, Sohail, & Research, 2022). Certain researchers propose that financial inclusion plays a role in enhancing environmental sustainability and decreasing CO2 emissions by encouraging increased investments in research and development as well as innovative technologies(Abdul Karim, Nizam, Law, & Hassan, 2022; Renzhi & Baek, 2020).

Zhang, Sun, and Wang (2022) The findings suggest that FI adversely impacts the efficiency of GHG emissions. Furthermore, the research indicates that financial inclusion may exacerbate the inefficiency of GHG emissions by facilitating the expansion of tertiary industries. Yang, Yu, Liu, Yin, and Xiao (2022) also suggest that FI has a positive impact on decreasing GHG emissions. Further analysis shows that FI impacts GHG emissions through two main channels: increasing vegetation coverage to enhance carbon sequestration capacity, and improving the industrial structure with better financial support. Hussain et al. (2024) assess the influence of FI on GHG emissions, noting its positive (or negative) effects in both the short and long term. This correlation is also applicable to developed nations, indicating a nonlinear relationship between FI and GHG emissions as time progresses. Developing nations demonstrate a more significant long-term positive effect than their developed counterparts. Research demonstrates that GHG emissions are affected by factors such as information and communication technology (ICT), financial development, energy consumption, and economic growth, all of which tend to elevate emissions. Conversely, the utilization of renewable energy and the facilitation of international trade contribute to a decrease in GHG emissions(Weili, Khan, Khan, & Han, 2022). Additionally, Anu, Singh, Raza, Nakonieczny, and Shahzad (2023) demonstrate that Financial inclusion exerts a more significant influence on the escalation of ecological footprints in nations that already possess elevated levels of such footprints, in contrast to those with lower levels. It is imperative for developed economies to focus on the advancement of green patents to attain beneficial results, including the implementation of carbon-neutral processes. Shabir (2022) shows that financial inclusion, technological innovation, and alterations in renewable energy have an adverse impact on GHG emissions, as indicated by their negative elasticity. In contrast, economic globalization and GDP are associated with positive elasticity.

Financial inclusion facilitates access to credit to invest in green technology, thereby reducing greenhouse gas emissions(Le, Le, & Taghizadeh-Hesary, 2020). Conversely, the enhanced accessibility of financial services, along with the expansion of manufacturing and industrial activities, leads to increased GHG emissions, thereby contributing to global warming. The escalation of these activities may also lead to energy poverty, which would further intensify carbon emissions. (Zhao, Jiang, Dong, & Dong, 2021). The mediating analysis reveals that digital financial inclusion (DFI) significantly aids in the decrease of carbon intensity, facilitated by an increase in per capita disposable income and the process of digitization. Du, Li, and Yan's (2019) findings indicate that the introduction of advancements in green technology has a pronounced threshold effect on income levels. In particular, these technological advancements do not significantly contribute to the reduction of CO2 emissions in economies with income levels below the threshold. Conversely, for those economies that exceed this threshold, the effect on reducing emissions is markedly significant.

Furthermore, the study indicates that innovations in green technology and the adoption of renewable energy sources contribute to a decrease in carbon dioxide emissions. Conversely, factors such as energy consumption, population growth, and per capita income are positively correlated with increased GHG emissions(Shan, Genç, Kamran, & Dinca, 2021). The availability of science and technology finance resources can lead to increased adoption of green energy consumption by businesses and households, thereby enhancing living standards and production environments(Mukalayi, Inglesi-Lotz, & Reviews, 2023). Moreover the intermediary effect model revealed that DFI can significantly decrease regional GHG emission intensity by fostering advancements in TI and promoting higher levels of green consumption(A. Yang, M. Yang, F. Zhang, A. A. M. Kassim, & P. Wang, 2024). The study demonstrates a strong and advantageous correlation between green TI and economic growth, as well as a significant and harmful association with GHG emissions, applicable in both the short-term and long-term contexts(Meirun, Mihardjo, Haseeb, Khan, & Jermsittiparsert, 2021). On a global scale, technological innovation does not play a significant role in the reduction of GHG emissions. However, research focused on specific groups suggests that in high-income countries characterized by advanced technology and elevated CO_2 emissions, such innovation can lead to a notable decrease in emissions in adjacent countries. Furthermore, the degree of globalization within a nation is directly related to the effectiveness of TI in lowering CO_2 emissions (Chen & Lee, 2020).

This study contributes to the existing literature in three significant ways. Firstly, it aims to address the gap in current research by exploring the impact of FI on GHG emissions in developing nations. Second, this analysis highlights the detrimental moderating effect of innovative activities on the association between FI and the degradation of regional environments. Third, we implement a more comprehensive approach than prior studies by employing the D_K (OLS) and FGLS methods, as well as analyzing a more extensive dataset covering the years 2004 to 2020 across 50 developing nations. This research has the capacity to enhance the field of FI and technological innovation by employing a more comprehensive model and dataset. A significant number of studies have examined the impact of FI on GHG emissions (Shahbaz, Li, Dong, & Dong, 2022; Wang & Guo, 2022; Yin & Yang, 2024). However, as far as we know, there exists a limited number of studies that have directly assessed the impact of the concurrent management of TI and GHG emissions(Shabir, 2022). Fourthly, the implementation of the DOI theory illustrates the vital importance of digitization and FI in enhancing technological innovation as a developmental strategy for developing nations. This theory serves as a resource for policymakers, offering them the necessary information to adjust technology and FI policies to specific scenarios for optimal effectiveness. Finally, this research creates multidimensional and intricate financial inclusion and technology indexes, just as in prior studies. To analyze the combined influence of FI and TI on GHG emissions within a single framework, these indices were developed using the z-score normalization approach.

Literature Review

Financial Inclusion and Greenhouse Gas

Previous studies examining the relationship between financial inclusion (FI) and GHG emissions have primarily aimed to assess the extent to which financial development (FD) can contribute to a reduction in greenhouse gas emissions. The importance of FD in this context has been recognized, there is still no unanimous agreement on how exactly it influences carbon emissions. The majority of studies have discovered that financial inclusion does indeed help mitigate carbon emissions(Renzhi & Baek, 2020). Different theoretical frameworks within the literature offer distinct insights into the relationship between FI, climate change, and greenhouse gas emissions. Zaidi, Hussain, and Uz Zaman (2021) A favorable link has been discovered connecting FI, energy consumption, and carbon emissions GHG. Moreover Wang and Guo (2022) the results validate that the advancement of digital inclusive finance contributes positively to the drop of urban carbon GHG emissions when viewed from a spatial perspective. This research employs a panel dataset comprising 272 cities in China, covering the years 2011 to 2017. According to Kwakwa (2020), various factors, including income, urbanization, trade, and FD, play a substantial role in influencing GHG emissions. Generally, these factors tend to result in a rise in GHG emissions. Urbanization and FD are interconnected in a manner that aids in the reduction of GHG emissions. Moreover, the use of primary energy, energy intensity, electricity consumption, and fossil fuel consumption has a favorable influence on the levels of GHG emissions. Sharif, Mehmood, Tariq, Haq, and Sustainability (2024) Investigate the ASIAN countries' sustainable development from 1990 to 2019, finding strong associations between GDP and CO2 emissions equations. Population growth and per capita income increase GHG emissions, while FI notably reduces GHG emissions. However, Shahbaz et al. (2022) conducted a study from 2011 to 2017 that investigated the potential effects of FI on pollutant and GHG emissions in 30 provinces of China. The results indicate that although FI may play a crucial role in decreasing GHG emissions by fostering developments in the renewable energy sector, its direct influence on overall GHG emissions is considered minimal. Hussain et al. (2024) analyze that financial inclusion (FI) in emerging economies results in heightened production driven by loans rather than investments in green technology. This shift occurs in response to the demands of economic growth, ultimately exacerbating environmental degradation.

H1: Financial inclusion has a significant positive impact on greenhouse gas emissions

Technology Innovation acts as a Moderator on Financial Inclusion and Greenhouse Gas

To understand the evolution of the globally recognized environment, we examine the stages of the rise of technological innovation. The idea of technology innovation seems like a new development in a new revolution; in fact, they've been around for a while. Siddalingeshwara & Practice (2024) spanning the period from 1990 to 2020, this research provides a noteworthy contribution to Germany. It also underscores that the detrimental aspects of renewable energy and technology significantly influence the decrease in GHG emissions. The impact of trade on emissions is influenced by the beneficial effects of trade openness on carbon output(Ibrahim et al., 2024). In certain OECD economies between 2000 and 2014, Ganda (2019) employed the method of Moments (GMM) to examine the interplay between renewable energy consumption, R&D investment, and carbon dioxide emissions. The consequences indicate a statistically significant inverse association between renewable energy consumption and R&D expenditure concerning GHG emissions. Furthermore, the analysis demonstrates a constructive and substantial correlation between the number of triadic patent families and GHG emissions, whereas the association with the number of researchers was positive but not statistically significant. Cheng and Yao (2021) analyzed the influence of renewable energy technology innovations on the levels of carbon intensity in 30 Chinese provinces during the period of 2000 to 2015. By employing advanced panel estimation techniques, the findings reveal that a 1% increase in the level of renewable energy technology innovation leads to a notable 0.051% decrease in carbon intensity. Ren, Cheng, Wang, and Yan (2021) Utilize real-time panel data from 1990 to 2015 across 16 European nations. The study reveals that renewable energy is reducing GHG emissions. The swift advancement of financial technology (fintech) developments offers a revolutionary chance to improve global financial inclusion. Fintech, utilizing tools like mobile banking, blockchain, and digital payments(Ololade & Journal, 2024). The transformation in conventional finance, coupled with the emergence of significant data analytics, has established digital inclusive finance (DFI) as a crucial element in the efforts to manage carbon emission reductions. This assessment is based on regional data from China spanning the years 2011 to 2022. (A. Yang, M. Yang, F. Zhang, A. A. M. Kassim, & P. J. J. o. t. K. E. Wang, 2024).

Fareed et al. (2022) investigate how innovation activities moderate the relationship between FI and environmental degradation, using panel data collected from 27 European countries over the time period from 1995 to 2018. The euro area stands as one of the largest single market regions worldwide, with a foundational commitment to promoting open trade on a global scale. Therefore, it is likely that the moderating role of innovation activities will yield beneficial effects for conservation efforts. M. Ahmad et al (2022) Empirical research indicates that FI, economic growth, and energy consumption contribute to an increase in GHG emissions. Conversely, advancements in technology and a commitment to green practices lead to a reduction in GHG emissions. While FI is generally beneficial, it can also adversely affect the environment. The drive for economic advancement often leads individuals to obtain loans aimed at purchasing luxury items such as houses, air conditioners, refrigerators, cars, and washing machines, consequently contributing to higher emissions and a more significant environmental impact (Saqib, Ozturk, & Usman, 2023).

Salim (2020) emphasizes The necessity of advancing financial technology as vital for enhancing the role of FI. The strong association and effect of greater FI on poverty reduction and the mitigation of income inequality are significant and warrant attention. Continuous dialogue surrounding financial inclusion highlights its significance in alleviating poverty and fostering economic advancement, transitioning into a discourse within the sustainable development goals paradigm. Anticipating future policy trajectories involves examining various theoretical viewpoints on carbon emissions(Hussain, Gul, & Ullah, 2023). Innovations in finance enable international investments, broadening the reach of eco-friendly products and technologies, which in turn have a beneficial effect on the environment. Nevertheless, financial inclusion may have adverse environmental consequences by promoting excessive borrowing for non-essential items, resulting in increased emissions. Additionally, it reduces financial barriers for businesses, leading to an expansion in production facilities, locations, and machinery, consequently raising emission levels even further.

H2: Technology innovation has a significant negative impact on financial inclusion and greenhouse gas emissions

This research focuses on developing countries, which represent the most active region in the world and include the nations experiencing the quickest growth. Despite the substantial inclusive growth attained in this region, financial exclusion remains a critical issue. Developing countries illustrate a unique situation in this matter. In summary, several empirical research efforts have validated that inclusive FD plays a constructive role in encouraging environmental sustainability. Research has indicated a negative correlation between GHG emissions and FD; however, alternative viewpoints suggest that increasing financial inclusivity may enhance environmental performance by enabling companies to utilize advanced eco-friendly technologies. As a result, the discussion above shows that FI can yield both advantageous and adverse consequences for the environment, underscoring the importance of further investigation to gain a comprehensive understanding of this dynamic. Research concerning technology adoption indicates that financial inclusion can enhance investment in emerging technologies by supplying vital financial resources. Despite the significance of TI, its role in reducing the impact of FI on GHG emissions is not thoroughly comprehended. Earlier studies typically regard financial inclusion and technological innovation as independent variables(Hidayat-ur-Rehman & Hossain, 2024; Meirun et al,2021; Siddalingeshwara & Practice, 2024). Here is a significant gap in research regarding the combined effects of FI, TI, and environmental outcomes. While each of these elements has been studied independently, their interactions and the overall impact on greenhouse gas emissions have not been sufficiently investigated.

Data and Methodology

Data and Variables

We obtained data on 50 developing countries for the timeframe spanning 2004 to 2020 through the World Bank's Global Financial Development Database (WDI). The purpose of this study is to analyze how FI can aid developing countries in combating climate change through the decrease in greenhouse gas emissions. A sample of fifty developing nations has been chosen to assess the moderating influence of technological innovation alongside the effects of financial inclusion on greenhouse gas emissions. For the purpose of empirical analysis, we designate greenhouse gas emissions (GHG), measured in terms of CO_2, as the dependent variable. The control variables consist of population growth (POPG), urbanization (URB), and industrialization (IND). Financial inclusion serves as the key independent variable in this study. This investigation seeks to establish a composite FI index that addresses three dimensions of FI for developing countries, taking into account various perspectives as presented in the prevailing literature. The methodology involves the application of principal component analysis (PCA) to reduce extensive variable datasets into a single composite index. To assess the role of TI in shaping the relationship between FI and greenhouse gas emissions, we have formulated a composite index of technological innovation, which considers four essential dimensions of innovation.

Methodology

Table 2 suggests that financial inclusion and technological innovation possess distinct scales and units. Furthermore, Table 2 illustrates that certain variables exhibit a higher variance, whereas others display a lower variance. To enhance variance, it is essential to normalize the variables before applying Principal Component Analysis (PCA) to transform the indicators into a composite index. There are different methods of normalization indicators, but in this study, we use the z-score technique(Tian, Li, & Research, 2022), which is the most common standardized technique for normalizing indicators.
We calculate normalization through z-score by using this formula:

$$\text{zee} = \frac{\text{xi} - \text{x}}{\sigma}$$

Where,
Zee = standard score
xi = observed value
x = group average
σ = standard deviation

Principal component analysis (PCA) is a dimensional mathematical method that reduces data by converting correlated input data into an uncorrelated output dataset. PCA is a widely used technique to show data variation as well as data structure. The information or variance explained is maximized. Therefore, PCA reduces the following dimensions: Create input datasets while ensuring that the maximum amount of information is retained(Ma, Han, Badeeb, & Khan, 2022). The reason to use PCA is that you can reap the benefits. Explore correlations between variables in a high-dimensional population system to create smaller dimensional population system that can generate comparable yield curve models (Ahmad, Khan, & Magda, 2022; Ali, Jianguo, Kirikkaleli, Bács, & Oláh, 2023; Hussain, Gul, & Ullah, 2023; Khan, Luo, Ullah, Rasheed, & Li, 2023).

We apply pre-requisite tests for principal component analysis (PCA), these are the Bartlett test of sphericity and Kaiser-Meyer Olkin (KMO)(Hussain, Akbar, Gul, Shahzad, & Naifar, 2023). These tests were conducted to determine the appropriateness of PCA for developing a composite index that represents proxies for FI and technological innovation. The purpose of these tests was to assess the stability of the data for subsequent analysis. In the Bartlett test of sphericity, a test value of less than 0.05 ($P<0.05$) indicates that Principal Component Analysis (PCA) is appropriate for developing a composite based on proxies for financial inclusion and technology innovation. Furthermore, according to the (KMO) measure, a result equal to 0.05 or higher signifies that PCA is suitable for constructing a composite of FI and TI (Le et al., 2019). A series of procedures was implemented during the panel data analysis to examine the impact of FI on GHG emissions in developing countries. For the entire dataset, we employed Driscoll-Kraay (D-K) standard errors to account for heteroscedasticity, serial correlation, and contemporaneous correlation across the complete sample (Driscoll, Kraay, & statistics, 1998). Furthermore, the Driscoll-Kraay approach was used to examine the correlation between FI, TI, and GHG emissions in subsamples of various financial economies in developing countries. Moreover, the study used the Feasible General Least Squares (FGLS) model(Hunjra, Azam, Bruna, & Taskin, 2022), which permits thorough and reliable regression coefficients even when residuals have autocorrelation and heteroscedasticity (Hussain, Gul, Ullah, Waheed, & Naeem, 2023).

Econometric Model

$CO_2=\beta_0+\beta_1 FIindex+\beta_2 Techindex+\beta_3 POPG+\beta_4 URB+\beta_5 IND_+\beta 6(FIindex*Techindex) +\varepsilon_0$

Table 1

Developing Countries
Afghanistan, Albania, Algeria, Angola, Antigua and Barbuda, Argentina, Armenia, Aruba, Azerbaijan, Bahrain, Bangladesh, Belize, Benin, Bhutan, Bolivia, Brazil, Brunei Darussalam. ulgaria, Cambodia, Cameroon, Central African Republic, China, Colombia, Comoros, ominica, Egypt, Arab Rep, El Salvador, Eswatini, Ethiopia, Fiji, Gabon, Gambia, Ghana, India, Indonesia, Iran, Islamic Rep. Iraq. Kuwait, Malaysia, Maldives, Nepal, Pakistan, Panama, Romania, Russian Federation, South Africa, Sri Lanka, Turkey, Ukraine and Uzbekistan.

Table 2

Developing Countries Financial Indicators Considered in the Study (2004-2020)

Variable	Source	Indicator	Unit
CO_2	WDI	CO2 emissions (metric tons per capita)	
FI1	WDI	Automated teller machines (ATMS) (per 100.000 adults)	
FI2	WDI	Domestic credit to the private sector by banks (% of GDP)	%
FI3	WDI	Commercial bank branches (per 100.000 adults)	
Patent	WDI	No of Patent total residents	
Technology	WDI	High-technology exports (% of manufacturing exports)	%
Internet	WDI	Internet of Population)	
Mobile	WDI	Mobile (subscription per 100)	
POPG	WDI	Population, growth (annual %)	
URB	WDI	Urban population (% of total population)	%
IND	WDI	Industry (including construction), value added (% of GDP)	%

Results and Discussion

Table 3

Descriptive Discussion

Variable	Obs	Mean	Std. Dev.	Min	Max
CO^2	847	3.775	5.224	.025	31.274
FII	847	34.722	31.484	0	185.41
F12	847	14.319	12.407	.3	92.34
F13	847	39.667	27.348	1.266	182.868
POPG	847	1.496	1.327	-1.833	7.895
URB	847	54.472	21.069	14.841	100
IND	847	29.697	13.889	8.058	74,812
Patent	847	26571.024	111045.62	I	1400000
Technology	847	6.776	7.96	0	95.618
Internet	847	32.261	25.819	.106	99.702

The findings presented in Table 3 indicate that the descriptive statistics reveal the mean values for three financial inclusion proxies: Automatic Teller Machines (ATMs) per 100,000 adults, Domestic credit to the private sector by banks as a percentage of GDP, and Commercial bank branches per 100,000 adults. The calculated means and variances for these proxies are 3.775 and 5.225, respectively, both of which are below the specified threshold (Hussain, Gul, & Ullah, 2023; Renzhi & Baek, 2020). In addition, the mean annual percentage of population growth, the proportion of the urban population within the total population, and the contribution of industry, including construction, to GDP as a percentage are all below, the findings of Awais Ur Rehman, Malik, Md Isa, and Jais (2023) reveals lesser financial inclusiveness in developing countries. The average values for technology innovation-related indicators, including mobile subscriptions per 100 people (M = 87.433), internet penetration as a percentage of the population (M = 32.261), number of patents per resident (M = 26371.024), and the percentage of manufacturing experts in technology (M = 6.776), exceed the reported value by(Nchofoung & Asongu, 2022). This suggests that developing countries in the region have better access to technology innovation-related resources.

Table 4

Result of Bartlett of Sphericity and Kaiser-Mayer Olkin Measure of Sampling Adequacy

	Bartlett test of sphericity			Kaiser-Mayer Olkin Measure of Sampling Adequacy
	Chi-square	Degrees of Freedom	p-value	
Financial Inclusion Z-score normalization	416.017	3	0.0000	0.63
Technological Innovation Z-score normalization	812.877	6	0.0000	0.49

The evaluation of the data's appropriateness for factor analysis was conducted through Bartlett's test of sphericity and the KMO measure of sampling adequacy. For the financial inclusion variable, which was subjected to Z-score normalization, the results of Bartlett's test indicated a significant chi-square value of 416.017 with 3 degrees of freedom, reflecting a strong correlation among the variables ($p < 0.0001$). The sampling adequacy, as measured by the Kaiser-Mayer-Olkin statistic, was found to be 0.63, which reflects an acceptable level for conducting factor analysis. Furthermore, for the normalized Technology innovation variable, Bartlett's test produced a significant chi-square value of 812.877, accompanied by 6 degrees of freedom ($p < 0.0001$). Le et al. (2019). The findings demonstrated a significant correlation among the variables. However, the KMO measure of sampling adequacy was found to be 0.49, suggesting that the level of sampling adequacy was lower when compared to the financial inclusion variable.

These findings imply that both financial inclusion and technology innovation variables are sufficiently correlated for further factor analysis(Awais Ur Rehman, Malik, Isa, & Jais, 2023). The significant result of Bartlett's test indicates that the variables exhibit dependence rather than independence, supporting the use of factor analysis to identify underlying factors. Moreover, the Kaiser-Mayer-Olkin sampling adequacy measure confirms that the sample size is appropriate for factor analysis, despite the slightly lower adequacy of the technology innovation variable compared to financial inclusion.

Table 5

Total Variance Explained

	Component	Eigenvalues	% of Variance	Cumulative variance %
Financial Inclusion Index				
Normalized variables	1	1.80071	0.6002	0.6002
using standardized	2	0.742185	0.2474	0.8476
Z-score	3	0.457107	0.1524	1.0000
Technological Innovation Index				
Normalized variables	1	1.77186	0.4430	0.4430
using standardized	2	1.30972	0.3274	0.7704
Z-score	3	0.674675	0.1687	0.9391
	4	0.243745	0.0609	1.0000

In Table 5, we estimate the factor and its eigenvalue. Based on the eigenvalue, we decide the first three proxies of financial inclusion whether employ them for the PCA or not. Component selection is based on the

Eigenvalue; if the eigenvalue is equal to or greater than 1, would be considered for the construction of a composite(Tanveer et al., 2023). In this section, the empirical outcomes of the analysis are detailed and deliberated upon. The paper follows a sequential approach to derive the empirical results. Firstly, principal components analysis (PCA) is utilized to condense the three dimensions of the financial indicators into a single index. This is crucial because none of the three indicators alone can adequately represent financial inclusion. By employing PCA, we can extract a significant amount of information from all the indicators while avoiding the issue of multicollinearity that arises when multiple proxies are included in an equation. Secondly, four indicators of technology innovation variables are used to construct the technology innovation Index-2. Over 90% of the standardized variation can be explained by the first main component, as the table's eigenvalues show. Because it more accurately reflects the fluctuations in the dependent variable than any other linear combination of explanatory factors, the first principal component is, thus, a more pertinent indicator of financial inclusion. Consequently, while creating a composite indicator, only data pertaining to the first principal component is taken into account.

Table 6

Matrix of Correlations

	1_co2	Flindex	Techindex	POPG	URB	IND
1_co2	1.00					
Flindex	0.61***	1.00				
zee-Techindex	0.63***	0.65***	1.00			
POPG	-0.13***	-0.40***	-0.22***	1.00		
URB	0.66***	0.36***	0.49***	0.03	1.00	
IND	0.44***	-0.00	0.11**	0.15***	0.39***	1.00

Source: Authors' calculations

The correlation matrix in Table 6 displays the Pearson pairwise Hunjra et al. (2022) connections among variables such as greenhouse gas emissions, financial inclusion, technology innovation, population growth, urbanization, and industrialization. Analyzing these correlations can provide insights into the relationship between financial inclusion, technology innovation, and CO2 emissions, especially in terms of the moderating impact of technology innovation. The correlation table reveals a strong positive association between greenhouse gas (GHG) emissions and both financial inclusion (FI) and technological innovation (TI). Specifically, the correlation between TI and GHG emissions is 0.63, in contrast to the 0.61 correlation observed between FI and GHG emissions. This suggests that the link between TI and GHG emissions is more robust than that between FI and GHG emissions. These findings indicate that the relationship between FI and GHG emissions is considerably moderated by the influence of technological innovation.

Table 7

Estimation Results: Drisoll-Karry Standard Errors and FGLS

1_co2	DK(OLS)	FGLS
Flindex	0.437***	0.437***
	-0.0254	-0.0273
zee_Techindex	0.315***	0.315***
	-0.0873	-0.0351
zee_Flindex_Techindex	-0.250***	-0.250***
	-0.051	-0.0265
POPG	0.0261	0.0261
	-0.0399	-0.021

1_co2	DK(OLS)	FGLS
URB	0.0177***	0.0177***
	-0.00371	-0.00152
IND	0.0307***	0.0307***
	-0.00107	-0.00199
Constant	-1.364***	-1.364***
	-0.089	-0.0839
P-value	0.0000	0.0000
F-stats	20962.4	
Wald test		2196.07
Observations	847	847
R-squared	0.722	
Number of groups	50	50
Number of id	50	50

Standard errors in parentheses
*** p<0.01 ** p<0.05 p<0.1

Note: Standard errors are presented in brackets with *** p<0.01, ** p<0.05, and * p<0.1. GLS stands for Generalized Least Squares. Driscoll and Kraay (1998) used pooled Ordinary Least Squares/Weighted Least Squares and Generalized Least Squares random-effects regressions to estimate coefficient standard errors. Statistical analysis reveals a strong correlation between FI and the escalation of GHG emissions in developing countries, as demonstrated by the Drisoll-Karray (DK) standard errors and FGLS results based on the data shown in Table 6. One possible reason for this association is that the rise of financial services has resulted in the creation of sectors with higher pollution levels. As a result, it may be stated that the implementation of financial inclusion measures was not ecologically favorable. This conclusion is strengthened by the studies undertaken by Le et al. (2020; Mehmood & Research, 2022). However, it's worth noting that this observation contradicts the results obtained by Shabir (2022), who stated that financial inclusion may be an effective instrument for reducing environmental pollution. With a regression coefficient of 0.437 for FIindex, a change of one unit in FIindex is equivalent to a change of 0.437 units in GHG emissions, and a regression coefficient of 0.315 for zee_Techindex, a change of one unit in zee_Techindex is equivalent to a change of 0.315 units in GHG emissions. Both findings suggest that technological innovation and financial inclusion alone increase greenhouse gas emissions. Therefore, policymakers aiming to lower CO2 emissions should prioritize encouraging technological innovation in tandem with initiatives to expand financial inclusion. These results are in line with previous studies (Chen & ee, 2020). Additionally, the interaction term coefficient is negative and statistically significant, indicating that FI and TI lower the GHG level. (***) Show that there is a statistically significant connection between the variables. In other words, high levels of financial inclusion and technological innovation emphasize a synergistic effect on environmental sustainability, which combined have an even higher influence on cutting GHG emissions.

In addition, the results obtained from the z-score normalization method, as illustrated in Tables 4 and 5; further substantiate the positive correlation between the creation of an inclusive financial system and the attainment of sustainable development through TI. These results support the diffusion theory of innovation, which asserts that enhancements in financial service offerings facilitated by technological advancements and associated with decreased social and economic costs hold significant importance in the current environment. Moreover, the timing of how individuals adapt to innovations is essential for their acceptability. These observations support the diffusion theory of innovation, which asserts that technological advancements in financial services can lead to improvements while simultaneously reducing social and economic challenges. (Hussain, Gul, & Ullah, 2023).

Conclusion

This research analyzes the association between technological innovation, FI, and GHG emissions in a sample of 50 developing nations between 2004 and 2020. The analysis focuses on population growth, urbanization, and industrial factors as control variables that influence FI, technology innovation, and carbon emissions. The primary goal is to investigate the potential link between financial inclusion and technological innovation in relation to greenhouse gas emissions. To facilitate this investigation, PCA is employed to extract two financial indicators from standardized variables. The results indicate that the patterns identified within the research sample are not static. Notably, both the FIindex and zee_Techindex have a substantial effect in the D-k (OLS) and FGLS estimations. Moreover, the interaction term zee_FIindex_Techindex shows a considerable negative coefficient in both evaluations, suggesting that the synergistic effect of FI and technological innovation is connected with a reduction in GHG emissions. This emphasizes the supportive relationship between FI and TI, where elevated levels of both lead to a significant decrease in GHG emissions, thereby showcasing their collaborative impact on promoting environmental sustainability.

This study's empirical findings lead to several policy recommendations applicable to all nations. Primarily, since energy-efficient technologies and clean energy initiatives necessitate significant investment, it is advantageous for countries to have accessible financial resources at low interest rates, a robust financial infrastructure, and stable financial institutions to facilitate the development of these projects aimed at reducing energy consumption and CO2 emissions. Additionally, it is imperative for nations to enhance their international cooperation and exchanges, promote the development of green environmental protection technologies, eliminate technological barriers that restrict the transfer of innovative technologies, and assist other countries in advancing their green environmental protection efforts. Thirdly, economic globalization has adversely affected environmental sustainability in developing nations, highlighting the necessity for initiatives aimed at resolving this concern. As a result, government representatives in developing nations are adopting strategic measures to facilitate the uptake of eco-friendly products by individuals and businesses alike. Moreover, it is imperative for the government to extend tax advantages to both local and overseas companies to foster enhanced investment in clean, progressive, and sustainable energy initiatives. Furthermore, it is essential for them to reduce tariffs and promote the acquisition and exchange of advanced technology by drawing in new investors. Most importantly, developing nations need to align economic globalization with climate change strategies to encourage green FI and achieve carbon neutrality goals. Consequently, officials in the governments of developing nations implement effective strategies aimed at promoting the use of more environmentally sustainable products by individuals and businesses. Additionally, it is essential for the government to offer tax incentives to both national and international enterprises to encourage increased investment in clean, modern, and renewable energy initiatives. Moreover, reducing tariffs and encouraging new investors to invest in and exchange innovative technologies is vital. It is also imperative for developing countries to harmonize economic globalization with climate change policies to advance green financial inclusion and attain carbon neutrality targets.

A notable limitation of this research is its exclusive focus on developing nations. The results emphasize the critical need to weave financial inclusion and innovative approaches into comprehensive sustainability frameworks, thereby enhancing the interconnections between social, economic, and environmental aims. Future research avenues may explore additional dimensions of this correlation, such as the influence of regulatory frameworks, differences among various sectors, and the diversity observed across nations, to enhance our understanding of these dynamics.

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