*Original Article*

# Can Human Capital Mitigate the Environmental Costs of Urbanization? Empirical Evidence from Asia's Five Largest Economies

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**Abstract**

Rapid urbanization in Asia has intensified concerns over rising $CO_2$ emissions, yet the moderating influence of human capital in this process remains underexplored. This study examines whether human capital can mitigate the environmental impact of urbanization in five major Asian economies—China, India, Japan, South Korea and Indonesia—during 1990–2021. Employing advanced panel econometric techniques, including cross-sectional dependence tests, panel co-integration analysis and a panel ARDL framework with Panel Mean Group (PMG), MG and DFE estimators, the study captures both long- and short-run dynamics. Robustness is ensured through dynamic OLS estimation, while Granger causality and variance decomposition provide insights into the direction and strength of causal linkages. The results reveal that urbanization significantly increases $CO_2$ emissions, with a 1% rise in the urban population contributing to a 7.53% increase in emissions. In contrast, human capital directly reduces emissions by 1.68% and, when interacting with urbanization, offsets its adverse effect by 11.76%. Evidence broadly supports the Environmental Kuznets Curve, although country-specific heterogeneity emerges: human capital fosters sustainable urbanization in China and South Korea, and moderates environmental stress in India, while financial development intensifies emissions in Japan and Indonesia. By quantifying the moderating role of human capital, this study adds novel evidence to the environmental economics literature and underscores human capital development as a key policy instrument for achieving sustainable urban growth and low-carbon development in Asia.

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**Keywords**

Urbanization, human capital, $CO_2$ emissions, panel ARDL, Asia, sustainable development

## I. Introduction

Sustainability is among the most urgent challenges confronting humanity, as escalating environmental crises increasingly threaten ecosystems, economies and human well-being globally. Climate change, resource depletion and pollution have emerged as interconnected global threats demanding coordinated international action. Addressing these challenges is crucial not only for climate mitigation but also for securing essential resources and fostering resilient societies across the globe. Within this context, Asia, home to 59.05% of the world's population, plays a decisive role in shaping economic and environmental outcomes. Leading economies, including China, Japan, India, South Korea and Indonesia, rank among the world's largest by GDP and are central to international trade, industrial development and technological innovation. However, this rapid growth has incurred substantial environmental costs. The International Energy Agency (IEA, 2024) estimates that global emissions from fuel combustion reached approximately 34.1 billion tonnes in 2022, with energy consumption identified as the largest source of greenhouse gases. Continued reliance on fossil fuels—coal, oil and natural gas across electricity generation, transportation and industrial sectors—has kept emissions well above targets set under international accords such as the Paris Agreement. The Asia Pacific region accounted for over half of global $CO_2$ emissions in 2022, reflecting both rapid industrialization and fossil fuel dependence. Five major economies—China, Japan, India, Indonesia and South Korea—collectively emitted 17,465.3 Mt of $CO_2$, positioning Asia as the epicentre of global carbon output (IEA, 2024). Structural shifts over past decades have intensified this trend: China's share of global emissions surged from 14.26% in 1996 to 32.88% in 2022, reaching 13,260 Mt $CO_2$ in 2023; India's share rose from 3.38% to 6.99%, totalling 2,955 Mt $CO_2$ in 2023. Indonesia contributed 675 Mt $CO_2$, driven by fossil fuel use and deforestation, whereas Japan's share declined from 5.25% in 1996 to 2.81% in 2022, though its per capita emissions remain elevated at 7.54 Mt $CO_2$. South Korea, accounting for 1.65% of global emissions (574 Mt $CO_2$), exhibits the highest per capita emissions among these economies at 11 Mt$CO_2$. Within Asia, China alone contributed 10,613.2 Mt over 60% of the regional total followed by India (2,517 Mt), Japan (974 Mt), Indonesia (652 Mt) and South Korea (574 Mt), illustrating the varied yet collectively significant contributions of these economies to the region's carbon footprint.

Urbanization has been a primary driver of economic transformation in major Asian economies, facilitating industrial expansion, infrastructure development and improved living standards (Henderson, 2010). However, it has simultaneously amplified environmental pressures, as increased energy consumption and industrial activity have accelerated greenhouse gas emissions, deforestation and pollution (Shahbaz et al., 2016; World Bank, 2023; Zhang & Lin, 2012). Mukim and Roberts (2023) emphasize the importance of fostering green, resilient and inclusive cities in a changing climate. Understanding the nexus between urbanization and $CO_2$ emissions is therefore vital for designing effective policies and identifying mechanisms such as human capital development that can reconcile economic growth with environmental sustainability. While prior studies have examined the relationship either between urbanization and emissions (Azam & Qayyum Khan, 2015; Kim & Baik, 2005; Lee et al., 2023; Shahbaz et al., 2016; Zhao et al., 2006) or between emissions and human capital (Adikari et al., 2023; Bano et al., 2018; Mahmood et al., 2019; Rahman et al., 2021; Zafar et al., 2019), the role of human capital in moderating the urbanization–emission link remains underexplored. Investments in human capital generate multiple benefits beyond productivity and growth (Becker, 1994; Romer, 1990; Schultz, 1961), including improved health, reduced crime and enhanced civic engagement (Sianesi & van Reenen, 2003). Yet, its potential environmental advantages are less understood, representing a critical research gap.

This study addresses this gap by examining the role of human capital in the urbanization–$CO_2$ nexus across five leading Asian economies—China, Japan, India, South Korea and Indonesia—over the period 1990–2021. These countries are selected due to their substantial economic size, large populations, significant contributions to global $CO_2$ emissions and pressing sustainability challenges, making them pivotal for understanding broader implications of urbanization and environmental policy. The study contributes in three main ways. First, it introduces an innovative interaction term between urbanization and human capital, marking the first attempt, to our knowledge, to examine how human capital moderates urbanization's impact on emissions in Asia's largest emerging economies. Second, it provides region-specific empirical evidence, offering insights into the sustainability challenges confronting rapidly urbanizing nations. Third, it incorporates additional determinants, including financial development and economic growth, to provide a comprehensive analysis of the complex interplay among urbanization, human capital and carbon emissions. The findings are expected to inform policymakers and urban planners, highlighting the potential of human capital investment as a strategic tool for promoting sustainable urbanization while mitigating environmental harm in Asia's most significant economies. The article is organized as follows: Section I introduces the topic; Section II reviews the literature; Section III presents results and discussion; and the final section provides conclusions, policy implications, limitations and directions for future research.

## II. Literature Review

Globally, modernization and industrialization have fuelled urbanization, often intensifying environmental pressures. However, empirical evidence on the urbanization–$CO_2$ nexus remains mixed. Several studies identify urbanization as a major driver of emissions through rising energy demand, transport expansion and industrial activity (Shahbaz et al., 2016; Zhang et al., 2017), with similar findings reported for Turkey (Pata, 2018), MENA countries (Al-Mulali & Ozturk, 2015) and a global panel of 86 nations (Cole & Neumayer, 2004). Yet, other scholars highlight the potential for urbanization to support sustainability through economies of scale, efficient service delivery and technological progress (Phetkeo & Kaneko, 2010; Satterthwaite, 2009; Sharma, 2011). For Asia, evidence is particularly nuanced: in China, urbanization has shown a long-run positive impact on emissions (Liu & Bae, 2018), while in India, emissions rise alongside demographic and economic expansion, with urbanization as a central factor (Rehman & Rehman, 2022). Contradictory results also emerge, with Azam and Qayyum Khan (2015) reporting a negative effect linked to service-sector growth. Urban form and spatial planning further complicate outcomes, as observed in Japan, where city configurations shape sectoral emissions (Makido et al., 2012), and in South Korea, where urban expansion reduces carbon absorption through green-space loss (Hwang et al., 2025).

Beyond urbanization, financial development (FD) has also been widely studied as a determinant of emissions, though with equally divergent findings. Some studies suggest that FD aggravates environmental degradation by driving industrial growth and energy consumption (Alabi et al., 2021; Khan et al., 2025c; Nawaz et al., 2020; Shahbaz et al., 2020), while others contend it can support sustainability by financing renewable energy and green technologies (Charfeddine & Kahia, 2019; Du et al., 2022; Khan et al., 2025d; Zafar et al., 2019). These contrasting outcomes are shaped by institutional and governance quality (Dasgupta et al., 2001; Khan et al., 2021), and in several cases, FD shows no significant impact at all (Asumadu-Sarkodie & Owusu, 2016; Chen et al., 2019; Haseeb et al., 2018). The evidence from Asia thus remains highly context-dependent.

Similarly, the relationship between economic growth (EG) and $CO_2$ is often framed within the Environmental Kuznets Curve (EKC) hypothesis, which predicts that environmental degradation rises with income before declining as economies transition to cleaner technologies (Grossman & Krueger, 1995). Several studies confirm this inverted U-shape (Danish et al., 2019; Zafar et al., 2019), yet others argue growth continues to exacerbate emissions in the absence of stringent regulation and innovation (Dietzenbacher & Mukhopadhyay, 2007). Rahman et al. (2021) identified partial EKC evidence in newly industrialized countries but without consistent validation. For Asia, findings remain mixed: in China and India, rapid industrial growth has significantly increased emissions (Pal & Mitra, 2017), while in Japan, the positive growth–emission relationship has been partially offset by renewable energy adoption (Nawaz et al., 2025).

More recently, human capital (HC) has emerged as a critical, though underexplored, factor in the emissions debate. Studies on OECD countries show that HC's effect has evolved over time, shifting from positive to negative as education and technology diffusion reduced environmental pressures (Yao et al., 2019). Similarly, Rahman et al. (2021) demonstrated that HC combined with growth can enhance environmental quality, consistent with EKC dynamics. Other research highlights long-run benefits of HC through technology adoption, renewable energy diffusion and behavioural awareness (Bano et al., 2018). However, contrasting evidence exists: Du et al. (2022) found that HC increased emissions in 28 emerging economies due to scale effects and lack of EKC validation. Within Asia, Khan et al. (2025a) showed that innovative and education-driven HC reduced degradation in China, while Khan et al. (2025b) confirmed that HC and renewable adoption curbed emissions in India. In advanced Asian economies such as Japan and South Korea, HC integrated with ICT has supported productivity-led, low-emission growth (Ahmed, 2012). These findings suggest that HC reduces emissions in advanced economies (Japan, South Korea, post-2000 China and increasingly India) via technological and behavioural spillovers, but in emerging contexts (Indonesia, early-stage China), scale effects dominate, leaving the HC–$CO_2$ nexus ambiguous.

While prior research has extensively examined the independent roles of urbanization, financial development, economic growth and human capital in driving emissions, little is known about how human capital shapes the *urbanization–$CO_2$ nexus* in rapidly urbanizing Asian economies. This gap is particularly critical given Asia's simultaneous urban expansion, energy transition and investment in human capital, making it necessary to investigate whether HC can transform urbanization from a source of emissions into a pathway for sustainability.

## III. Theoretical and Conceptual Framework, Empirical Modelling and Techniques of Estimation

### *Theoretical and Conceptual Framework*

This study examines the moderating role of HC in the relationship between urbanization (URB) and carbon emissions ($CO_2$) while also considering the influences of FD and EG. The conceptual framework is grounded in established theories that link economic development, innovation and institutional factors with environmental sustainability. The Ecological Modernization Theory (EMT) serves as the primary foundation. Emerging in the 1980s, EMT posits that economic growth and technological innovation can be aligned with environmental improvements when supported by robust social institutions, effective policy interventions and sound governance structures (Glynn et al., 2017, pp. 22–46). EMT suggests that environmental degradation is often an unintended consequence of early industrialization and urban expansion, but as economies advance, ecological concerns take precedence, fostering investments in cleaner technologies, energy efficiency and regulatory reforms aimed at mitigating emissions (Hashmi et al., 2021). Complementing EMT, the Urban Environmental Transition Theory explains how environmental impacts vary systematically across different stages of development. In early stages, rapid industrialization and urban growth often lead to heightened pollution, whereas later stages benefit from technological advancements and regulatory frameworks that reduce emissions. Urbanization, in particular, is a widely acknowledged driver of environmental stress, contributing to rising $CO_2$ levels through increased energy consumption, transportation expansion and industrial activities (Liu & Bae, 2018; Rehman & Rehman, 2022). In emerging economies, where economic priorities frequently overshadow environmental considerations, urban expansion can significantly exacerbate carbon emissions. The green finance hypothesis further enriches this framework by emphasizing the role of financial markets in directing capital towards environmentally sustainable sectors. By offering targeted incentives, financial institutions can support investments in renewable energy, clean technologies and efficient industrial practices, thereby contributing to emission reductions (Nawaz et al., 2020; Shahbaz et al., 2020). However, the relationship between financial development and emissions is complex and context-dependent. While FD has often supported energy-intensive industries and heightened carbon emissions (Du et al., 2022; Zafar et al., 2019), the Endogenous Growth Theory highlights the significant role of human capital in promoting both economic expansion and environmental sustainability. Investments in education, innovation and knowledge diffusion enhance productivity and create pathways for energy efficiency and environmentally responsible behaviours over time. Schultz (1961), Romer (1990) and Becker (1994) argue that investments in human capital yield benefits beyond productivity and growth, including improved health outcomes, reduced crime rates and increased civic engagement (Sianesi & van Reenen, 2003). Recent empirical evidence further demonstrates that human capital fosters sustainable practices by enabling technological advancement and raising environmental awareness (Khan et al., 2025a, 2025b). Additionally, the EKC hypothesis offers a widely applied framework for understanding the non-linear relationship between economic growth and environmental degradation. According to this hypothesis, carbon emissions rise in the early phases of development due to industrialization and resource exploitation but decline as economies transition to higher income levels, cleaner technologies and stronger governance mechanisms (Grossman & Krueger, 1995; Nawaz et al., 2025). However, the validity of the EKC in the context of emerging Asian economies remains an open empirical question.

### *Integrative Framework*

Drawing on these theoretical perspectives, this study proposes an integrative framework that incorporates four key dimensions—URB, FD, EG and HC—to explain variations in carbon emissions across emerging Asian economies. Urbanization, financial development and economic growth are generally expected to intensify emissions due to increased industrial activity, energy demand and consumption patterns. Human capital, however, is hypothesized to play a moderating role by facilitating technological innovation, enhancing environmental awareness and encouraging sustainable behaviours that can offset the environmental pressures associated with urban expansion. By empirically investigating this complex interplay, the study seeks to contribute to a deeper understanding of sustainable development pathways in rapidly evolving economies and to assess how human capital can serve as a critical enabler for balancing growth with environmental stewardship.

## *Empirical Modelling*

Following the IPAT model developed in the 1970s by Holdren and Ehrlich (1974), a widely applied framework for assessing the impact of human activities on environmental outcomes, we define the environmental impact function as follows:

$$I = P \times A \times T \tag{1}$$

The IPAT model expresses environmental impact ($I$) as a function of population ($P$), affluence ($A$) and technology ($T$) (Dietz & Rosa, 1994). Despite its simplicity, it lacks statistical flexibility for hypothesis testing. To address this, Dietz and Rosa (1997) and York et al. (2003) introduced the STIRPAT model, incorporating stochastic elements for better analysis. This study applies the STIRPAT model, as specified in the following equation:

$$I_t = \beta_0 P_t^{\beta_1} A_t^{\beta_2} T_t^{\beta_3} \mu_t \tag{2}$$

In the model, environmental impact ($I$) is the dependent variable, while affluence ($A$), population ($P$) and technology ($T$) are independent variables. The constant term is $\beta_0$, and the elasticity of $P$, $A$ and $T$ are $\beta_1$, $\beta_2$ and $\beta_3$, respectively. $CO_2$ emissions measure environmental impact (Le TH et al., 2020). Following the literature, $P$, $A$ and $T$ are decomposable (Chikaraishi et al., 2015), with urbanization rate (UR) representing population (Guo et al., 2019). $A$ is quantified by economic growth, and the quadratic of growth presents the relation with $CO_2$ in EKC fashion, steered by the EKC hypothesis (Grossman & Krueger, 1995). Building on Adom et al. (2018) and Tao et al. (2023), $T$ represents a transformational process between production and consumption and encompasses the inputs into production. In the transformational process between production and consumption, a country's human capital plays an important part as laid down by endogenous growth theorists (Becker, 1964; Romer, 1990; Schultz, 1961). Following the literature, financial development is also an important input (Tao et al., 2023; Zhang, 2011). Therefore, the extended STIRPAT model is finally specified as follows:

$$CO_{2,it} = \beta_0 + \beta_1\, URB_{it} + \beta_2\, HCI_{it} + \beta_3\, FD_{it} + \beta_4\, GDP_{it} + \varepsilon_{it} \tag{3}$$

To investigate the impact of human capital induced urbanization on emissions, the equation can be specified as follows:

$$\begin{aligned} CO_{2,it} = \beta_0 + \beta_1 URB_{it} + \beta_2 HCI_{it} + \beta_3 (URB \times HCI)_{it} + \\ \beta_4 FD_{it} + \beta_5 GDP_{it} + \beta_6 GDPS_{it} + \varepsilon_{it} \end{aligned} \tag{4}$$

The study adopts a log–linear specification (Shahbaz et al., 2012) as it reduces heteroscedasticity, normalizes skewed variables and improves estimation efficiency. This form enables coefficients to be interpreted as elasticities while the logarithmic interaction term captures the moderating role of human capital in the urbanization–emissions nexus; the empirical model is specified as follows:

$$\begin{aligned} \ln CO_{2,it} = \beta_0 + \beta_1 \ln URB_{it} + \beta_2 \ln HCI_{it} + \beta_3 (\ln URB \times \ln HCI)_{it} + \\ \beta_4 \ln FD_{it} + \beta_5 \ln GDP_{it} + \beta_6 \ln GDPS_{it} + \varepsilon_{it} \end{aligned} \tag{5}$$

Where,

**Table 1.** Description of Variables.

| Variable | Symbol | Definition | Source |
|---|---|---|---|
| $CO_2$ emissions | $CO_2$ | $CO_2$ emissions (tons per capita) | WDI |
| Urban population | URB | Proportion of urban population to the total population | WDI |
| Human capital index | HCI | Human capital index based on years of schooling | Penn World Table 10 |
| Financial development index | FDI | Relative ranking of countries on the depth, access and efficiency of financial institutions and markets | IMF |
| Gross domestic product per capita | GDP | GDP per capita (constant 2015 US$) | WDI |

$CO_2$ is carbon emission, *URB* represents the proportion of urban population, *HCI* connotes the human capital index, $URB \times HCI$ is the product of urbanization and human capital index, *FD* connotes the financial development, *GDP* per capita represents economic growth and *GDPS* represents the square of the growth. The variable description, measurements and sources are presented in Table 1. The mediating role of human capital is determined by the estimated long-run parameters of degree of urbanization ($\beta_1$) and the interaction term ($\beta_3$). There are four likely outcomes of the indicated parameters:

1. If both $\beta_1$ and $\beta_3$ are positive (>0), it implies that urbanization positively contributes to carbon emissions and the level of human capital intensify and complements the positive link.
2. If both $\beta_1$ and $\beta_3$ are negative (<0), it implies that urbanization retards carbon emission levels and the level of human capital aggravates the negative effect and hence helps in maintaining environmental quality.
3. If $\beta_1$ is positive (>0) and $\beta_3$ is negative (<0), it implies that urbanization positively contributes to carbon emissions but the human capital helps to bring down the environmental degradation.
4. If $\beta_1$ is negative (<0) and $\beta_3$ is positive (>0), it means urbanization negatively contributes to carbon emissions, but the level of human capital enhances the negative effect.

## *Techniques of Estimation*

### *Cross-sectional Dependency and SG Unit Root*

This study employs the cross-sectional dependence (LM) test developed by Breusch and Pagan. The test statistic is based on the following specification:

$$y_{it} = \alpha_i + \beta_i x_{it} \tag{6}$$

and is computed as:

$$LM = T\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}^{2} \rightarrow \chi^{2}_{N(N-1)/2} \tag{7}$$

Where $\hat{\rho}_{ij}$ denotes the sample estimate of the pairwise correlation of residuals.

Since first-generation unit root tests do not account for cross-sectional dependence, this study applies second-generation (S-G) unit root tests. Specifically, the CIPS and CADF tests are used, defined as follows:

$$CIPS(N,T) = \frac{1}{N}\sum_{i=1}^{N} t_i(N,T) \tag{8}$$

where $t_i$ $(N,T)$ represents the cross-sectionally augmented Dickey–Fuller (CD-ADF) statistic.

### *Panel Co-integration Test*

Following the stationary analysis, we applied the Westerlund (2006) co-integration test to examine the long-run relationship between $CO_2$ and its explanatory variables. This test, which incorporates the bootstrap method, provides robust results even in the presence of cross-sectional dependence (CD), heterogeneity and small sample sizes. The Westerlund test comprises two panel-based (pooled) and two group-mean-based statistics.

The model specification is given as follows:

$$\Delta Y_{it} = \rho_0 d_t + \theta_i Y_{i,t-1} + \pi_0 x_{i,t-1} + \sum\nolimits_{j=1}^{m_i}\theta_{ij}\Delta Y_{i,t-j} + \sum\nolimits_{j=-n}^{m_i}\gamma_{ij}\Delta x_{i,t-j} + \varepsilon_{it} \tag{9}$$

Where $d_t$ represents the deterministic components, and $m$ and $n$ refer to the lag and lead lengths, respectively.

### *Panel Autoregressive Distributed Lag Model*

We employed the Panel Mean Group Autoregressive Distributed Lag (PMG-ARDL) approach developed by Pesaran et al. (2001), 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 data set covering leading Asian countries from 1990 to 2021. Following Sarkodie and Strezov (2018), the general form of the ARDL($p$, $k$) specification is:

$$\ln CO_{2_{it}} = \sum\nolimits_{j=1}^{p}\lambda_{1j}\ln CO_{2_{i,t-j}} + \sum\nolimits_{j=0}^{k}\delta'_{ij}X_{i,t-j} + \mu_{it} + \varepsilon_{it} \tag{10}$$

where In $CO_{2it}$ is the natural logarithm of $CO_2$ emissions; $X_{it}$ is the vector of explanatory variables: urban population (URB), human capital index (HCI), urbanization and human capital index (URB × HCI), financial development index (FD), economic growth (GDP), square of the growth (GDPS); $\lambda_{1j}$ are the lagged coefficients for $CO_2$; $\delta_{ij}$ are the distributed lag coefficients for the regressors; $\mu_{it}$ captures individual fixed effects and $\varepsilon_{it}$ is the error.

$$\Delta\ln CO_{2,it} = \beta_0 + \sum_{j=1}^{p} \delta_j \, \Delta\ln CO_{2,i,t-j} + \sum_{j=0}^{k} \beta_{1j} \, \Delta\ln URB_{i,t-j} + \sum_{j=0}^{k} \beta_{2j} \, \Delta\ln HCI_{i,t-j} + \sum_{j=0}^{k} \beta_{3j} \, \Delta(\ln URB \cdot \ln HCI)_{i,t-j} + \sum_{j=0}^{k} \beta_{4j} \, \Delta\ln FDI_{i,t-j} + \sum_{j=0}^{k} \beta_{5j} \, \Delta\ln GDP_{i,t-j} + \sum_{j=0}^{k} \beta_{6j} \, \Delta\ln GDPS_{i,t-j} + \theta_1 \ln CO_{2,i,t-1} + \theta_2 \ln URB_{i,t-1} + \theta_3 \ln HCI_{i,t-1} + \theta_4 (\ln URB \cdot \ln HCI)_{i,t-1} + \theta_5 \ln FDI_{i,t-1} + \theta_6 \ln GDP_{i,t-1} + \theta_7 \ln GDPS_{i,t-1} + \mu_{it} + \varepsilon_{it}. \quad (11)$$

### *Granger Causality Tests*

To complement ARDL estimates which show associations but not direction, this study applies panel Granger causality tests to examine causal links between the food production index and explanatory variables. Originally proposed by Granger (1969) for time series, Dumitrescu and Hurlin (2012) extended the method to heterogeneous panel data, accounting for cross-sectional differences and short-run dynamics. If variables are cointegrated, theory suggests at least unidirectional causality. The Dumitrescu–Hurlin test helps identify possible bidirectional causality and interdependencies across the panel.

$$Y_{i,t} = a_i + \sum_{k=1}^{K} \delta_{ik} Y_{i,t-k} + \sum_{k=1}^{K} \Pi_{ik} X_{i,t-k} + \varepsilon_{i,t} \quad (12)$$

$$X_{i,t} = a_i + \sum_{k=1}^{K} \delta_{ik} X_{i,t-k} + \sum_{k=1}^{K} \Pi_{ik} Y_{i,t-k} + \varepsilon_{i,t} \quad (13)$$

Here, $X_{i,t}$ and $Y_{i,t}$ are the respective independent and dependent variables for country $i$ over time $t$.

## IV. Results and Discussion

### *Preliminary Analysis*

The trends of variables across China, Japan, South Korea, India and Indonesia (Figure 1) reveal distinct developmental pathways shaped by structural factors, policies and historical contexts. China underwent rapid transformation: GDP per capita rose from \$905 in 1990 to \$11,470 in 2021, $CO_2$ emissions from 1.9 Mt/capita in 1990 to 8.9 Mt/capita in 2021, urbanization from 26.4% in 1990 to 62.5% in 2021, financial development from 0.28 in 1990 to 0.63 in 2021 and human capital from 1.96 to 2.72. Japan, a mature high-income economy, saw GDP per capita increase in the same time period from \$28,422 to \$35,741, $CO_2$ decline slightly from 8.8 to 8.6, urbanization rise from 77.3% to 91.9%, financial development from 0.66 to 0.89 and human capital from 3.18 to 3.61. South Korea transitioned from emerging to advanced: GDP per capita increased from \$9,367 to \$32,771, $CO_2$ emissions from 5.8 to 12.2, urbanization from 73.8% to

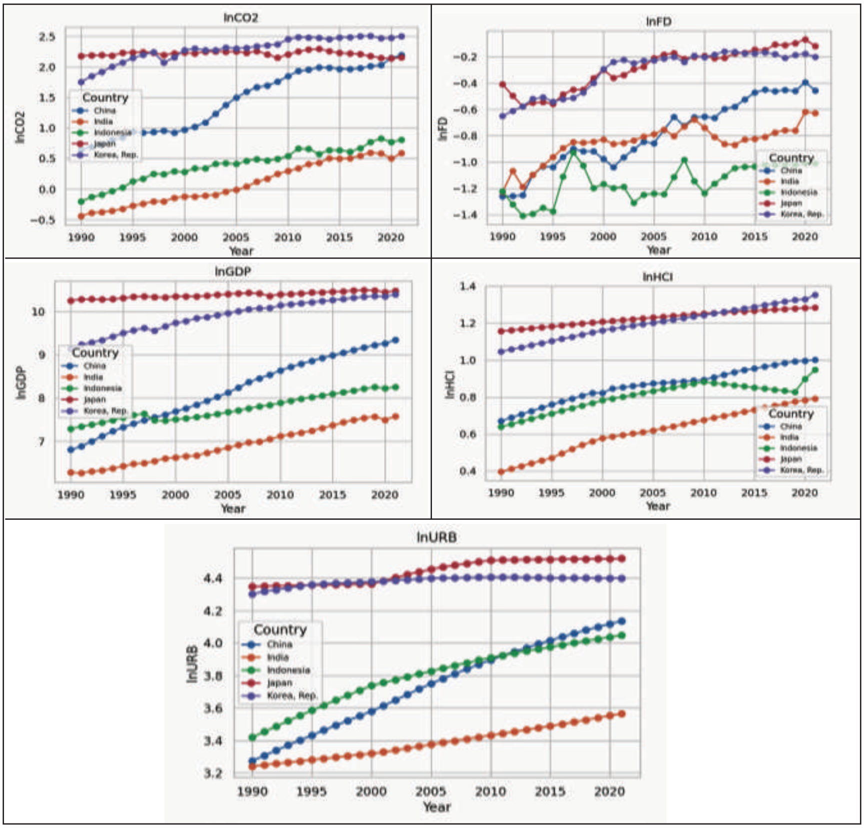


**Figure 1.** Trends of Individual Variables Across Combined Cross Sections.

above 81%, human capital from 2.85 to 3.87 and financial development advanced steadily. India's GDP per capita grew from \$534 to \$1,965, $CO_2$ from 0.65 to 1.80, urbanization from 25.5% to 35.4%, human capital from 1.49 to 2.20 and financial development increased gradually. Indonesia followed a similar trajectory: GDP per capita rose from \$1,471 to \$3,851, $CO_2$ from 0.82 to 2.24, urbanization and human capital increased moderately and financial development from 0.29 to 0.36. Collectively, Japan and South Korea exemplify high-income economies with stabilized emissions; China shows rapid industrialization with sharp increases in emissions and socio-economic indicators; India and Indonesia represent emerging economies with growth potential but significant sustainability challenges.

The descriptive statistics presented in Table 2 derived from the panel data set comprising these five countries further elucidate the distribution and variability of these key indicators. It shows while human capital remains a relatively stable feature across these nations, carbon emissions, urbanization, financial development and economic growth display considerable heterogeneity and reflect the diverse stages of development and structural characteristics inherent to these representative Asian economies.

**Table 2.** Descriptive Statistics.

| Statistics | $lnCO_2$ | *lnURB* | *lnHCI* | *lnFD* | *lnGDP* |
|---|---|---|---|---|---|
| Mean | 1.29 | 3.95 | 0.94 | −0.67 | 8.62 |
| Median | 1.54 | 3.96 | 0.88 | −0.66 | 8.25 |
| Maximum | 2.50 | 4.52 | 1.35 | −0.06 | 10.49 |
| Minimum | −0.43 | 3.24 | 0.39 | −1.40 | 6.27 |
| Std dev | 0.96 | 0.43 | 0.25 | 0.37 | 1.39 |
| Skewness | −0.23 | −0.16 | −0.11 | −0.06 | 0.01 |
| Kurtosis | 1.46 | 1.50 | 1.86 | 1.76 | 1.50 |
| Observations | 160 | 160 | 160 | 160 | 160 |

**Table 3.** Results of the Residual Cross-sectional Dependence (Breusch–Pagan LM) Test.

| Variable | $lnCO_2$ | *lnURB* | *lnHCI* | *lnURB × HCI* | *lnFD* | *lnGDP* | $lnGDP^2$ |
|---|---|---|---|---|---|---|---|
| Breusch–Pagan LM | 425.7321 | 310.4526 | 287.1648 | 295.3782 | 332.9057 | 401.6724 | 389.2816 |
| *p* values | .0000 | .0000 | .0000 | .0000 | .0000 | .0000 | .0000 |

**Table 4.** Second-generation (S-G) Unit Root Test Results (CIPS and CADF).

| Variable | CIPS (Level) | CIPS (1st Diff.) | CADF (Level) | CADF (1st Diff.) |
|---|---|---|---|---|
| $lnCO_2$ | −2.245 | −2.501* | −2.44 | −3.14* |
| *lnURB* | −3.089 | −3.278* | −2.9 | −5.36* |
| *lnHCI* | −2.374** | −2.601* | −2.21 | −6.74* |
| *lnGDP* | −3.251 | −3.472* | −3.16 | −2.54* |
| $lnGDP^2$ | −2.951 | −3.165* | −1.21** | −3.30* |

**Notes:** This is Pesaran's CIPS and CADF panel unit root test accounting for cross-sectional dependence.
The null hypothesis assumes non-stationarity.
Lags are selected based on the Akaike information.
**Significant at 5% and * at 10%.

## *Cross-sectional Dependence, Panel Unit Root Analysis and Panel Co-integration Analysis*

The cross-sectional LM test results (Table 3) confirm the presence of cross-sectional dependence, as the null hypothesis of no correlation is rejected at the 1% significance level. To account for this interdependence, second-generation unit root tests—namely, the CIPS and CADF (Table 4)—are employed, given that conventional tests ignoring dependence may yield biased results. The findings indicate that human capital (HCI) is stationary at level $I(0)$, whereas $CO_2$ emissions, URB, GDP and $GDP^2$ attain stationarity only after first differencing $I(1)$. These mixed integration orders justify the use of the ARDL framework, which accommodates both $I(0)$ and $I(1)$ variables and captures short- and long-run

**Table 5.** Results of Westerlund Panel Co-integration Tests.

| Test | Test Statistic | *Z* Value | *p* Value |
|---|---|---|---|
| G-t (Westerlund) | −3.44 | −1.34 | .006*** |
| G-a (Westerlund) | −14.45 | −4.24 | .000*** |
| P-t (Westerlund) | −16.12 | −2.65 | .001*** |
| P-a (Westerlund) | −19.07 | −6.31 | .000*** |

**Notes:** ***Significance at the 1% level.
Results confirm a long-run co-integration

**Table 6.** ARDL Long-run and Short-run Results.

| Variable | PMG (Coefficient, *p* Value) | MG (Coefficient, *p* Value) | DFE (Coefficient, *p* Value) |
|---|---|---|---|
| *lnURB* | 7.53 (.00)*** | 6.22 (.01)*** | 5.99 (.02)*** |
| *lnHCI* | −1.68 (.03)** | 0.98 (.10) | 2.87 (.21) |
| *lnURB × LHCI* | −11.76 (.00)*** | −4.88 (.01)*** | −9.54 (.02)*** |
| *lnFD* | −0.32 (.03)** | −0.28 (.15) | −0.30 (.19) |
| *lnGDP* | 4.80 (.00)*** | 0.77 (.01)*** | 1.75 (.02)*** |
| *lnGDPS* | −2.004 (.00)*** | 0.003 (.01)*** | 0.003 (.02)*** |
| *D(lnURB)* | −2.78 (.38) | −3.56 (.40) | −1.48 (.42) |
| *D(lnHCI)* | −15.72 (.12) | −11.45 (.14) | −2.30 (.16) |
| *D(URB × LHCI)* | −7.38 (.45) | 7.12 (.47) | −7.05 (.48) |
| *D(lnFDI)* | −0.03 (.80) | −0.04 (.81) | −0.02 (.83) |
| *D(lnGDP)* | 6.87 (.37) | 6.62 (.39) | 6.55 (.41) |
| *D(lnGDPS)* | −37.77 (.32) | −37.40 (.34) | −37.10 (.36) |
| *ECT* | −0.45 (.00)*** | −0.38 (.01)*** | −0.32 (.02)*** |
| Hausman test | PMG, MG = 3.21 (.14) | MG, DFE = 5.85 (.03)** | |

**Note:** *** denotes significance at the 1% level, ** at the 5% level.

dynamics efficiently under cross-sectional dependence. To further address potential biases, the Westerlund (2006) second-generation co-integration test is applied. As reported in Table 5, all four statistics (G-t, G-a, P-t, P-a) are significant at the 1% level, confirming robust evidence of a long-run equilibrium relationship among the variables across the sampled Asian economies (Table 5).

## *Panel ARDL Estimation*

The vector auto regression framework is used to select the optimal lag order, with AIC identifying lag 2 as optimal. Subsequently, three panel ARDL estimators—PMG, MG and DFE—are applied to analyse the long-run and short-run relationships. The Hausman test, reported in Table 6, confirms the efficiency of the PMG estimator by failing to reject the null hypothesis of long-run homogeneity, making PMG the preferred model. The results of pooled ARDL are presented in Table 6. The results show that urbanization exerts a significant impact on $CO_2$ emissions in Asian economies, in both the long run and the short run. The long-run estimates based on the pooled mean group (PMG) method reveal that a 1% increase in urbanization (*lnURB*) leads to a 7.53% rise in $CO_2$ emissions as presented in Table 6. This confirms that rapid urban expansion contributes substantially to environmental degradation, likely through increased energy consumption, industrial activities and transportation demand. In contrast, the short-run coefficient (*D*(*lnURB*) = −2.78) is negative but statistically insignificant, indicating that urbanization's immediate impact on emissions may be muted due to adjustment delays or transitional dynamics. These findings are consistent with prior studies such as Zhang et al. (2017) and Shahbaz et al. (2016), which highlight that urban growth exacerbates emissions by intensifying resource use and pollution. However, they contradict studies such as Phetkeo and Kaneko (2010), Sharma (2011) and Satterthwaite (2009), which argue that urbanization can enhance environmental sustainability by leveraging economies of scale, improving public service efficiency and fostering technological innovation.

Regarding human capital (*lnHCI*), the long-run results presented in Table 6 indicate a negative and significant effect on emissions, with a 1% increase in human capital leading to a 1.68% reduction in $CO_2$ emissions. This highlights the role of education, awareness and skill development in promoting cleaner technologies and sustainable behaviours. In the short run, the coefficient (*D*(*lnHCI*) = −15.72) is also negative but statistically insignificant, suggesting that improvements in human capital take time to influence environmental outcomes. These results align with studies by Khan, Ganai & Sheergujree (2025a, 2025b) and Bano et al. (2018), which collectively affirm that human capital plays a pivotal role in mitigating emissions by enabling technological advancement and informed policymaking. In contrast, Hassan et al. (2019) and Du et al. (2022) report insignificant or even opposing effects, suggesting that institutional frameworks, energy infrastructure and development stages can influence how human capital affects environmental sustainability.

Crucially, this study's main hypothesis centres on understanding how human capital moderates the relationship between urbanization and $CO_2$ emissions. The main finding of the study presented in Table 6 demonstrated that the interaction term (*lnURB* × *lnHCI*) in the long run has a negative impact on $CO_2$ emissions in Asian economies. The long-run coefficient of −11.76 indicates that a 1% simultaneous increase in urbanization and human capital leads to an 11.76% reduction in emissions in Asian economies, implying that the harmful environmental effects of urban growth can be substantially mitigated when accompanied by improvements in education and awareness. The short-run coefficient (−7.38) is negative but not statistically significant, pointing to a lag in realizing these benefits. The moderating role of human capital is consistent across estimation methods, with MG (−9.88%) and DFE (−9.54%) approaches also confirming the negative relationship, though PMG suggests a stronger mitigating effect. The results fall under the third category outlined in Equation (5), where $\beta_1$ is positive and $\beta_3$ is negative, reinforcing the theory that urbanization's scale effect can be offset by human-capital-driven technological and behavioural shifts. Possible reasons for this interaction include the capacity of educated populations to adopt and demand cleaner energy solutions, efficient urban planning and robust regulatory frameworks. These findings support the technique, composition and awareness effects of human capital. As human capital improves, industries and households transition to cleaner technologies, service-sector growth replaces polluting industrial activity and environmentally conscious behaviours become widespread. Countries such as Japan and South Korea exemplify how integrating human capital into urban policies facilitates investments in renewable energy, green infrastructure, and low-carbon transportation systems. Conversely, where institutional and policy support is lacking, urbanization outpaces human capital development, resulting in persistent reliance on fossil fuels and uncontrolled industrial expansion. In sum, the long-run analysis confirms that urbanization alone accelerates $CO_2$ emissions, but when combined with enhanced human capital, it fosters sustainability, validating the moderating hypothesis. This dual dynamic emphasizes the need for integrated policies that promote education, skill development, and technological innovation to transform urban expansion into a pathway toward greener economies across Asia.

Another major finding indicates that financial development negatively impacts $CO_2$ emissions in Asian economies, as presented in Table 6. The long-run coefficient of financial development (*lnFD* = −0.32) suggests that a 1% increase in financial development leads to a 0.32% reduction in emissions in the long run. In the short run, the coefficient is smaller (−0.03) and statistically insignificant. The findings are supported by the green finance hypothesis: that financial expansion promotes investments in clean technologies and sustainable industries (Charfeddine & Kahia, 2019; Du et al., 2022; Zafar et al., 2019). The results are contrary to the findings of Nawaz et al. (2020), Shahbaz et al. (2020) and Alabi et al. (2021).

Another major finding demonstrates that economic growth significantly drives carbon emissions in Asian economies. The long-run estimates as presented in Table 8 show that a 1% increase in economic growth (*lnGDP* = 4.80) raises emissions by 4.80%, while a 1% increase in squared growth (*lnGDPS* = −2.004) reduces emissions by 2.00%, indicating that emissions decline after crossing a certain income threshold, consistent with the EKC hypothesis. The short-run results exhibit a similar trend, where a 1% rise in growth (6.87) increases emissions, but a 1% rise in squared growth (−37.77) significantly lowers emissions, reflecting how early economic expansion aggravates pollution, whereas later stages promote cleaner technologies and environmental policies. These findings corroborate prior studies (Danish et al., 2017; Zafar et al., 2019), which report that economic development eventually fosters pollution control. In contrast, Rahman et al. (2021) and Pal and Mitra (2017) find that higher income does not necessarily reduce emissions in Asian economies.

### *ARDL Short-run Coefficients (Individual Cross Sections)*

In Table 7, the short-run ARDL results highlight significant variations in the dynamic relationships between urbanization, human capital and economic

**Table 7.** Measurement of Short-run ARDL Results for the Individual Countries.

| Variable | India | China | Japan | Indonesia | Korea Republic |
|---|---|---|---|---|---|
| *D(lnURB)* | −0.537 (.003***) | 1.813 (.470) | −9.010 (.000***) | −15.498 (.729) | 0.353 (.098*) |
| *D(lnHCI)* | −1.822 (.953) | 10.662 (.216) | −48.227 (.794) | −33.865 (.825) | −5.332 (.959) |
| *D(lnURB × LHCI)* | 1.602 (.008***) | −9.740 (.004***) | 0.044 (.006***) | 45.850 (.009***) | −0.871 (.004***) |
| *D(lnFDI)* | −0.140 (.002***) | −0.352 (.000***) | 0.092 (.003***) | −0.256 (.000***) | 0.485 (.003***) |
| *D(lnGDP)* | −7.364 (.883) | 8.438 (.007**) | −3.722 (.996) | 36.464 (.861) | 0.550 (.000***) |
| *D(lnGDPS)* | 15.098 (.943) | −43.979 (.007**) | −3.722 (.996) | −190.068 (.973) | −0.001 (.000***) |
| *ECT* | 0.123 (.000***) | −0.764 (.000***) | −0.000 (.000***) | −0.038 (.000***) | −0.178 (.000***) |

**Note:** *** Significance at the 1% level, ** at the 5% level and * at the 10% level.

indicators across individual countries. Across countries, as presented in Table 7, the HC–urbanization interaction is consistently significant: it mitigates emissions in China, Japan and South Korea, but exacerbates them in India and Indonesia. Financial development reduces emissions in China and Indonesia, but raises them in Japan and South Korea. The EKC is validated in China and South Korea but not in India or Indonesia. All countries show significant ECTs, confirming long-run stability with varying adjustment speeds.

## *Robustness Check (DOLS)*

In the long run, issues such as serial correlation, where error terms are correlated over time, and endogeneity, where explanatory variables are linked to the error term, can lead to biased and inconsistent estimates. To address these concerns, this study applies the dynamic OLS (DOLS) to address issues of endogeneity and serial correlation. The results presented in Table 8 indicate that urbanization has a significant positive impact on $CO_2$ emissions in the leading Asian economies, with a coefficient of 6.95. However, human capital exerts a negative effect of −1.32, potentially due to transition costs or delays in skill development. The interaction between urbanization and human capital reduces the environmental impact, as indicated by a negative coefficient of −10.88, reinforcing the role of human capital in sustainable urban expansion. Financial development shows a minor negative impact (−0.25), suggesting an insignificant effect on $CO_2$ emissions in Asian economies. Additionally, economic growth negatively influences carbon emissions, reflecting a shift towards cleaner production methods. The high explanatory power of the model, with an $R^2$ of 0.82 and an adjusted $R^2$ of 0.79, confirms the robustness of the findings.

**Table 8.** DOLS Estimates.

| Variable | Coefficient |
|---|---|
| *lnURB* | 6.95 (.00)*** |
| *lnHCI* | −1.32 (.02)** |
| *lnURB × lnHCI* | −10.88 (.00)*** |
| *lnFDI* | −0.25 (.12) |
| *lnGDP* | 4.52 (.00)*** |
| *lnGDPS* | −1.89 (.00)*** |
| $R^2$ | 0.82 |
| Adjusted $R^2$ | 0.79 |

**Note:** *** Significance at the 1% level, ** at the 5% level.

**Table 9.** Panel Causality (Dumitrescu–Hurlin Test).

| Causality Direction | W-Stat. | Prob. | Significance |
|---|---|---|---|
| $lnCO_2 \rightarrow lnURB$ | 6.06127 | 0.233 | No causality |
| $lnCO_2 \rightarrow lnHCI$ | 4.36253 | 0.439 | No causality |
| $lnURB \times lnHCI \rightarrow LCO_2$ | 3.17091 | 0.003*** | 1% (Significant) |
| $lnCO_2 \rightarrow lnFDI$ | 5.39544 | 0.029** | 5% (Significant) |
| $lnGDP \rightarrow lnCO_2$ | 3.96399 | 0.009*** | 1% (Significant) |
| $lnGDPS \rightarrow lnCO_2$ | 3.17333 | 0.041** | 5% (Significant) |
| lnHCI → lnURB | 6.51546 | 0.006*** | 1% (Significant) |
| lnFDI → lnURB | 1.39905 | 0.4628 | No causality |
| lnGDP → lnURB | 4.21912 | 0.009*** | 1% (Significant) |
| lnGDPS → lnURB | 2.20928 | 0.001*** | 1% (Significant) |
| lnFDI → lnHCI | 8.04246 | 6.E-08*** | 1% (Significant) |
| lnGDP → lnHCI | 13.2484 | 0.000*** | 1% (Significant) |
| lnGDPS → lnHCI | 13.2257 | 0.000*** | 1% (Significant) |
| lnFDI → lnURB × lnHCI | 2.73568 | 0.613 | No causality |
| lnGDP → lnURB × lnHCI | 3.33135 | 0.289 | No causality |
| lnGDPS → lnURB × lnHCI | 1.86305 | 0.761 | No causality |
| lnGDP → lnFDI | 6.14640 | 0.892 | No causality |
| lnFDI → lnGDPS | 7.18198 | 0.698 | No causality |
| lnGDP → lnGDPS | 0.87122 | 0.220 | No causality |

**Notes:** *** Significance at the 1% level, ** at the 5% level.
This table presents results from the Dumitrescu–Hurlin panel causality test, indicating the direction and significance of short-run causal relationships between variables.

## *Granger Causality*

The Dumitrescu–Hurlin panel causality test results presented in Table 9 reveal key causal relationships among the variables. The findings suggest that both GDP and GDPS granger causes $CO_2$ supporting the finding of positive impact of GDP and negative impact of GDPS on $CO_2$ emission evidencing long run EKC in the study. The interaction of human capital and urbanization also granger caused $CO_2$ emissions confirming the long run results where this human capital induced urbanization decreased the emissions.

## V. Conclusions, Policy Implications and Limitations

### *Conclusions*

This study examined the role of human capital in moderating the relationship between urbanization and $CO_2$ emissions across five major Asian economies—China, Japan, India, South Korea and Indonesia—over 1990–2021. Using advanced panel econometric techniques, including cross-sectional dependency tests, second-generation unit root tests, panel co-integration and panel ARDL framework with PMG, MG and DEF estimators, the analysis confirms a long-run equilibrium among urbanization, human capital, financial development, economic growth and emissions while revealing significant country-specific heterogeneity. At the panel level, urbanization substantially increases emissions, whereas human capital directly reduces emissions and mitigates the environmental impact of urban expansion. The EKC hypothesis is broadly supported, with cross-country variations: human capital fosters sustainable urban practices in China and Korea, and reduces emissions pressures in India, while inadequate human capital contributes to higher emissions in Indonesia. Financial development exhibits mixed effects across countries, highlighting the need for context-specific strategies.

### *Policy Implications*

The findings indicate that leveraging human capital is critical for sustainable urbanization. Policies should enhance education, vocational training and knowledge dissemination to enable the workforce to adopt low-carbon practices, while aligning financial incentives with environmental objectives to support green technologies and sustainable infrastructure. Country-specific measures include integrating human capital and green finance in China, promoting clean technology incentives in Japan, ICT-aligned skill development in Korea, green skills and smart city planning in India and vocational training combined with sustainable urban planning in Indonesia. These targeted interventions can help achieve low-carbon, resilient and sustainable urban development across diverse Asian contexts.

### *Limitations and Future Directions*

Despite robust findings, the study has limitations. Focusing on only five major Asian economies limits generalizability, and future research could extend the analysis to developed economies. Human capital was measured primarily through educational indicators; incorporating health and sector-specific skills would provide a more comprehensive understanding. The linear panel ARDL framework may not capture non-linear or asymmetric effects, suggesting the potential use of non-linear ARDL or other advanced econometric approaches. Including regional, sectoral and policy-specific data could yield more granular insights, guiding context-sensitive strategies for sustainable, low-carbon urban development.

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