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Financial Inclusion, Technology Innovation and CO2 Emissions: International Evidence

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Abstract: *This research examines the elaborate association between FI, CO2 emissions, and the moderating role of technological innovation across 83 countries. The study, which includes the years 2003 to 2022, uses data from the WDI to investigate the dynamics and consequences of these interrelated factors. The major goal is to determine the influence of FI on CO2 emissions, taking into consideration the moderating role of technical progress. Through principal component analysis, the study seeks to understand the underlying mechanisms driving these associations by employing various statistical approaches such as correlation analysis and Driscoll-Kraay standard errors. Initial data show a significant link between FI and CO2 emissions, but the degree of the association varies by nation. Furthermore, technological innovation has been shown to have a significant moderating effect, increasing the effect of FI on CO2 emissions. Based on these findings, the research suggests policies that make use of the associations between FI and technological innovation in order to promote sustainable development. Overall, this study advances our consideration of the complex relationship between FI, CO2 emissions, and technological innovation, providing significant insights for policymakers and stakeholders working for environmental sustainability and economic inclusiveness.*

Key Words: Financial Inclusion, CO2 Emission, Technological Innovation, International Evidence

Introduction

We explore the association between financial inclusion and CO_2 emissions and how technological innovation alters evidence from other countries. Being fully aware of the pressing need for ecologically sustainable development solutions, we consider the elaborate interrelationship between financial growth and the conservation of the environment. We test how technology innovation might have a moderating role in understanding various economic contexts through which financial inclusion initiatives influence CO2 emissions. Our research explains the complex linkages of global sustainability projects through the use of empirical data and theoretical frameworks from economics, environmental science, and technology studies. This research is meant to contribute to the knowledge base in policymaking and strategic planning through thorough research and critical analyses that stimulate or voice fair economic growth while ensuring lower levels of environmental issues. The development economics and the diffusion of innovation theory could, therefore, explain the link between financial inclusion, CO2 emissions, and technological innovation. Under Development Economics, financial inclusion encourages economic growth because of the expansion in the availability of more financial facilities, which may increase productivity and standards of living. However, in cases where industrial activities have grown, economic growth could result in an increased rate of CO2 emissions. The innovation diffusion hypothesis explains the degree to which financial inclusion and technology are diffused into society. Financial inclusion, being an innovation itself, may

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diffuse into people, thereby enhancing economic activities capable of increasing the level of CO2 emissions. (Dauda, Long, Mensah, & Salman, 2019).

In this study, Said, Bhatti, and Mancuso Tradenta (2022) reviewed the relationship that existed between FI and CO_2 emissions. Our estimates also diverge considerably from the extant literature and also between our two regions of interest. Overall, financial inclusion tends to exert a strong positive effect on CO2 emissions in Latin American nations but not in the MENA nations.

Adeneye and Rasheed (2023) examined the seeks to establish the association between financial inclusion and CO_2 emissions and financial sustainability within the purview of 17 African countries. The study revealed that the penetration rate of ATMs improved. According to the econometric finding, FI did not imply any significant reduction in emissions in African nations. However, this study ascertained that economic sustainability moderates the link between financial inclusion and CO_2 emissions. Based on the findings from this study, while financial sustainability was found to decrease CO_2 emissions, it weakened the favourable effects that bank accounts, ATM penetration, and loans had on CO_2 emissions.

Zhang, Sun, and Wang (2022) conducted a study on the connection between FI and CO_2 emission efficiency by applying panel data from 30 Chinese regions from 2011 to 2019. The findings indicate that financial inclusion reduces the efficiency of CO_2 emissions. Furthermore, enhancing the number of tertiary businesses through financial inclusion may lower carbon emissions efficiency. Moreover, the level of impact depends on the location. In accordance with the obtained results, COP28 demonstrated the significance of the inclusion of finance along with sustainable technologies for climate action to be successful. Our data also show that FI has a significant effect on CO_2 emissions. However, financial inclusion is an important mediator in the negative correlation between aid and CO_2 emissions. Apart from this, our figures illustrate the fact that increasing the output of energy and improving technology are the two key factors which contribute to the decrease in CO_2 emissions. Also, they are beneficial for the environment quality (Gao et al., 2024).

This study concludes that digitized Financial Inclusion has a positive relation to CO2 emission reduction as there is a vital difference in the counties and the periods. In addition, the study showed that digital FI has the possibility to bring down emissions by restructuring the industry and promoting technological innovation (Lei, Chen, Xu, Qiu, & Zhang, 2024). The findings indicate an association between FI and CO_2 emissions. FI has an effect on CO2 emissions in industrialized nations. This is a negative influence that should be noted. In contrast, FI has a favourable and noteworthy impact on CO_2 emissions in developing nations (M. Ibrahiem, 2023).

Zaidi, Hussain, and Uz Zaman (2021)This study focuses on the relationships between FI and CO2 emissions. The results indicate that financial inclusion has a negative association with CO2 emissions.

Niu (2021) This study investigates at the link between technological innovation and CO2 emissions. Empirical investigations from all provinces across the nation show that technical innovation has a positive impact on lowering carbon emissions. However, present technological innovation has a negative impact on future CO_2 emissions.

Chen and Lee (2020) Using spatial econometric models, this research looks at how technological innovation impacted CO_2 emissions in 96 countries between 1996 and 2018. According to pooled statistics, top-income, advanced technology nations not only reduce their own CO2 emissions but also help to reduce CO2 emissions of countries nearby. Developing nations with little technology and CO_2 emissions experience no harmful direct or indirect repercussions, but technological development is crucial in certain sectors. This study examines the effect of technological advancements on CO_2 emission efficiency. Technological advancements have increased the efficiency of carbon emissions. (Zhao, Long, Yin, & Zhou, 2023).

Mpeqa, Sun, and Beraud (2022) This study will investigate at how various variables influence CO2 emissions in 29 developing nations that signed part in the One Belt, One Road configure between 2008 and 2019. We created a complete STIRPAT model to explore the impact of export, import, and Technology advancements on CO2 emissions in the analyzed countries. To minimize CO2 emissions, the 29 countries must adopt innovative technologies, notably eco-innovations. Imports have both optimistic and undesirable effects on CO2 emissions.

Ashiq and Ali (2023) The aim of this research is to employ OLS and fixed effects methods to assess the effect of innovation on CO_2 emissions in five South Asian countries between 1980 and 2019. The study's results indicate that CO_2 emissions have a detrimental influence on environmental quality, but technological advancements can help minimize them. The findings support policies that encourage and disseminate technological advancements, mostly in South Asian countries.

Contributions from our research: First, the researched region is less explored, where financial inclusion has not been investigated with CO2 emissions in the presence of technological innovation. We seek to fill this gap by examining the relationships between these three variables. Most of the prior studies have examined either socioeconomic aspects (e.g., financial inclusion) or environmental dimensions (technological innovation), but fewer studied both sides together. Consequently, this investigation aims to offer a complete understanding of the convoluted dynamics determining FD paths. Second, the study brings interdisciplinarity to bear on economic and environmental literature. Said methodological, multidisciplinary measurement strategy enhances investigation of the elaborate nexus between FI, CO2 emissions and technology advancements across different determinant categories with new knowledge into underlying mechanisms as well policy guidance. This research is interdisciplinary in nature and integrates disciplinary silos, which should encourage broader collaborations and idea interchange among researchers as well as practitioners across fields. Third, this research adds value to the current literature by employing advanced regression methods to understand intricate linkages between financial inclusion, CO2 emissions and technological innovation. Such methodological rigour increases the reliability and validity of our results, making a very valuable contribution to the available scientific toolkit for researchers in this area. This proposal should help policymakers develop more environmentally sustainable financial inclusion policies that better balance environmental sustainability with economic growth by identifying potential technological solutions for mitigating the effects of energy use and emissions on household-level financial access. In addition, the results of our research propose what types of technology and infrastructure investments to think about first to maximize their financial inclusion and environmental benefits. Taken together the literary contribution from our study transcends academic discourse to inform real-life endeavors that pursue inclusive and economic growth targets. To do so, we should normalize the index to evaluate financial inclusion and carbon emissions side by side in conjunction with a unifying framework that includes technology and innovation as moderating variables. We apply several methods of the econometric model which tackle the issue of cross-sectional dependency and heteroscedasticity. To get efficient and consistent parametric estimates, we use Driscoll-Kraay standard errors (D-K), pooled OLS model, and GLS (Le, Le, & Taghizadeh-Hesary, 2020).

Literature Review

FI and Corban Emission (CO_2)

Investigate how digital FI affects carbon emissions in developing markets and emerging nations. Using the Global Findex database to create an overall digital FI index and subindex. The findings are assessed to exert a dynamic 2-step system GMM procedure. The study's results indicate that digital FI is considerably noteworthy related to CO_2 emissions. The findings are robust when using sub-indices of digital and conventional financial inclusion as control variables (Khan, Luo, Ullah, Rasheed, & Li, 2023). The findings revealed that FI, green savings and green loans have a noteworthy association with the SED of Vietnam (Van Hoa et al., 2022). Based on data collected between 2004 and 2019, this research investigates the short- and long-term impact of several vital factors such as financial inclusion, ICT, sustainable energy, worldwide and financial advance on CO2 emissions in the top ten emitter nations in the OBOR county. This study used the CS-ARDL approach. The results show a significant link between FI, ICT, and CO2 emissions in both the long and short term. Sustainable forms of energy have been shown to reduce CO2 emissions in both the long and short term. Globalization and CO2 emissions have had an unfavourable connection for a long time (Marcelline et al., 2023).

Liu, Hong, and Sohail (2022) Five independent proxies of financial inclusion were evaluated using the ARDL approach, and the IV validated the optimistic influence of FI on eco-friendly quality in China. Likewise, education has proven to be effective in lowering CO2 emissions in China. Among the control factors, GDP and population had an undesirable influence on CO2 emissions, but R&D activities increased

carbon emissions. Our results indicate that FI and education may play a significant part in the battle against worldwide warming. Funds should be distributed to organizations, companies, and individuals engaged in eco-innovation.

Brahmi et al. (2023) conducted this research to evaluate the effect that technological advancements show in attaining FI and zero emission. The papers examined in this study demonstrate that technological advances may play a vital role in FI for zero emission while also providing substantial policy consequences. Indeed, a favourable regulatory environment may have good benefits in the near term, with significant eco-friendly, economic, and societal implications.

Xiangling and Qamruzzaman (2024) This study examines at the association between ICT venture, digital FI, ecological taxation, and maintainable energy change. The DCE model is useful for analyzing energetic effects and possible correlations, whereas the involved variable-adjusted DCE model deals with endogeneity difficulties. The findings show that ICT ventures and the advancement of digital FI have a large and beneficial influence on maintainable energy expansion in the MENA area. The impact of reducing carbon intensity reduces, then expands. The impact of increased carbon appropriation is reducing. Reduce carbon intensity through increased income and digitalization. Encourage carbon sequestration by supporting green interplanetary and green technology. Conduct a heterogeneity study using various features of finance and cities (Lee et al., 2022). Shahzad Hussain et al. (2023) suggest that FI has a long (short)-term beneficial effect on CO_2 emissions in Asia.

Mhlanga (2022) showed that financial inclusion via FinTech might increase the resilience of houses, people, and companies in the event of an unanticipated weather disaster or the measured significance of shifting rainfall forms, rising sea levels, or saltwater invasion. Assurance, investments, loans, monetary transfers, and innovative digital delivery networks may all assist sufferers of global warming and those in charge of handling with the new ecological reality.

The findings showed that FI accelerates the increase of CO2 emissions in Saudi Arabia, with the coefficient of financial development indicating that every 1% rise in financial development increases CO2 emissions by 0.167% (M. Ibrahiem, 2023). This effect is stronger in underdeveloped nations but weaker in industrialized countries (S. et al., 2023).

Dauda et al. (2019). The research explored the effect of technological advancement and financial development on CO2 emissions in 18 industrial and developed nations from 1990 to 2016. The research employed a panel approach to accomplish trade with cross-sectional dependency effects. A panel cross-sectional augmented Dickey-Fuller (CADF) element basis was used to identify the instructions for incorporation. We used panel CMOLS and panel DOLS to evaluate the long-term association. The findings indicate that energy usage enhances carbon emissions across all panel levels. However, technological advancements reduce CO2 emissions in the G6, while increasing emissions in the MENA and BRICS nations.

H_1: Financial inclusion has a significant impact on CO_2 emissions.

Financial Inclusion, Carbon Emission (CO_2) with Moderate Technologies Innovation

Basty and Ghachem (2023) conducted a study uses parametric and semiparametric regression analysis on a sample of 32 countries in the OECD from 2015 to 2020. Our parametric results reflect prior research's inverted U-shaped relationship between technological advancements and CO2 emissions, as well as the extremely optimistic impact enterprise occurrence has on securing a change in energy. The findings showed that technological innovation enhances the chance of carbon neutrality due to a positive correlation (Kabir, 2022). Saqib, Ozturk, and Usman (2023) GDP and financial inclusion were positively connected with the ecological footprint. Technology and renewable energy are negatively connected with environmental impact. The moderating impacts of technology and financial inclusion reduced environmental harm. Renewable energy and financial inclusion have moderating effects that reduce environmental impact (Saqib et al., 2023).

Ali, Jianguo, Kirikkaleli, Oláh, and Altuntaş (2023) conducted a study that found that financial policy variability, economic development, development in the economy, expenditure of energy, and trade reduce the quality of the environment by boosting CO_2 emissions, while innovative green technology and

institutional quality rise environmental degradation by decreasing CO_2 emissions. Our study indicates noteworthy results for green technical advancement and the role of quality institutional conditioning in decreasing CO_2 emissions in OECD nations.

H_2: Technological innovation moderates the relationship between financial inclusion and CO_2 emission.

Our research studies the elaborate association between FI, CO2 emissions, and technological innovation play a moderating role. The study's empirical aims include investigating the impact of FI on CO2 emissions while calculating the moderating role of technological innovation. The research covers a sample period from 2003 to 2022 and includes a wide group of countries to provide thorough insights. Taking data from WDI, the research applies a variety of statistical approaches, including correlation analysis and Driscoll-Kraay standard errors, to determine the underlying dynamics. The findings of the literature assessment indicate a complex association between FI, CO_2 emissions, and technological innovation.

The literature review concludes that it is critical to study the interconnected influences of FI and technology innovation when tackling environmental concerns and attaining financial development goals.

While various studies have found both significant and insignificant impacts of FI on the environment, no comprehensive research that takes into consideration the moderating influence of technological innovation across different nations exists. Some research shows that FI encourages economic activity that may raise CO_2 emissions, but others argue that the approach to financial facilities might support investments in cleaner technology and sustainable businesses, thereby reducing CO_2 emissions. This study aims to explain these contradicting findings by evaluating data from 83 countries from 2003 to 2022 and using various statistical techniques to present an expanded overview of how technological innovation affects the relationship between FI and CO2. By addressing these gaps, the research provides a more nuanced understanding of the global system at play, providing crucial insights for policymakers and stakeholders interested in supporting financial development. Second, the previous review recommends that, according to the innovation diffusion theory, the association between FI, CO_2 emissions, and technological advancements is still unclear. Prior research has focused on the independent variable of FI and the dependent variable of CO_2 emissions (Liu et al., 2022). Our research attempts to discover the association between FI and carbon emissions (CO2), with technology innovation playing a moderating role.

Research Methodology

Data and Variable

The goal of this study is to develop a composite financial inclusion indicator based on international evidence and consider many aspects based on available literature. PCA is used to determine which indicators have the most impact on the index for international evidence as a whole and specific nations in the study sample. We collected data on financial inclusion, control variables, and technology innovation variables from WDI. Our sample has 83 international evidences from 2003 to 2022; the list of these countries is shown in Table 1.

This research studies the association between FI, CO_2 emissions and technology innovation in 83 international countries. Table 2 shows the variables used to create composite financial indicators: financial inclusion. The factors for the single composite financial indicator were chosen according to WDI categorizing and the availability of data in the study across a significant time duration. Table 3 shows the statistical summary of the variables.

Table 1

The research includes 83 nations

S.No	Names	S.No	Names	S.No	Names	S.No	Names
1	Australia	23	Denmark	45	Kenya	67	Qatar
2	Austria	24	Egypt	46	Kuwait	68	Russian Federation
3	Argentina	25	Arab Rep	47	Lebanon	69	Romania
4	Belgium	26	Estonia	48	Lithuania	70	Senegal

S.No	Names	S.No	Names	S.No	Names	S.No	Names
5	Brazil	27	Finland	49	Mali	71	Serbia
6	Bahrain	28	Germany	50	Mauritius	72	Slovenia
7	Bangladesh	29	Greece	51	Morocco	73	Sri Lanka
8	Benin	30	Guinea-Bissau	52	Malaysia	74	South Africa
9	Burkina	31	Ghana	53	Mexico	75	Singapore
10	Faso	32	Hungary	54	Netherlands	76	Spain
11	Bosnia	33	Hong Kong SAR	55	Newzealand	77	Sweden
12	Herzegovina	34	Ireland	56	Norway	78	Switzerland
13	Botswana	35	Israel	57	Niger	79	Saudi Arabia
14	Bulgaria	36	Italy	58	Nigeria	80	Trinidad
15	Canada	37	India	59	Oman	81	Tobago
16	Chili	38	Indonesia	60	Portugal	82	Ukraine
17	China	39	Japan	61	Pakistan	83	Thailand
18	Colombia	40	Jordan	62	Peru	84	Turkey
19	Czech republic	41	Korea	63	Philippines	85	Togo
20	Cote d'Ivoire	42	Jamaica	64	Poland	86	Tunisia
21	Croatia	43	Kazakhstan	65	Panama	87	Vietnam
22	United Kingdom	44	United States	66	United Arab Emirates		

Note: Data source: WDI 2024

Table 2

Financial indicators considered in the study (2003-2022)

Variables	Topic	Indicators	Unit
CO2		CO2 emissions (metric tons per capita)	
F11	Access	Automated teller machines (ATMs) (per 100,000 adults)	
F12	Access	Domestic credit to private sector by banks (% of GDP)	%
F13	Access	Commercial bank branches (per 100,000 adults)	
URB		Urban population (% of total population)	%
INC		GDP per capita (constant 2015 US$)	
TRADE		Trade (% of GDP)	%
Internet	technology innovation	Individuals using the Internet (% of the population)	%
patent	technology innovation	Patent applications, residents	
technology	technology innovation	High-technology exports (% of manufactured exports)	%
mobile sub	technology innovation	Mobile cellular subscriptions (per 100 people)	

Table 3

Summary of statistical descriptions of the variables of interest

Variable	Obs	Mean	SD.	Min	Max
CO2	1411	6.564	6.467	0.051	47.657
Atm	1411	62.279	47.913	0.13	288.59
Credit	1411	64.647	43.085	0.186	258.903
Cbank	1411	18.826	15.429	0.14	104.34
INC	1411	19031.088	19936.905	390.425	87123.66
URB	1411	65.808	20.751	16.208	100
TRADE	1411	88.922	58.725	22.106	442.62
Mobile	1411	103.62	40.515	1.29	291.499
Internet	1411	50.412	30.089	0.19	100
Patent	1411	22909.257	97918.051	1	1393815
Technology	1411	12.673	10.178	0	69.647

Table 3 shows a descriptive summary of the DV and financial inclusion proxies. The mean value of CO_2 emission is 6.56 metric tons per capita, with an SD of 6.467. The mean value of FI1 is greater than the mean value of (Liu et al., 2022). The mean of FI2 is less than the mean value of (Mhlanga, 2022). The mean of FI3 is greater than the mean value of (Liu et al., 2022).

Methodologies

This indicates those variables have different dimensions and levels. Table 3 shows that some factors are very inconsistent, whereas others have less variation. As PCA aims to maximize standard deviation, it emphasizes high standard deviation. The selected indicators must be turned into standardized variables. This modification is essential before aggregating indicators into a composite index. This study exploits a normalization method, including z-score.

The z-transformation standardizes indicators by scaling them based on their deviation from the mean. To ensure accurate results, it's vital to study two factors: (1) the sample size and (2) the necessity for recalibration with newly collected data points.

The following procedure is used to standardize using z-score Normalization.

$$zee = \frac{Xi - \bar{X}}{\sigma}$$

Where,

$\bar{X}$= group average

σ = standard deviation

The resulting equation was employed to investigate the suggestion between FI and carbon emissions, which play a moderating role in technological innovation.

$$CO_2=\beta_o+\beta_1 FIindex+\beta_2 INC+\beta_3 URB+\beta_4 TRADE+ \beta_5 Techindex+\beta_6(FIindex*Techindex) +\varepsilon_0$$

Table 4

Results of Bartlett test of sphericity and Kaiser-Meyer-Olkin measure of sampling adequacy

	Bartlett test of Sphericity			Kaiser-Meyer-Olkin measure of Sampling Adequacy
	Chi-square	Degrees of Freedom	p-value	
Financial Inclusion				
z-score normalization	723.785	3	0.000	0.674
Innovation of technology				
z-score normalization	316.199	6	0.000	0.556

Source: Authors calculations: note: Bartlett test & KMO test

Two tests, Bartlett's test of sphericity and the KMO test, were used at the start of the analysis to determine whether the information was suitable for the factor study. Bartlett's test of sphericity checks if the association matrix employed in the PCA is a unique matrix. Factor analysis requires substantial ($p < 0.05$) results. Meanwhile, the Kaiser-Meyer-Olkin test was utilized to evaluate sampling adequacy. It denotes the part of shared variance that could be attributed to fundamental variables. The KMO index operates from 0 to 1, with values > 0.5 suggesting suitable factor analysis. The Bartlett test for sphericity examines if the association matrix of the variables differs significantly from a unique matrix, indicating that the factors are intercorrelated. A significant p-value ($p < 0.05$) rejects the H_0, suggesting that the variables are linked. Financial inclusion ($p < 0.001$) and technological innovation ($p < 0.001$) indicate determined intercorrelation of variables within each construct. The KMO Measure of Sampling Adequacy assesses the sample's suitability for completing a factor analysis. A KMO score closer to one suggests that the variables are highly connected and appropriate for factor analysis. The outcomes of these tests are shown in Table 4. The values of KMO for financial inclusion (0.674) and technological innovation (0.556) indicate moderate to suitable sampling adequacy, implying that the variables within each construct are adequately associated with component analysis. The research shows that the factors of FI and technological innovation are

interrelated and suitable for further investigation, therefore establishing the validity of the constructs in the research study. As a consequence, the findings of the two analyses validate the use of the PCA in this research.

Empirical Results

Table 5

Total variance explained

	Component	Eigenvalues	% of Variance	Cumulative Variance %
Financial Inclusion Index				
Normalized Variables using Standardized Z-Score	1	1.93593	0.6453	0.6453
	2	0.588352	0.1961	0.8414
	3	0.475719	0.1586	1.0000
Innovation Technology				
Normalized Variables using Standardized Z-Score	1	1.63278	0.4082	0.4082
	2	1.14797	0.287	0.6952
	3	0.667723	0.1669	0.8621
	4	0.551526	0.1379	1.0000

Source: Author's calculations

Table 5 shows the total variation and explains the components of the FI index and the Innovation Technology index. When analyzing the Financial Inclusion index, the first component appears as the most significant, explaining 64.53% of the variance. Subsequent components contribute progressively less, with the second explaining 19.61% and the third 15.86%, accounting for the full variance at 100%. Similarly, in the Innovation Technology index, the 1st component accounts for 40.82% of variance, followed by the second (28.7%), third (16.69%), and fourth (13.79%) components, for a total variance of 100%. These results highlight the importance of the discovered components in fully defining the underlying entities. The cumulative variance percentages represent the aggregate explanatory power of the components. This indicates their ability to explain the changes within the original variables.

Table 6

Correlation Matrix

Variables	CO2	FIindex	tech index	INC	URB	TRADE
CO2	1.00					
FIindex	0.32***	1.00				
tech index	0.43***	0.56***	1.00			
INC	0.58***	0.57***	0.61***	1.00		
URB	0.58***	0.50***	0.63***	0.63***	1.00	
TARDE	0.17***	0.16***	0.42***	0.29***	0.31***	1.00

Source: Authors Calculations

Table 6 shows the correlation matrix and explains the components of the FI index and the Innovation Technology indexes. The correlation coefficient between CO_2 emission and the FI index is 0.32, showing a positive but modest relationship. This indicates that the link between FI and CO_2 emissions is slightly marginally favourable. The correlation coefficient between CO_2 emission and the technology innovation index is 0.43, showing a moderate positive correction. It implies that technological innovation has a larger positive association with CO_2 emissions than FI. These correlations indicate that both financial inclusion and technological innovation are positively associated with CO_2 emissions. The correlation coefficient between FIindex and techindex is 0.56, which is statistically noteworthy at 99% confidence (***). This indicates a substantial positive relationship between FI and technological innovation. A value of 0.56 suggests a significant positive correlation between these variables.

Table 7

Estimation result: Driscoll-Kraay standard errors

Variables	Pooled OLS Regression	GLS Regression
FIindex	0.204*** (0.0611)	0.204*** (0.0186)
tech index	0.152** (0.0609)	0.152*** (0.0222)
FIindex_tech	-0.230*** (0.0350)	-0.230*** (0.0133)
INC	1.01e-05*** (1.89e-06)	1.01e-05*** (1.41e-06)
URB	0.0239*** (0.00301)	0.0239*** (0.00136)
TRADE	0.000595 (0.000444)	0.000595 (0.000368)
Constant	-0.310 (0.218)	-0.310*** (0.0913)
R-squared	0.706	
F-Stats (P Value)	0.000	
Wald (Test)		0.000
Observations	1,411	1,411
Number of countries	83	83

Table 7 shows estimated findings using Driscoll-Kraay standard errors, with a concentration on the Financial Inclusion Index (FIindex), technology index (tech index), and their interaction term (FIindex_tech) as moderating variables. In both the pooled OLS regression and GLS regression, the value of regression for FIindex and Techindex are statistically significant; the regression coefficient of FIindex is 0.204, suggesting that a single unit change in FIindex leads to 0.204 unit change in CO_2 emissions, and the value of regression for Techindex is 0.152, suggesting that one unit change in Techindex leads to 0.152 units change in CO_2 emissions. The coefficient for FIindex_tech is -0.230 in both the pooled OLS and GLS regression models, which are statistically significant (***), showing a strong association. This negative coefficient indicates that while the interaction between financial inclusion and technology innovation (measured by FIindex_tech) increases by one unit, the dependent variable (such as CO2 emissions) decreases by 0.230 units, while other variables remain constant. The R^2 value of 0.706 IVs explains almost 70.6% of the volatility in the DV. This suggests that the model, which contains variables like FIindex, techindex, FIindex_tech, INC, URB, TRADE, and a constant term, accounts for a significant percentage of the variance in the DV.

Conclusions

The aim of this research was to evaluate the link between FI, innovative technology, and CO2 emissions, giving empirical insights into their linked dynamics between 2003 and 2022. The study intended to explain these elements' ability to influence global environmental consequences. The study showed significant evidence of a relationship between FI, technology innovation, and CO2 emissions. Moreover, both financial inclusion (measured by the FIindex) and technological innovation (described by the tech index) have a major influence on CO2 emissions. Furthermore, the interaction term FIindex_tech had a strong moderating impact, emphasizing the collaborating potential of FI and technological innovation in reducing environmental degradation. These findings have important consequences for governments, companies, and civil society enterprises.

By understanding the evaluative role of FI and technology innovation in the preservation of the environment, stakeholders may develop focused strategies to capitalize on their transformational potential. Embracing inclusive financial institutions and promoting technological advances will help create more sustainable and stronger economies. Furthermore, utilizing the complementary nature of financial

inclusion and technological innovation could provide new opportunities for financial development, stimulating innovation and creating inclusive growth. However, this study has many limitations. The dependence on secondary data sources and aggregate analysis may limit the depth of findings.

Furthermore, the study's conclusions are dependent on data availability and quality, which may result in neglecting complex regional or sectoral patterns. In addition, despite efforts to control for significant variables, the inclusion of unknown variables or variability problems may add bias, prompting caution in determining causation. Addressing these constraints in future research attempts may improve our knowledge of the complex link between FI, technological innovation, and environmental impacts.

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Appendix

Table 8

Results of diagnostic tests for heteroscedasticity and serial correlation

Test	Error process	Test statistic	
		Chi2	p-value
Modified Wald (x^2)	Heteroscedasticity	2.20E+05	0.0000
Wooldridge Test (F-test)	Serial correlation	151.138	0.0000

Table 9

Pesaran (2003) CD test for cross-section independence in macro panel data

Variable	CD-test statistic	p-value
CO2	7.01	0.000
INC	127.06	0.000
IND	60.89	0.000
TRADE	31.85	0.000

*Note: ststistical significance is donated by ***,**,* at 1,5,10 percent, respectively*