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Urbanization, Population Growth and Per Capita CO2 Emissions in Pakistan, 1990–2024: An ARDL Bounds-Testing and Error-Correction Analysis

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Abstract

This article investigates the short- and long-run link between per capita carbon dioxide emissions, urbanization and population increase in Pakistan over the period 1990-2024. We employ annual data from the World Bank World Development Indicators and apply the Autoregressive Distributed Lag (ARDL) bounds-testing approach of Pesaran, Shin and Smith (2001) and related error-correction model (ECM). Unit-root test results show that log per capita CO2 is I(1), population growth is I(1) or close to trend-stationary, and log urbanization is an I(2) process due to its smooth, accelerating path. The ARDL (1,0,1) specification passed serial-correlation, normalcy, functional-form and ARCH diagnostics, while it discovered residual heteroscedasticity. The Bayesian information criteria picked the ARDL (1,0,1) specification. The boundaries F-statistic (5.06) is in the inconclusive region at 5% level and above the upper bound only at 10% and the t-bounds test does not reject the null of no level association. The long-run elasticities of urbanization and population growth are not statistically significant. The error-correction term is negative (−0.32) and indicates an adjustment of approximately one-third of any deviation every year, but caution is warranted in the absence of demonstrated cointegration. We conclude that the data do not show strong evidence of a steady long-run influence of urbanization or population growth on per capita emissions in Pakistan, and examine data and methodological explanations for this finding.

Keywords: *CO2 emissions; urbanization; population expansion; ARDL; limits test; error-correction model; Pakistan, JEL classification: Q53; Q56; R11; C22.*

INTRODUCTION

The link between urban transition and environmental quality is an important issue in sustainability studies. Urbanization can lead to higher emissions due to increased energy demand, transport use and development, but can also lead to reduced per capita emissions through agglomeration economies, denser infrastructure and efficiency benefits. Population expansion introduces a different kind of scale effect, however its influence on emissions per head is theoretically ambiguous.

Pakistan is an instructive case. Its share of the urban population increased from around 31% in 1990 to about 39% in 2024, although the rate of population growth dropped from above 3% to about 1.5% a year. Per capita emissions are low by international standards at roughly 0.8 tons CO2-equivalent but have been trending upwards for most of the time. Understanding whether urbanization and demographic change have a durable link with emissions is crucial for national climate policy and comparative work across South Asia.

The contributions of this paper are threefold. First, it offers a clear ARDL–ECM analysis for Pakistan with the new WDI emissions indicator (EN.GHG.CO2.PC.CE.AR5). Second, it specifically examines the integration order of each variable and demonstrates that the typical ARDL limits inference is problematic when urbanization is I(2). Third, it gives detailed diagnostics and small sample critical values so that readers can determine the reliability of the evidence.

The rest of the paper is organized as follows. Section 2 gives a quick survey of the related literature. Section 3 describes the data and the empirical approach. The results are given in Section 4. Results and constraints are presented in section 5. Section 6 ends.

REVIEW OF LITERATURE

The academic literature on the environmental impacts of urbanization is organized around three conflicting paradigms: Ecological Modernization Theory, Urban Environmental Transition Theory and the Compact City Hypothesis. Each theory makes different predictions about whether urban structural transformation increases or reduces carbon dioxide (CO2) emissions.

First, Ecological Modernization Theory (Mol & Spaargaren, 2000; Huber, 2004) argues that industrialization and rapid urban growth lead to environmental degradation in the early stages, but as urbanization progresses, economies change institutionally, technologically and behaviorally toward sustainability. Cities in advanced stages of urban development stimulate technological innovation, structural change toward eco-efficient service economies, increased environmental awareness and more stringent environmental regulations, ultimately resulting in an absolute decoupling of urban economic activity from environmental degradation.

Second, Urban Environmental Transition Theory (McGranahan & Satterthwaite, 2002, 2014) highlights that environmental concerns evolve with the levels of urban development.

Low-income cities in developing countries are confronting localized environmental problems that are ‘poverty-related’ (e.g. poor sanitation, contaminated water, uncollected solid waste). As cities industrialize into middle income status, secondary and tertiary urban hubs throughout

Pakistan—environmental burdens shift to “City Regional industrial pollution and rapid surges in Energy related carbon emissions due to fossil fuel intensive power generation and manufacturing. Only high income cities switch to Global Environmental foot prints with significant consumption driven carbon emissions.

Thirdly, the Compact City Hypothesis (Capello & Camagni, 2000; Newman & Kenworthy, 1989) suggests that dense high-density urban agglomerations enable optimal resource allocation and economies of scale in energy use. High urban density reduces per capita energy demand by decreasing commutes, boosting public transit use and permitting the shared heating and cooling of infrastructure. In contrast, suburban expansion and unregulated horizontal growth of metropolitan areas increase the transportation dependence, land transformation and per capita greenhouse gas emissions.

DATA AND METHODOLOGY

Data

Annual data for Pakistan cover 1990–2024 (35 observations).

Variable	Definition	WDI indicator	Unit
CO2_PC	CO2 emissions excluding LULUCF, per capita	EN.GHG.CO2.PC.CE.AR5	t CO2e per capita
URBAN	Urban population	SP.URB.TOTL.IN.ZS	% of total
POP_GROW	Population growth	SP.POP.GROW	annual %

CO2 per capita and urbanization are used in natural logarithms (LN_CO2, LN_URBAN) so that coefficients on LN_URBAN are elasticities. Population growth is already a rate and is not logged. Values were transcribed from World Bank WDI tables as distributed through secondary sources and should be re-verified against the original World Bank download before final submission.

Table 1. Descriptive statistics (n = 35)

Variable	Mean	Std. dev.	Min	Max
CO2_PC	0.772	0.107	0.565	0.966
URBAN	34.47	2.33	30.80	39.20
POP_GROW	2.30	0.59	1.30	3.34
LN_CO2	−0.268	0.140	−0.571	−0.035
LN_URBAN	3.538	0.067	3.428	3.669

The correlation of LN_CO2 with LN_URBAN is 0.88 and with POP_GROW is −0.78, while LN_URBAN and POP_GROW are correlated at −0.89. These high correlations reflect common trends and indicate multi-collinearity among regressors.

Empirical model

The long-run relationship is specified as

$$LN_CO2(t) = \alpha + \beta1 \cdot LN_URBAN(t) + \beta2 \cdot POP_GROW(t) + u(t).$$

The ARDL(p, q1, q2) model in levels is

$$LN_CO2(t) = c + \Sigma\, \varphi(i) \cdot LN_CO2(t-i) + \Sigma\, \theta1(j) \cdot LN_URBAN(t-j) + \Sigma\, \theta2(j) \cdot POP_GROW(t-j) + \varepsilon(t),$$

and its unrestricted error-correction representation is

$\Delta LN_CO2(t) = c + \rho \cdot LN_CO2(t-1) + \delta 1 \cdot LN_URBAN(t-1) + \delta 2 \cdot POP_GROW(t-1) + \Sigma$ short-run terms + $\varepsilon(t)$.

Cointegration is tested through the joint null $\rho = \delta 1 = \delta 2 = 0$ (F-bounds test) and the null $\rho = 0$ (t-bounds test). Long-run coefficients are computed as $-\delta/\rho$ with delta-method standard errors, and the ECM is estimated using the lagged residual from the long-run relation as the error-correction term (ECT).

Estimation strategy

- Augmented Dickey–Fuller (ADF) tests with intercept, and with intercept and trend, with lag length chosen by AIC, applied to levels, first differences and second differences.
- ARDL lag selection over $p \in \{1,2,3\}$ and $q \in \{0,\ldots,3\}$ on a common sample, using AIC and BIC. Given the small sample, the parsimonious BIC choice is retained.
- Bounds test with simulated small-sample critical values (20,000 replications, n = 34, k = 2, unrestricted intercept, no trend, under the null that the dependent variable is a random walk and regressors are either I(0) or I(1)).
- Diagnostics: Breusch–Godfrey serial correlation, Jarque–Bera normality, Breusch–Pagan heteroskedasticity, ARCH(1), Ramsey RESET, and CUSUM/CUSUMSQ stability.

RESULTS

Unit-root tests

Table 2. ADF tests (5% critical values approx. −2.96 intercept; −3.56 intercept and trend)

Variable	Level (intercept)	Level (trend)	1st difference (intercept)	2nd difference (intercept)	Order
LN_CO2	−1.76	−2.84	−4.65*	–	I(1)
LN_URBAN	2.23	−0.24	−1.10	−9.25*	I(2)
POP_GROW	−1.11	−4.68*	−3.55*	–	I(1) / trend-stationary

Significant at 5%.LN_CO2 is clearly I(1). POP_GROW is non-stationary with an intercept only but stationary around a deterministic trend, so its order is ambiguous. LN_URBAN is not stationary in first differences and becomes stationary only after second differencing. This is consistent with the smooth and accelerating urban transition: annual increases in the urban share rose from about 0.2 percentage points in the 1990s to 0.4–0.5 points in recent years.

This finding matters because the ARDL bounds approach is valid for variables that are I(0) or I(1), but not I(2). Results involving LN_URBAN must therefore be treated as indicative rather than conclusive.

ARDL estimates

Lag selection by BIC chooses ARDL(1,0,1); AIC favors an over-parameterized ARDL(2,2,3), which is inadvisable with 34 effective observations.

Table 3. ARDL (1,0,1) estimates (dependent variable: LN_CO2; 1991–2024)

Regressors	Coefficient	Std. error	t-stat	p-value
LN_CO2(−1)	0.681	0.149	4.57	0.000
LN_URBAN	−0.120	0.439	−0.27	0.787
POP_GROW	0.082	0.059	1.39	0.176
POP_GROW(−1)	−0.147	0.056	−2.65	0.013
Constant	0.503	1.636	0.31	0.761

$R^2 = 0.903$; adjusted $R^2 = 0.890$; Durbin–Watson = 1.96; AIC = −109.65; BIC = −100.49.

Emissions are strongly persistent, with an autoregressive coefficient of 0.68. Current urbanization is not significant, while the lagged population growth term is significant and negative.

Bounds test

Table 4. Bounds test for a level relationship

Statistic	Value	10% (I0 / I1)	5% (I0 / I1)	1% (I0 / I1)
F-statistic	5.06	3.41 / 4.41	4.24 / 5.34	6.24 / 7.70
t-statistic on ρ	−1.96	−2.58 / −3.21	−2.93 / −3.59	−3.69 / −4.43

The F-statistic exceeds the 10% upper bound but lies between the bounds at 5%, which is inconclusive. The t-statistic is above the lower bound at every conventional level, so the null of no level relationship cannot be rejected on that criterion. Together with the I(2) behavior of LN_URBAN, the evidence for co-integration is weak.

Long-run coefficients

Table 5. Long-run elasticities (delta method)

Variable	Coefficient	Std. error	t-stat	p-value
LN_URBAN	−0.375	1.518	−0.25	0.807
POP_GROW	−0.203	0.152	−1.34	0.192
Constant	1.575	5.727	0.28	0.785

Neither long-run coefficient is statistically distinguishable from zero.

Error-correction model

Table 6. ECM estimates (dependent variable: ΔLN_CO2)

Regressors	Coefficient	Std. error	t-stat	p-value
Constant	−0.001	0.026	−0.04	0.969
ΔLN_URBAN	0.019	3.317	0.01	0.996
ΔPOP_GROW	0.082	0.049	1.69	0.101
ECT(−1)	−0.320	0.079	−4.03	0.000

$R^2 = 0.374$; adjusted $R^2 = 0.311$; Durbin–Watson = 1.96.

The ECT has the predicted negative sign and suggests that over 32% of a departure from the long-run path is corrected each year, a half-life of around 1.8 years. Since the ECT is based on estimated long-run coefficients that are not significant themselves and co-integration is not established, the t-statistic of the ECT should not be interpreted as evidence of stable long-run equilibrium. The short-run effect of urbanization and population expansion is not significant at 5 per cent.

Diagnostic tests

Table 7. Residual diagnostics for ARDL (1,0,1)

Test	Statistic	p-value	Conclusion
Breusch–Godfrey LM (1 lag)	0.05	0.827	No serial correlation
Breusch–Godfrey LM (2 lags)	3.76	0.152	No serial correlation
Jarque–Bera	0.58	0.750	Normal residuals
Breusch–Pagan	11.02	0.026	Heteroskedasticity present
ARCH(1)	1.72	0.190	No ARCH effects
Ramsey RESET	2.20	0.131	Correct functional form
CUSUM	–	–	Stable (within 5% bounds)
CUSUMSQ	–	–	Marginally outside 5% band

The model passes most of the diagnostics. There is heteroskedasticity. The inference should be based on heteroscedasticity and autocorrelation consistent (Newey-West) standard errors. The CUSUM test indicates parameter stability, but the CUSUMSQ test moves slightly beyond its band indicating possible variance instability or structural change in the later half of the sample.

DISCUSSION

The main finding is that there is no compelling evidence of any long-run relationship between urbanization, population growth and per capita CO2 emissions in Pakistan during the period 1990–2024. There are a number of reasons possible.

Urbanization Integration Sequence. The I (2) behavior of LN_URBAN weakens the conventional bounds-testing methodology. Smoothly trending series will be highly correlated with other trending variables and any association observed may be false or not recognizable with only 35 observations.

Small sample size. " Power is low 34 effective observations 5 parameters The wide confidence intervals around the long-run coefficients (e.g., the standard error on LN_URBAN of roughly 1.5) indicate that the results are consistent with either huge positive or large negative effects.

Drivers omitted. Emissions in Pakistan are driven by income, energy mix, industrial structure and policy shocks. None of those is considered in this model. Without them, urbanization and demographic variables may fail to explain emission patterns. Including actual GDP per capita and energy use would also enable studies for an environmental Kuznets link.

Potential structural change. Emissions peaked in 2022 and decreased substantially in 2023–2024, even as urbanization continued to grow. This divergence and the CUSUMSQ result show a structural break that is not captured by a linear ARDL model.

Multi-collinearity The −0.89 connection between urbanization and population increase makes it hard to distinguish their separate effects.

- **LIMITATIONSOFTHESTUDY**
  Small sample size and one nation. I(2)regressors, thus bounds-test inference is just suggestive. Heteroscedastic residuals and marginal instability of parameters. Data taken from WDI secondary distributors and requires verification. Critical values are acquired by simulation and not from published tables. The results should be reproduced in appropriate econometric software.

Potential robustness checks

1. Replace LN_URBAN by its first difference (urban population increase) or use the level of URBAN with a deterministic trend.
2. Introduce real GDP per capita and energy use per capita in the model.
3. Include a structural-break dummy or perform a Zivot–Andrews test and a break-robust co-integration test (e.g. Gregory–Hansen).
4. Compare with a Fully Modified OLS or dynamic OLS estimator and with Toda–Yamamoto causality tests that are resilient to mixed integration orders.
5. The research is extended to a panel of the five South Asian economies (Pakistan, India, Bangladesh, Sri Lanka and Nepal) to increase power.

CONCLUSION

In this paper, an ARDL bounds-testing and error-correction model is calculated for per capita CO2 emissions, urbanization and population increase in Pakistan for 1990–2024. Diagnostics are typically OK but boundaries test is equivocal or negative, long-run elasticities are small and urbanization is I (2) which restricts the validity of inference. Negative ECT of -0.32 shows reasonably fast adjustment. However, it cannot be construed as evidence of the existence of a stable equilibrium. The results caution against the assumption of a simple and consistent mapping from urban development or slowing population growth to national emission levels for policy. Future work should include income and energy variables, consider structural change and employ cross-country panels.

Data availability statement

Data are from the World Bank World Development Indicators (EN.GHG.CO2.PC.CE.AR5 , SP.URB.TOTL.IN.ZS , SP.POP.GROW). The obtained data set is accessible from the author upon request.

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