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Dynamic influence of financial structure, green innovation, urbanization, and trade on consumption-based CO₂ emissions in Asian countries

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Abstract

The world economies have environmental sustainability as one of their main concerns. Although numerous studies have been conducted to determine the factors contributing to ecological problems, little has been done to determine the consumption-based CO₂ emission as a sign. The current research focuses on analyzing the factors that define consumption-based CO₂ emissions based on financial growth, innovation of green technology, urbanization and trade openness of Asian nations between 1991 and 2020. We employed CS-ARDL to address the cross-section dependency and heterogeneous slopes in a panel estimation. The outcomes indicate that the overall trend of financial development is that of the rise of carbon emissions, but the application of green technology considerably decreases it. Furthermore, the relationship between the financial development and green innovation assists in neutralizing some of the environmental effects of financial growth. Urbanization and openness to trade, on the other hand, have minimal effect on the CO₂ emissions. The Granger causality tests also point towards the interrelationships between financial structure, industrial activity, green technology and emissions dynamics. The general conclusions imply that the government comes up with effective financial policies that offer financial incentives in encouraging green innovation to mitigate carbon emissions.

Keywords Consumption-based carbon emissions, Financial development, Green technology, Urbanization, Trade openness, Economic growth

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Introduction

Environmental sustainability in road transportation has emerged as a central pillar of the global climate agenda, particularly under United Nations Sustainable Development Goal (SDG) 13, Climate Action. Transport is responsible for roughly 23% of global energy-related CO₂ emissions, and nearly 70% of this share originates from road vehicles, making it one of the fastest growing greenhouse gas sources in recent decades [1]. The transition toward cleaner and low emission transport systems is therefore indispensable to achieving the targets of COP28, which called for a global transition away from fossil fuels and pledged to triple renewable energy capacity and double energy efficiency gains by 2030, and COP29, which established a new climate finance framework including mobilizing USD 300 billion per year by 2035 and a broader pathway toward USD 1.3 trillion annually for climate investment. Recently there has been a negative environmental disintegration in the emerging Asian economies to shift to economic development and produce elevated carbon emission rates [2]. The Asian countries are estimated to contribute 53% of the total carbon emission as a result of high dependence on enhancing fossil fuels that emit a large quantity of carbon emission. Asia is the largest region in the world with the highest carbon emission, and its population rate is the highest at 60 percent of the total population, 51% of the population lives in urban centers [3]. This spatial and population shift increases energy use and environmental pressure, creating the urgency to comprehend the forces behind consumption-based CO₂ emissions (CCO₂), which take into consideration emissions reflected in domestic consumption and global commerce. Speaking of this issue, proper carbon emission indicators are crucial in the development of relevant and effective climate policies to prevent adverse environmental outcomes [4].

Conventional production-based inventories that quantify emissions in the national boundaries usually understate the ecological footprint that is transferred in the trade. Conversely, the consumption-based accounting approach incorporates imports of emissions in the goods and does not incorporate exports, which provides a more detailed indicator of national environmental accountability [5]. Because, the amount of carbon emissions on the earth would be the aggregation of the emissions on the products used on the national territory whether they are consumed there or not, the emissions do not give the exact view of the environmental degradation. In order to develop evidence-based policies to effectively balance the nature and development of economic growth and environmental sustainability of the region, it is important to establish the nexus between the existing determinants of consumption-based CO₂ emission. Although it is relevant to the policy, there has been little research on the

joint effect of financial development, green innovation, urbanization and trade openness on consumption-based emissions in emerging Asian economies. The majority of literature considers these factors independently or based on production-related models without taking into account the multifacetedness of the interdependence between economic, technological, and structural forces in globally integrated markets [6, 7].

The mechanisms and regulatory reforms to steer a well-developed financial market towards sustainability will be to direct credit and investment into green sectors. The green financial regulations, including the obligatory disclosure of carbon, green bond structures, and the use of ESG as the basis of lending criteria will facilitate the elimination of information asymmetry as well as the encouragement of the environmentally friendly investment. Such steps promote the use of renewable energy sources and sustainable patterns of consumption by companies and households and, in this way, improve their environmental performance [7, 8]. In spite of the fact that energy-intensive growth and ecological degradation may be also perpetuated by financial development, green finance policies and incentives can reshape financial flows towards low-carbon activities and make it sustainable, eliminating adverse environmental outcomes [9].

Therefore, the two variables have a direct relationship with each other [6, 10]. Nevertheless, Acheampong et al. [11] recently conducted a study to investigate the inconsistency of the findings regarding both variables of concern. Since the actions of financial sectors have negative impacts on the global economy, the governments pay more attention to the implementation of green technologies. Most of the studies delved into the positive effects of eco-innovation on Consumption based CO₂ emission [7, 12]. Nevertheless, the countries are at different levels of economic growth and technological revolution, which resulted in dissimilar effects across them [13, 14].

Urbanization is the worldwide structural process of transferring the excess labor in rural regions to the urban regions and it is estimated that the rate of urbanization will rise by 65 percent up to 2050 in the emerging countries. This will be a considerable higher rate, especially in countries of Asia and Africa, and will increase two times by 2030 [2]. The urbanization has a two-fold effect on environment, it has a positive as well as negative influence on ecology. In such a way, most of the studies discovered inconclusive results between them [15]. A single thread of research confirms the ecological modernization theory according to which urbanization does not destroy the environmental conditions, it helps to save it by increasing income and encouraging environmentally conscious behavior. The ecological modernization theory states that the environment deteriorates at the initial phases of modernization but becomes better after the green

technologies are implemented [16, 17]. Comparatively, the second strand will ascertain the urban environmental transition theory, urban development, there are many environmental issues that crop up as they pass through the processes of industrialization and development. In such a way, the environmental issues nationally and in the international arena shift to brown (water-related concerns), grey (auto and industrial pollution), and green (anthropogenic gases); consequently, the natural ecology is also endangered and exhausted [18, 19]. On the same note, another driver of the emissions of carbon is the foreign trade. On the one hand, international trade develops the economy of the countries by making them efficient and competitive in the foreign market. Some studies have found that when countries open up to more trade, their carbon emissions go down [20, 21]. However, the Pollution Haven Hypothesis suggests that richer countries may move their dirty, high-pollution industries to poorer countries through trade because those countries often have weaker environmental rules. Thus, it is mentioned in some works that trade openness raises carbon emissions [22].

Table 1 compares production and consumption-based CO₂ emissions for selected Asian economies. By 2020, most countries record higher consumption-based than production emissions, indicating that they are net importers of carbon-intensive goods through trade. In contrast, China, India, and Malaysia remain net exporters, reflecting their role as global manufacturing hubs. Over the 1991–2020 period, consumption-based emissions increased across nearly all countries except Japan, which shows a decline after 2000. China and India are the primary players whereas emerging economies like Indonesia and Bangladesh are showing increasing consumption-based emission gaps. Notably, consumption-based emissions give a more precise and fair measure of environmental responsibility to the Asian economies. This measure takes into consideration carbon in traded goods because of the fact that most of the Asian nations

produce emissions to meet international demand. Production related metrics are themselves unfair in the regions of export-driven manufacturing where domestic accountability of emissions is falsely exaggerated. Thus, a consumption-based measure is more representative of the actual carbon footprint of economic activity and global trade connections and provides a more equitable basis of climate policy and international systems of emission sharing in Asia.

The study attempts to answer the following research questions.

What is the effect of financial development on consumption-based CO₂ emissions?

How green technologies affects consumption-based CO₂ emissions?

What is the impact of trade openness on consumption-based CO₂ emission?

To what extent, urbanization affect consumption-based CO₂ emission?

Although past researches have largely discussed production-based CO₂ emission, there has been little concern on consumption-based emission in Asian economies under a multidimensional analytical structure. To fill this gap, the current research contributes in three distinct ways. It explores, first, how the dynamic impacts of financial structure, green innovation, urbanization, and trade on consumption-based CO₂ emissions, and how financial development affects the impacts of green technology on emissions. Second, the study uses consumption-based CO₂, which is a trade-adjusted measure of the environment, and this is more realistic in the representation of environmental degradation as compared to traditional measures of production that have been used previously. Third, it applies the developed cross-sectionally augmented autoregressive distributed lag (CS-ARDL) model which enables the pre-emption of cross-sectional dependence and slope heterogeneity that would guarantee a stronger dynamic panel estimation. The rest of the structure of the study is as follows: Section two involves

Table 1 Carbon emission level in Asian nations

Countries	Production-based emissions				Consumption based emissions			
	1991	2000	2010	2020	1991	2000	2010	2020
China	2606.1	3649.2	8620.6	10,905.7	2400.2	3041.4	7337.1	9972.8
India	615.9	986.4	1677.3	2421.6	599.3	897.0	1577.5	2247.8
Japan	1169.7	1264.0	1214.8	1040.5	1340.7	1531.7	1445.5	1185.8
South Korea	275.7	440.0	594.3	597.6	342.4	484.0	650.9	658.2
Indonesia	174.9	281.3	445.8	608.2	160.1	237.6	445.6	623.7
Pakistan	67.5	103.9	154.2	230.8	70.5	113.3	166.1	248.0
Malaysia	65.8	122.9	199.4	263.2	72.7	111.4	178.5	245.8
Bangladesh	14.7	26.5	54.0	95.5	19.2	32.7	53.0	140.4
Sri Lanka	4.1	10.1	13.1	20.6	6.9	15.0	22.1	36.3

Emissions are measured in MtCO₂

Source: [23]

literature review of the previous studies. The third section explains the econometric plan and data description. Section four illustrates the empirical results and the final section five concludes with conclusion and policy recommendations.

Literature review

The increasing focus on carbon emissions resulted into extensive research on identifying their economic and structural determinants. Table 2 presents systematic review of the literature that explores the development of financial, green technology, trade openness, and urbanization and their consequences on the environment. In the reviewed articles, more advanced econometric methods such as ARDL, FMOLS, DOLS, and CS-ARDL are used to investigate the direct and indirect impacts of these variables on CO₂ emissions. Interestingly, the literature indicates a jumble of outcomes: although the financial and trade liberalization tend to escalate carbon emission in economies of the third world, the spread of

green technologies and the sustainable financial systems have turned out to be important compensatory factors. Recent papers, including Behera et al. [24, 25], add to the discussion with the inclusion of political stability and renewable energy into the carbon-finance-innovation nexus, which strengthens the role of multidimensional sustainability models in the policy.

Overall, the reviewed literature reveals mixed evidence across the determinants of consumption-based CO₂ emissions. Financial development and trade openness display dual environmental effects depending on structural and institutional factors, while green technology consistently contributes to emission reduction. Urbanization remains predominantly emission-intensive across Asian economies, emphasizing the need for sustainable urban planning and green infrastructure investment.

Table 2 Review of empirical literature on consumption-based CO₂ emissions drivers

Theme	Author(s)/Year	Region/Sample	Period	Methodology	Key Findings	Direction of Impact
Financial Development	Bui [9]	100 economies	1990–2012	Panel regression	Financial development increases CO ₂ emissions; nonlinear relationship	Positive
Financial Development	Shoib et al. [10]	Developed & developing economies	1999–2013	PMG-ARDL	Financial development significantly raises emissions	Positive
Financial Development	Kirikaleli et al. [8]	Chile	1990–2017	ARDL, FMOLS, DOLS	Financial structure helps reduce CO ₂ emissions	Negative
Financial Development	Yang et al. [7]	China	1980–2019	Bootstrap ARDL	Financial development enhances ecological conservation	Negative
Financial Development	Acheampong et al. [11]	83 economies	1990–2017	Panel econometrics	Financial development reduces emissions in emerging economies; opposite in frontier economies	Mixed
Financial Development	Behera, B., Behera, P. & Sethi, N. [24]	Emerging economies	1995–2022	CS-ARDL, AMG	Renewable energy, green finance, and political stability jointly decouple emissions from growth, supporting SDG 13	Negative
Green Technology	Razzaq et al. [26]	BRICS	1990–2017	Panel quantile-on-quantile regression	Green innovation significantly reduces emissions at high quantiles	Negative
Green Technology	Wang et al. [27]	G7 countries	1980–2018	Panel regression	Eco-innovation lowers emissions amid industrial growth	Negative
Green Technology	Shao et al. [28]	N-11 nations	1980–2018	Panel data	Eco-technology negatively associated with carbon neutrality	Negative
Green Technology	Luo & Mabrouk [29]	Resource-rich nations	1990–2018	Panel estimation	Green innovation mitigates ecological erosion	Negative
Green Technology	Behera, B., Behera, P., Sucharita, S. & Sethi, N. [25]	BRICS	1990–2021	CS-ARDL, AMG	Clean energy and green innovation reduce ecological footprint; political stability amplifies sustainability outcomes	Negative
Trade Openness	Dou et al. [22]	China, South Korea, Japan	1970–2019	Time series	Trade positively linked with CO ₂ emissions	Positive
Trade Openness	Zhang & Xu [21]	10 NICs	1971–2013	Panel data	Trade reduces emissions through technology spillovers	Negative
Urbanization	Nosheen et al. [19]	11 Asian countries	1995–2018	Panel data	Urbanization deteriorates environmental quality	Positive
Urbanization	Mehmood & Mansoor [15]	East Asia & Pacific	1982–2014	Panel data	Urbanization reduces emissions in some, increases in others	Mixed

Financial development and consumption based consumption based CO₂ emissions

The high integration in the globalized world points to the occurrence of financial structures of development that make the world more economically prosperous through minimizing the asymmetric information and maximizing resource allocation at the same time. Digital finance, green finance, high-tech innovations, green governance, and green energy are important factors in enhancing the efficiency in carbon productivity, sustainable growth, and minimizing ecological footprint in different regions, as observed by Sun et al. [30], Zhang et al. [31], and Tariq et al. [32]. A strong financial system lowers the cost of funding and makes more money available for renewable energy projects [7, 8]. In country-specific analysis, Kirikkaleli et al. [8] also provided an empirical estimate between financial development and Consumption based CO₂ emissions in Chile. Contrastingly, other researchers had detected that an established financial system will result in environmental degradation [9, 10]. Shoab et al. [10] contrastively examined the relationship between financial structure and carbon emission in developed and developing countries. Farhani and Ozturk [6] established the direct association between carbon emissions and the financial structure in Tunisia. Nevertheless, there are also inconsistent findings that are studied in 83 different economies [11]. In conclusion, the empirical literature in this regard presents mixed findings, the overall evidence shows that the nature and direction of the relationship between financial development and environmental outcomes depend largely on the quality of financial institutions, regulatory frameworks, and the alignment of financial growth with sustainable and green investment practices.

Green technology and consumption based CO₂ emissions

The most suitable approach to enhance environmental quality is sustainable or eco-technology that will result in energy efficiency and carbon emission reduction. The opportunity of the beneficial impact of green technologies on environmental sustainability was debated in many studies [26, 27, 29, 33]. Environmental sustainability is influenced by tourism and energy efficiency, as tourism contributes to environmental deterioration, while energy-efficiency R&D plays a crucial role in advancing green technology [34, 35]. Additionally, financial development helps mitigate ecological footprints, whereas urbanization poses challenges to renewable energy investments (Aytun et al., 2024; [36]. In fact, other researchers found the adverse or insignificant effect of green technology on environmental pollution [14, 28, 37]). The heterogeneous nations have a variant effect of eco-innovation as a result of various economic conditions and technological advancements. Sustainable technologies found in a study

by Khattak et al. [37] show no real effect in the reduction of carbon emissions. Equally, Ali et al. [38] studied that in Malaysia, carbon pollution was not affected by technical innovation. Therefore, the relationship between the two variables remains ambiguous, as evidenced by the findings of previous empirical studies.

Trade openness and consumption based CO₂ emissions

International trade plays a critical role in promoting the economic welfare of the Asian countries that are emerging, yet at the same time, the importation of the pollutant commodities and the dirty technologies magnifies environmental degradation. Some of the studies also observed that trade openness has been responding negatively to Consumption based CO₂ emissions in the literature [13, 39]. According to Zhang and Xu [21], trade was significant in the reduction of carbon. Moghadam and Dehbashi [40] disclosed that bilateral trade helps minimize the harm to the environment in Iran by limiting the manufacturing of products that contain pollutants and satisfies the local demand by importing these products into Iran. Meanwhile, other studies like [22, 39] identified positive correlations between the two. Shahzad et al. [41] realized that trade was a major contributor of carbon pollution in Pakistan. Sharma [42] established that the trade did not have any impacts on carbon mitigation in 69 economies between the period 1985 and 2005, it indicates that the role of other relevant factors has to be included in the analysis. In conclusion, the impact of international trade on environmental quality remains inconclusive, suggesting that its effects depend on the composition of trade, the level of technological advancement, and the implementation of effective environmental and trade policies in emerging Asian economies.

Urbanization and consumption based CO₂ emissions

The increased urbanization population has adverse effects on sanitized facilities, human health, crimes, traffic system, and environmental quality. Studies have looked at how urbanization affects carbon emissions [19, 43, 44]. Unplanned and fast urban growth often leads to crowded cities and creates social, environmental, and economic problems that harm the environment [45]. In a similar manner, [46, 47] discovered urbanization to have led to the degradation of the environment in five South Asian economies and in Sub-Saharan African nations respectively. Similarly, Ali et al. [48] disclose that urbanization provokes both short-term and long-term carbon pollution. Other studies suggest that urbanization leads to economic well-being and lowers carbon emission through the shift to the use of renewable energy and infrastructure. Mehmood and Mansoor [15] used panel data from East Asian and Pacific countries for the period 1982 to 2014 found that urbanization mitigates carbon

emissions in some countries while stimulating them in other nations. However, a large number of studies analyzed the relationship of urbanization with terrestrial carbon emissions, and little attention has been given to consumption-based carbon emissions. Razzaq et al. [49] determined the asymmetric association between urbanization and trade-adjusted material footprint in China. Thus, there is an unclear nexus between ecological downfall and urbanization.

Hypotheses development

Existing empirical studies on carbon emissions indicate several research gaps. Empirical literature shows that few studies have been made on consumption-based carbon emissions; most of the studies were on terrestrial-based carbon emissions [6, 50, 51]. Thus, it is an empirical gap that combines all these relevant dimensions within the multidimensional model in the situation of Asian nations [8]. From an econometric perspective, previous panel studies usually applied linear panel estimation techniques (FMOLS, OLS, PARDL, etc.) that do not consider CSD and slope heterogeneity in estimation, thus producing deceptive and inconsistent results. Addressing the existing gaps in the literature, this study contributes by estimating the dynamic impact of green technology, financial development, trade openness, and urbanization on consumption-based carbon emissions for Asian economies. To derive more statistically robust and unbiased estimates of the nexus, the study employed the CS-ARDL model, which considers the slope heterogeneity and CSD

issues. Consistent with theoretical and empirical evidence, we propose the following hypotheses:

- H1. Financial development has a positive impact on Consumption based CO₂ emissions.
- H2. Green technology contributes to a reduction in Consumption based CO₂ emissions.
- H3. Trade openness leads to an increase in Consumption based CO₂ emissions.
- H4. Urbanization is positively associated with Consumption based CO₂ emissions.

Data and methodology

The methodology section consists of the description of data, econometric methodology, data sources, and econometric techniques.

Description of data

The article uses Asian economies panel data (China, Bangladesh, India, Indonesia, Japan, Malaysia, Pakistan, South Korea, and Sri Lanka) of 1991–2020. We chose these nine Asian economies since only this population has comparable and reliable information on financial development and the use of green technology as of 2020. The other countries including Vietnam, Philippines and Thailand were not included because of gaps and inconsistencies in the data that would weaken the validity of the analysis. Consumption based CO₂ emission is the dependent variable, which is measured in Metric tons per capita and the data are taken through the Global Carbon Atlas. The type of independent core variables are urbanization (percentage of the total population that is urbanized), open trade (import plus exports of GDP), Financial development (accumulating multidimensional IMF index) and green technology, which is measured as (eco patents as a percentage of total patents). The eco-patent is an appropriate proxy of green technology to use, in line with the recent environmental economics literature since eco-patents reflect the activity of innovation and technological advancement. The control variable of industrialization (value added% of GDP) and economic growth (GDP per capita in constant \$ 2010) is also included in the study. The statistics of urbanization, openness to trade, economic expansion and industrialization have been borrowed in the World Development Indicators [3]. The OECD Statistics [52] and IMF [53] have been used to gather the data on green technology and financial development, respectively. The model converts each and every variable into logarithmic values without the inclusion of the financial development index to normalize them. Table 3 mentions the acronym of the studied variables, their definitions, and the sources of variables.

Table 3 Variables of study

Symbol	Status	Description	Measurement unit	Source
CO ₂	Dependent	Consumption-based carbon emissions	Metric Tons Per Capita	Global Carbon Atlas
GT	Independent	Green Technology	Eco patents % of total patents	OECD Statistics
FD	Independent	Financial development	IMF cumulative Index	International Monetary Fund
URB	Independent	Urbanization	% Share of the total population	WDI
TO	Independent	Trade Openness	Import + Export/ GDP	WDI
GDP	Control	Economic Growth	GDP Per Capita (constant 2010 \$)	WDI
IND	Control	Industrialization	Value added % of GDP	WDI

Model specification and theoretical framework

This study uses the IPAT model to examine how population, affluence, and technology affect the environment. The original IPAT model was created by Ehrlich and Holdren [54]. However, because the IPAT model has some limitations, this study uses an extended version called the STIRPAT model (Stochastic Impacts by Regression on Population, Affluence, and Technology), introduced by Dietz and Rosa [55]. The model can be written as the following equation:

$$I = P * A * T \quad (1)$$

where the symbol I specifies the environmental impact which depends on three main factors: population (P), economic activity (A), and technology (T). Following earlier research [7, 12, 39, 46, 56–58], and modifies them for analyzing the determinants of consumption-based carbon emissions in the context of Asian nations. The equation of the model specification can be written as:

$$CO_{2it} = f(URB_{it}, GT_{it}, FD_{it}, TO_{it}, IND_{it}, GDP_{it}) \quad (2)$$

The specific form of Eq. (2) is presented as Eq. (3) for econometric estimation.

$$CO_{2it} = \alpha_{it} + \beta_1 URB_{it} + \beta_2 GT_{it} + \beta_3 FD_{it} + \beta_4 TO_{it} + \beta_5 GDP_{it} + \beta_5 IND_{it} + \varepsilon_{it} \quad (3)$$

We use the Eq. (4) to capture the moderating effects of green technology and financial development.

$$CO_{2it} = \alpha_{it} + \beta_1 URB_{it} + \beta_2 GT_{it} + \beta_3 FD_{it} + \beta_4 TO_{it} + \beta_5 GDP_{it} + \beta_5 IND_{it} + \beta_6 FD * GT_{it} + \varepsilon_{it} \quad (4)$$

In Eqs. 3 and 4, CO₂ refers to consumption-based carbon emissions. URB, GT, FD, TO, GDP, and IND represent urbanization, green technology, financial development, trade openness, gross domestic product, and industrialization, respectively. The term FD*GT is an interaction variable that captures the combined effect of financial development and green technology. The symbols α , the β coefficients, ε , and t represent the intercept, the variables' coefficients, the error term, and the time period, respectively.

Econometric strategy

Cross-sectional dependence and slope homogeneity tests

The empirical procedure takes place in two stages during which the study conducts an analysis of the cross-section dependency (CSD) of the model using Pesaran CD [59] test. The incidence of CSD is there as a result of financial, economic reforms and cultural values integration therefore, this could disorient the uniformity of the

estimates. Besides, unobserved factors and correlation of error terms with other explanatory variables lead to CSD. Henceforth, it is imperative to ascertain the concern of CSD because Asian countries are regionally or globally connected. After investigating the CSD issue, the study uses Pesaran and Yamagata [60] to identify the slope heterogeneity problem in the analysis. The standardized form of the slope homogeneity test can be expressed below:

$$\Delta_{SH} = (N)^{\frac{1}{2}}(2k)^{\frac{1}{2}} \left(\frac{1}{N}S - k \right) \quad (5)$$

$$\Delta_{ASH} = (N)^{\frac{1}{2}} \left(\frac{2k(T-k-1)}{T+1} \right)^{-\frac{1}{2}} \left(\frac{1}{N}S - 2k \right) \quad (6)$$

In Eqs. (5) and (6), Δ_{ASH} and Δ_{SH} denote delta-adjusted ASH and SH.

Panel unit root

The second one is the evaluation of the stationarity of the variables. Economic and financial data tend to be non-stationary, and this may give erroneous empirical findings. To begin, the study applies the first-generation Im-Pesaran-Shin (IPS) panel unit root test to examine stationarity. However, as the IPS test assumes cross-sectional independence, the Bai and Ng [61] PANIC test is also employed to address CSD by decomposing variables into common and idiosyncratic components. The consistency between the IPS and PANIC results confirms the reliability of variable order integration across panels, ensuring robustness for subsequent testing.

Panel cointegration tests

The study discovers the long-run relationship between the variables after testing on the preliminary tests. Since the existence of cross-sectional dependence (CSD) and slope heterogeneity was verified in the model, the second-generation Westerlund [62] cointegration test is used in this study. This method is especially suited by the fact that it explicitly considers cross-sectional correlations and heterogeneous country specific dynamics, which yields better and reliable estimates of the long-run as compared to first-generation methods. Although the Pedroni and Kao tests of cointegration conventional do not factor these problems and may provide false results, the present paper employs the Westerlund test. While the traditional cointegration tests of Pedroni and Kao do not consider these issues and may produce misleading results, the current study uses the Westerlund test. Further, the study also employed the Pedroni cointegration test; thus, the study applied both conventional and

advanced cointegration tests for unbiased findings. Following is the simplified form of the test:

$$\alpha_i(L) \Delta y_{it} = \gamma_1 i + \gamma_2 i t + \beta_i (y_{it} - 1 - \hat{a} i x_{it} - 1) + \gamma_i(L) v_{it} + \eta_i \quad (7)$$

where

$$\delta_1 i = \beta_i (1) \vartheta \Lambda_{2i} - \beta_i \lambda_{1i} + \beta_i \vartheta \Lambda_{2i} \text{ and } \gamma_{2i} = -\beta_i \lambda_{2i} \quad (8)$$

Equation 7 shows the cointegration vector between explained and explanatory variables. In contrast, β_i denotes the parameter of error correction.

Regression analysis through CS-ARDL model

The next cointegration enables the study to estimate both the long and the short-run coefficient of the model using the CS-ARDL model. The most suitable econometric method is the CS-ARDL method introduced by Chudik and Pesaran [63] in the scenario of CSD and slope heterogeneity. On the other hand, the traditional panel estimation procedures estimate inconsistent and misleading results since they do not face CSD and unobserved variables when estimating the short and long-run analysis. As such, the preposition of no CSD influences the explained variable and results in biased dependence on the residual term of panel cross-section. Self-intuitively, the panel data identities are subject of economic and social characteristics therefore, the unobservable factors could disturb the efficiency of the findings. In addition, the CS-ARDL technique effectively addresses potential endogeneity and non-stationarity issues among the variables. By accounting for cross-sectional dependence and allowing for heterogeneous dynamics across countries, the CS-ARDL approach provides consistent and unbiased long-run estimates. Therefore, this study employs the CS-ARDL method to comprehensively address these econometric challenges and ensure the robustness and reliability of the empirical findings. The mathematical equation of the CS-ARDL regression is as follows:

$$CO_{2it} = \sum_{i=0}^{pw} \gamma_{I,i} CO_{2i,t-1} + \sum_{j=0}^{pz} \beta_{I,i} Z_{i,t-1} + u_{i,t} \quad (9)$$

$$CO_{2it} = \sum_{i=0}^{pw} \gamma_{I,i} CO_{2i,t-1} + \sum_{j=0}^{pz} \beta_{I,i} Z_{i,t-1} + \sum_{j=0}^{px} a_{i,I} X_{i,t-1} + u_{i,t} \quad (10)$$

where $X_{t-1} = (CO_{2i,t-1}, Z_{i,t-1})$.

The long-run coefficient and the mean group technique are expressed as:

$$\hat{\pi}_{CS-ARDL,i} = \frac{\sum_{I=0}^{pz} \hat{\beta}_{I,i}}{1 - \sum_{I=0}^{pw} \gamma_{I,i}} \quad (11)$$

Panel granger causality test

The conventional causality method assumes homogeneous slopes across countries. Thus, it does not account for the slope heterogeneity concerns in panel data. The panel Granger causality test Dumitrescu and Hurlin [64] is appropriate for the heterogeneous panels in assuming the null hypothesis of no Granger causality exists in the model. Individual Wald test statistics are averaged over the panel cross-section identities in this test. The econometric procedure adopted in the empirical estimation is presented as a flow diagram in Fig. 1.

Empirical findings and discussion

Descriptive statistics of the considered variables are represented in Table 4, which specifies the mean, standard deviation, maximum, minimum, kurtosis, skewness, and number of observations. The average score values of CO₂, FD, GDP, GT, IND, TO, and URB are 5.729, 0.435, 8.147, 5.744, 3.457, 3.881, and 3.738, respectively. Likewise, the CO₂, FD, GDP, GT, IND, TO, and URB have minimum values of 1.930, 0.11, 6.030, -0.693, 2.865, 2.761, 2.901, and maximum values of 9.153, 0.9, 10.800, 11.276, 3.882, 5.395, and 4.519, respectively. Figure 4 visualizes the scatter plots of all the model's variables in the appendix, showing heterogeneity across all cross-sections.

Empirical estimation of the current study starts by the investigation of the CSD in the variables; Table 5 reports the results of the CSD test. The results indicate that all the variables reject the null hypothesis significantly. It shows that there are CSD concerns in GT, FD, URB, TO, GDP and IND. The second step after the occurrence of CSD is the exploration of the heterogeneity of the slope in the variables.

The study applied the slope homogeneity test, whose results are mentioned in Table 6.

The substantial test statistics of delta and adjusted delta indicate that all the targeted variables do not have homogenous parameters because of various economic structure, technical advancement, and industrial revolutions.

As an initial step, we check whether the variables in the model are stationary by using the Bai and Ng PANIC test and the IPS unit root test. The empirical findings of all unit root tests are presented in Table 7.

The table shows that all the variables are co-integrated at order one. The overall result of the stationary estimation allows the study to employ the cointegration test to assess the long-run association in the studied variables.

The Westerlund test is appropriate in presences of CSD and slope heterogeneity; the study conducted the test and results are presented in Table 8. Moreover, the Pedroni cointegration test was employed to determine the relationship in the long-run and the findings are presented in Table 8. The null hypotheses of Pedroni cointegration

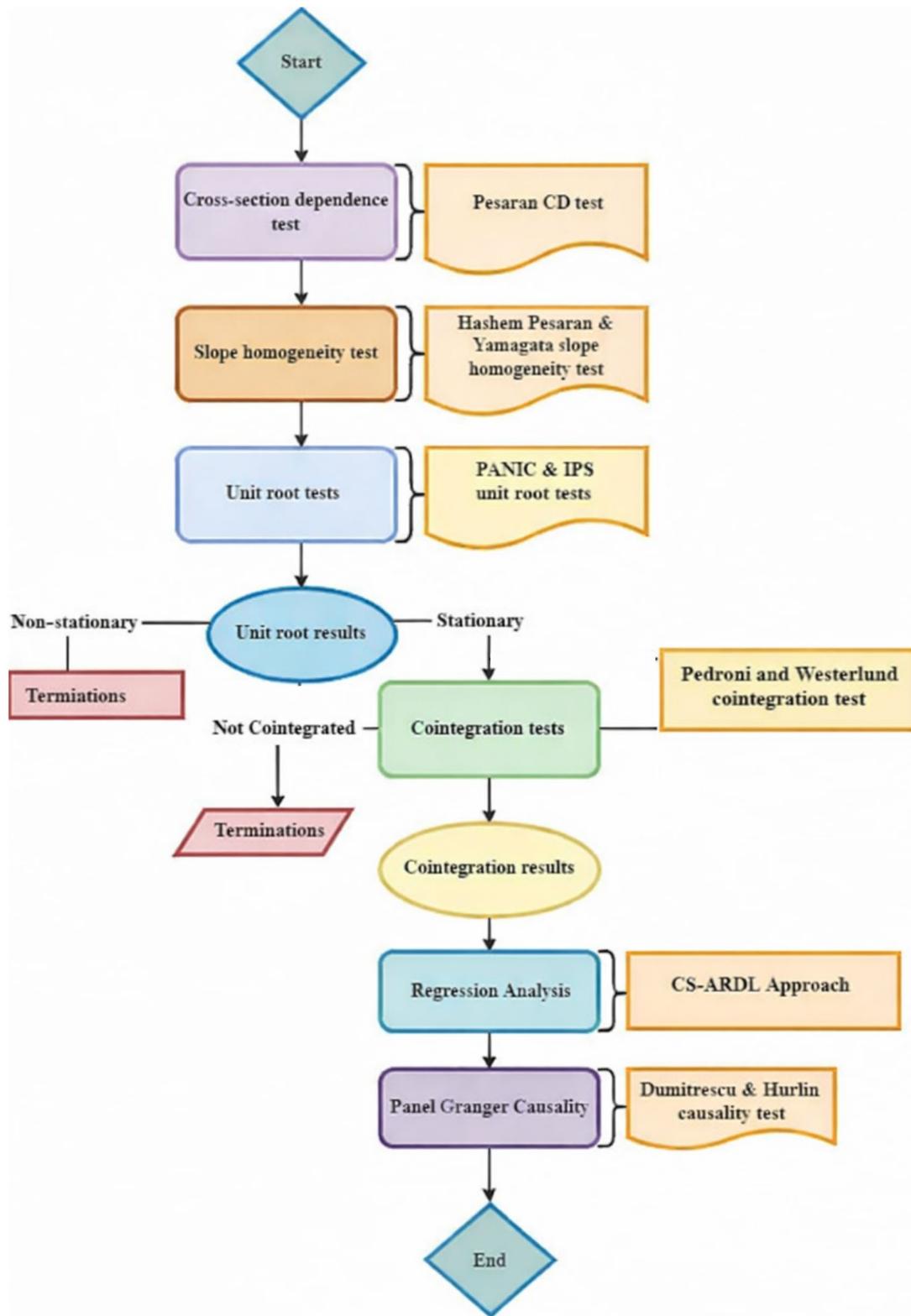


Fig. 1 Flowchart of econometric analysis: Source: Authors' drawing

Table 4 Descriptive statistics

Variables	Mean	Median	Maximum	Minimum	Std. Dev	Skewness	Kurtosis
CO ₂	5.729	5.771	9.153	1.930	1.724	-0.122	2.302
GDP	8.147	7.797	10.800	6.030	1.386	0.500	2.070
IND	3.457	3.432	3.882	2.865	0.270	-0.164	2.053
URB	3.738	3.613	4.519	2.901	0.508	-0.031	1.800
TO	3.881	3.823	5.395	2.761	0.603	0.664	3.086
GT	5.744	4.818	11.276	-0.693	3.395	0.267	1.728
FD	0.435	0.39	0.9	0.11	0.217	0.515	2.095

Source: Authors' calculations

Table 5 Pesaran CSD test results

Variables	Statistics	P-value
CO ₂	22.84***	0.000
GT	29.89***	0.000
FD	20.78***	0.000
URB	19.97***	0.000
TO	2.79***	0.005
GDP	31.48***	0.000
IND	2.06**	0.040

*** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$

Source: Authors' estimation

Table 6 Slope homogeneity test results

Delta	Adjusted delta	
	Statistics	P-value
9.410***	11.058***	0.000

*** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$

Source: Authors' estimation

Table 7 Unit root test

Variables	Bai and Ng PANIC		IPS	
	I(0)	I(1)	I(0)	I(1)
CO ₂	-0.598	-7.332***	6.513	-7.105***
GT	-2.491	-3.468***	3.040	-7.082***
FD	-2.064	-3.658***	-1.694	-9.175***
URB	-0.258	-1.735**	0.353	-6.663***
TO	-2.218	-5.972***	0.426	-7.506***
GDP	0.116	-5.507***	7.985	-3.054***
IND	-1.991	-6.381***	1.497	-7.196***

*** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$

Source: Authors' estimation

tests and Westerlund test were rejected on 1 percent and 10 percent significance level respectively confirming the cointegration in the model.

The study uses the CS-ARDL to examine the dynamic relationships among the variables and to estimate both the long-run and short-run effects. As shown in Table 9, the long-run results show that the relationship between GT and CO₂ is negative; an increment of 1 percent in GT reduces CO₂ by 0.58 percent. The findings suggest that green technologies can improve the ecological quality. The results can be compared with those of Shao et al. [28]: N-11 economies with the best solution to carbon

Table 8 Panel cointegration test

	Within dimension statistics	prob
Panel v-Statistic	0.634	0.263
Panel rho-Statistic	2.877	0.998
Panel PP-Statistic	-2.976	0.001
Panel ADF-Statistic	-2.638	0.004
	Between dimension statistics	prob
Group rho-Statistic	3.476	0.999
Group PP-Statistic	-1.910	0.028
Group ADF-Statistic	-1.944	0.026
Westerlund Cointegration Test	Statistic	prob
Variance ratio	-1.539	0.062

Source: Authors' calculations

Table 9 Long-run CS-ARDL results

Variables	Coefficient	t-value
GT	-0.588*	-1.81
FD	0.662*	1.98
URB	0.965	0.37
TO	0.365	0.29
GDP	0.467**	2.22
IND	0.444**	2.53

*** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$

Source: Authors' estimation

neutrality being green innovation. Equally, results are similar to those of Wang et al. [27] on G-7 countries who detected negative correlation between eco-innovation and carbon emissions. Green innovations can improve the quality of the environment that emits fewer carbon emissions, substitutes fossil fuels with renewable energy, and makes resources more efficient and productive [65]. These findings are opposite to those of Khan et al. [66] regarding the BRICS countries where green innovation fails to influence the decrease in the ecological degradation. The findings suggest that green innovations enhance economic resilience and create a win-win scenario by harmonizing growth with sustainability. Green technologies are instrumental in achieving the goals of the 2015 Paris Climate Agreement, (United Nations, 2015).

The other variable that is relevant is FD that promotes CO₂, an increase of 1% in FD increases CO₂ by 0.66%. The financial sector is a contributor of the ecological breakdown using the energy demand and economic growth

channel. A well-developed financial system makes it easier to access financial resources by reducing information gaps and lowering costs. This gives firms more capacity to invest in heavy machinery, which increases energy use and leads to higher carbon emissions. Similarly, consumers are likely to spend on luxurious long-lasting commodities such as electricity appliances, vehicles, and real estate. These are the products rich in carbon that affect the ecological state negatively [9]. Our results are aligned Zhang et al. [67] that studied G-7 countries and found that FD is directly associated with the ecological footprint by using a sophisticated financial system that enhances economic prosperity, fastens the financial access and income level, which destroys the environment as emissions. On the same note, Ke et al. [68] found that financial development (FD) has a negative effect on ecological quality at 77 developing countries, which supports the growth of the financial activities at the expense of environmental quality. Nevertheless, these results are opposite to the case of Chile according to Kirikkaleli et al. [8], who believe that the financial market has a positive role in the reduction of environmental degradation. The credits offer financial gratification to the investment in renewable energy and sustainable energy interventions. The results highlight those Asian countries should align financial investments with green initiatives. The government should boost green financing and regulatory frameworks such as carbon pricing and renewable energy investments to ensure financial decisions support environmental goals, i.e., mitigate carbon emissions with economic prosperity.

We found that IND triggers CO₂ as a 1% increase in the IND triggers 0.44% in the CO₂. The findings are the similar with the ones of Liu and Bae [18] which found that industrialization worsens the environment in China. On the same note, the results followed Rahman and Kashem [69] in Bangladesh, whereby industrial operations result in increased carbon pollution of the ecology. The study therefore demonstrates the fact that industrialization causes degradation of the environment. We found that economic growth also has a positive effect on CO₂ and a 1 percent growth in GDP increases CO₂ by 0.46 percent. The results are similar to those of Gyamfi [46] of

Sub-Saharan economies where GDP per capita is a major stimulus of the CO₂. It implies that such economies have success in the economic development at the expense of the ecological conditions. Their priority in the early development phases of developing economies is more economical growth, and they do not care about the quality of the ecological environment and, in turn, contribute to the climate risks.

Nevertheless, the trade openness is an inconsequential predictor of CO₂ in the long-run. These findings are in line with Sharma [42] for 69 countries in which trade has no impact on carbon reduction, which shows that other relevant factors play a bigger role in carbon emissions than the impact of trade openness in the countries under study. On the contrary, the outcomes are against Jiang and Liu [70], where the authors examined the impact of trade openness on carbon neutrality in BRICS and G-7 countries. The study reveals that trade expansion contributes to increased carbon emissions in BRICS countries, while it helps reduce emissions in G7 economies, consistent with the Pollution Haven Hypothesis. Furthermore, in the long run, urbanization (URB) does not significantly affect CO₂ emissions. The results are consistent with those of Sadorsky [71], which found the presence of an insignificant relationship between the two variables in 16 developing countries. They are, however, opposite to the findings of Chen et al. [17], that determined the fast urban population increases aggravates the ecological footprint. The fact that the impact of trade openness and urbanization is insignificant implies that it depends on certain factors including energy use and industrial structure, as well as the strictness of environmental policy. In economic terms, trade and urbanization does not have independent efforts to contribute to carbon emission, but the effect becomes actualized once the interactions occur with the complementary policy that can either sustain or taper the level of emission.

This trend is coherent meaning that the insignificance is a part of the economic and environmental processes. This is reconfirmed through Pedroni, P.[72] FMOLS and Kao, C., and Chiang, M.-H.[73] DOLS framework as reported in Table 10.

The FMOLS and DOLS coefficients are found consistent in terms of direction and significance. The two core variables GT and FD show the same signs of coefficients and are statistically significant that indicate directional consistency, which is one of the major indicators showing the robustness of the model in long-run cointegration analysis. Though the significance levels are different in URB, whereas TO is insignificant in both methods. FMOLS and DOLS provide very high adjusted R² values, which demonstrate the stability and good specification of an estimated long-run relationship. Combined, the sign, magnitude and significance of the core explanatory

Table 10 Robustness check using FMOLS and DOLS

Variables	FMOLS		DOLS	
	Coefficient	t-value	Coefficient	t-value
GT	-0.0000136***	-2.89982	-0.0000103*	-1.915565
FD	0.56275***	3.439786	0.229463**	2.541797
URB	0.046299***	7.147856	0.029487*	1.81222
TO	-0.122076	-0.965891	0.191483	1.434425
	Adj R ²	0.98123	Adj R ²	0.999213

*** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$

Source: Authors' estimation

variables confirms that the CS-ARDL long-run coefficients are empirically stable and thus reliable to interpret and draw policy implications.

The short-run results of the CS-ARDL model are consistent with the long-run findings, as shown in Table 11. The results indicate that GT helps improve environmental sustainability by reducing CO₂ emissions by about 0.06%. In contrast, financial development (FD) and economic growth (GDP) increase CO₂ emissions by 0.78% and 0.18%, respectively. The impact of industrialization (IND) in the short run insignificant.

The negative value of the error correction term (ECT) shows that the model adjusts back toward its long-run equilibrium at a rate of 42.16% whenever there is a short-run disturbance. Figure 2 highlights the findings endorsed by the CS-ARDL technique. This study analyze how green technology changes the relationship between financial development and CO₂ emissions. To measure this, we include an interaction term (FD*GT) in the regression, following earlier studies [74, 75]. Table 12 presents the short- and long-run results of the CS-ARDL model after adding this moderating factor. The results show that FD*GT helps reduce CO₂ emissions by 0.174% in the long run and 0.134% in the short run. The effect of this interaction is stronger than the effect of green technology on its own. This means that when financial resources are directed toward green technology, the impact on reducing emissions becomes much stronger. In simple terms, when the financial sector provides low-interest loans or invests in things like solar panels, carbon storage, wind turbines, batteries, and other clean technologies, it speeds up the use of green technology. This helps countries move toward cleaner and more sustainable growth. These findings support the results of Yang et al. [7], who showed that green technology helps the financial sector reduce carbon emissions in China. Habiba et al. [76] also found that green innovation weakens the link between financial development and environmental pollution in major carbon-emitting countries. Thus, policymakers should prioritize green financing initiatives and policies such as green bonds, climate mitigation funds, and green credits in controlling CO₂.

The cointegration and slope heterogeneity are estimated. However, the results are not mentioned for brevity purposes.

Finally, we test the causal relationship between the model variables; the outcomes are highlighted in Table 13 and Fig. 3. The results show unidirectional causality from CO₂ to financial development and industrialization is similar to Yang et al. [7]. There is a two-way relationship between CO₂ emissions and green technology, which matches the findings of Yang et al. [7] for China. There is also evidence that trade openness helps predict CO₂ levels. In addition, urbanization and CO₂ influence

Table 11 Short-run CS-ARDL results

Variables	Coefficient	t-value
GT	-0.065**	-2.73
FD	0.789***	3.11
URB	0.673	0.21
TO	0.071	0.91
GDP	0.180**	2.94
IND	0.322	1.72
ECT (-1)	-0.4216***	-15.23

*** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$

Source: Authors' estimation

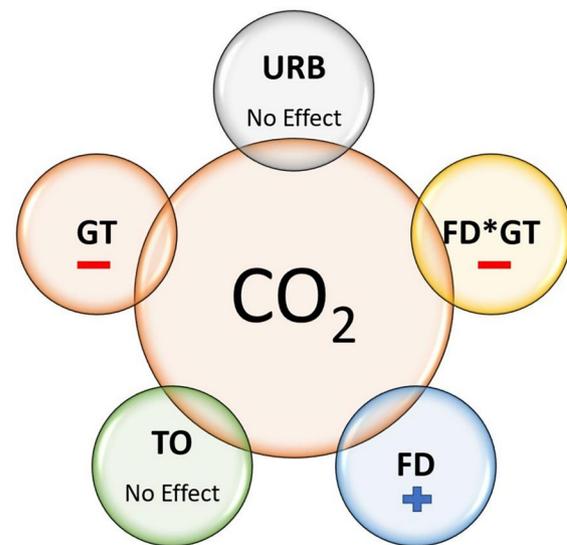


Fig. 2 Empirical outcomes estimated through the CS-ARDL approach.

Source: Authors' drawing

Table 12 CS-ARDL for model with moderating term

Variables	Short-run Coefficients	t-value	Long-run Coefficients	t-value
GT	-0.0521*	-1.81	-0.0765*	-1.69
FD	0.6483***	3.85	0.7806***	4.38
URB	2.6784	1.58	3.428	1.64
TO	-0.0656	-0.51	-0.1791	-0.96
GDP	1.2651*	1.65	1.8013	1.60
IND	0.1059	0.65	0.1548	0.85
FD*GT	-0.1347***	-3.09	-0.1746**	-2.92
ECT (-1)	-1.364***	-12.050		

*** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$

Source: Authors' estimation

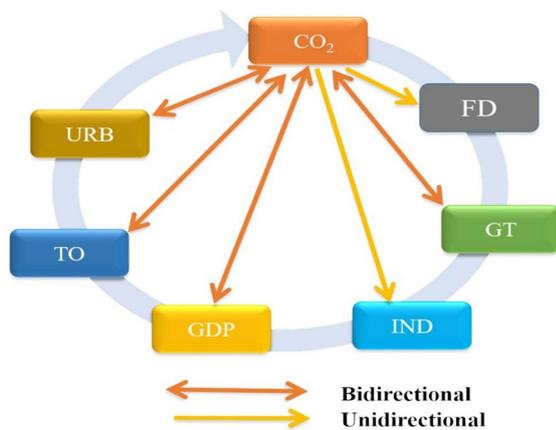
each other. This result is similar to Gyamfi [46], who also found a two-way link between these variables in Sub-Saharan countries.

We found two-way causality between CO₂ and green technology, and also between CO₂ and urbanization. This means each one affects the other. For example, new green technologies can lower emissions, but rising emissions can also push countries to adopt more green technology.

Table 13 Panel granger causality tests

Ho	W-Stat	Zbar-Stat	Prob	Decision
FD \nrightarrow CO ₂	1.883	1.454	0.146	Unidirectional causality from CO ₂ to financial development
CO ₂ \nrightarrow FD	2.609	2.779	0.005	
GT \nrightarrow CO ₂	4.399	6.047	0.000	Bidirectional causality exists between green technologies and CO ₂
CO ₂ \nrightarrow GT	2.991	3.477	0.000	
CO ₂ \nrightarrow IND	4.430	6.102	0.000	Unidirectional causality from CO ₂ to industrialization
IND \nrightarrow CO ₂	1.519	0.789	0.430	
URB \nrightarrow CO ₂	4.276	5.823	0.000	Bidirectional causality exists between urbanization and CO ₂
CO ₂ \nrightarrow URB	63.32	113.619	0.000	
TO \nrightarrow CO ₂	4.844	6.858	0.000	Bidirectional causality exists between trade openness and CO ₂
CO ₂ \nrightarrow TO	3.125	3.720	0.000	
GDP \nrightarrow CO ₂	3.605	4.596	0.000	Bidirectional causality exists between economic growth and CO ₂
CO ₂ \nrightarrow GDP	3.138	3.743	0.000	

Source: Authors' calculations

**Fig. 3** Depiction of Causal association among variables.

Source: Author's drawing

In the same way, urbanization increases emissions, but environmental pressures can also influence how cities grow. We also found a two-way relationship between trade openness and CO₂. This suggests that trade policies and environmental outcomes influence each other—for instance, reducing emissions can change what countries produce and export. Overall, these two-way relationships show that policies in finance, technology, trade, and the environment are closely linked. To achieve low-carbon growth in Asia, countries need coordinated policies that work together rather than in isolation.

Conclusions and policy implications

Emerging Asian economies face higher climate risks because their economic growth often comes with environmental damage. However, many earlier studies have already identified the key factors that drive CO₂ emissions from production. This study investigated the dynamic effects of green technology, financial development, trade openness, and urbanization on consumption-based CO₂ emissions in nine Asian economies from 1991 to 2020 using the CS-ARDL approach within a STIRPAT framework. Consumption-based CO₂ emissions is a less explored but policy-relevant measure across major Asian economies. The integration of the FD and GT interaction offers new empirical evidence on how financial systems can amplify or mitigate environmental outcomes depending on their green orientation. The model accounted for cross-sectional dependence and slope heterogeneity. The long-run results show that green technology helps reduce CO₂ emissions by 0.58%, while financial development increases emissions by 0.66%. Industrialization and economic growth also add to emissions, but trade openness and urbanization do not show significant effects. The interaction term between financial development and green technology (FD*GT) significantly lowers emissions, showing that green finance strengthens the impact of green technology. The negative and significant error-correction term suggests that 42% of any imbalance adjusts back to equilibrium each year. Causality tests also show two-way relationships between emissions and green technology, trade, and urbanization, meaning these factors influence each other. Overall, the findings show that technological innovation and environmentally friendly financial systems play a key role in helping Asian countries move toward low-carbon growth.

Policy implications

The results show that spreading and using green technologies is essential for reducing carbon emissions across Asia. Governments should promote clean and efficient technologies in key sectors like transport, industry, and housing, as eco-innovation is one of the best ways to support economic growth while protecting the environment. For China, improving the green bond market and enforcing carbon-disclosure rules can help direct funding toward renewable energy and battery storage. India can benefit from increasing eco-innovation subsidies and creating green infrastructure funds to attract private investment. Pakistan can reduce its dependence on imported fossil fuels by supporting distributed solar and micro-hydro systems through low-interest green loans. Malaysia and Indonesia could establish regional green investment banks to finance low-carbon transport and energy-efficiency projects, supported by tools like carbon pricing and green-tax rebates. Japan and South Korea,

with their advanced financial markets, should expand ESG-based lending and require climate-risk reporting to guide capital toward net-zero goals. Across Asia, governments should integrate green financial rules into monetary and credit policies—such as green credit quotas, interest-rate incentives for clean energy, and ASEAN-aligned green taxonomies—while improving carbon accounting and environmental-risk checks in the banking sector. Stronger regional cooperation through SAARC and ASEAN can also help harmonize carbon standards, support the transfer of clean technologies, and move the region toward a shared carbon market.

Limitations and future directions

Although the study provides strong evidence, several limitations remain. First, the analysis covers only nine Asian economies because of data availability. Including additional countries such as Vietnam, Thailand, and the Philippines would improve how well the results represent the region. Second, while this study examines the effects of green innovation, financial development, urbanization, and trade on consumption-based emissions, other important factors such as digitalization, fiscal decentralization, and institutional quality may also play a role. Exploring these factors offers opportunities for future research. Finally, the dataset includes information only up to 2020 and focuses on a limited group of Asian economies. Extending the dataset to cover more countries and a longer time period including regions outside Asia would provide deeper insights and more reliable policy suggestions for reducing emissions in emerging economies.

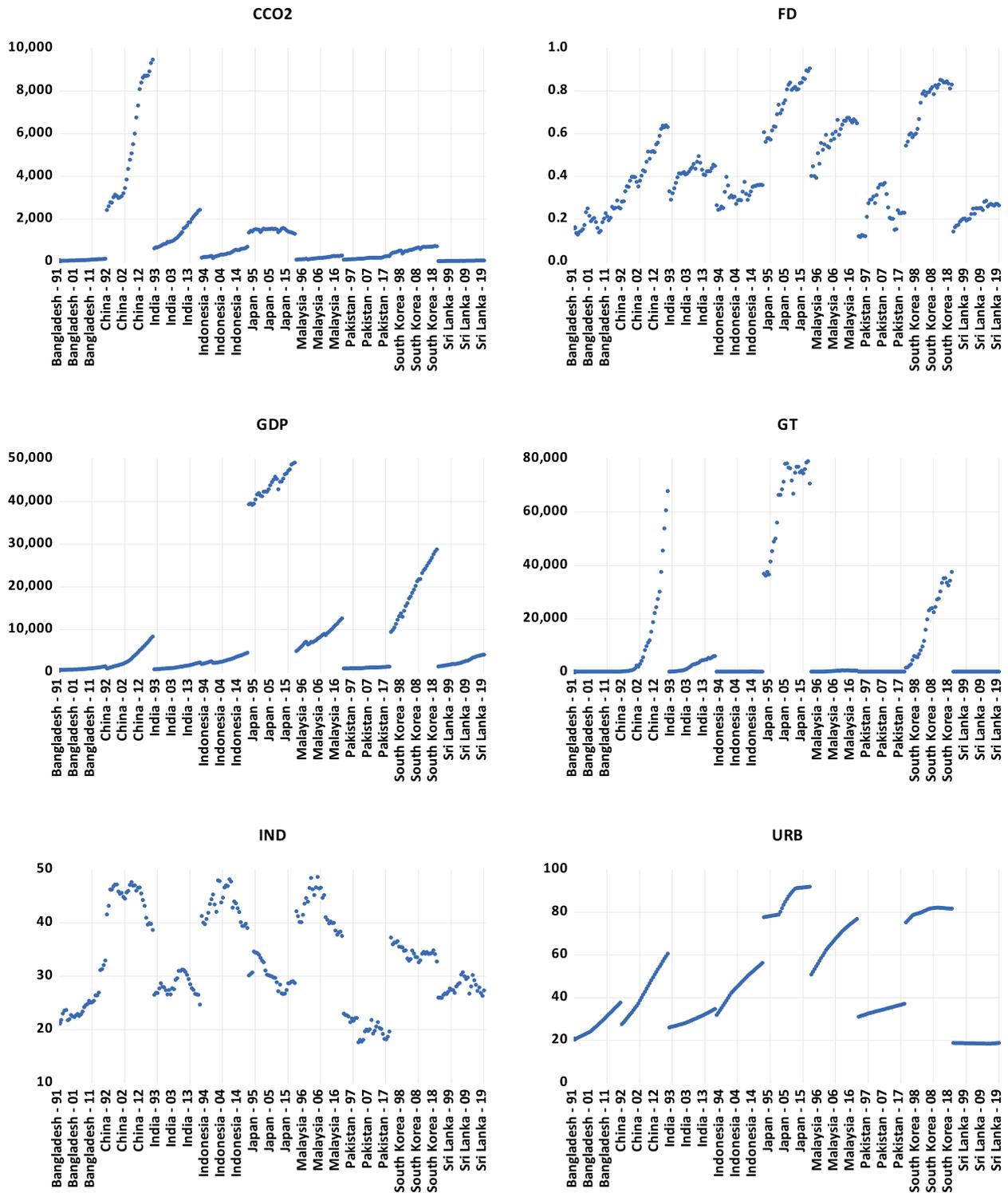


Fig. 4 Scatter plots of variables.
Source: Author's Estimation

Appendix
See Fig. 4

Author contributions

I.S.: Conceptualization; Data curation; Writing initial draft; F.S.Q.: Conceptualization; Resources, Formal analysis; M.R.: Software, Methodology; B.H.: Investigation, Writing original draft; S.M.: Validation; reviewing and editing.

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Data availability

Data will be available on request from the corresponding author.

Declarations

Ethics and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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