An empirical investigation of financial development and carbon emissions nexus: insights from Asia's leading economies

Abstract

1. Introduction

FD with climate goals. FD – characterized by market depth, access and efficiency – plays a crucial role in Asia's economic growth by enhancing resource allocation, investment and resilience. Classical and endogenous growth theories ([illegible]) highlight its importance in reducing information asymmetries and improving investment efficiency. [illegible] financial systems [illegible] by managing risk and mobilizing capital ([illegible] et al., 2020). However, the environmental impact of FD remains underexplored and inconclusive. This study investigates the FD-CO_2 emissions nexus in five major Asian economies – China, India, Japan, South Korea and Indonesia – between 1990 and 2023. These rapidly developing nations are among the top global emitters, making them central to understanding the environmental consequences of financial growth ([illegible] and World Population Review, 2024; [illegible]).

1.1 Trends in CO_2 emissions in leading Asian economies

CO_2 emissions remain a major challenge in Asia, where rapid industrialization and economic integration have intensified environmental stress. Since the early 2000s, global greenhouse gas (GHG) emissions have risen, largely due to fossil fuel-driven CO_2 from emerging economies, particularly China and India ([illegible]). [illegible] per capita emission trends (1990–2023), as represented in Figure 1, across China, India, Japan, South Korea and Indonesia. China's emissions surged from [illegible] to [illegible] tonnes, India's rose gradually from [illegible] to [illegible] tonnes, while Japan's [illegible]. South Korea's increased from [illegible] to nearly [illegible] tonnes, and Indonesia's [illegible] from [illegible] to [illegible] tonnes due to coal reliance. These disparities reflect differences in energy portfolios and policy capacity. With emissions [illegible] public health ([illegible], 2024), sustained mitigation by top emitters – especially China and India – is crucial to achieving global climate targets.

The link between FD and environmental quality remains debated and empirically inconclusive. One school argues that FD supports environmental sustainability by channeling capital into green technologies and energy-efficient sectors ([illegible]). Efficient financial markets can reduce borrowing costs, improve access to green finance and boost renewable energy investments, particularly in well-regulated institutions ([illegible] et al., 2023; [illegible] et al., 2023). Conversely, other scholars

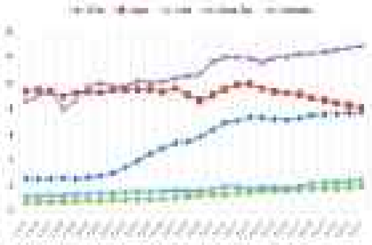

Figure 1. CO_2 per capita in leading Asian economies. [illegible]

argue that unregulated financial growth may increase CO_2 emissions by promoting credit-fueled expansion in fossil fuel-based industries (Xu et al., 2020; Rehman et al., 2021; Alam et al., 2021; Acheampong, 2020). In contrast with weak environmental oversight, financial liberalization often aligns with higher energy consumption, industrial emissions and deforestation (Rehman et al., 2020; Abid et al., 2021), underscoring the importance of sustainability-oriented financial policies. These empirical findings remain inconclusive regarding the resulting impact of FD and CO_2. With this background, this study addresses three critical gaps in the existing literature. First, the relationship between FD and CO_2 emissions remains empirically inconclusive, with findings differing across regions and development levels. This study contributes by focusing on five underexplored Asian context – specifically China, India, Japan, South Korea and Indonesia – selected for their economic size, rapid financial expansion and significant carbon emissions. Their varied financial systems and energy profiles offer a strong foundation for comparative analysis. Second, much of the existing research is focused on global or single-country studies, overlooking regional-level heterogeneity. This study fills this gap by providing a comparative, cross-regional perspective. Third, many studies omit critical control variables such as economic growth, human capital (HC) and urbanization, which this study incorporates to enhance analytical depth and policy relevance.

The structure of the study is organised as follows: Section 1 presents the Introduction. Section 2 reviews the relevant literature. Section 3 outlines the Empirical Modelling and Techniques of Estimation. Section 4 provides the results and discussion. Finally, Section 5 offers the summary, policy implications and research limitations.

2. Review of literature

2.1 Financial development (FD) and carbon emissions (CO_2)

The nexus between FD and carbon emissions (CO_2) remains widely debated, with literature revealing mixed, region-specific and often contradictory findings. Several studies argue that FD exacerbates CO_2 by accelerating energy-intensive economic activity (Shahbaz, 2020; Ali et al., 2024; Dabboor et al., 2020; Rehman et al., 2020; Alam et al., 2021), while others assert that financial systems in developing economies prioritise short-term growth over environmental sustainability (Adams et al., 2020; Bagchi et al., 2022). Regional evidence reinforces this view: Yuan et al. (2020) found that FD increased emissions in ASEAN-5 (1980–2016), Le et al. (2020) observed a positive FD-CO_2 relationship in 31 Asian countries (2004–2014) and Tsou et al. (2021) found private sector credit expansion increased emissions. In the G-7 countries, Ali et al. (2023) concluded that FD impairs sustainability, and Sethi et al. (2020) reported that globalization and FD worsened India's environmental quality (1980–2015), while Khan et al. (2020) advocated strict, evidence-based policy to reduce emissions in China's energy sector. Wu et al. (2024) found that in OBOR, financial technologies may reduce carbon emissions, but digital banking and natural resources still contribute to degradation. On the other hand, some studies suggest that FD can enhance environmental sustainability when supported by robust regulation and governance. For example, Chaabi et al. (2024) and Chamara and Tokal (2017) emphasized FD's role in channelling funds to green sectors, while Zafarabadi et al. (2023) and Charfeddine and Kahia (2019) highlight the potential of FD to support green finance and cleaner technologies. Dzhe et al. (2023) support the Environmental Kuznets Curve (EKC) in OECD countries, showing that advanced FD eventually reduces emissions and Khan et al. (2021), as well as Dasgupta et al. (2001), underline the importance of institutional quality in aligning FD with environmental goals. Zhang et al. (2022) found that financial inclusion lowers emissions in emerging economies, and in China, Fan et al. (2023) demonstrated that a developed financial sector reduces GHG emissions by promoting green technology adoption. However, other research finds no significant FD–CO_2 relationship. For example, Chen et al. (2020) in 33 Central and Eastern European countries (1995–2011), Mhadi et al. (2021) in OECD and Acaravci-Ozturk and Ozturk (2020) in 54 LMICs, despite observing temporary links through energy use. These conflicting findings highlight a critical research gap. Limited focused studies on the dynamic FD–CO_2 relationship in Asia's five leading economies, China, India, Japan, South Korea and Indonesia – using recent data that reflects post-2020 financial and environmental reforms. Given these countries' significant economic size and environmental impact, investigating their financial systems' role in shaping carbon emissions is both timely and policy relevant, thereby justifying the current study. Based on the review, the following hypothesis is proposed:

H1. In leading Asian economies, financial development does not significantly impact CO_2 emissions.

2.2 Economic growth (GDP) and carbon emissions (CO_2)

The relationship between economic growth and CO_2 is central to sustainability research, most prominently examined through the EKC, which posits that environmental damage initially rises with growth but eventually declines as economies mature and adopt cleaner technologies (Grossman and Krueger, 1991). Several empirical studies have supported the EKC hypothesis across different contexts, including Shahbaz and Bhattacharya [illegible], Sahu and Bhattacharya [illegible], [illegible] and [illegible], [illegible] et al. [illegible] and [illegible] et al. [illegible], showing that long-run economic expansion often aligns with declining pollution. In South Asia, however, growth has been found to significantly worsen environmental quality, with Zhu et al. (2023) highlighting that development is frequently achieved at the expense of increased carbon pollution. On the contrary, some studies challenge the universality of EKC, arguing that economic growth may not guarantee environmental improvement ([illegible]; [illegible] et al., [illegible]). Furthermore, carbon emissions are shaped by multiple factors, including energy consumption patterns, technology diffusion and environmental regulations ([illegible]). For instance, [illegible] et al. [illegible] [illegible] that coal and gas drove up CO_2 [illegible] ecological footprint, while [illegible] ecological footprint [illegible] CO_2, whereas renewables reduce both. In fossil fuel-dependent emerging Asian economies, reconciling economic development with sustainability remains complex ([illegible]). Given this theoretical and empirical background, economic growth emerges as a necessary and appropriate control variable in the current study, as it captures the scale effect of development on emissions and ensures that the independent effect of financial development on CO_2 emissions is accurately estimated by controlling for growth-induced environmental pressures.

2.3 Human capital (HC) and carbon emissions (CO_2)

The relationship between HC and environmental outcomes has gained increasing scholarly attention, particularly as human capital plays a pivotal role in shaping both the drivers and mitigation of CO_2. Yao et al. (2020), using data from [illegible] OECD countries ([illegible]), showed that HC's influence on carbon emissions transitioned from positive to negative post-[illegible], illustrating education's growing role in promoting environmental awareness. Similarly, [illegible] and [illegible] confirmed the significance of HC in reducing CO_2 across [illegible] countries and [illegible] et al. [illegible] linked higher education attainment to better environmental performance. In Thailand, Chankrajang and Muttarak (2017) found that formal education increased environmental awareness, though it did not always translate into energy-saving behavioral changes. Firm-level evidence from Canada, Lan and Munro [illegible] further revealed that both internal and external HC promote corporate [illegible] environmental compliance and adoption of green practices. However, this relationship is not uniform. [illegible] et al. [illegible] found that in emerging economies ([illegible]), HC was associated with increased CO_2, even as [illegible] development improved environmental quality. [illegible] et al. [illegible] found HC and growth [illegible] environmental quality in newly industrialized countries but did not observe EKC support, while [illegible] et al. [illegible] reported that HC reduces emissions in low-growth regimes but raises them in high-growth contexts through increased industrial and [illegible]

[illegible]

Investments in higher education have been shown to significantly cut CO_2 emissions – by as much as 20.1% to 43.9% – according to Dar et al. (2020, 2020, 2021) and Rahman et al. (2018), reinforcing HC's environmental benefits. Additionally, HC, rising incomes and renewable energy support the EKC hypothesis (Dar et al., 2022; Mahmood et al., 2022; Zhang et al., 2022). Nonetheless, some findings complicate the narrative – Khan et al. (2020) found that HC, and low capacity in Pakistan, increased CO_2, challenging the assumption that HC is always environmentally beneficial. This growing yet inconclusive body of evidence underscores the necessity of including HC as a control variable in the present study. Given that HC influences technological adaptation, energy behavior, policy awareness and innovation uptake – all of which are closely linked to carbon emissions – it is essential to control for its effects to isolate the true impact of financial development on CO_2 emissions. Moreover, as recent studies increasingly account for HC's dual role in both advancing and mitigating environmental harm, its inclusion ensures robustness and theoretical completeness in empirical estimations.

2.4 Urbanization and carbon emissions (CO_2)

Urbanization is taken as another key control variable in the present study, given its complex and evolving relationship with carbon emissions (CO_2) across countries and stages of development. The literature presents contrasting views on the urbanization-environment nexus. Several studies suggest that urbanization contributes significantly to CO_2 due to increased energy consumption, transportation emissions and industrial expansion. Zhang et al. (2021), Shahbaz et al. (2016) found a strong and positive relationship between urbanization and CO_2 emissions in developing nations, emphasizing the need for sustainable urban development strategies. Similarly, Lee et al. (2023) reported that rapid urbanization correlates with environmental decline, while Ali Cosman et al. (2023) showed that global urban emissions are rising sharply, especially in developing countries where urban growth is rapid and per capita emissions are comparatively high. In China, Liu and Bae (2018) documented a long-run positive effect of urbanization on emissions. Wang et al. (2022), however, found a nonlinear inverted U-shaped curve in OECD economies, suggesting that urbanization may initially raise emissions but reduce them after reaching a certain threshold due to technological and policy advancements. Wang and Dong (2023) supported this idea by arguing that urbanization can promote environmental efficiency through economies of scale and cleaner energy use. Likewise, Sadorsky (2014) contended that urbanization leads to rising consumption patterns that drive greenhouse gas emissions. Despite extensive inquiry, the empirical evidence remains mixed, particularly in its regional variations and developmental contexts. Given this ambiguity, urbanization is an essential control variable in the current analysis to accurately isolate the independent impact of financial development on CO_2 emissions. Its inclusion ensures the model accounts for both direct and indirect environmental consequences of urban population shifts in Asia's leading economies.

3. Empirical modeling and techniques of estimation

3.1 Empirical modeling

The study adopts the IPAT model by Ehrlich and Holdren (1971), which links environmental impact (I) to population (P), affluence (A) and technology (T):

$$I = PAT \tag{1}$$

Although widely used (Dietz and Rosa, 1994, 1997; York et al., 2003), IPAT lacks statistical flexibility. To overcome this, Dietz and Rosa (1994) proposed the stochastic STIRPAT model:

$$I = aP^{b}A^{c}T^{d}e \quad (1)$$

Here, I is the environmental impact, and b, c, d are elasticities for P, A and T respectively. To evaluate the impact of financial development and control variables on environmental quality, CO_2 emissions are used as a proxy for EI [illegible]. Adopting the STIRPAT framework, which decomposes environmental impact into Population (P), Affluence (A) and Technology (T) [illegible]. Urbanization serves as a proxy for population [illegible], while affluence is captured through GDP and its square to examine the Environmental Kuznets Curve (EKC) hypothesis (Grossman and Krueger, 1995). Technology (T) reflects changes in production and consumption structures, with financial development playing a central role in guiding investment and enabling structural transformation [illegible]. As access to credit and capital allocation drive the green transition, financial development is appropriately incorporated into T. [illegible] in endogenous growth theory, further influences innovation, productivity and sustainable growth [illegible].

Accordingly, the extended STIRPAT model includes financial development, GDP, GDP^2, HC, and urbanization. Variable definitions and sources are summarized in Table 2, as key determinants of CO_2 emissions.

$$CO_{2it} = \beta_0 + \beta_1 FD_{it} + \beta_2 GDP_{it} + \beta_3 GDP^2_{it} + \beta_4 HC_{it} + \beta_5 URB_{it} + \varepsilon_{it} \quad (2)$$

Taking logs, the equation becomes:

$$\ln CO_{2it} = \beta_0 + \beta_1 \ln FD_{it} + \beta_2 \ln GDP_{it} + \beta_3 \ln GDP^2_{it} + \beta_4 \ln HC_{it} + \beta_5 \ln URB_{it} + \varepsilon_{it} \quad (3)$$

2.2 Techniques of estimation

2.2.1 Testing for cross-sectional dependence. When estimating with panel data models, it is imperative to assess cross-sectional dependence in the error terms to avoid misleading or spurious results — an issue particularly relevant in the context of integrated [illegible] economies. Cross-sectional dependence, which may arise from common shocks or unobserved components, is first examined using the Breusch-Pagan Lagrange Multiplier (LM) test (1980). Given the panel structure where the number of cross-sectional units (N) is less than the time dimension (T), this test is appropriate for detecting interdependencies across units. When N is fixed and $T \to \infty$, the LM statistic follows a chi-square distribution with $\frac{N(N-1)}{2}$ [illegible]

Table 2. Description of variables

Variable's definition Variable	Symbol	Definition	Source
CO_2 Emissions	CO_2	CO_2 emissions (tons per capita)	World Development Indicators
Financial Development Index	FD	Index combining information on the depth, access and efficiency of the financial institutions and markets	International Monetary Fund
Gross Domestic Product Per Capita	GDP	GDP Per capita constant 2015 USD	World Development Indicators
Human Capital	HC	Human capital index based on years of schooling	Penn World Table 10
Urban Population	URB	Urban population (% of total population)	World Development Indicators

Note: [illegible] Table 3 [illegible]

[illegible]

degree of freedom under the null hypothesis of cross-sectional independence. The outcome of this test informs the choice between first-generation (which assume cross-sectional independence) and second-generation unit root tests.

2.2.2 Pesaran's Cross-Sectionally Augmented Dickey–Fuller (CADF) test. Following the detection of cross-sectional dependence, the study employs Pesaran's Cross-Sectionally Augmented Dickey–Fuller (CADF) test (Pesaran, 2007) to assess the stationarity properties of the panel series. As a second-generation panel unit root test, the CADF approach extends the conventional ADF regression by incorporating cross-sectional averages of both lagged levels and first differences. This allows it to effectively account for interdependencies across cross-sectional units, such as countries in a regional context. The CADF regression equation is expressed as follows:

$$\Delta Y_{it} = \alpha_i + \beta_i Y_{i,t-1} + \gamma_i \bar{Y}_{t-1} + \phi_i \Delta \bar{Y}_t + \varepsilon_{it}$$

where, $\bar{Y}_{t-1}$ and $\Delta \bar{Y}_t$ represent the cross-sectional averages of the lagged level and first-differenced series, respectively. The unit root hypothesis is tested using the t-ratio of the estimated coefficient β_i derived from the above regression. Pesaran's CADF statistic, denoted by $t_i(N, T)$, is then used to evaluate the presence of unit roots. The full derivation involves CIPS aggregation and matrix operations to adjust for cross-sectional dependence, but the essential feature of the test lies in its ability to control for unobserved common factors through augmentation with cross-sectional averages.

2.2.3 Panel cointegration test. Upon confirming that the variables are integrated of order one, the study applies Pedroni's (1999, 2004) panel cointegration test. The test includes seven statistics – four "within-dimension" (panel tests) and three "between-dimension" (group tests) – that accommodate heterogeneity in cointegrating vectors and account for individual fixed effects and deterministic trends. The following long-run equation is estimated to test for cointegration:

$$Y_{it} = \alpha_i + \delta_i t + \beta_{1i} X_{1i,t} + \beta_{2i} X_{2i,t} + \dots + \beta_{Mi} X_{Mi,t} + \varepsilon_{it}$$

where, Y_{it} is the dependent variable, $X_{m,i,t}$ are explanatory variables, α_i denotes individual fixed effects, and $\delta_i t$ captures individual time trends. The null hypothesis of no cointegration is rejected if the computed statistics fall below the Monte Carlo based critical values provided by Pedroni (2004). For this situation, we also applied the Westerlund (2007) approach to ensure robust results despite cross-sectional dependence (CD). The Westerlund test comprises two panel-based (pooled) and two group-mean transformations. The model specification is given as follows:

$$\Delta Y_{it} = \delta_i' d_t + \alpha_i Y_{i,t-1} + \lambda_i' X_{i,t-1} + \sum_{j=1}^{p_i} \alpha_{ij} \Delta Y_{i,t-j} + \sum_{j=-q_i}^{p_i} \gamma_{ij} \Delta X_{i,t-j} + e_{it}$$

where d_t represents the deterministic components, and p_i and q_i refer to the lag and lead lengths, respectively.

2.2.4 Panel autoregressive distributed lag model. We employ the Pooled Mean Group Autoregressive Distributed Lag (PMG-ARDL) approach developed by Pesaran et al. (1999), which is suitable for heterogeneous dynamic panels and allows for both short-run heterogeneity and long-run homogeneity. This method is appropriate for our balanced panel dataset covering [illegible] African countries from 1990 to 2020. The PMG estimator addresses the limitations of standard ARDL models, particularly issues of endogeneity arising from correlation between lagged variables and the error term, by pooling long-run parameters while allowing group-specific short-run dynamics. Following Samargandi and [illegible] (2015), the general form of the ARDL(p, q) specification is:

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$$\ln CO_{2it} = \sum_{j=1}^{p} \lambda_{ij} \ln CO_{2i,t-j} + \sum_{j=0}^{q} \delta_{ij}' X_{i,t-j} + \mu_i + \varepsilon_{it} \quad \text{[illegible]}$$

where $\ln CO_{2it}$ is the natural logarithm of per capita carbon emissions, and X_{it} is the vector of explanatory variables: financial development (FD), economic growth (GDP), squared GDP (GDP2), NC and urbanisation (UP). λ_{ij} are the lagged coefficients for CO_2, δ_{ij} is the distributed lag coefficient for the regressors, μ_i captures individual fixed effects and ε_{it} is the error.

Assuming all variables are I(1) and cointegrated, the model can be reparameterised into an error correction form as follows:

$$\Delta \ln CO_{2it} = \phi_i [\ln CO_{2i,t-1} - \theta_1 \ln FD_{i,t-1} - \theta_2 \ln GDP_{i,t-1} - \theta_3 \ln GDP2_{i,t-1} - \theta_4 \ln NC_{i,t-1} - \theta_5 \ln UP_{i,t-1}] + \sum_{j=1}^{p-1} \lambda_{ij}^{*} \Delta \ln CO_{2i,t-j} + \sum_{j=0}^{q-1} \delta_{1ij}^{*} \Delta \ln FD_{i,t-j} + \sum_{j=0}^{q-1} \delta_{2ij}^{*} \Delta \ln GDP_{i,t-j} + \sum_{j=0}^{q-1} \delta_{3ij}^{*} \Delta \ln GDP2_{i,t-j} + \sum_{j=0}^{q-1} \delta_{4ij}^{*} \Delta \ln NC_{i,t-j} + \sum_{j=0}^{q-1} \delta_{5ij}^{*} \Delta \ln UP_{i,t-j} + \mu_i + \varepsilon_{it} \quad \text{[illegible]}$$

Here, ϕ_i is the error correction coefficient capturing the speed of adjustment back to long-run equilibrium. A significant and negative ϕ_i confirms cointegration among the variables. The long-run coefficients θ_k for each variable are computed as [illegible] for k = FD, GDP, GDP2, NC, UP. This transformation reflects the cumulative long-run effect, where the numerator captures the total short-run influence and the denominator adjusts for autoregressive persistence in the dependent variable. Short-run coefficients are derived as: [illegible]. The error correction coefficients can be averaged across cross-sections using the Mean Group estimator as: [illegible], with its variance given by: [illegible]. The PMG-ARDL estimator is preferred when long-run homogeneity is plausible across countries, while allowing heterogeneity in short-run adjustments, intercepts and error variances (Pesaran and Shin, 1999). In contrast, the Mean Group (MG) estimator by Pesaran and Smith (1995) allows full heterogeneity and the Dynamic Fixed Effects (DFE) estimator imposes full homogeneity, which are used for the robustness of the results. The PMG model remains valid even when regressors are a mix of I(0) and I(1), making it highly suitable for our data structure.

3.2.3 Granger causality tests. To complement ARDL estimates – which identify associations but not direction – this study applies panel Granger causality tests to assess causal links between CO_2 emissions and explanatory variables. While Granger (1969) first proposed the concept for time series, Dumitrescu and Hurlin (2012) extended it for heterogeneous panel data. The test accounts for cross-sectional heterogeneity and captures short-run causal dynamics across countries. [illegible] suggests at least unidirectional causality must exist. The Dumitrescu–Hurlin procedure enables the identification of potential bidirectional causality and complex interdependencies within the panel. To investigate this, the following two-way panel Granger causality models are estimated:

[illegible]

$$Y_{i,t} = \alpha_i + \sum_{k=1}^{K} \gamma_{ik} Y_{i,t-k} + \sum_{k=1}^{K} \beta_{ik} X_{i,t-k} + \varepsilon_{i,t} \quad (10)$$

$$X_{i,t} = \alpha_i + \sum_{k=1}^{K} \gamma_{ik} X_{i,t-k} + \sum_{k=1}^{K} \beta_{ik} Y_{i,t-k} + \varepsilon_{i,t} \quad (11)$$

Here, $X_{i,t}$ and $Y_{i,t}$ are the respective independent and dependent variables for country i at time t. Equation (10) tests whether X causes Y; Equation (11) tests the reverse. The null hypothesis for both is:

$$H_0: \beta_{i1} = \beta_{i2} = \dots = 0 \;\; \forall i = 1, \dots, N \quad (12)$$

This implies no causal effect from one variable to the other in any country. The alternative hypothesis allows for causality in at least a subset of countries:

$$H_1: \beta_{i1} \neq 0 \;\; \forall i = N_1 + 1, \dots, N \quad (13)$$

Thus, causality may be present in some but not all panel units. This approach is suitable for capturing heterogeneous causal patterns across countries. The research design and methodology are summarized graphically in Figure 2.

4. Results and discussion

4.1 Preliminary analysis

The graphical trends from [illegible] to [illegible] offer critical insights into macroeconomic transformations across five key Asian economies: China, Japan, India, Korea (Rep.) and Indonesia – excluding CO_2 emissions, which are discussed separately in Figure 3. As presented in Figure 3, Japan maintains consistently high financial development, underlining its advanced economic structure. In contrast, China shows rapid improvement, surpassing India and Korea [illegible] growth. Indonesia remains the weakest, with fluctuating financial indicators. China leads in GDP expansion, reflecting its aggressive economic ascent, while Japan's growth is stable but subdued. Korea displays moderate consistency, whereas India and Indonesia exhibit gradual, but uneven increases, highlighting their developmental transitions. [illegible] trends reinforce Japan's dominance, with Korea close behind. China demonstrates a strong upward trajectory, narrowing the gap with developed peers. India and Indonesia, while improving, still trail due to structural and investment challenges. Urbanization rises sharply in China, contrasting with the mature, saturated levels in Japan

Figure 2. Research methodology

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and Korea. India and Indonesia reflect steady, older growth, indicating ongoing demographic and economic shifts. These contrasts reveal China's robust multidimensional development, Japan's institutional maturity, Korea's balanced trajectory and the evolving growth paths of India and Indonesia – framing the region's diverse but converging development narrative. Table 2 summarizes the descriptive statistics for five leading Asian economies. Carbon emissions ([illegible]) have a mean of [illegible] and a standard deviation of [illegible], reflecting wide variation in environmental impact across countries. Financial development ([illegible]) shows limited fluctuation, with a mean of [illegible] and a standard deviation of [illegible], indicating relatively stable investment inflows. Gross domestic product ([illegible]) displays significant economic activity, with a mean of [illegible] and a standard deviation of [illegible]. Human capital ([illegible]) and urbanization ([illegible]) exhibit relatively stable distributions, with standard deviations of [illegible] and [illegible], respectively.

[illegible]

Traditional first-generation unit root tests overlook cross-sectional dependence, potentially biasing panel data inferences. To overcome this, we applied the Breusch–Pagan LM test (Breusch and Pagan, [illegible]), appropriate when the cross-sectional dimension (N) is smaller than the time dimension (T). As shown in Table 3, the test statistic ([illegible]) confirms significant cross-sectional dependence at the 1% level, suggesting that shocks in one country influence others – affecting the interconnectedness of the sampled Asian economies. Given

Table 2. Descriptive statistics

Statistic	CO2	FD	GDP	HC	UR
Mean	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Median	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Maximum	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Minimum	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Std. dev.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Skewness	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Kurtosis	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Jarque-Bera	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Probability	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Sum	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Sum Sq. dev.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Observations	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Source(s): [illegible]

Table 3. [illegible]

Test/Variable	Breusch-Pagan LM test	[illegible]	
Test/Variable		[illegible]	[illegible]
CO2	[illegible]	[illegible]	[illegible]
FD	[illegible]	[illegible]	[illegible]
GDP	[illegible]	[illegible]	[illegible]
HC	[illegible]	[illegible]	[illegible]
UR	[illegible]	[illegible]	[illegible]

Note(s): [illegible]

Source(s): [illegible]

[illegible]

[illegible]

[illegible]

Table 4. [illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible] [illegible]	[illegible] [illegible]	–	–	–	–
[illegible]	[illegible] [illegible]	[illegible] [illegible]	–	–	–	–
[illegible]	[illegible] [illegible]	[illegible] [illegible]	–	–	–	–
[illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	–	–	–
[illegible]	–	[illegible] [illegible]	–	–	–	–
[illegible]	–	[illegible] [illegible]	–	–	–	–
[illegible]	–	[illegible] [illegible]	–	–	–	–
[illegible]	–	–	–	[illegible]	[illegible]	[illegible]
[illegible]	–	–	–	[illegible]	[illegible]	[illegible]
[illegible]	–	–	–	[illegible]	[illegible]	[illegible]
[illegible]	–	–	–	[illegible]	[illegible]	[illegible]

[illegible]

[illegible]

[illegible]

4.4 Panel ARDL Estimation

To determine the optimal lag length, the Vector Auto Regression (VAR) framework is employed. Based on the Hannan–Quinn (HQ) and Schwarz (SC) information criteria, the optimal lag order is selected as [illegible], as presented in Table 5. Subsequently, the study applies the Panel ARDL estimator using the PMG approach to examine both the long-run equilibrium relationships and short-run dynamics among the variables. PMG is particularly suitable in this context as it allows for heterogeneity in short-run coefficients while constraining the long-run relationship to be homogeneous across cross-sectional units. Table 6 reveals [illegible] the long- and short-run coefficients between carbon emissions and other variables, while also representing the adjustment speed across the [illegible] methods of estimation. The long-run estimates from the PMG-ARDL model indicate that financial development, economic growth [illegible], REC, and urbanization have statistically significant and negative impacts on CO_2 emissions in leading Asian economies.

The empirical results presented in Table 6 reveal that financial development (variable of interest) plays a significant role in mitigating carbon emissions in leading Asian economies. The long-run coefficient, estimated at [illegible], indicates that a 1% increase in financial development is associated with a [illegible]% reduction in CO_2 emissions, underscoring its critical function in advancing environmentally sustainable economic growth. However, the short-run coefficient remains [illegible] positive but not statistically significant, which reflects that financial development represents the viability of sustainability as a long-run policy variable. These findings are in alignment with a growing body of literature. Notably, our results support

Table 5. Lag length VAR

Lag	LogL	LR	FPE	AIC	SC	HQ
0	[illegible]	NA	[illegible]	[illegible]	[illegible]	[illegible]
1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

Source(s): Authors' estimation

Table 6. ARDL [illegible]

Variables	Coefficient/Test value	p-value
Long-Run Coefficients		
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]		
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]

[illegible]

Source(s): Authors' estimation

[illegible]

the Green Finance Hypothesis, which posits that the aligned financial markets mobilize capital [illegible] environmentally friendly technologies and energy-efficient sectors (Cai et al., 2021). This is reinforced by Fu et al. (2023), who observed that in China, financial development exerts a negative impact on CO_2 emissions by enabling sustainable investment. Similarly, our findings resonate with the Porter Hypothesis, which suggests that financial deepening – when complemented by effective environmental regulation – fosters innovation in clean technologies. Evidence from China's evolving green industrial policies, as discussed by [illegible] et al. (2024), supports this proposition. Furthermore, the observed long-run dynamics correspond with the EKC framework, which argues that emissions initially rise during financial and industrial expansion but decline over time as economies transition to greener structures ([illegible] et al., 2018; Habiba et al., 2022). Studies by [illegible] et al. (2023) and [illegible] et al. (2023) illustrate how financial liberalization channels investments into renewable energy, carbon markets and sustainable infrastructure – mechanisms consistent with our empirical observations. Contrarily, our findings diverge from those of [illegible] et al. (2023), [illegible] et al. (2020) and [illegible] et al. (2022), who documented either a positive or insignificant impact of financial development on EF. These discrepancies may arise from differences in methodological frameworks, country-specific institutional quality or stages of financial maturity across regions. Taken together, the analysis suggests that financial development, when effectively regulated and aligned with sustainability objectives, acts as a crucial lever for decarbonization in leading Asian economies. The interplay of financial liberalization, regulatory governance and innovation ecosystems appears to be central in determining whether finance becomes a catalyst for environmental improvement or degradation ([illegible] et al., 2020; [illegible] et al., 2022).

Another important empirical finding of this study, as detailed in Table 5, provides strong evidence in favor of the EKC hypothesis within the context of leading Asian economies – namely China, India, Japan, South Korea and Indonesia. The long-run estimation results indicate a statistically significant and positive coefficient for economic growth ([illegible]), implying that in the early stages of development, economic expansion aggravates carbon emissions due to dependence on fossil fuel consumption and industrial intensification. However, the negative and significant coefficient of the squared GDP term ([illegible]) indicates a turning point beyond which further economic growth contributes to environmental improvement, thereby validating the EKC's inverted U-shaped framework. The short-run estimates further reinforce this nonlinear trajectory, with economic growth showing a strong positive impact ([illegible] and its squared term [illegible]) confirming a decline in emissions once a critical income threshold is surpassed. This observed pattern underscores the structural evolution in these Asian economies, where initial phases of industrialization and energy-intensive growth elevate emissions, while advanced stages of development are characterized by regulatory reforms, technological advancements, renewable energy adoption and greater public demand for environmental quality. These economies increasingly transition toward less carbon-intensive sectors – such as services – while enhancing energy efficiency and institutional capacity, which collectively contribute to long-term emission reductions. Our findings are well-aligned with the empirical literature supporting the EKC hypothesis, including studies by [illegible] and [illegible] (2021) on African economies, [illegible] et al. (2023), [illegible] et al. (2021), [illegible] and [illegible] (2023), [illegible] and Lin (2019), [illegible] et al. (2022) and [illegible] et al. (2020), who all identify similar nonlinear relationships between economic growth and environmental quality. Nevertheless, our analysis also acknowledges contrasting perspectives. For instance, [illegible] et al. (2021), [illegible] et al. (2017) and Zhang et al. (2021) argue that economic growth alone is insufficient to mitigate emissions without the presence of strong institutional frameworks and stringent environmental regulations. These divergences highlight that while the EKC holds in the context of leading Asian economies, its realization is contingent upon proactive governance and policy coordination. This is particularly evident in countries like China and Japan, where the integration of renewable energy and sustainability-focused

[illegible]

economic planning, as demonstrated by Li et al. (2020), has played a critical role in curbing carbon emissions amid ongoing growth.

Another important finding of the study, as reported in Table 6, establishes that [illegible] significantly and negatively influences carbon emissions in leading Asian economies. The long-run estimate indicates that a 1% increase in [illegible] results in a [illegible]% reduction in emissions, reflecting its pivotal role in promoting environmental sustainability. The short-run coefficient (−[illegible]) further reveals an immediate and substantial effect, suggesting that improvements in education, skills and health infrastructure can lead to an immediate [illegible]% reduction in emissions. These results underscore the transformative potential of [illegible] in environmental management across the region. Our findings are consistent with existing literature. Studies by [illegible] (2020), [illegible] et al. (2021) and [illegible] et al. (2023) also reveal a negative [illegible] relationship, highlighting [illegible] as a vehicle for sustainable development. [illegible] et al. (2023) provide country-level evidence for China and India, showing that [illegible] reduces ecological footprints. In a related study on India, [illegible] et al. (2023) link [illegible] to sustainability through institutional reforms and energy transitions. [illegible] et al. (2023) also confirm the vital role of [illegible] in supporting green development across the OECD. Several mechanisms may explain this relationship. First, [illegible] fosters a scale effect, enhancing productivity while supporting technique effects such as the adoption of low-emission technologies. It also drives behavioural changes through increased environmental awareness ([illegible] et al., 2024). Productivity-based studies further support this view: Ahmed and [illegible] (2022) demonstrate [illegible]'s contribution to cleaner growth across ASEAN and East Asian economies. However, contrasting findings from [illegible] and [illegible] (2013), [illegible] and [illegible] (2017), [illegible] et al. (2021), Zhang et al. (2021) and [illegible] et al. (2022) point to contextual differences. These studies suggest that the impact of [illegible] on emissions may vary due to differences in education quality, policy frameworks or institutional capacity. Thus, while [illegible] appears to be a key driver of environmental improvement in leading Asian economies, its effectiveness may depend on complementary governance and infrastructure conditions.

Another important finding of this study, as presented in Table 6, is the significant long-run impact of urbanization on carbon emissions in leading Asian economies. The estimated long-run coefficient of urbanization is [illegible], indicating that in countries such as China, India, Indonesia, Japan and South Korea, a 1% increase in urbanization results in a [illegible]% rise in CO_2 emissions. Although the short-run coefficient is negative (−[illegible]), it is statistically insignificant, suggesting that immediate effects may be dampened or subject to short-term adjustments. The long-run result highlights the environmental costs of rapid urban growth in these economies, where expanding cities have driven up energy demand, industrial activity and transportation – all heavily reliant on fossil fuels. This trend is particularly evident in fast-urbanizing nations like China and India, where industrial corridors, vehicular congestion and construction booms have significantly contributed to carbon emissions. From a theoretical standpoint, these findings in leading Asian economies reinforce the scale effect of the EKC, which suggests that during early development, urbanization amplifies pollution due to increased economic and industrial activities. However, whether urbanization contributes positively to long-term sustainability in these economies depends heavily on green urban planning, clean energy use and infrastructure efficiency. Our results align with prior studies, including [illegible] et al. (2020) and Lee et al. (2022), who also found that rapid urbanization has led to higher CO_2 emissions and [illegible] in Asian settings. However, the findings contrast with [illegible] et al. (2022) and [illegible] et al. (2022), who observed that in some Asian economies, urbanization – when coupled with sustainable policy measures – can help reduce emissions. These diverging results suggest that urbanization's environmental impact in leading Asian economies is highly contingent on policy direction, planning and institutional capacity.

The adjustment speed, as indicated by the coefficient of convergence, is negative and statistically significant across all the estimations, confirming the existence of a long-run relationship [illegible]. The [illegible] error correction term, with a coefficient of −[illegible] and p-value of [illegible], implies that approximately [illegible]% of deviations from long-run equilibrium are corrected in each [illegible]

[illegible]

period. This indicates a moderate speed of adjustment towards equilibrium, reinforcing stability and robustness of estimated long-run relationships.

4.[illegible] Robustness check: DOLS
In the long run, to ensure robustness and mitigate issues such as serial correlation and endogeneity – where regressors may be correlated with the error term – this study applies the Dynamic Ordinary Least Squares (DOLS) technique. DOLS addresses these concerns by including leads and lags of the differenced variables, yielding consistent and efficient estimates. The results presented in Table 7 indicate that financial development significantly reduces emissions ([illegible]), highlighting its role in promoting green finance and cleaner investment channels. Economic growth increases emissions ([illegible]), reflecting scale effects associated with industrial expansion. In contrast, structural change negatively affects emissions ([illegible]), supporting the transition toward a service-based, cleaner economy. HC reduces emissions ([illegible]), suggesting that investment in education and skills contributes to environmental awareness and technological innovation. Urbanization also shows a marginally negative effect ([illegible]), indicating that sustainable urban planning can mitigate CO_2. The high explanatory power of the model confirms the robustness of the findings.

4.[illegible] Granger causality
The results of panel Granger causality presented in Table 8 and in the flow chart in Figure 4 offer a comprehensive analysis of the causal relationships among the variables. Employing Dumitrescu–Hurlin (individual coefficients), [illegible] short-run causality patterns emerge. The results indicate unidirectional causality from the financial development to emissions and from economic growth to emissions in leading Asian economies. Additionally, the study confirms bidirectional causality between HC and urbanization. These results highlight the critical role of financial development, economic growth and HC in shaping environmental outcomes, emphasizing the need for targeted policy interventions to enhance environmental quality. The graphical presentation is presented in Figure 5.

4.[illegible] AMG [illegible] coefficient (individual cross sections)
The study also examines cross-sectional relationships among CO_2 emissions, financial development, economic growth, HC and urbanization. Table 9 presents short-run AMG estimates for leading Asian economies. Financial development negatively impacts emissions in Indonesia ([illegible]), China ([illegible]) and Japan ([illegible]) and positively in India ([illegible]) and Korea ([illegible]). Economic growth contributes to emissions, notably but follows an inverted U-shaped EKC in Japan, India, Korea and Indonesia, while China shows a U-shaped EKC. China exhibits a U-shaped EKC, where economic growth initially reduces carbon emissions

Table 7. DOLS estimates

Variable	Coefficient (Std. error)
[illegible]	[illegible]
LGDP	[illegible]
[illegible]	[illegible]
LHC	[illegible]
[illegible]	[illegible]
Observations	[illegible]
Adjusted R-squared	[illegible]

Note(s): *** denotes significance at 1% level; ** at 5% level and * at 10% level
Source(s): Authors' own work

[illegible]

Table [illegible]

[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

[illegible]

5. [illegible]

[illegible]

[illegible]

and sustainable growth pathways in economies like China, India and Japan. The study further highlights HC as a complementary factor in environmental management. A 1% increase in HC results in a 2.38% decline in CO_2 emissions in the long run and a remarkable 12.28% reduction in the short run, highlighting its crucial role in fostering low-emission development through education, skill-building and behavioral shifts. In contrast, urbanization contributes significantly to ED in the long run, with a 1% increase in urbanization associated with a 1.32% rise in emissions. Although the short-run coefficient (−1.48) is negative, it is statistically insignificant, reflecting limited immediate effects but suggesting long-term environmental costs due to energy-intensive urban expansion. The DOLS results affirm the model's robustness, confirming the long-run impact of financial development, growth, HC and urbanization on emissions in leading Asian economies. The Dumitrescu–Hurlin Granger causality test reveals unidirectional causality from financial development and economic growth to emissions and bidirectional causality between HC and carbon emissions, highlighting their dynamic interlinkages in leading Asian economies. Cross-sectional AMG results show that financial development reduces emissions in Indonesia, China and Japan, but increases them in India and Korea. Economic growth follows the EKC in Japan, India, Korea and Indonesia, while China displays a U-shaped pattern. HC and urbanization exhibit mixed effects, emphasizing the need for tailored environmental policies in leading Asian economies.

5.1 Policy implications

The study offers several vital policy implications for fostering sustainable development in leading Asian economies. First, the significant negative relationship between financial development and carbon emissions reflects the need to strengthen green financial systems. Policymakers should expand access to green instruments like bonds and sustainability-linked loans, while integrating environmental risk into financial decision-making. Regulatory reforms must align financial markets with environmental goals, ensuring capital flows support low-carbon infrastructure and clean technologies. Second, the validation of the EKC emphasizes the need for targeted growth strategies. Governments must direct economic expansion toward green sectors by incentivizing renewable energy, improving energy efficiency and promoting sustainable industrialization. Tools such as carbon pricing, emissions standards and green subsidies can accelerate this transition. Institutional reforms and regulatory enforcement are essential to support sustainable development, particularly in rapidly growing economies like China and India. Third, the strong role of HC in reducing emissions highlights the value of education and skill-building for sustainability. Integrating environmental awareness, green training and climate literacy into education systems can shape an eco-conscious workforce. Aligning HC development with national climate strategies and boosting R&D in clean technologies will ensure long-term productivity and lower emissions through innovation and behavioral shifts. Finally, the positive long-run impact of urbanization on emissions calls for sustainable urban planning. Investment in public transit, compact city layouts and green infrastructure must be prioritized. Smart city initiatives, strong land-use regulations and resilient urban design can minimize the ecological costs of expanding urban populations. For fast-urbanizing nations like India and Indonesia, balancing urban growth with environmental protection is critical. Collectively, these policy directions offer a strategic blueprint to align economic, social and environmental goals, ensuring that the region's development remains inclusive, resilient and climate-smart.

5.2 Limitations and future research potential

This study provides robust empirical evidence on the role of financial development in mitigating carbon emissions in five leading Asian economies. However, several limitations remain. First, the use of aggregate financial development indicators may overlook finer aspects. Future research should integrate disaggregated measures such as private credit, financial

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