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Testing non-linear effect of urbanization on environmental degradation: Cross-country evidence

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The contribution of structural transformation and urban development is considered crucial for the long run socio-economic growth but has adversely affected environmental sustainability over last few decades. This empirical research makes an innovative and holistic addition to the prior literature by examining the non-linear effect of economic growth and urban dynamics on environmental degradation in a comprehensive panel data of 66 countries and across respective income groups for the period 1990–2016. For empirical analysis, the robust econometric methods of two-way fixed effects (2W-FE), panel fully modified ordinary least squares (PFMOLS), and Driscoll-Kraay regressions have been applied to account for all econometric issues. The study unveils the bell-shaped effect of economic growth on environmental degradation which confirms the Environmental Kuznets Curve (EKC) and structural change hypotheses. The results of this study signifies the inverted U influence of urbanization and urban agglomerations on CO_2 emissions and hence supports Ecological Modernization Theory (EMT). Our empirical findings also unfold the heterogeneous non-linear effects of urban dynamics across various income categories of selected economies. By employing the heterogeneous Dumitrescu and Hurlin (D-H) (Granger non-causality tests), the findings of this study confirm the prior estimations and establish significant unilateral and bilateral causal nexus of structural change and urban dynamics with environmental degradation. By verifying the existence of Environmental Kuznets Curve phenomenon in Low and Lower Middle Income (LLMI) and Upper Middle Income (UMI) group countries, this study necessitates for the policy makers to adopt the eco-friendly industrial and energy policies for the long run social, economic and environmental sustainability.

KEYWORDS

structural change, urban dynamics, CO2 emissions, extended non-linear STIRPAT model, environmental degradation

1 Introduction

The industrial revolution, emerging at the end of the 18th century, brought a substantial change in the socio-economic structure of countries in the world. Structural change in industrial composition has tremendously increased since the 1970's in many industrialized countries, stimulating the energy demand for production and industrial processes and raising concerns for environmental pollution (Jänicke et al., 1989). The rapid growth in industrialization and urbanization has also adversely affected the ecological balance and agricultural activities due to environmental degradation and climate change (Talib et al., 2021). Since 1970, industrial processes have extensively relied upon fossil fuel energy consumption causing 78 percent global greenhouse gas (GHG) emissions (IPCC, 2014). Moreover, the rise of the non-metallic industry, especially the cement sector, in developing countries has substantially increased carbon emissions during 1971–2010 due to massive demand for infrastructure and construction projects in urban areas (Wang J.-W. et al., 2017). According to recent estimates of the World Resource Institute, the energy sector, including manufacturing, electricity and heat production, transportation, construction, fossil fuel consumption, and fugitive emissions, is the largest contributor of GHG emissions, amounting to approximately 73 percent of such emissions worldwide (Ge and Friedrich, 2020). Kuznets (1955) introduced the idea of the Environmental Kuznets Curve (EKC), which postulates an inverted U-shaped relation between economic growth and the environment. Initially, economic growth degrades environmental quality due to rapid industrial and urban growth. However, during the successive phase of economic development, the ecological quality improves after reaching a certain threshold due to the emergence of the service sector and energy-efficient technology (Ozturk and Al-Mulali, 2015; Bilgili et al., 2016). Linked with EKC is the structural change hypothesis, proposed by Kuznets (1957), which assumes that economic growth affects the sectoral composition of an economy by moving from a high-polluting industrial sector to a low-polluting service sector. In other words, initially, the production system of an economy shifts from agriculture to energy-intensive and highly polluting manufacturing sector due to urban growth and economic development; however, it ultimately shifts to a less-polluting service sector (Marsiglio et al., 2015).

Several studies have testified to the EKC hypothesis using diverse sample characteristics, different periods, country-settings, econometric methods, income level, regional differences, and various additional control variables. However, the empirical findings of prior studies are controversial and inconclusive. For instance, some researchers document a bell-shaped nexus between economic growth and environmental degradation (Shahbaz et al., 2012; Katircioğlu, 2014; Ben Jebli et al., 2016; Usman et al., 2019; Prastiyo and Hardyastuti, 2020). Furthermore, Udemba et al. (2022a) confirmed the EKC hypothesis using both symmetric and asymmetric models. Conversely, Onafowora and Owoye (2014) found mixed evidence; an inverted-U shaped relation in South Korea and Japan while an N-shaped effect in the other six countries. Some studies have also found a U-shaped effect of economic growth and environmental quality (Cho et al., 2013; Udemba and Philip, 2022; Udemba and Tosun, 2022). Moreover, several papers even fail to confirm or validate the EKC theory in different country settings (Lantz and Feng, 2006; Ozturk and Al-Mulali, 2015; Zoundi, 2017). The validity of the EKC hypothesis also depends upon the type of environmental degradation measures used in empirical analysis (Altıntaş and Kassouri, 2020). They found an inverted U-shaped relationship between income level and ecological footprints, while U-shaped nexus of income level with carbon emissions. Similarly, some recent studies also confirm that the economic growth enhances carbon emissions in specific country settings (Udemba, 2022; Udemba and Alola, 2022). Therefore, the EKC hypothesis remains a fragile concept because researchers still lack robust econometric approaches and statistical methods (Galeotti et al., 2008; Wagner, 2015). Moreover, the income-pollution nexus varies across various income-level groups of countries. For instance, Al-mulali et al. (2015) and (Bilgili et al., 2021) validated the EKC hypothesis only in high-income and upper-middle-income countries, while U-shaped relationship in low-income countries.

A large number of studies have investigated the linear effect of urbanization on environmental degradation via CO_2 emissions. The extensive use of fossil fuel energy consumption in urban areas has intensified environmental damage worldwide (Wang et al., 2016; Behera & Dash, 2017). The migration of people and resources from rural to urban areas have caused greater energy demands due to economic output, energy structure, development of city infrastructures, transport intensity, industrialization growth, and population-scale effect, etc. (Al-mulali et al., 2013; Arvin et al., 2015; Wang J.-W. et al., 2017; Huo et al., 2020). An extensive set of these empirical studies find the pollution-enhancing role of urban development (Jia et al., 2009; Li et al., 2011; Wang et al., 2012; Ali et al., 2019). Khoshnevis Yazdi and Dariani (2019) argue that urbanization positively affects environmental degradation. Udemba and Keleş (2021) also confirmed the negative role of urban population in environmental and sustainable development. Some studies have also found insignificant nexus between urbanization and environmental degradation (Liddle and Lung, 2010; Sharif Hossain, 2011). However, other researchers have explored the mixed and varied effect of urban dynamics on carbon emissions across various regions and income levels (Zhang and Lin, 2012; Onafowora and Owoye, 2014; Li and Lin, 2015; Zhou et al., 2019). Behera and Dash (2017) also documented mixed and inconclusive findings and reported that the effect of urbanization significantly varies across income groups. In a spatial study, Kassouri (2021) has documented heterogeneous

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effects of urbanization across various measures of ecological footprints. Some recent papers have also empirically proven the pollution-mitigating role of urbanization at country level (Udemba et al., 2022b). The empirical literature provides controversial discoveries about the nexus between urban dynamics and environmental degradation. Therefore, some researchers have also examined the non-linear effect of urbanization on pollution across time and space.

There is another strand of papers that have tested the non-linear nexus between urbanization and the environment. However, the empirical outcomes of such studies are mixed and inconclusive. For instance, some researchers have proved an inverted U-shaped effect of urbanization on environmental degradation (Zhang N. et al., 2017; Bekhet and Othman, 2017; Ahmed et al., 2019). However, another set of papers provide mixed and heterogeneous results across regions and income groups (Zi et al., 2016; He et al., 2017b; Zhu et al., 2018; Chen et al., 2019). Moreover, Muhammad et al. (2020) verify the bell-shaped nexus between urbanization and CO_2 emissions in high-income countries, supporting the theory of ecological modernization (EMT). Poumanyvong and Kaneko (2010) proposed the ecological modernization theory, which holds that urbanization degrades the environment during the early phase of development due to heavy investment in infrastructures and transportation activities based on extensive use of fossil fuel consumption. However, during the later stage of economic growth, urbanization improves the environment due to environmentally friendly technology, energy efficiencies, and public awareness and preference for cleaner environment.

Some researchers also oppose the ecological modernization theory and provide contradictory evidence or a U-shaped relationship between urbanization and environmental degradation (Zhu et al., 2012; Shahbaz et al., 2016). Moreover, Du and Xia (2018) reports that urbanization degrades the environment at a relatively higher rate when urban agglomerations and largest cities ratio crosses the threshold of approximately 20 percent and 48 percent, respectively. However, Zi et al. (2016) argue that urbanization degrades the environment significantly after reaching the threshold level of roughly 43 percent. The contradictory findings of these studies identify certain pitfalls or drawbacks of ecological modernization theory. For example, some authors argue that this theory assumes that the modernization process automatically improves the environmental quality through efficient urban planning, energy-efficient infrastructure and transportation system, improved institutional quality, and environmentally-friendly innovation (Ewing, 2017). The controversial and inconclusive findings of structural change and urban dynamics require further investigation and empirical inquiry using a large sample across different income groups. Therefore, the purpose of the current study is to investigate the non-linear effect of structural change variables and urban dynamics on environmental degradation in a cross-country setting. Our study contributes to the existing literature in the following manners. Firstly, we revisit the EKC hypothesis using a large sample of countries and across income groups, which could provide more generalized findings and policy implications keeping in view the varying growth patterns of different countries in our panel. As prior literature provides mixed evidence about the EKC theory, it is imperative to testify the impact of economic growth on environmental degradation of a large panel that may further be explored across different income groups to reveal concrete findings. Second, our empirical work extends the EKC hypothesis by testing the non-linear effect of urbanization and urban agglomerations on environmental degradation. The current study links the EKC hypthesis with structural change hypothesis and the ecological modernization theory (EMT) to provide more enriched findings as EKC hypothesis mainly describes the overall effect of economic growth on environment. On the other hand, the structural shifts in industrial and service sector, and changes in urbanization patterns or paths could have profound implications for the EKC theory. Contrary to the EKC theory, The EMT does not singularly focus on the overall impact of income level, but it also considers other institutional and structural factors. Therefore, the current study provides more enriched and in-depth findings with regards to specific sectors or urban regions i.e. urban concentrations in largest cities (York, 2007; Hashmi et al., 2021). Therefore, our model is comprehensive and integrated to avoid omitted variable bias, a common problem with longitudinal time-series and short-panel studies, considering only a few main variables. Third, the prior studies have mainly examined the non-linear nexus between urbanization and the environment. However, the phenomenon of urban agglomerations in large metropolitan cities has been overlooked in the cross-country settings, which could have a differential impact on the environment (Du and Xia, 2018; Hashmi et al., 2020a; Fan et al., 2020). Urban concentrations in larger cities in selected cities may have varying levels of effects on environmental degradation as compared to the overall urbanization trends. Therefore, the current study has evaluated the non-linear effects of urbanization and urban agglomerations (in big metropolitan cities) in separate models. Models Fourth, we examine and check the sensitivity of all these non-linear effects across different income groups-low and lower-middle-income, upper-middle-income, and high-income- to determine how the level of economic development significantly alters our mainstream findings. Lastly, we identify the unidirectional or bidirectional causal nexus of urban dynamics, and other control variables using the advanced heterogeneous Dumitrescu Hurlin (DH) Granger non-causality method.

The rest of the paper is organized as follows. The next section describes the current study's conceptual model and derives the equations of the Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT) model. The third section entails the methodology encompassing data and variables description, cross-sectional dependence and unit-root testing, and econometric modeling. The fourth section elaborates the results and discussion, and the last section provides conclusions, policy implications, and directions for future research.

2 Model construction

The current study employs a dynamic STIRPAT model to examine the effect of structural change and urban dynamics on environmental degradation. Dietz and Rosa (1997) proposed the baseline model of STIRPAT in the following exponential form:

$$I_{it} = \alpha P_{it}^{\beta} A_{it}^{\gamma} T_{it}^{\lambda} \mu \tag{1}$$

Where I indicates environmental degradation (CO_2 emissions metric tons per capita in this case), P denotes the country-level population of a country, and A represents affluence (GDP per capita), T measures technology (energy efficiency), and μ is the residual term explaining the stochastic nature of the model. We have converted Eq. 1 into log-linear form for the analysis:

$$\ln I_{it} = \alpha_0 + \alpha_1 \ln P_{it} + \alpha_2 \ln A_{it} + \alpha_3 \ln T_{it} + \mu_{it} \tag{2}$$

Donglan et al. (2010) has further refined the model. The prior studies have also included the additional factors to extend the basic STIRPAT model (Li et al., 2015; Wang C. et al., 2017; Niu and Lekse, 2018; Koçak and Ulucak, 2019). Our extended and modified STIRPAT model includes both the variables of structural change and urban dynamics along with additional factors of financial development and natural resources, which have been mainly ignored by previous researchers.

$$\begin{aligned} \ln CO_{2_{it}} = \alpha_0 + \alpha_1 \ln EI_{it} + \alpha_2 \ln GDP_{it} + \alpha_3 \ln AGR_{it} \\ +\alpha_4 \ln IND_{it} + \alpha_5 \ln SRV_{it} + \alpha_6 \ln URB_{it} + \\ \alpha_7 \ln TOP_{it} + \alpha_8 \ln FDV_{it} + \alpha_9 \ln NRR_{it} + \mu_{it} \end{aligned} \tag{3}$$

Here CO_2 emissions measure environmental impact, EI denotes energy intensity, which is a proxy for technology (T), GDP per capita represents affluence (A). Moreover, AGR (industry), IND (service), and SRV (service) represent structural change variables, URB denotes urbanization to substitute for population effect. At the same time, trade openness (TOP), financial development (FDV), and natural resources (NRR) are additional control variables. The lower energy intensity (EI) signals greater use of green technology, more dependence on cleaner energy, and less consumption of primary energy sources (fossil fuel consumption). Therefore, the prior studies have used EI as a proxy for technological effect on the environment (Li & Lin, 2015; Shahbaz et al., 2016; Ahmed et al., 2019; Fan et al., 2020). We remove AGR from Eq. 3 to avoid the multicollinearity problem (see Table 3). Thus, the revised equation can be stated as follows:

$$\begin{aligned} \ln CO_{2_{it}} = \alpha_0 + \alpha_1 \ln EI_{it} + \alpha_2 \ln GDP_{it} + \alpha_3 \ln IND_{it} \\ +\alpha_4 \ln SRV_{it} + \alpha_5 \ln URB_{it} + \alpha_6 \ln TOP_{it} + \\ \alpha_7 \ln FDV_{it} + \alpha_8 \ln NRR_{it} + \mu_{it} \end{aligned} \tag{4}$$

The previous studies have also successfully applied the non-linear version of the STIRPAT model to test the EKC hypothesis (Wen and Liu, 2016; Wang S. et al., 2017; Zaman and Moemen, 2017). Therefore, we include a squared term of GDP per capita in Eq. 5 to examine the bell-shaped nexus between economic growth and environmental degradation.

$$\begin{aligned} \ln CO_{2_{it}} = \alpha_0 + \alpha_1 \ln EI_{it} + \alpha_2 \ln GDP_{it} + \alpha_3 \ln GDP_{it}^2 \\ +\alpha_4 \ln IND_{it} + \alpha_5 \ln SRV_{it} + \alpha_6 \ln URB_{it} + \\ \alpha_7 \ln TOP_{it} + \alpha_8 \ln FDV_{it} + \alpha_9 \ln NRR_{it} + \mu_{it} \end{aligned} \tag{5}$$

Eq. 5 tests the EKC hypothesis by incorporating the quadratic term of GDP. We expect an inverted U-shaped nexus between GDP and CO_2 emissions if the coefficient of GDP is positive (α_2 >0) and the coefficient of its quadratic term is negative-lower than zero (α_3 <0). We have added the quadratic term of urbanization (URB^2) and urban agglomerations (UAG^2) in Eqs 6–7 to testify to the ecological modernization theory (EMT), which suggests that a higher level of urban development brings improvement in city infrastructures and transportation mechanism, change in energy structure from fossil fuel to cleaner energy production and consumption, and public awareness and demand about ecological balance and quality of life (Poumanyvong and Kaneko, 2010; Ahmed et al., 2019; Muhammad et al., 2020). The expected sign of the coefficient of squared terms of URB^2 and UAG^2 should be negative to hold EMT theory ($\alpha_6 < 0$).

$$\begin{aligned} \ln CO_{2_{it}} = \alpha_0 + \alpha_1 \ln EI_{it} + \alpha_2 \ln GDP_{it} + \alpha_3 \ln IND_{it} \\ +\alpha_4 \ln SRV_{it} + \alpha_5 \ln URB_{it} + \alpha_6 \ln URB_{it}^2 \\ \alpha_7 \ln TOP_{it} + \alpha_8 \ln FDV_{it} + \alpha_9 \ln NRR_{it} + \mu_{it} \end{aligned} \tag{6}$$

$$\begin{aligned} \ln CO_{2_{it}} = \alpha_0 + \alpha_1 \ln EI_{it} + \alpha_2 \ln GDP_{it} + \alpha_3 \ln IND_{it} \\ +\alpha_4 \ln SRV_{it} + \alpha_5 \ln UAG_{it} + \alpha_6 \ln UAG_{it}^2 \\ \alpha_7 \ln TOP_{it} + \alpha_8 \ln FDV_{it} + \alpha_9 \ln NRR_{it} + \mu_{it} \end{aligned} \tag{7}$$

3 Methodology

3.1 Data and measurement of variables

Based on data availability of all the indicators, we have collected annual data from 1990 to 2016 from the World Development Indicators (WDI) database of the World Bank. Carbon emissions (metric tons per capita) is the dependent variable of our study. While the independent variables include energy intensity (kilograms of oil equivalent per capita), economic growth (GDP per capita), industry (value-added as a percent of GDP), services (value-added as a percent of GDP), urbanization (percent of the total population), urban

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TABLE 1 Description of variables and their measurement.

Variable Name	Symbol	Proxy or Definition of Variables
Carbon Emissions	CO_2	CO_2 emissions per capita
Energy Intensity	EI	energy use per capita divided by GDP per capita
Income level	GDP	GDP per capita (constant 2010 US dollars)
Urbanization	URB	urban population percentage of the total population
Urban agglomerations	UAG	urban agglomerations percentage of the total population
Industry	IND	industrial valued-added percentage of GDP
Services	SRV	services value-added percentage of GDP
Trade Openness	TOP	trade as percent of GDP
Financial Development	FDV	domestic credit to private sector percent of GDP
Natural Resources	NRR	natural resource rents percent of GDP

Source: Authors' calculation based on collected data.

TABLE 2 Descriptive statistics for cross-country data.

Variables	Mean	SD	Min	Max
CO_2	4.3334	5.0714	0.0392	35.6783
EI	0.2952	0.2437	0.0400	2.6214
GDP	12,513.5748	18,332.2541	161.8340	91,617.2969
URB	60.3101	20.3153	16.7480	94.9450
UAG	26.0071	13.9700	4.1026	64.7059
IND	29.8807	10.2340	2.5255	77.4137
SRV	51.7650	10.0170	17.9913	76.3759
TOP	70.0145	35.8621	11.0875	220.4070
FDV	51.5108	45.8208	1.6155	221.2880
NRR	6.9175	10.0945	0.0007	63.5501

agglomerations (agglomerations more than one million as a percent of the total population), trade openness (trade as a percent of GDP) and financial development (domestic credit to private sector percent of GDP) and natural resources (natural resource rents percent of GDP). The vaiables are based on related literature (Balsalobre-Lorente et al., 2018, Bekun et al., 2019, Gokmenoglu and Taspinar, 2018, Hashmi et al., 2020b, Kisswani et al., 2018, Li and Zhou, 2019, Liu and Bae, 2018, Sohag et al., 2017).

Table 1 provides the complete details of all variables, their respective proxies, and related source of data. Based on the availability of consistent data for all variables, the current study utilizes panel data of 66 countries for the period 1990–2016. The countries are further divided into four income groups using the World Bank's classification system. The complete details of countries and their grouping is provided in Supplementary Table S2. As the low-income group contains only a few countries, we have combined it with the lower-middle-income category for empirical analysis.

Table 2 provides summary statistics for the overall panel. The average value of CO_2 emissions is approximately 4.33 metric tons per capita, with a standard deviation of 5.0714 metric tons per capita. The energy intensity in sample countries amounts to, on average, 0.2952 energy consumption (kg. of oil equivalent) per dollar, ranging from 0.04 to 2.6214. The average GDP per capita (in real terms) in selected countries is approximately 12,514 dollars per capita, with a substantial fluctuation of 18,322.25 dollars per capita ranging from 161.83 to 91,617.30 dollars per capita. This considerable variation can be attributed to different income groups (i.e., lower-income, upper-middle, and high-income) in our panel data countries.

Table 3 provides a correlation matrix to identify the magnitude and direction of the relationship between environmental degradation, structural change, and urban dynamics. All the independent variables except energy intensity, and natural resources have a positive and significant association with CO_2 emissions at a 1 percent level of significance. Energy intensity is negatively associated with environmental degradation. Similarly, natural resources have a negative and significant association with environmental degradation, which supports the pollution-mitigating role of this variables. On the other hand, economic growth, industry, service sector, urban dynamics, trade openness, and financial development are positively related to CO_2 emissions; these variables may positively affect pollution. However, we need a more robust regression analysis to investigate the impact of explanatory variables on the environment. All the correlation coefficients signifying the relationship between independent variables (IVs) are much lower than the threshold value of 80 percent, and all the values of Variance Inflation Factors (VIFs) are below 5; these results indicate that our empirical analysis is not contaminated by the multicollinearity issue.

3.2 Cross-sectional dependence and unit root testing

Before applying any econometric model, checking cross-sectional dependence (CD) and data stationary is imperative to select a suitable data analysis model. Panel data may have the inherited feature of cross-sectional dependence due to some common characteristics such as rising economic and regional integration, globalization, and some common events which may create spillover effects (De Hoyos and Sarafidis, 2006; Dong et al., 2018). Following the studies of Baloch et al. (2019a) and Wang et al. (2020b), we have applied three CD tests, namely, the Breusch-Pagan LM proposed by Breusch and Pagan (1980), Pesaran LM, and CD tests developed by Pesaran (2004).

Supplementary Table S3 in the supplementary file reports CD results, and all test statistics are statistically significant at a 1 percent critical level, which indicates the existence of the CD phenomenon in

TABLE 3 Correlation matrix.

Variables	CO_2	EI	GDP	URB	UAG	IND	SRV	TOP	FDV	VIF
CO_2	1									
EI	-0.517***	1								1.77
GDP	0.877***	-0.787***	1							2.10
URB	0.768***	-0.683***	0.814***	1						3.31
UAG	0.499***	-0.501***	0.520***	0.702***	1					2.15
IND	0.335***	-0.0720**	0.211***	0.230***	0.209***	1				2.92
SRV	0.425***	-0.519***	0.526***	0.443***	0.247***	-0.425***	1			3.70
TOP	0.126***	-0.0273	0.0888***	0.0970***	-0.0875***	0.207***	-0.0783**	1		1.17
FDV	0.682***	-0.426***	0.626***	0.443***	0.278***	0.0659**	0.551***	0.191***	1	2.26
NRR	-0.232***	0.379***	-0.314***	-0.258***	-0.179***	0.348***	-0.539***	0.037	-0.394***	2.11

Note: *** and ** represents 0.1 and 1% significance levels for correlation coefficients, respectively. We detected the highest correlation coefficient of 89.8 percent between our independent variables (IVs)-GDP, and AGR, while association between other IVs, is lower than the threshold level of 80 percent for existence of multicollinearity problem. Therefore, we have removed the AGR, variable from our base-line model due to multicollinearity issue.

our panel data. As our data contain CD features, the first-generation unit root tests may provide biased and unreliable estimates. Therefore, Pesaran (2007) proposed the CADF (cross-sectional augmented Dickey-Fuller) test to address the CD issue. In this test, we calculate cross-sectional averages of lagged values at the level and first difference for each cross-sectional unit and run ADF regressions with this updated information by augmenting ADF regressions. Following the studies of Baloch et al. (2019a) and Wang et al. (2020a), we apply second-generation unit root tests to account for cross-sectional dependence. CADF test can be formulated as follows:

$$\Delta y_{it} = \alpha_i + b_i y_{i,t-1} + c_i \bar{y}_{t-1} + \sum_{j=0}^{p} d_{ij} \Delta \bar{y}_{t-j} + \sum_{j=1}^{p} \delta_{ij} \Delta \bar{y}_{i,t-j} + e_{it} \quad (8)$$

Where $\bar{y}_t$ denotes the average value of all countries in a given year. After estimating the CADF test, the CIPS (Cross-sectional Im Pesaran Statistic) can be derived in the following form.

$$CIPS = N^{-1} \sum_{i=1}^{N} t_i (N, T) \quad (9)$$

The above equation $t_i(N, T)$ represents the t-statistics relating to CADF regression in Eq. 14. Supplementary Table S4 displays the unit root results generated from CADF and CIPS for both constant and linear trends. The results indicate that all variables become stationary at the first difference (both constant and linear trend) using a 1 percent level of significance, and all series have I 1) order (order one) of integration.

3.3 Panel cointegration test

Following the study of Muhammad et al. (2020), the current research has applied Kao (1999) test proposed by McCoskey and Kao to determine the cointegration relationship among considered variables. As our empirical analysis utilizes more than seven variables, we have not used other cointegration tests such as Pedroni and Westerlund panel Cointegration tests which are constrained by the number of variables. Kao test employs the ADF format and follows the two-step method of the Eagle Granger framework. The ADF test statistic accounts for econometric issues such as heteroscedasticity and autocorrelation (HAC) and provides consistent estimates (McCoskey and Kao, 1999). Kao test assumes the panel homogeneity and adopts the following ADF regression:

$$u_{i,t} = \rho u_{i,t-1} + \sum_{j=1}^{n} \phi_j \Delta u_{i,t-j} + v_{it} \quad (10)$$

Furthermore, this test is based on the following ADF test statistic to test null-hypothesis of no-cointegration.

$$ADF = \frac{t_{ADF} + \sqrt{6N}\hat{\sigma}_v / (2\hat{\sigma}_{0v})}{\sqrt{\hat{\sigma}_{0v}^2 / (2\hat{\sigma}_v^2) + 3\hat{\sigma}_v^2 / (10\hat{\sigma}_{0v}^2)}} \quad (11)$$

3.4 Estimating long-term and non-linear effects

After estimating panel cointegration, the next step is to determine the long-term elasticities and non-linear effect of urban dynamics on environmental degradation using two-way fixed effects (2W-FE), fully modified ordinary least squares (FMOLS), and Driscoll-Kraay (DK) Regression. Following Zhang N. et al. (2017), the current study applies a two-way fixed effect to control the unobserved cross-sectional and yearly variations. The Hausman test is used to make a final selection between fixed effect and random effect models. We choose two-way fixed effects because the Hausman value is significant, which indicates that the fixed effect model is the most appropriate one for empirical analysis (Khan et al., 2019).

As selected variables exhibit long-term cointegrating relationship, the current study also employs FMOLS introduced by Phillips and Hansen (1990) and Kao and Chiang (2001) to estimate long-term elasticities and non-linear for the period 1990–2016. This method has been widely utilized by prior researchers because it serves as an additional robustness test, accounts for econometric and modeling issues of endogeneity, and can be aptly applied whether variables are integrated at level, first difference or have mixed order of integration (Phillips, 1995; Pedroni, 1996; Baltagi and Kao, 2001; Ramirez, 2007; Salim and Rafiq, 2012; Liddle, 2013; Rafiq et al., 2016; Hailemariam et al., 2020). Following the work of Kassouri et al. (2022), we have applied FMOLS to allow for cross-sectional heterogeneity and other biases resulting from non-stationary longitudinal panels.

Along with 2W-FE and FMOLS, we have also applied DK regression proposed by Driscoll and Kraay (1998) as an additional robustness measure to confirm the non-linear effects of urban population on environmental degradation. DK regression is more flexible in handling missing values and can be applied for both unbalanced and balanced panel data. This approach utilizes the average values calculated from the respective multiplicative term of explanatory variables and model residuals in HAC estimation to produce robust standard errors (Jalil, 2014; Baloch et al., 2020). The prior studies have extensively employed DK regression, which is the most popular, highly robust, and non-parametric technique to mitigate the econometric issues such as heteroscedasticity, temporal and cross-sectional dependence (TCD), and serial correlation (Baloch et al., 2019b; Sarkodie and Strezov, 2019; Zhang et al., 2020). We have also estimated the turning points (TPs) of EKCs based on the previous studies (Ali et al., 2017; Dong et al., 2018; Ouédraogo et al., 2021). The TPs are important for further validating the ECK hypothesis as they signify the maximum (minimum) threshold level of economic growth after which the environmental degradation starts decreasing (increasing) in case of an inverted-U (U-shaped) curve. The formula of TP is given as follows:

$$TP = e^{\left(\frac{-\beta_1}{2\beta_2}\right)} \tag{12}$$

3.5 Panel causality analysis using dumitrescu hurlin test

Estimating the causal nexus among environmental degradation and urban dynamics is essential for identifying unidirectional or bidirectional linkages to develop appropriate environmental and urban policies to mitigate pollution. The current study deploys the D-H causality approach introduced by Dumitrescu and Hurlin (2012). This test is more efficient and appropriate than the traditional Granger causality method because D-H estimation addresses both sample heterogeneity and cross-sectional dependence (Dumitrescu and Hurlin, 2012; Dogru and Bulut, 2018; Khoshnevis Yazdi and Dariani, 2019; Saqib and Benhmad, 2020). This test can be used for both longitudinal panels (T > N) and short-panels (N > T). The generalized form of D-H can be mathematically stated as follows:

$$y_{it} = \sum_{k=1}^{K} \gamma_i^{(k)} y_{i,t-k} + \sum_{k=1}^{k} \beta_i^{(k)} x_{i,t-k} + \varepsilon_{i,t} \tag{13}$$

In this equation, y and x are considered variables for panel data. K represents the lag length, $\gamma_i^{(k)}$ stands for autoregressive coefficient, and $\beta_i^{(k)}$ denotes the group-specific regression coefficients. This causality approach is based on two statistics, namely, Z-bar and W-bar statistics. The former is a standardized statistic based on the normal distribution, while the latter statistic represents average values. We state the following null and alternative hypotheses under D-H estimation:

$$H_0 \quad = \beta_i = 0 \text{ (Null Hyothesis)}$$
$$H_1 \quad = \beta_i \neq 0 \text{ (Alternate Hypothesis) where } \forall_i = 1, 2......N$$
$$\text{and } \forall_i = N+1, N+2.....N$$

4 Results and discussion

This section is divided into several parts for a systematic discussion. First, we discuss the results of the panel cointegration test for establishing long-term nexus among CO_2 emissions and urban dynamics, and other control variables. Second, the current study examines the non-linear effect of urbanization and urban agglomerations on carbon emissions. Lastly, we provide the empirical results of the panel causality test to identify the unidirectional or bidirectional relationship between considered variables.

4.1 Results of panel cointegration test

Before examining the long-term non-linear effects of urbanization on environmental degradation, the current study determines the long-term equilibrium relationship among considered variables. The results of the Kao panel Cointegration test are reported in Supplementary Table S5 for both the overall sample and sub-samples of income groups. The value of the ADF test is significant at a 1 percent level of significance for selected countries, which indicates a long-term cointegrating relationship among CO_2

TABLE 4 Testing EKC hypothesis for selected countries.

Variables	2W-FE-1	2W-FE-2	PFMOLS-1	PFMOLS-2	DK-1	DK-2
EI	0.7905***	0.7903***	0.8118***	0.8237***	0.7987***	0.7996***
	(0.0281)	(0.0298)	(0.0160)	(0.0150)	(0.0270)	(0.029)
GDP	2.3661***	2.3233***	2.5548***	2.5107***	2.4589***	2.4045***
	-0.119	(0.1209)	(0.0661)	(0.0595)	(0.2823)	(0.3179)
GDP^2	-0.0864***	-0.0840***	-0.0986***	-0.0961	-0.0942***	-0.0911***
	(0.0068)	(0.0069)	(0.0037)	(0.0033)	(0.0150)	(0.0171)
URB	0.4930***	0.4795***	0.2861***	0.2789***	0.3585**	0.3509**
	(0.0737)	(0.0741)	(0.0365)	(0.0323)	(0.1414)	(0.1375)
IND	---	0.0537**	---	0.0519***	---	0.0612
	---	(0.0271)	---	(0.0134)	---	(0.0405)
SRV	---	0.0506	---	0.0891***	---	0.0629
	---	(0.0403)	---	(0.0200)	---	(0.0591)
TOP	0.0162	0.0156	0.0086	0.0106	0.0065	0.0067
	(0.0196)	(0.0201)	(0.0103)	(0.0093)	(0.0292)	(0.0319)
FDV	0.0803***	0.0773***	0.0708***	0.0670***	0.0698***	0.0668***
	(0.0105)	(0.0106)	(0.0059)	(0.0052)	(0.0115)	(0.0111)
NRR	0.0174***	0.0165***	0.0096***	0.0100***	0.0091*	0.0084*
	(0.0053)	(0.0054)	(0.0029)	(0.0026)	(0.0046)	(0.0047)
β_0	-14.1740***	-14.2984***	n/a	n/a	-13.7523***	-13.9335***
	(0.4307)	(0.4447)	---	---	(0.7852)	(0.7446)
Country Effect	Yes	Yes	---	---	Yes	Yes
Year Effect	Yes	Yes	---	---	---	---
Adj. R-square	0.9035	0.9045	0.9915	0.9915	0.6919	0.693
F-stat	116.10***	109.34***	---	---	3,071.82***	1925.34***
p-value (F-stat)	(0.0000)	(0.0000)	---	---	(0.0000)	(0.0000)
Hausman value	73.05***	67.660***	---	---	---	---
Turning Point	884,438.57	1,013,749.78	423,104.83	471,161.05	465,788.15	538,765.79

Note: ***, **, * indicate 1, 5, and 10% significance levels, respectively; 2W-FE, two-way fixed effect; PFMOLS, panel fully modified OLS; DK, driscoll kraay regression; standard errors are reported in parentheses ().

emissions, structural changes, and urban dynamics, trade openness, financial development, and natural resources. The ADF test values are also significant at 1% critical value for all three income-groups-lower-and lower-middle income, upper-middle-income, and high-income countries. These results indicate long-term cointegrating nexus among considered variables for sub-samples.

4.2 Testing the EKC hypothesis

The next step is determining the non-linear effect of economic growth (ECK hypothesis and urbanization paths (urbanization and urban agglomerations to confirm ecological modernization theory) on CO_2 emissions. The EKC hypothesis results are reported in Table 4 for selected 66 countries by applying three panel regression models, namely, two-way fixed effects, FMOLS, and DK regression. Economic growth (GDP per capita) has a positive and significant impact on CO_2 emissions in all six models. The GDP coefficient indicates that a 1 percent increase in GDP leads to 2.3661, 2.3233, 2.5548, 2.5107, 24,589, and 2.4045 percent increase in carbon emissions. However, the quadratic term of GDP in all six models has a negative and significant effect on CO_2 emissions at a 1 percent significance level; a 1 percent increase in squared term of GDP leads to approximately 9–10 percent decrease in carbon emissions. Based on these results, we find an inverted U-shaped effect of GDP on environmental degradation, which further confirms the EKC hypothesis for selected countries. Our outcome is consistent with the similar findings of prior studies, which have documented a bell-shaped relationship between economic growth and pollution (Ben Jebli et al., 2016; Danish et al., 2017; Usman et al., 2019).

These findings imply that economic growth initially degraded the environmental quality, but after reaching a certain threshold, economic progress has improved the environment. However, the quadratic term of GDP has an inelastic effect on environmental degradation, which implies more room for environmental policy

TABLE 5 Testing non-linear effect of urbanization on environmental degradation.

Variables	2W-FE-1	2W-FE-2	PFMOLS-1	PFMOLS-2	DK-1	DK-2
EI	0.7502***	0.7584***	0.7629***	0.7813***	0.7614***	0.7694***
	(0.0290)	(0.0307)	(0.0163)	(0.0156)	(0.0278)	(0.0287)
GDP	0.9235***	0.9167***	0.8875***	0.8753***	0.8686***	0.8656***
	(0.0336)	(0.0336)	(0.0184)	(0.0169)	(0.0362)	(0.0377)
URB	3.6620***	3.4932***	4.8646***	4.6793***	4.5227***	4.2637***
	(0.4646)	(0.4668)	(0.2520)	(0.2280)	(0.4923)	(0.6014)
URB^2	-0.3917***	-0.3736***	-0.5899***	-0.5654***	-0.5347***	-0.5029***
	(0.0652)	(0.0654)	(0.0343)	(0.0310)	(0.0737)	(0.0878)
IND	—	0.0901***	—	0.0740***	—	0.101*
	—	(0.0278)	—	(0.0139)	—	(0.0490)
SRV	—	0.1095***	—	0.1431***	—	0.1211**
	—	(0.0414)	—	(0.0206)	—	(0.0579)
TOP	0.0379*	0.0387*	0.0151	0.0223**	0.0105	0.0122
	(0.0203)	(0.0207)	(0.0107)	(0.0098)	(0.0291)	(0.0317)
FDV	0.0815***	0.0758***	0.0690***	0.0623***	0.0697***	0.0644***
	(0.0109)	(0.0110)	(0.0060)	(0.0055)	(0.0093)	(0.0102)
NRR	0.0216***	0.0204***	0.0215***	0.0225***	0.0132**	0.0122*
	(0.0055)	(0.0056)	(0.0032)	(0.0030)	(0.0056)	(0.0060)
β_0	-14.8020***	-15.0662***	—	—	-15.3212***	-15.5608***
	(0.8319)	(0.8429)	—	—	(0.9469)	(1.0517)
Country Effects	Yes	Yes	—	—	Yes	Yes
Year Effects	Yes	Yes	—	—	—	—
R-square	0.876	0.8792	0.9901	0.9902	0.6659	0.6692
F-value	104.09***	98.82***	—	—	1902.42***	1,670.19***
p-value	(0.0000)	(0.0000)	—	—	(0.0000)	(0.0000)
Hausman Stat	45.72***	46.91***	—	—	—	—

Note: ***, **, * indicate 1, 5, and 10% significance levels, respectively; 2W-FE, two-way fixed effect; PFMOLS, panel fully modified OLS; DK, driscoll kraay regression; standard errors are reported in parentheses ().

improvement for our selected countries. The other factors, such as energy intensity, urbanization, financial development, and natural resources, have a positive and significant impact on CO_2 emissions in all six models.

4.2 Testing non-linear effect of urbanization

Next, we examine the non-linear effect of urbanization (URB) on environmental degradation for the overall panel to test ecological modernization theory. The results are reported in Table 5 to investigate the bell-shaped nexus between urban development and CO_2 emissions, along with other control variables. The current study adds the quadratic term of URB in all models to examine the non-linear relationship. The regression results using two-way fixed effects, PFMOLS, and DK models showed that a 1 percent variation in URB and its squared term caused approximately 3.49–4.86 percent increase and 0.37–0.59% decree n carbon emissions. These findings reveal an inverted U-shaped effect of urbanization on environmental degradation for selected economies, which verifies ecological modernization theory. The empirical outcome indicates that urbanization initially degrades the environment, during the earlier phase of economic and urban development, due to higher demand for fossil fuel energy consumption, energy-intensive production technology, and more concern for earnings. However, after reaching a certain threshold level, urban development brings improvement in the environment caused by public awareness and demand for a better quality of life, introduction of efficient and green technologies, the emergence of a low-polluting service economy, higher use of cleaner and energy sources, efficient transportation mechanism and city-level infrastructures.

Similar to prior studies' outcomes, we document an inverted U-shaped linkage between urban growth and carbon emissions for the overall panel. Our results are well synchronized with Bekhet and Othman (2017) for Malaysia and Muhammad et al. (2020) for high-income countries, who also confirmed the bell-shaped effect of urbanization. The

TABLE 6 Non-linear effect of urban agglomerations on environmental degradation.

Variables	2W-FE-1	2W-FE-2	PFMOLS-1	PFMOLS-2	DK-1	DK-2
EI	0.8113***	0.8026***	0.8103***	0.8121***	0.8017***	0.7947***
	(0.0290)	(0.0308)	(0.0160)	(0.0145)	(0.0336)	(0.0326)
GDP	0.9935***	0.9827***	0.9411***	0.9416***	0.9282***	0.9256***
	(0.0344)	(0.0343)	(0.0172)	(0.0146)	(0.0282)	(0.0292)
UAG	1.5884***	1.4071***	1.6959***	1.5117***	1.6741***	1.4780***
	(0.2429)	(0.2468)	(0.1356)	(0.1170)	(0.1784)	(0.1898)
UAG^2	-0.2086***	-0.1820***	-0.2396***	-0.2122***	-0.2290***	-0.1992***
	(0.0403)	(0.0408)	(0.0223)	(0.0192)	(0.0329)	(0.0322)
IND	—	0.1325***	—	0.1234***	—	0.1362**
	—	(0.0286)	—	(0.0133)	—	(0.0574)
SRV	—	0.1006**	—	0.1205***	—	0.1054
	—	(0.0436)	—	(0.0202)	—	(0.0771)
TOP	0.0471**	0.0421*	0.0287***	0.0243***	0.0253	0.0223
	(0.0213)	(0.0217)	(0.0108)	(0.0094)	(0.0253)	(0.0296)
FDV	0.0716***	0.0656***	0.0652***	0.0594***	0.0633***	0.0580***
	(0.0114)	(0.0114)	(0.0062)	(0.0053)	(0.0098)	(0.0105)
NRR	0.0172***	0.0144**	0.0099***	0.0081***	0.0106**	0.0079
	(0.0057)	(0.0057)	(0.0030)	(0.0026)	(0.0051)	(0.0052)
β_0	-9.8488***	-10.2710***	—	—	-9.2628***	-9.7743***
	-0.3976	-0.4141	—	—	-0.232	-0.2967
Country Effects	Yes	Yes	—	—	Yes	Yes
Year Effects	Yes	Yes	—	—	—	—
R-square	0.865	0.8709	0.9901	0.9903	0.6427	0.6479
F-value	92.54***	88.68***	—	—	1,257.97***	1,445.96***
p-value	(0.0000)	(0.0000)	—	—	(0.0000)	(0.0000)
Hausman Stat	28.34***	85.00***	—	—	—	—

Note: ***, **, * indicate 1, 5, and 10% significance levels, respectively; 2W-FE, two-way fixed effect; PFMOLS, panel fully modified OLS; DK, driscoll kraay regression; standard errors are reported in parentheses.

current research also found the positive role of energy intensity, industrialization, service sector, GDP, financial development, trade, and natural resources in environmental degradation.

4.3 Testing non-linear effect of urban agglomerations

Lastly, the current research examines the non-linear effect of urban agglomerations (UAG) in large metropolitan cities on CO_2 emissions for the overall panel by utilizing two-way fixed effect, PFMOLS, and DK regressions. Our empirical work is the first to investigate the inverted U-shaped relationship between urban agglomerations and environmental degradation at the cross-country level. These regression results are reported in Table 6. The results showed that a 1 percent increase in UAG and its quadratic term caused an approximately 1.41–1.70 percent increase and 0.20–0.24 percent decrease, respectively, in carbon emissions. The empirical findings indicate that UAG and its squared term have a significant positive and negative impact, respectively, at 1 percent significance level on pollution, which testifies the inverted U-shaped nexus between UAG and carbon emissions and support ecological modernization theory. These findings imply that a higher level of agglomerations in metropolitan cities improve the environment in the long-run. Similar results are provided by Zhang N. et al. (2017) and Su et al. (2018), who documented that urban growth in cities inhibits CO_2 emissions. On the other hand, our findings contrast with Ou et al. (2019), who found heterogeneous effects of city-level populations on pollution across different types of cities.

4.4 Non-linear effects of economic growth and urbanization paths across income groups

After establishing the non-linear effects of structural change and urban dynamics for the overall panel, the next step is to examine these non-linear relationships across income groups.

TABLE 7 Non-linear effects of economic growth and urbanization paths-low- and lower-middle income group.

Variables	EKC		URB^2		UAG^2	
EI	0.5746***	0.6205***	0.5391***	0.5463***	0.6107***	0.6210***
	(0.0345)	(0.0311)	(0.0309)	(0.0298)	(0.0307)	(0.0285)
GDP	1.7963***	1.9196***	0.8391***	0.7860***	0.9545***	0.9609***
	(0.2321)	(0.2020)	(0.0381)	(0.0373)	(0.0372)	(0.0329)
GDP^2	-0.0674***	-0.0763***				
	(0.016)	(0.014)				
IND		-0.0064		-0.0128		0.0143
		(0.0203)		(0.0204)		(0.0204)
SRV		0.1261***		0.0907***		0.0326
		(0.0301)		(0.0299)		(0.0308)
URB	0.5362***	0.5526***	2.7861***	2.8068***		
	(0.0698)	(0.0606)	(0.4768)	(0.4291)		
URB^2			-0.3202***	-0.3146***		
			(0.068)	(0.061)		
UAG					1.4938***	1.4492***
					(0.2264)	(0.2047)
UAG^2					-0.2371***	-0.2310***
					(0.0394)	(0.0356)
TOP	0.0622***	0.0695***	0.1068***	0.1232***	0.1337***	0.1273***
	(0.0233)	(0.0203)	(0.0215)	(0.0203)	(0.0215)	(0.0197)
FDV	0.1886***	0.1791***	0.1815***	0.1801***	0.1838***	0.1816***
	(0.0131)	(0.0114)	(0.0123)	(0.0117)	(0.0128)	(0.0115)
NRR	0.0071	0.0124**	0.0025	0.0062	-0.0021	-0.0016
	(0.0062)	(0.0055)	(0.0057)	(0.0052)	(0.0059)	(0.0053)
Adj.R^2	0.9731	0.9731	0.9731	0.971	0.9723	0.9722
Turning Point (TP)	612,722.644	290,480.657				

Note: ***, **, * represent 1, 5 and 10% levels of significance, respectively; PFMOLS, is panel fully modified OLS; Adj. R^2 is adjusted R-square.

Table 7 reports the empirical outcomes for low-and lower-middle-income (LLMI) countries.

4.4.1 Non-linear effects in LLMI countries

First, the current study also tested the EKC hypothesis for LLMI countries, and results are reported in Table 7. Our empirical results from PFMOLS regressions revealed that a 1 percent increase in economic growth (GDP per capita) and its quadratic term resulted in around 1.80–1.92 rise and 0.07–0.08% decrease, respectively, in carbon emissions, which verify the bell-shaped nexus between GDP and CO_2 emissions and confirm EKC hypothesis for LLMI group. Our findings are congruent to Ozturk et al. (2016) and Pata (2018). However, our results contradict those of Sarkodie and Strezov (2019), who found mixed evidence for the EKC hypothesis in developing countries. The current study also examines the non-linear effect of urbanization paths on CO_2 emissions for LLMI countries. The results of PFMOLS regressions showed that a 1 percent increase in urbanization (URB) increased carbon emissions by roughly 2.79–2.81%, while its squared term negatively affected the environmental quality and decreased CO_2 emissions by around 0.31–0.32% for LLMI economies. These empirical outcomes implied that urbanization significantly increased environmental degradation at 1% significances level during the initial phase of urban development. Still, after reaching a certain maximum level, urban growth significantly reduced environmental degradation at a 1% critical level. Therefore, the current study observed an inverted U-shaped effect of urbanization on environmental degradation. Thus, this non-linear nexus verifies the ecological modernization theory indicating that a higher level of urban development leads to environmental sustainability due to increased public awareness, development of energy-efficient infrastructure and transportation, green technology, and higher utilization of renewable energy resources. Our findings are synchronized with Bekhet and Othman (2017) and He et al. (2017a), who also found the bell-shaped linkage between urbanization and carbon emissions.

Another aspect of urban dynamics, namely, urban agglomerations (UAG), also significantly improve the environment according to PFMOLS regression results. More specifically, the current research documented that a 1% variation in UAG and its quadratic term caused approximately 1.44–1.49% increase and 0.23–0.24% decrease in carbon emissions, respectively, at 1% critical level for the LLMI group. Similar to urbanization, these findings confirmed a bell-shaped effect of urban agglomerations on environmental degradation, which supported ecological modernization theory. These empirical outcomes are aligned with the results of prior studies such as Poumanyvong and Kaneko (2010) and Ahmed et al. (2019). Furthermore, Su et al. (2018) argue that urban agglomerations also reduce city-level pollutions. Our results imply that larger cities bring economies of scale, development of state-of-the-art infrastructure, efficient transportation, and environmentally friendly technology, and earnings level of people increase. The other control variables, such as trade openness, financial development, and natural resources, significantly affect CO_2 emissions in LLMI countries. These outcomes unveil that these factors enhance environmental degradation by supporting those trade and financing activities, which do not account for ecological concerns and significantly deplete natural resources.

4.4.2 Non-linear effects in UMI countries

The current study also empirically tests the EKC hypothesis by including the quadratic term of GDP in all three PFMOLS models as shown in Table 8. The results showed that a 1% increase in GDP brought about a 1.62–2.01% increase in carbon emissions at a 1% critical level. Its quadratic term significantly reduced carbon emissions by 0.04–0.06% at 1% significance level. These findings indicate the bell-shaped effect of GDP on carbon emissions in UMI countries, which further supports the EKC hypothesis. These outcomes are congruent to those of Zhang S. et al. (2017) and Nazir et al. (2018), who successfully tested the EKC hypothesis in cross-country settings. The countries in the UMI group have achieved a higher level of economic development, which is improving the environmental quality in the long run because the income level of masses have substantially increased in these countries, and they are now in a better position to demand quality of life and environment. Moreover, during the later phase of economic growth, the introduction of efficient technologies, cleaner energy production, and advanced infrastructures have also improved the environment in these countries. Similar results are also provided by Muhammad et al. (2020) for the upper-middle-income group in the case of Belt and Road Initiative (BRI) economies.

After establishing the EKC hypothesis for UMI countries, the next task is to test the non-linear effect of urban dynamics and CO_2 emissions. The regression outcomes of PFMOLS indicate that a 1% change in the coefficient of urbanization (URB) leads to about 0.34–3.13% increase in carbon emissions, while a 1% variation in the coefficient of its quadratic term causes around 0.03–0.14% decline in carbon emissions in upper-middle-income economies. Based on these empirical outcomes, the current study reveals a bell-shaped nexus between URB and CO_2 emissions, which confirms the theory of ecological modernization. Therefore, urban development in UMI countries has enhanced the environmental quality in the long-run. These findings are consistent with those of Zhang N. et al. (2017) and Ahmed et al. (2019), who successfully tested the inverted U relationship between URB and carbon emissions.

On the other hand, urban agglomerations (UAG) have a U-shaped effect on environmental degradation in the UMI group. The empirical outcomes revealed that UAG positively affects carbon emissions at a 1% critical level, while the quadratic term of UAG negatively influences the environment at 1% level of significance. Based on these findings, we document a U-shaped effect of UAG on carbon emissions in UMI countries. Therefore, we reject ecological modernization theory and infer that urban agglomerations in big metropolitan cities degrade the environment in the long-run. This outcome is also supported by Shahbaz et al. (2016) for Malaysia and Muhammad et al. (2020) for UMI countries.

4.4.3 Non-linear effects in HIC

Lastly, the current research also investigates the non-linear effect of economic growth on urban dynamics on environmental degradation in high-income countries (HIC). Table 9 reports the regression results using PFMOLS for HIC. First, the current study also tested the EKC hypothesis by including the quadratic term of GDP in the PFMOLS model, as reported in Table 9. The regression outcomes showed that a 1% variation in GDP and its squared term led to an approximately 1.67–1.72% increase and around 0.04% decline, respectively, in carbon emissions at a 1% critical level. These empirical outcomes suggest a bell-shaped relationship between economic growth and environmental degradation, which further verified the EKC hypothesis in high-income countries. The economic growth in HIC has improved the environment in the long-run. As these countries have the highest earnings level of people compared to LLMI and UMI economies, the public is more concerned about environmental quality and climate change. These economies have developed and utilized advanced, energy-efficient technologies and infrastructures, implemented stricter environmental regulations, and deployed renewable energy resources to promote environmental quality. Our findings are duly supported by the past studies of Cansino et al. (2019) for Latin American countries and Muhammad et al. (2020) for high-income BRI countries.

Second, the current study verified the inverted U-shaped relationship between urbanization (URB) and CO_2 emissions. The regression outcomes in Table 9 unveiled that a 1% variation in URB significantly raised carbon emissions by 3.35–9.41%, while its squared term declined such emissions by about 0.28–0.99%. Based on these findings, we found a bell-shaped nexus between URB and carbon emissions for high-income

TABLE 8 Non-linear effects of structural change and urbanization paths-upper middle income group.

Variables	EKC		URB^2		UAG^2	
EI	0.8930***	0.8708***	0.8723***	0.8626***	0.9097***	0.8981***
	(0.0212)	(0.0199)	(0.0215)	(0.0206)	(0.0206)	(0.0189)
GDP	2.0142***	1.6247***	0.9914***	1.0109***	1.0163***	1.0441***
	(0.1453)	(0.1492)	(0.0247)	(0.0232)	(0.0193)	(0.0181)
GDP^2	-0.0618***	-0.0374***				
	(0.0086)	(0.0089)				
IND		0.1414***		0.1880***		0.2340***
		(0.0253)		(0.0238)		(0.0234)
SRV		-0.0088		0.0382		0.0786**
		(0.0388)		(0.0383)		(0.0377)
URB	0.0407	0.047	1.1536***	0.3356		
	(0.0451)	(0.0418)	(0.3357)	(0.3258)		
URB^2			-0.1411***	-0.0372		
			(0.0433)	(0.0419)		
UAG					-0.7584***	-1.1492***
					(0.1856)	(0.1713)
UAG^2					0.1340***	0.1930***
					(0.0292)	(0.0269)
TOP	0.0241**	0.0185*	0.0178	0.0177	0.0327***	0.0334***
	(0.0115)	(0.0106)	(0.0118)	(0.0112)	(0.0120)	(0.0110)
FDV	-0.003	−0.0162**	−0.0088	−0.0255***	−0.0222***	−0.0402***
	(0.0064)	(0.0064)	(0.0066)	(0.0065)	(0.0066)	(0.0061)
NRR	0.0047	−0.0044	0.0042	−0.0072**	0.0006	−0.0130***
	(0.0033)	(0.0033)	(0.0034)	(0.0035)	(0.0035)	(0.0034)
Adj.R^2	0.9869	0.9872	0.9867	0.9871	0.9868	0.9875
Turning Point	11948502	2711013088				

Note: ***, **, * represent 1, 5 and 10% levels of significance, respectively; PFMOLS, is panel fully modified OLS; Adj. R^2 is adjusted R-square.

countries, which support the notion of ecological modernization theory. More specifically, the results suggest that urbanization has brought significant environmental quality improvement because high-income counties are well-recognized for introducing and implementing environmentally friendly technology, developing advanced and efficient city infrastructures and transportation mechanisms, formulating and adhering to stricter environmental regulations, and shifting towards renewable energy resources. This result is also confirmed by the previous studies of Fan et al. (2020) for the South-Asian region and Muhammad et al. (2020) for high-income economies. Lastly, we determined the inverted U-shaped effect of urban agglomerations (UAG) and CO_2 emissions for HIC, and the regression results revealed similar findings related to urbanization. We observed that a 1% fluctuation in UAG caused approximately 2.14–2.31% raise in carbon emissions, while its quadratic term declined such emissions by 0.25–0.27% at 1% significance level. These findings indicate that city agglomeration has an inverted-U effect on environmental degradation in the case of HIC, which further proves the ecological modernization theory. The urban agglomerations in big and metropolitan HIC cities have improved the environment by bringing efficiencies of city compactness, economies of scale, efficient urban planning, and energy-saving advanced infrastructures. This empirical outcome is synchronized with those of Su et al. (2018), who report that UAG reduces pollution at the city-level in China.

4.4.4 Results and discussion of D-H causality analysis

After testing the non-linear effects of economic growth and urban dynamics upon environmental degradation, we also determined the causal linkages among considered variables by utilizing the Dumitrescu and Hurlin (2012) (D.H) test. This approach not only investigates the causal relationships (i.e. bidirectional or unidirectional) among selected variables but also acts as a robustness measure for confirming previous results. The D-H causality results are provided in Table 10.

The panel causality results reveal that energy intensity has a bidirectional or feedback causality relationship between energy

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TABLE 9 Non-linear effects of structural change and urbanization paths-high income group.

Variables	EKC		URB^2		UAG^2	
EI	1.0087****	0.8970***	1.0064***	0.9012***	1.0221***	0.9441***
	(0.0230)	(0.0258)	(0.0264)	(0.0292)	(0.0257)	(0.0277)
GDP	1.6782***	1.7215***	0.9100***	0.9011***	1.0132***	0.9991***
	(0.1996)	(0.1833)	(0.0267)	(0.0235)	(0.0309)	(0.0263)
GDP^2	-0.0380***	-0.0410***				
	(0.0102)	(0.0094)				
IND		0.1425***		0.1488***		0.0237
		(0.0384)		(0.0460)		(0.0453)
SRV		−0.1654***		−0.1328**		−0.1805***
		(0.0549)		(0.0624)		(0.0603)
URB	0.8185***	0.8969***	9.4107**	3.345		
	(0.1205)	(0.1119)	(3.8880)	(3.5666)		
URB^2			−0.9946**	−0.2792		
			(0.4531)	(0.4164)		
UAG					2.3117***	2.1419***
					(0.5310)	(0.4516)
UAG^2					−0.2713***	-0.2459***
					(0.0778)	(0.0663)
TOP	−0.0947***	−0.1188***	−0.0617***	−0.0943***	−0.0621***	−0.0697***
	(0.0179)	(0.0168)	(0.0227)	0.0207	(0.0214)	(0.0187)
FDV	−0.0398***	−0.0465***	−0.0598***	−0.0611***	−0.0447***	−0.0474***
	(0.0097)	(0.0089)	(0.0116)	0.0102	(0.0143)	(0.0121)
NRR	−0.0032	−0.0062	0.0192**	0.0044	−0.0086*	−0.0103***
	(0.0042)	(0.0039)	(0.0086)	0.0080	(0.0046)	(0.0039)
Adj.R^2	0.9845	0.985	0.9836	0.9839	0.9864	0.9866
Turning Point	3889626394	1310798642				

Note: ***, **, * represent 1, 5 and 10% levels of significance, respectively; PFMOLS, is panel fully modified OLS; Adj. R^2 is adjusted R-square.

intensity and carbon emissions in low-and lower-middle-income (LLMI), upper-middle-income (UMI), high-income countries (HIC), and overall panel at 1–5% significance level. The bidirectional causality between EI and CO_2 emissions indicates a strong linkage between the two variables. Therefore, the respective governments of the selected countries should adopt careful and prudent energy-conservation policies. The bidirectional causality is also observed between GDP and carbon emissions for LLMI, UMI, and overall panel, while unidirectional causality runs from GDP to carbon emissions for high-income countries. This feedback relation unveils that economic growth and environmental degradation are strongly associated with each other in most countries, suggesting that any efforts to decouple the linkage between the two variables may involve the trade-off between economic growth and environmental quality. Therefore, the countries have adopted energy-saving and pollution-mitigating strategies to deploy environmentally conducive technology and state-of-the-art energy-efficient infrastructure, cleaner energy resources. Moreover, the higher level of pollution also affected public awareness to demand environmental quality. Thus, all the income groups and overall panel confirms the EKC hypothesis for the selected time.

Urbanization and urban agglomerations also have significant causality linkages with carbon emissions across income groups and in the case of the overall panel. Urbanization has bidirectional causal nexus with CO_2 emissions in LLMI, UMI, and overall sample, while unidirectional causality exists between URB and carbon emissions in HIC. This feedback nexus supports ecological modernization theory because urban development degrades the environment at the early stage of economic growth. However, after reaching a certain threshold of urbanization, the excessive level of pollution raises concerns for environmental damages and public awareness, leading to the development of environmentally friendly technology, stricter environmental policies, efficient urban infrastructures and transportation mechanism, and the adoption of renewable energy resources. Another dimension of urban dynamics, urban agglomerations, also

TABLE 10 Pairwise dumitrescu hurlin (D-H) panel causality tests.

Income Groups	LLMI			UMI			HI			Overall panel		
Null hypothesis	W-stat	Zbar-stat	Prob	W-stat	Zbar-stat	Prob	W-stat	Zbar-stat	Prob	W-stat	Zbar-stat	Prob
EI # CO_2	4.3847	4.0991	0.0000	3.4656	2.1834	0.0290	4.2292	3.4651	0.0005	3.9917	5.5462	0.0000
CO_2 # EI	4.6237	4.5580	0.0000	3.4752	2.2007	0.0278	4.8091	4.4807	0.0000	4.4206	6.9120	0.0000
GDP # CO_2	5.5449	6.3270	0.0000	4.5632	4.1549	0.0000	4.9474	4.7231	0.0000	4.9853	8.7101	0.0000
CO_2 # GDP	4.3937	4.1163	0.0000	3.6886	2.5840	0.0098	1.7775	-0.8291	0.4070	3.3617	3.5398	0.0004
URB # CO_2	7.0729	9.2610	0.0000	5.7077	6.2107	0.0000	6.1228	6.7818	0.0000	6.3111	12.9319	0.0000
CO_2 # URB	3.9688	3.3005	0.0010	4.7027	4.4056	0.0000	3.3226	1.8773	0.0605	4.4937	7.1448	0.0000
UAG # CO_2	2.8350	1.1233	0.2613	2.8854	1.1414	0.2537	3.8331	2.7713	0.0056	3.1155	2.7559	0.0059
CO_2 # UAG	4.2120	3.7675	0.0002	3.5226	2.2859	0.0223	2.9168	1.1664	0.2435	3.5071	4.0030	0.0001
IND # CO_2	4.0124	3.3843	0.0007	4.0051	3.1524	0.0016	2.3943	0.2512	0.8017	3.5439	4.1202	0.0000
CO_2 # IND	3.2222	1.8668	0.0619	2.9555	1.2672	0.2051	2.8718	1.0877	0.2767	3.2033	3.0357	0.0024
SRV # CO_2	1.9241	-0.6258	0.5314	3.6361	2.4897	0.0128	3.5931	2.3510	0.0187	2.9560	2.2482	0.0246
CO_2 # SRV	4.5289	4.3760	0.0000	2.6197	0.6641	0.5067	2.7034	0.7927	0.4280	3.3400	3.4710	0.0005
TOP # CO2	3.7749	2.9281	0.0034	3.4813	2.2117	0.0270	3.6885	2.5180	0.0118	3.6042	4.3123	0.0000
CO_2 # TOP	4.1606	3.6689	0.0002	3.6224	2.4651	0.0137	2.4418	0.3344	0.7381	3.4227	3.7344	0.0002
FDV # CO_2	4.6052	4.5225	0.0000	4.0579	3.2473	0.0012	4.8490	4.5507	0.0000	4.4379	6.9670	0.0000
CO_2 # FDV	4.5237	4.3660	0.0000	4.9279	4.8100	0.0000	2.2421	-0.0153	0.9878	3.9231	5.3276	0.0000
NRR # CO_2	5.1392	5.5479	0.0000	2.9743	1.3010	0.1933	3.7631	2.6487	0.0081	3.9966	5.5617	0.0000
CO_2 # NRR	2.7311	0.9238	0.3556	3.8359	2.8486	0.0044	3.5286	2.2380	0.0252	3.2956	3.3296	0.0009

reveals significant causal nexus with carbon emissions. More specifically, we found unidirectional causality from UAG to carbon emissions in high-income countries, while unidirectional causality runs from carbon emissions to UAG in LLMI and UMI economies. Furthermore, feedback linage is also found between UAG and carbon emissions for the overall sample. Urban agglomerations are strongly related to environmental degradation, which confirms previous empirical findings.

5 Conclusion and policy implications

The current study observed significant non-linear effects of economic growth and urban dynamics on CO_2 emissions across income groups and in the overall panel. Our empirical findings proved the EKC hypothesis in lower-and low-middle income, upper-middle, high-income groups, and overall sample. The current research also documented an inverted U impact of urbanization on CO_2 emissions in the selected sample of 66 countries and across income categories of countries concerning their level of development. These findings confirm ecological modernization theory because a higher level of urban development improves the environmental quality by developing and utilizing advanced and energy-saving built environment and infrastructure, efficient transportation system, effective city-level governance, stringent environmental regulations, and increased public awareness. Similarly, urban agglomerations also exhibit a bell-shaped nexus with environmental degradation in LLMI, HI countries, and the overall panel of countries. The higher level of urban agglomerations in metropolitan cities brings scale economies, benefits of high density and city compactness, optimally located goods and services, and efficient transport mobility, improving the environment. However, our regression outcomes using PFMOLS unveiled a U-shaped impact of UAG on carbon emissions in the case of upper-middle-income countries, which refutes ecological modernization theory. Such a controversial effect can be possibly attributed to overconcentration in cities, traffic congestion, and urban sprawl problems that may adversely affect environmental quality. The other control variables, such as trade openness, financial development, and natural resource depletion in most sample countries, positively affect environmental degradation. At the same time, financial development and natural resources improve the environment in UMI and HI economies. These countries have a more developed and efficient financial system coupled with a higher institutional quality level, which helps channelize public funds and savings to more equitable and environmentally friendly investments.

Our empirical research provides important policy implications for international environmental agencies, domestic national, provincial, and city-level authorities, related ministries of environment, trade and commerce, local pressure groups, and urban planners. These key stakeholders can utilize this research's findings for developing appropriate environmental policies, modifying and upgrading ecological and industrial regulations, formulating effective urban development policies, and fostering sustainable development in the long-run. Though we verify the existence of the EKC phenomenon in LLMI and UMI groups, yet the energy intensity in these economies have escalating effects on environmental degradation. These findings suggest revisiting energy-related issues and revise energy-structure by developing and utilizing energy-efficient technology and increasing the proportion of renewable energy in the energy mix. Such modifications in energy policy are expected to reduce the energy intensity and higher consumption of primary energy, leading towards environmental sustainability. As industrialization degrades the environment in low-and lower-middle-income countries, our study suggests the concerned authorities and related ministries to design such environmental and industrial policies and stricter regulations, which would regulate the polluting industries, introduce and implement eco-friendly production methods, promote green projects and recycling options.

Increased urbanization and urban agglomerations have improved the environment both in the overall panel and across income groups. However, urban agglomerations in the upper-middle-income group degrade the environmental quality because the rapidly increasing aggregations in big cities have created multifaceted challenges such as over-concentration and excessive population density, traffic congestion, urban sprawls, sanitation issues, inefficient transportation mechanism, and energy-intensive infrastructures. Therefore, these findings suggest that the city-level and municipal governments in emerging and upper-middle economies should modify and upgrade their urban policies by developing green investments in infrastructure, building state-of-the-art city energy-efficient city structures, introducing eco-friendly technology, utilizing cleaner energy resources, conserving and optimizing the natural resource utilization, and implementing stricter environmental regulations. In this regard, financial institutions' role is imperative to finance green investments and eco-friendly projects leading towards sustainable development in the region.

Our research has comprehensively addressed the role of economic growth and urban dynamics in a worsening environment across income levels and the overall panel of 66 countries. Our study has applied an extensive version of the non-linear STIRPAT model to test the non-linearity puzzle of EKC and ecological modernization theories. However, every research has certain limitations and constraints, which require further inquiry by using additional variables, alternative proxies and econometric models, and empirical studies in other regions and individual countries. The current research proposes different variables, such as institutional quality, city-level indicators, renewable energy, and technological innovation. As the city-level urbanization, industrial agglomeration, urban agglomeration data, and other related indicators were not available for the selected sample; we suggest undertaking specific regional and city-level analysis, which would help design specific city-level urban governance and industrial restructuring policies. Moreover, the current paper has utilized the consistently available data for the period-1990–2016. Future researchers can extend this period in their panel, regional, and individual country studies to address structural shifts and regime change effects.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://data.worldbank.org.

Author contributions

All authors equally contributed to this research article.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.971394/full#supplementary-material.

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