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DIGITAL FINANCIAL INCLUSION, ENVIRONMENTAL DEGRADATION, AND HUMAN CAPITAL NEXUS: EVIDENCE FROM SOUTH ASIAN COUNTRIES

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ABSTRACT: This study investigates the complex interrelations between Digital Financial Inclusion, Human Capital, and Greenhouse Gas Emissions in South Asian countries from 2005 to 2023. We applied second-generation unit root analysis and panel co-integration test of Westerlund, designed especially for cross-sectional dependence and slope heterogeneity, by subjecting them to rigorous testing of these data irregularities. The Westerlund test results confirm significant long-term co-integration, but findings suggest a mixed character of stationarity. The empirical results indicate that a 1% incline in human capital leads to a 1.81% decrease in greenhouse gas emissions. In contrast, a one-unit increase in digital financial inclusion is associated with a 0.33-unit increase in greenhouse gas emissions. This study addresses a neglected area of existing research through regional analysis and utilises approaches to handle cross-sectional dependence and slope heterogeneity. Policymakers are encouraged to integrate findings from this study into climate action strategies, emphasising the importance of promoting digital financial inclusion to support human capital development while addressing environmental impacts.

KEYWORDS: digital financial inclusion, greenhouse gas emissions, human capital, urbanization, panel ARDL

Introduction

With the increasing need to combat climate change and anthropogenic emissions of greenhouse gases (GHGs), it is necessary to explore the factors that influence environmental quality. The role of technological innovations, the financial sector, and economic determinants is critical in explaining environmental sustainability. Particularly, in developing economies, digital financial inclusion has become an important factor in increasing access to resources and investments in sustainable practices, largely due to the importance of human capital in the process of adopting environmentally friendly technologies. Digital finance can empower people and companies to invest in less emission alternatives while reducing GHG outputs in regions such as agriculture and energy (Majeed et al., 2024; Balafoutis et al., 2017; Kuzior et al., 2022; Yudaruddin et al., 2023). Digital financial inclusion (DFI) can help to mitigate GHG gas emissions by facilitating green technologies and efficient resource management. This effect is referred to as the technique effect.

As a society moves towards sustainable development, it is imperative to understand how the human capital index (HCI), DFI, and GHG emissions are dynamically related. Human capital (education and skills) plays an important role in the development of the innovation and sustainable practices capacity (Yudaruddin et al., 2023; Iqbal et al., 2021). Specifically, we hypothesise that with skilled human capital, better inclusion in the financial sector enables the most efficient use of resources available, resulting in lower GHG emissions. This study aims to enhance our knowledge of the extent to which digital financial inclusion and human capital can act as levers for policy interventions to alleviate GHGs (Yudaruddin et al., 2023).

The present research investigates the relationships between GHG emissions, DFI, and HCI in six South Asian countries over nearly two decades. Second-generation unit root tests and Westerlund panel co-integration methods are applied to consider the dynamics of financial practices and environmental consequences in emerging economies. Most previous studies on this topic have mainly concentrated on the isolation effect of financial inclusion on the growth and inequality of the economy (Park & Mercado, 2018; Qamruzzaman & Wei, 2019). Nevertheless, we reveal that DFI increases are driving up GHG emissions, and HCI increases lead to GHG downfalls, expanding the sustainability debate. Moreover, the presence of bidirectional causality between HCI and DFI is substantiated, wherein these interactions have not been analysed enough in the context of South Asia's rapid urbanisation (Hunjra et al., 2020; Thathsarani et al., 2021).

The existing studies have highlighted the role of financial development and financial inclusion on carbon emissions. To the best of the authors' knowledge, no prior study has considered the role of DFI in the case of South Asian countries. Besides, the role of HCI is overlooked in studies exploring the role of financial development in carbon emissions. This study considers the role of DFI and HCI in GHG emissions in South Asia. The past studies have focused on CO2 emissions, while the present study considers GHG emissions, which is a more comprehensive measure of environmental degradation.

The next section provides a relevant literature discussion. The data and methodology are discussed in Section 3. Results and discussion are provided in Section 4, and finally, Section 5 concludes the study.

Literature review

Digital Financial Inclusion and Greenhouse Gas (GHG) Emissions

The linkages between DFI and GHG gas emissions are complex and context-dependent, with results differing depending on the context and methodology. DFI can influence environmental degradation in the following ways. First, it creates a scale effect by supporting economic activities. The studies suggest that financial inclusion through digital means has been identified as the enabler of economic empowerment, as an avenue for underserved population groups to access financing and the avenue through which entrepreneurship is supported, especially in developing countries (Kim et al., 2018; Thathsarani et al., 2021). Nevertheless, the environmental impacts of deepened financial access are diverse; at the same time, financial adoption can boost economic development, and thus, escalate production and consumption processes that might yield increased greenhouse gas (GHG) emissions (Ahmad et al., 2022; Ullah et al., 2022).

It has been shown that financial inclusion has a positive effect on economic outcomes, while the relationship between this and environmental quality is more complex. A literature search reveals that there is a statistically significant and positive relationship between financial inclusion and carbon emissions, suggesting that if finance for all is expanded, then it can lead to carbon emissions that degrade the environment (Ahmad et al., 2022; Rehman et al., 2021). However, there are studies that show that digital financial inclusion can serve as a mediator of positive changes in energy consumption and move toward environmentally sustainable behaviour (Kaplan et al., 2024; Ofosu-Mensah Ababio et al., 2024). Digital finance is emphasised as essential for sustainability in order to reduce environmental problems, as well as in promoting equitable economic development.

Additional exploration of the regulatory environment for digital financial inclusion identifies financial services as a potential for contributing to environmental sustainability only if the respective environment is also underpinned by robust environmental regulations/policies. For example, Ding et al. (2022) and Zheng et al. (2024) stress the value of spanning the environment into financial services by leveraging technology for sustainability innovation. The eco-friendly investment practices may be incentivised by regulatory frameworks that bridge the financial inclusion efforts and the need to decrease GHG emissions (Li & Pang, 2023). Finally, evaluating the impact of financial inclusion on the quality of economic and environmental quality continues to be an important policy and research area.

Human Capital Index and Greenhouse Gas Emissions

The literature concerning the relation between human capital and greenhouse gas (GHG) emissions is characterised by different ways of understanding and conclusions. There is an emerging commonality across studies that the impact of human capital on emissions is dual. As an example, Hao et al. (2023) it demonstrates that human capital is positively correlated with GHG emissions, and this relationship may be explained in terms of mechanisms related to economic growth (although the context and other factors like technological advancement are stressed to be important). Contrary to this trend, various researchers point out that human capital has the capacity to reduce emissions through activities of innovation and efficient resource utilisation (Farooq et al., 2024; Kuziboev et al., 2023; Lin et al., 2021). That is a complicated relationship where human capital can either further emissions or decarbonise emissions, depending on the situation and policy frameworks in place.

Also, there are many studies about how other conditions, like financial development and technological innovation, have a relative impact on this relationship. According to Ganda, there is a unidirectional causal relationship between economic growth caused by human capital, which raises carbon emissions, but human capital improvement can enhance cleaner production techniques (Ganda, 2022). There is a need for high capital costs in terms of carbon pricing in developing countries and building the role and interaction between human capital and emissions dynamics, which limits its outreach across sectors (Hirth & Steckel, 2016). The contextual dependence of these findings underscores the importance of considering not just aggregate results, but localised interactions that may affect the returns to investment in human capital.

Finally, the relationship between human capital and GHG emissions is multidimensional. However, it is capable of either underpinning the increase or reduction in emissions based on external forces like economic conditions and the regulatory environment. This finds future research on the thresholds at which human capital changes from being an exacerbating to a mitigating factor for emissions, and how these mechanisms work in various economic contexts as an important research area (Farooq et al., 2024; Hao et al., 2023; Kuziboev et al., 2023).

Human Capital Index, Digital Financial Inclusion, and Greenhouse Gas Emissions

There is a vital research gap in the relationship between digital financial inclusion, human capital, and greenhouse gas in the context of South Asian economies. Previous studies assert that DFI promotes economic participation and alleviates poverty (Kass-Hanna et al., 2022; Park & Mercado, 2018). However, we have little knowledge of how it impacts human capital development for its environmental purposes. There is little research (Rasheed et al., 2024) that identifies financial inclusion

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with the reduction in carbon emissions; however, it is not explored how improved human capital through education and financial literacy can enable communities to utilise digital financial tools to support innovation around sustainable practices. Forming the intersection of these factors can have significant influences on growth trajectories and is commonly not recognised in current research. Furthermore, the South Asian countries face the need to adopt green technology as much as they need financial empowerment for mitigating greenhouse gas (Banik & Roy, 2023). According to the literature, financial access should be complemented with a knowledge of environmental sustainability to bring out its potential in fostering low-carbon development. As a result, there is a substantial gap worth covering by the scholars while considering how human capital combines with digital financial inclusion to spur environmentally viable practices.

Data and Methodology

Data

This study investigates the relationship between GHG emissions, DFI, and HCI in selected South Asian countries, i.e., Pakistan, India, Bangladesh, Nepal, Maldives, and Sri Lanka, from 2005 to 2023. World Development Indicators (WDI, 2024) serves as one data source in addition to the Penn World Table. The chosen countries and timeframes exist mainly because relevant data were available. The table contains three segments that present variables through their symbols, definitions and data collection sources.

Table 1. Data Description

Variables	Symbol	Description	Source
Human Capital	HCI	"Human Capital Index" primarily based on the average years of schooling data from sources like Barro and Lee, combined with an assumed rate of return to education, essentially reflecting the quantity and quality of education within a country, allowing for cross-country comparisons of human capital levels.	Penn World Table https://www.rug.nl/ggdc/productivity/pwt/?lang=en
Greenhouse Gas Emissions	GHG	Total annual emissions of the six greenhouse gases (GHG) covered by the Kyoto Protocol (carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and Sulphur hexafluoride (SF6)) from the energy, industry, waste, and agriculture sectors, standardized to carbon dioxide equivalent values divided by the economy's population.	World Development Indicators https://databank.worldbank.org/source/world-development-indicators
GDP Per Capita	GDPPC	GDP Per Capita is gross domestic product divided by midyear population. GDP is the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products.	
Urbanization	URBAN	Urban population refers to people living in urban areas as defined by national statistical offices.	
Digital Financial Inclusion	DFI	We took three variables from the WDI data source i.e. Domestic credit to private sector by banks, mobile cellular subscriptions per hundred people, and individuals using internet (percent of population), and by using Stata and these three variables, we estimate the index called Digital Financial Inclusion.	

The presented descriptive statistics appear in Table 2. The Maldives currently holds the position of highest GHG emissions, while India maintains the second spot, followed by Pakistan. The GHG emissions level is lowest in Bangladesh among the analysed countries. The variable DFI indicates the index based on the indicators of both digital and financial inclusion. The selected South Asian nations exhibit the Maldives as the country with the highest DFI index, while Nepal has the lowest value. HC in the Maldives exceeds all other countries, and Nepal occupies the second position. The highest urban population exists in India, with Pakistan and Bangladesh ranking after it. The economic value of the Maldives stands as the highest, while Sri Lanka follows, and Nepal takes the position with the lowest GDP per capita value.

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Table 2. Descriptive Statistics

Digital Financial Inclusion					
Country	Mean	Max	Min	Std. Dev.	Obs.
Bangladesh	-0.26	1.13	-1.05	0.76	19
India	-0.31	1.07	-0.95	0.54	19
Maldives	1.34	3.13	-0.73	1.29	19
Nepal	-0.14	1.37	-1.02	0.77	19
Pakistan	-0.43	0.56	-0.75	0.36	19
Sri Lanka	-0.21	1.40	-0.98	0.82	19
All	0.00	3.13	-1.05	1.00	114
Human Capital Index					
Bangladesh	1.95	2.10	1.74	0.11	19
India	2.04	2.17	1.86	0.10	19
Maldives	2.06	2.61	1.51	0.36	19
Nepal	1.66	1.82	1.46	0.13	19
Pakistan	1.78	1.80	1.77	0.01	19
Sri Lanka	2.88	2.90	2.86	0.01	19
All	2.06	2.90	1.46	0.42	114
Urban Population					
Bangladesh	33.57	40.47	26.81	4.30	19
India	32.55	36.36	29.24	2.21	19
Maldives	38.10	41.97	33.75	2.43	19
Nepal	18.31	21.90	15.15	2.11	19
Pakistan	35.88	38.04	33.98	1.23	19
Sri Lanka	18.43	19.21	18.20	0.30	19
All	29.47	41.97	15.15	8.42	114
Greenhouse Gas Emissions					
Bangladesh	1.41	1.64	1.15	0.16	19
India	2.38	2.87	1.84	0.29	19
Maldives	4.27	5.87	2.51	1.10	19
Nepal	1.62	1.91	1.32	0.22	19
Pakistan	2.04	2.30	1.87	0.13	19
Sri Lanka	1.66	1.94	1.40	0.17	19
All	2.23	5.87	1.15	1.08	114
GDP Per Capita					
Bangladesh	1372.99	2716.49	480.09	778.78	19
India	1582.10	2480.79	710.49	518.36	19
Maldives	8550.10	12530.36	3796.52	2468.56	19
Nepal	847.18	1385.91	309.02	351.84	19
Pakistan	1236.54	1569.34	827.62	228.86	19
Sri Lanka	3227.35	4401.06	1207.22	1066.79	19
All	2802.71	12530.36	309.02	2924.64	114

Source: Author's calculations

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Theoretical framework

According to the theoretical framework, DFI and HCI are taken as independent variables, while GHG emissions are taken as the dependent variable. DFI could be an enabler for performing more efficient financial practices, which leads to performing sustainable economic activities and consequently to GHG emission reduction. For instance, it enables access to financing of green technologies, facilitates environmental innovation, and energy efficiency in energy-related sectors (Salman & Ismael, 2023; Shi et al., 2022). Furthermore, human capital, in terms of education and the development of skills, also plays an important role in environmental sustainability. A stronger human capital base leads to a labour force that can better use digital financial instruments for sustainable practices and consequently decreases emissions (He et al., 2022; Yudaruddin et al., 2023). The studies suggest that regions with more human capital and DFI lead to lower GHG emissions therein, or in other words, education and access to financial resources are the main solutions to climate change (Jóźwik et al., 2023; Kuzior et al., 2022). As such, facilitating the development of human capital together with digital financial inclusion is important for effective environmental policy-making and the reduction of GHG outputs. Because of the existing background, this model needs to be formulated in this way:

$$\mathrm{GHG} = \mathrm{F}(\mathrm{DFI}, \mathrm{HCI}, \mathrm{URBAN}, \mathrm{GDPPC}).$$

ARDL Model

The ARDL model was constructed to evaluate both short- and long-term impacts. This model is flexible in the integration order. That is, it is robust whether variables are integrated in order zero or one or a mixture of both. It allows simultaneous estimation of coefficients for both the short and long run. Moreover, its performance is superior in the case of small samples, such as an analysis of South Asian countries. The general form of the ARDL model is specified as follows:

$$\Delta \mathrm{GHG}_t = \alpha_0 + \sum_{i=1}^{p} \beta_i \, \Delta GHG_{i,t-i} + \sum_{i=0}^{q} \gamma_i \, \Delta \mathrm{DFI}_{i,t-i} + \sum_{i=0}^{r} \delta_i \, \Delta \mathrm{HCI}_{i,t-i} + \sum_{i=0}^{s} \theta_i \, \Delta \mathrm{URBAN}_{i,t-i} + \sum_{i=0}^{t} \lambda_i \, \Delta \mathrm{GDPpc}_{i,t-i} + \eta \mathrm{GHG}_{i,t-1} + \kappa_1 \mathrm{DFI} + \kappa_2 HCI_{i,t-1} + \kappa_3 \mathrm{URBAN}_{i,t-1} + \kappa_4 \mathrm{GDPpc}_{i,t-1} + \epsilon_{i,t}. \quad (1)$$

Where Δ denotes the first difference operator. The letters (p), (q), (r), (s), and (t) are the lag lengths for the dependent and independent variables, respectively. The notation (α_0) is the constant term. The letters β,γ,δ,θ and λ are the short-term coefficients, and κ_1 to κ_4 are the long-term coefficients.

In the next step, the **Error Correction Model (ECM)** form is given as follows:

$$\Delta GHG_t = \alpha_0 + \sum_{i=1}^{p} \beta_i \, \Delta \mathrm{GHG}_{i,t-i} + \sum_{i=0}^{q} \gamma_i \, \Delta \mathrm{DFI}_{i,t-i} + \sum_{i=0}^{r} \delta_i \, \Delta \mathrm{HCI}_{i,t-i} + \sum_{i=0}^{s} \theta_i \, \Delta \mathrm{URBAN}_{i,t-i} + \sum_{i=0}^{t} \lambda_i \, \Delta \mathrm{GDPpc}_{i,t-i} + \psi \mathrm{ECT}_{i,t-1} + \epsilon_{i,t}, \quad (2)$$

where Error Correction Term (ECT) reflects the deviation from long-run equilibrium in the previous period:

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$$\mathrm{ECT}_{i,t-1} = \mathrm{GHG}_{i,t-1} - \hat{\kappa}_1 \mathrm{DFI}_{i,t-1} - \hat{\kappa}_2 \mathrm{HCI}_{i,t-1}$$
$$-\hat{\kappa}_3 \mathrm{URBANn}_{i,t-1} - \hat{\kappa}_4 \mathrm{GDPpc}_{i,t-1}. \quad (3)$$

(ψ) reflects the speed of adjustment coefficient. Its expected sign is negative, which confirms the long-run adjustment of the relationship between variables.

We apply the log-log transformation of the model in order to overcome the different unit of measurement among the variables. The log transformation help us to find the proportionate change in the dependent variable due to the proportionate change in the respective independent variables.

$$LGHG_{it} = \beta_o + \beta_1 DFI_{it} + \beta_2 LHCI_{it} + \beta_3 LURBAN_{it} + \beta_4 LGDPPC_{it} + E_{it}. \quad (4)$$

Where i represents the countries (i=1, 2, 3, ..., 5) while t indicates the time (2005 to 2023). The expected sign of β_1 is negative as an increase in DFI leads to environmental improvement, β_2 is expected to be negative as HCI declines the GHG. The signs of β_3 and β_4 is expected to be positive, as an increase in GDP per capita and urban population deteriorates the environmental quality.

Results and Discussions

The results from Table 3 verify that cross-sectional dependence exists within the panel dataset because of the Residual Cross-Sectional Dependence tests. The results from Breusch-Pagan LM measurement together with Pesaran Scaled LM and Bias-corrected Scaled LM, appear in the statistical analysis. Statistical evidence from Pesaran CD estimates reaches significant heights to demonstrate the rejection of no cross-sectional dependence at the 1% level. All variables present identical uniform statistical significance to indicate that residuals relate across the entire cross-sections, therefore preventing proper evaluation of cross-sectional dependence in model development.

Table 3. Cross-Sectional Dependence Results

Variables	Breusch-Pagan LM	Pesaran scaled LM	Bias-corrected scaled LM	Pesaran CD
GHG	198.11***	32.34***	32.17***	13.98***
HC	282.14***	47.68***	47.51***	-1.127
DFI	243.33***	40.59***	40.42***	15.57***
GDPPC	222.6***	36.81***	36.64***	14.88***
URB	251.98***	42.17***	42.004***	15.80***

Notes: *** represents a rejection of the null hypothesis at a 1% level of significance; null hypothesis: no cross-section dependence (correlation) in residuals. Cross-sections included = 6; Total panel observations = 114; Periods included = 19 (2005-2023); GHG (Greenhouse gas emissions), HC (Human Capital), DFI (Digital Financial Inclusion), GDPPC (Gross Domestic Product per Capita), URB (Urbanization)

Table 4 shows the information on slope heterogeneity. According to the research premise, all measured slope coefficients should exhibit uniformity in their values. Hashem Pesaran and Yamagata (2008) explained that the Delta and adjusted Delta test statistics' statistical significance produces evidence of slope heterogeneity that allows rejection of the null hypothesis in the dataset. Unit root tests from the second generation detect unit roots in data when cross-sectional dependence exists, together with slope heterogeneity.

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Table 4. Testing for Slope Heterogeneity

Estimates	p-value
3.54***	0.000
4.28***	0.000
Notes: H0 – slope coefficients are homogenous; *** represents a rejection of the null hypothesis at a 1% level of significance; variables partialled out: constant. Sources: Author's calculations; Pesaran and Yamagata (2008).	

The analysis presents the test results derived from Hashem Pesaran and Shin (2007). This advanced methodology works better than other approaches because it takes slope heterogeneity alongside cross-sectional dependence into account during order of integration analysis, thereby making results more dependable. The research conducted stationarity analysis using two methods: Cross-Sectionally augmented IPS (CIPS) together with Cross-Sectionally augmented ADF (CADF).

$$\Delta Y_{it} = \gamma_i + xi\, Y_{i,t-1} + \lambda i\, T + \sum_{k=1}^{n} \pi_{ik} \Delta Y_{i,t-k} + \mu_{it}\,. \tag{5}$$

Here, *i* and *t* denote the intercept and time trend, respectively. The second test applied for stationarity is the CADF, which includes the usual "augmented Dickey-Fuller (ADF)" regression. This can be conveyed by containing the averages of the cross-sectional lagged levels (X) and the first differencing of the individual series.

$$\Delta X_{it} = \alpha_i + \beta i\, X_{i,t-1} + \delta i\, \bar{x} + \lambda \Delta \bar{x}_t + \mu_{it}. \tag{6}$$

The computation utilises the mean value x_t that includes all N time period observations at time t. "The analysis utilised this term as a representation of unexplained factors from common elements." The results gathered from stationarity tests appear in Table 5. Most variables within the data set demonstrate non-stationarity through the results obtained from CIPS and CADF tests at varying degrees. The 1(1) stationary level exists for GHG, DFI, and GDP per capita after performing the first difference test. However, HCI and the Urban population are integrated at the second order difference i.e. I (2).

Table 5. Second Generation Panel Unit Root Analysis

Variables	CIPS			CADF		
	Level	1st Difference	2nd Difference	Level	1st Difference	2nd Difference
LGHG	-2.07	-3.632***		-2.377*		
LHC	-0.705	-0.987	-2.594**	-2.66**		
DFI	-1.766	-3.466***		-2.09	-3.614***	
LURBAN	1.631	-0.308	-3.52***	-1.934	-0.895	-2.342*
LGDPPC	-2.068	-3.691***		-1.565	-2.829***	

Critical values – 2.21, – 2.34, and – 2.6 at 10%, 5%, and 1% in CIPS and CADF, having – 2.21, – 2.34, and – 2.6 at 10%, 5%, and 1% level of significance, respectively. Probabilities *p <0.1,**p <0.05, ***p <0.01
GHG (Greenhouse gas emissions), HC (Human Capital), DFI (Digital Financial Inclusion), GDPPC (Gross Domestic Product per Capita), URB (Urbanization)

Westerlund co-integration testing showed trustworthy results through integration order testing because it enables the correct detection of long-term variable relationships during situations of CSD and slope heterogeneity effects (Westerlund, 2007). The Westerlund co-integration analysis of panel data generates its results by means of Gt, Ga, Pt and Pa statistics in Table 6. The Gt and Ga serve to test whether unit-level data in the panel model contain co-integrating elements. The aim of both Pt and Pa tests is to determine if each unit across the entire panel system contains co-integrated variables.

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The essential variables achieve long-run co-integrated relations based on a 1% and 5% significant P-values for Gt and Pt.

Table 6. Westerlund Panel Cointegration Results

Statistic	Value	Z-value	P-value	Robust P-value
Gt	-12***	-24.509	0.000	0.000
Ga	-0.08	4.117	1.000	1.000
Pt	-2.59**	2.47	0.993	0.025
Pa	-0.13	2.965	0.999	0.900
Probabilities *p <0.1,**p <0.05, ***p <0.01				

Granger causality tests are performed by Dumitrescu and Hurlin (2012) for their analysis to yield considerable insights regarding the causal links among GHG, DFI, HCI, URBAN, and GDP per capita. The results confirm that urbanization Granger causes DFI, while there exists a bidirectional causality between HCI and DFI, hence confirming that these elements are interdependent in economic contexts (Udoh et al., 2021). Furthermore, a unidirectional causal effect from GHG to DFI implies that the economic parameters are being influenced by the environmental factor, but the precise relationships between urbanisation and GDP per capita have not been fully explored in existing literature (Li et al., 2023; Raphael, 2023). Alignment of digital financial strategies, note the demand for financial inclusion and the need to marry human capital development with GHG considerations that increasingly inform economic growth trajectories (Odugbesan et al., 2022). Digital financial inclusion initiatives to advance are becoming increasingly influenced by urbanisation as an important factor in bridging the gap between the attainment of environmental sustainability and economic progress (Thathsarani et al., 2021). This study unveils the causative relationships between environment and economy, and this is an area of great significance for policymakers (Song et al., 2022).

Table 7. Pairwise Dumitrescu-Hurlin Panel Causality Results

Null Hypothesis	W-Stat	Zbar-Stat	Prob.	Decision
DDHC heterogeneously causes DDFI	16.07	18.89	0.000	HCI → DFI
DDFI heterogeneously causes DDHC	12.63	14.54	0.000	DFI → HCI
DDURBAN heterogeneously causes DDFI	3.52	2.97	0.003	Urban → DFI
DDFI heterogeneously causes DDURBAN	0.79	-0.49	0.623	
DGDPPC heterogeneously causes DDFI	1.57	0.53	0.599	
DDFI heterogeneously causes DGDPPC	1.48	0.41	0.683	
DGHG heterogeneously causes DDFI	4.62	4.15	0.000	GHG → DFI
DDFI heterogeneously causes DGHG	0.28	-1.12	0.261	
DDURBAN heterogeneously causes DDHC	0.05	-1.44	0.151	
DDHC heterogeneously causes DDURBAN	0.37	-1.03	0.303	
DGDPPC heterogeneously causes DDHC	1.57	0.49	0.624	
DDHC heterogeneously causes DGDPPC	0.79	-0.50	0.615	
DGHG heterogeneously causes DDHC	2.12	1.03	0.301	
DDHC heterogeneously causes DGHG	0.41	-0.96	0.339	
DGDPPC heterogeneously causes DDURBAN	0.56	-0.79	0.430	
DDURBAN heterogeneously causes DGDPPC	1.90	0.91	0.361	

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Null Hypothesis	W-Stat	Zbar-Stat	Prob.	Decision
DGHG heterogeneously causes DDURBAN	4.09	3.32	0.001	GHG → Urban
DDURBAN heterogeneously causes DGHG	0.39	-0.98	0.327	
DGHG heterogeneously causes DGDPPC	2.68	1.79	0.074	GHG → GDPPC
DGDPPC heterogeneously causes DGHG	0.43	-0.95	0.344	
Probabilities *p <0.1,**p <0.05, ***p <0.01				

The main interactions are examined between the selected variables, using the PMG-ARDL model in the time period from 2005 to 2023. In view of the above, the PMG-ARDL model is justified for use in this context as it accommodates the dynamics of the dataset with mixed stationary levels, along with variables first differenced and second differenced. (Anoruo et al., 2024). An examination of both short-term and long-term impact among variables is performed when a (1,2,2,2,2) one was selected due to the Akaike Information Criterion. The findings specifically indicate that a unit increase in DFI may result in a 0.33 unit increase in GHG emissions, and a 1% increase in HCI may lead to a 1.81% reduction in GHG emissions (Majeed et al., 2024). The model also shows mixed elasticities for GDP per capita and urbanisation that are consistent with prior studies on the long-term sustainability of economic development and their ecological consequences (Abid et al., 2024; Jiaduo et al., 2023). Finally, the economic-ecological link presented in the model is validated by the analysis. Table 8 results indicate the results of the Pooled Mean Group – Autoregressive Distributed Lag Model (PMG-ARDL) analysis.

Table 8. Pooled Mean Group – Autoregressive Distributed Lag Model (PMG-ARDL)

Variable	Coefficient	Std. Error	t-Statistic	Prob.*
Long Run Equation				
DFI	0.33***	0.05	6.23	0.000
LHC	-1.81***	0.40	-4.53	0.000
LURBAN	-0.36***	0.11	-3.37	0.001
LGDPPC	0.47***	0.05	8.79	0.000
Short Run Equation				
COINTEQ01	-0.35**	0.15	-2.35	0.023
D(DFI)	-0.12**	0.06	-2.13	0.038
D(DFI(-1))	-0.01	0.07	-0.21	0.832
D(LHC)	4.38	3.27	1.34	0.186
D(LHC(-1))	4.18	2.79	1.50	0.140
D(LURBAN)	-14.43	40.99	-0.35	0.726
D(LURBAN(-1))	1.31	38.41	0.03	0.973
D(LGDPPC)	0.03	0.05	0.65	0.518
D(LGDPPC(-1))	-0.07587	0.061379	-1.23616	0.2216
Notes: P-values and any subsequent tests do not account for model selection; ***, ** and * represents a rejection of the Null Hypothesis at 1%, 5% and 10% levels of significance; number of observations = 102; log likelihood = 247.92; ARDL = (1,2,2,2,2); Model selection method = Akaike info criterion; Dependent variable = D(LGHG);				

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Conclusion

The research comprehensively investigates the interactions between GHG emissions, DFI, and HCI across six South Asian countries – Bangladesh, India, Maldives, Nepal, Pakistan, and Sri Lanka – from 2005 to 2023. By effectively employing second-generation unit root tests and Westerlund panel co-integration methodologies, this study establishes a robust framework to understand the mixed stationary behaviour of variables and their long-term co-integration. The examination reveals significant causation dynamics, notably that urbanisation Granger causes DFI, with confirmed bidirectional causality between HCI and DFI. Additionally, results suggest that an increase in DFI correlates with a rise in GHG emissions, while an increase in HCI is associated with a reduction in GHG emissions. The equilibrium adjustment coefficient further evidences the self-stabilising behaviour of GHG emissions within the studied model, contributing essential insights into the interplay between economic indicators and environmental sustainability.

Policymakers are encouraged to integrate findings from this study into climate action strategies, emphasising the importance of fostering DFI to support human capital development while addressing environmental impacts. Initiatives that promote green technologies and sustainable practices in financial services may yield significant benefits, balancing economic growth with ecological integrity. Additionally, region-specific policies tailored to enhance the resilience of financial systems in the face of environmental challenges could bolster sustainable development in South Asia. This study considers South Asia, while future studies can conduct a comparative analysis of other regions in Asia. This study measures environmental degradation with GHG emissions, while future studies need to assess the role of FDI and HCI on the ecological footprint. Future research should focus on exploring the causal mechanisms behind the observed relationships, particularly the impact of GDP per capita and urbanisation on GHG emissions.

The contribution of the authors

Conceptualization, M.T.M. and U.J.; literature review, M.A., and F.S.; methodology, F.S., and U.J.; formal analysis, M.T.M., F.S., and M.A.; writing, M.A., and U.J.; conclusions and discussion, M.T.M., U.J. and F.S.

The authors have read and agreed to the published version of the manuscript.

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