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Original Article

URBANIZATION, POPULATION PRESSURE, AND ENVIRONMENTAL SUSTAINABILITY: EVIDENCE FROM INDIAN CITIES

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ABSTRACT

This study examines whether demographic scale and decadal population growth are systematically associated with environmental sustainability among 31 Indian million-plus cities. It harmonizes Census of India urban-agglomeration populations for 2001 and 2011 with city-level Quality of Life, Economic Ability and Sustainability scores from the Ease of Living Index 2020. An entropy-weighted Urban Pressure Index combines log population and decadal growth; a Coupled Stress Index then identifies cities where high pressure coincides with a large sustainability gap. Spearman correlations, ordinary least squares with HC3 heteroskedasticity-robust inference, and 5,000-replication non-parametric bootstrap intervals are reported. The bivariate coefficient on urban pressure is positive (0.081, HC3 p=0.047; R^2=0.106), but population growth is small and statistically indistinguishable from zero after controlling for quality of life and economic ability (−0.015, p=0.851; bootstrap 95% interval −0.204 to 0.117). The result is not evidence that population pressure improves the environment. Rather, it indicates that large cities may simultaneously possess environmental burdens and stronger administrative, fiscal and infrastructure capacities captured by the composite sustainability score. Delhi, Bengaluru, Chennai, Greater Mumbai and Hyderabad record the highest coupled stress. The paper therefore shifts attention from city size alone to the mismatch between demographic pressure and sustainability capacity.

Keywords: Urbanization, Population Pressure, Environmental Sustainability, Indian Cities, Entropy Weighting, Robust Regression

INTRODUCTION

India's urban transition concentrates people, investment, infrastructure demand and ecological risk in the same places. Population growth increases demand for land, mobility, water, housing and energy, while also expanding the tax base and the scale at which networked services can be supplied. Urban size is therefore neither an intrinsically environmental liability nor an automatic efficiency advantage. The empirical question is whether measured sustainability deteriorates with demographic pressure once differences in urban capacity are considered.

Urban systems research describes cities as coupled social–ecological systems Grimm et al. (2008) and documents systematic scaling relationships between population, infrastructure and innovation Bettencourt et al. (2007), Bettencourt (2013). Compactness can reduce travel and dwelling-energy demand, but the gains depend on urban form, energy systems and governance

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Transparency: The authors affirm that this manuscript presents an honest, accurate, and transparent account of the study. All essential aspects have been included, and any deviations from the original study plan have been clearly explained. The writing process strictly adhered to established ethical standards.
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Ewing and Cervero (2010), Glaeser and Kahn (2010). Conversely, land expansion can displace biodiversity and cropland, lock in carbon-intensive infrastructure and amplify heat or pollution exposure Seto et al. (2012), Bren et al. (2016), Creutzig et al. (2016).

This paper contributes a transparent city-level assessment in three ways. First, it converts demographic scale and growth into an entropy-weighted pressure index whose weights are determined by information dispersion rather than imposed judgment. Second, it treats sustainability as a capacity-adjusted outcome and estimates progressively richer models with HC3 inference and bootstrap uncertainty. Third, it introduces a geometric-mean Coupled Stress Index that is high only when pressure and sustainability deficit are jointly high. All 31 observations, derived indicators and numerical results are reproduced inside the manuscript.

The central finding is a caution against monocausal interpretation. Simple urban pressure is weakly and positively related to the official sustainability score, but the association is not robust to controls. A governance-and-capacity explanation is more credible than a claim that demographic pressure is environmentally beneficial. The practical implication is to target mismatches: rapidly growing, large cities with persistent sustainability gaps require coordinated land, transport, water, waste and green-infrastructure policy.

LITERATURE, CONCEPTUAL MECHANISM AND HYPOTHESES

SCALE, DENSITY AND ENVIRONMENTAL BURDEN

Urban concentration changes both the quantity and efficiency of resource use. Cross-city carbon accounting shows wide variation in emissions at similar population sizes Kennedy et al. (2009), Moran et al. (2018). Density may shorten trip distances and enable public transport, yet its benefits depend on building stock, electricity carbon intensity and infrastructure timing Güneralp et al. (2017). Climate resilience additionally depends on institutions, redundancy and adaptive capacity rather than physical exposure alone Leichenko (2011). These mechanisms predict that population pressure may raise environmental stress, but they do not imply a uniform slope across cities.

SUSTAINABILITY AS A MULTIDIMENSIONAL CAPACITY

Urban sustainability indicators combine environmental quality, service access, mobility, waste management and resilience. Reviews warn that index results depend on indicator selection, normalization and aggregation Cohen (2017), Michalina et al. (2021), Haase et al. (2014). Sustainability science accordingly emphasizes joint social, economic and ecological performance Kates et al. (2001). Green infrastructure can deliver health and cooling benefits, but distributional justice matters Wolch et al. (2014), Hoover et al. (2021). Health evidence further links urban environmental exposures with respiratory risks Anderson et al. (2009), Eckert and Kohler (2014).

INDIAN CONTEXT AND TESTABLE EXPECTATIONS

Indian urbanization combines metropolitan concentration, peripheral expansion and uneven municipal capacity. The environmental consequences include congestion, heat, air pollution, water stress and conversion of open land Wankhade (2015), Anonymous, 2013). Urbanization can support growth, but the relationship is mediated by institutions and infrastructure Turok and McGranahan (2013). Emerging Indian sustainability-index work also reinforces the value of spatially differentiated benchmarking Venkatesh and Velkennedy (2026).

Two expectations guide the analysis. H1 predicts that sustainability declines as urban pressure increases. H2 predicts that the pressure coefficient attenuates once quality-of-life and economic-capacity proxies are introduced. Because the sample is cross-sectional and the city definitions are not perfectly harmonized, the hypotheses concern conditional association, not causation.

The entropy procedure is compatible with decision analysis under heterogeneous information Zadeh (1965), Bellman, and Zadeh (1970). Recent author-selected, non-Scopus methodological studies illustrate optimization, fuzzy multi-criteria assessment and sustainability-oriented design applications N et al. (2024), Mohammad et al. (2026), Nijalingappa et al. (2026), N et al. (2025). These sources motivate transparent weighting and explicit uncertainty but do not substitute for the observed city data.

DATA AND METHODS

SAMPLE AND MEASUREMENT

The analytical sample contains 31 cities that can be matched between the Census of India's 2001 and 2011 million-plus urban-agglomeration series and the Ease of Living Index (EoLI) 2020 results for Quality of Life, Economic Ability and Sustainability. Population is measured in millions. The EoLI dimensions are reported on a 0–100 scale. The principal limitation is geographic: Census urban-agglomeration populations are matched by city label to EoLI municipal scores. This ecological boundary approximation is disclosed and the results should not be interpreted as precise within-boundary exposure estimates.

Table 1

Table 1 Variables, Construction and Analytical Role		
Variable	**Definition / unit**	**Role**
Population 2001, 2011	Census urban-agglomeration population (million)	Demographic scale
Growth	Percent change, 2001–2011	Demographic momentum
Quality of Life	EoLI 2020 dimension score, 0–100	Urban service/capacity control
Economic Ability	EoLI 2020 dimension score, 0–100	Economic-capacity control
Sustainability	EoLI 2020 dimension score, 0–100	Dependent variable
UPI	Entropy-weighted scale and growth index, 0–100	Composite pressure
CSI	Geometric mean of UPI and sustainability gap, 0–100	Priority diagnostic

Note: EoLI = Ease of Living Index; UPI = Urban Pressure Index; CSI = Coupled Stress Index. Sources: Census of India. (2011) and Ministry of Housing and Urban Affairs. (2021).

INDICATOR CONSTRUCTION

Decadal population growth for city i is computed as:

$$g_i = 100\left[\frac{P_{i,2011}}{P_{i,2001}} - 1\right] \tag{1}$$

For the two pressure variables—log population in 2011 and growth—min–max normalization produces z_ij. Entropy weights reward indicators that discriminate more strongly across cities:

$$z_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} \tag{2}$$

$$p_{ij} = \frac{z_{ij}}{\sum_i z_{ij}}\ ; \quad e_j = -\frac{1}{\ln n}\sum_i p_{ij}\ln(p_{ij}) \tag{3}$$

$$w_j = \frac{1-e_j}{\sum_k (1-e_k)}\ ; \quad UPI_i = 100\sum_j w_j z_{ij} \tag{4}$$

The resulting weights are 0.684 for log population and 0.316 for growth. The sustainability gap and coupled stress measure are:

$$Gap_i = 100 - S_i\ ; \quad CSI_i = 100\sqrt{\frac{UPI_i}{100}\cdot\frac{Gap_i}{100}} \tag{5}$$

STATISTICAL SPECIFICATION

Three nested OLS models are estimated: (M1) sustainability on UPI; (M2) sustainability on log population and growth; and (M3) those demographic terms plus Quality of Life and Economic Ability. The most complete specification is:

$$S_i = \alpha + \beta_1\ln(P_{i,2011}) + \beta_2 g_i + \beta_3 QOL_i + \beta_4 EA_i + \varepsilon_i \tag{6}$$

Inference uses HC3 covariance estimates, which inflate each squared residual by leverage and are suitable for a small, heterogeneous cross-section. A 5,000-replication pairs bootstrap provides an additional percentile interval for the growth coefficient. Spearman rank correlations reduce sensitivity to extreme values.

$$\hat{V}_{HC3} = (X'X)^{-1}X'\operatorname{diag}\left(\frac{e_i^2}{(1-h_{ii})^2}\right)X(X'X)^{-1} \quad (7)$$

RESULTS

COMPLETE CITY-LEVEL ANALYTICAL DATASET

Table 2

Table 2 Complete Analytical Dataset for 31 Indian Million-Plus Cities

City	Pop. 2001	Pop. 2011	Growth %	QOL	Econ.	Sustain.	UPI	CSI
Greater Mumbai	16.37	18.41	12.5	51.12	32.12	60.74	70.7	52.7
Delhi	12.79	16.31	27.5	51.22	50.73	56.02	76.3	57.9
Chennai	6.42	8.7	35.5	60.84	34.16	57.05	65.3	53
Bengaluru	5.69	8.5	49.4	55.67	78.82	59.97	72.7	53.9
Hyderabad	5.53	7.75	40.1	51.28	30.05	58.69	65.1	51.9
Ahmedabad	4.52	6.35	40.5	57.46	48.19	64.22	60.3	46.5
Pune	3.75	5.05	34.7	58.1	48.88	75.74	51.3	35.3
Surat	2.81	4.59	63.3	57.96	30.29	62.41	65.4	49.6
Jaipur	2.32	3.07	32.3	52.99	25.08	51.6	37.5	42.6
Kanpur	2.69	2.92	8.6	51.33	10.93	52.33	22.6	32.8
Lucknow	2.27	2.9	27.8	51.3	10.05	54.81	33.5	38.9
Nagpur	2.12	2.5	17.9	50.59	15.35	59.43	24.1	31.3
Indore	1.64	2.17	32.3	59.86	15.09	61.62	28.9	33.3
Coimbatore	1.45	2.15	48.3	60.33	32.48	48.25	37.8	44.2
Patna	1.71	2.05	19.9	47.02	24.61	49.32	20.3	32.1
Bhopal	1.45	1.88	29.7	57.92	14.01	51.68	23.8	33.9
Vadodara	1.49	1.82	22.1	58.1	24.06	57.22	18.6	28.2
Agra	1.32	1.75	32.6	45.72	7.91	56.52	23.7	32.1
Visakhapatnam	1.33	1.73	30.1	51.93	19.42	65.18	21.9	27.6
Ludhiana	1.4	1.61	15	56	26.25	55.24	11.5	22.6
Nashik	1.15	1.56	35.7	53.29	17.25	53.94	22.6	32.2
Varanasi	1.21	1.44	19	55.5	5.49	57.51	11	21.6
Madurai	1.19	1.46	22.7	54.49	11.96	59.96	13.5	23.2
Meerut	1.17	1.42	21.4	48.98	7.25	51.98	12	24
Vijayawada	1.01	1.49	47.5	50.4	11.57	53.78	28.3	36.1
Faridabad	1.05	1.4	33.3	45.57	14.1	53.17	18.5	29.5
Rajkot	1	1.39	39	51.86	13.52	59.55	21.6	29.6
Jabalpur	1.12	1.27	13.4	50.75	4.41	53.31	4.6	14.7
Dhanbad	1.06	1.2	13.2	34.71	6.42	50.9	3.1	12.3
Prayagraj	1.05	1.22	16.2	55.33	5.42	63.57	5.2	13.8
Amritsar	1.01	1.18	16.8	51.5	9.46	57.05	4.8	14.3

Note: Population is in Millions. Growth is 2001–2011. EoLI Scores Refer to 2020. UPI and CSI are Authors' Calculations. Census Urban-Agglomeration and EoLI Municipal Geographies Are Label-Matched and Not Boundary-Identical. All Observations Used in Estimation Are Shown.

Table 3

Table 3 Descriptive Statistics					
Variable	**Mean**	**SD**	**Minimum**	**Median**	**Maximum**
Population 2011 (m)	3.78	4.24	1.18	1.88	18.41
Growth (%)	28.97	12.89	8.55	29.66	63.35
Quality of Life	52.87	5.31	34.71	51.93	60.84
Economic Ability	22.11	16.79	4.41	15.35	78.82
Sustainability	57.19	5.61	48.25	57.05	75.74
UPI	31.49	22.68	3.1	23.66	76.34
CSI	33.93	12.75	12.34	32.24	57.94

Note: N=31 for Every Variable. SD Denotes Sample Standard Deviation.

Figure 1

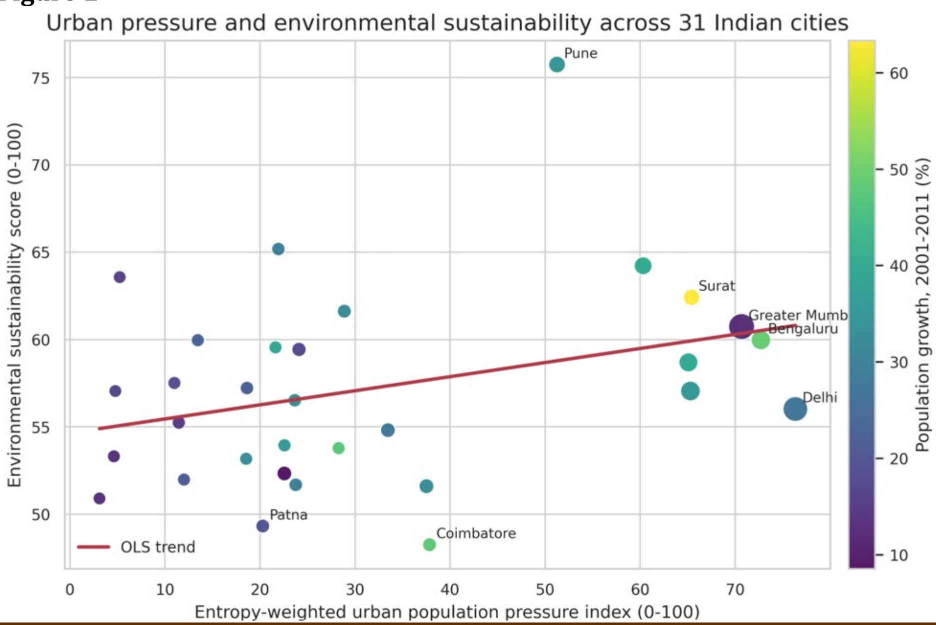

Figure 1 Urban pressure and sustainability across Indian cities

Note: Bubble Size Represents 2011 Population; the Fitted Line is Descriptive and Does Not Imply Causation.

CORRELATION AND REGRESSION EVIDENCE

Table 4

Table 4 Spearman Rank-Correlation Matrix						
	Population	**Growth**	**UPI**	**QOL**	**Economic**	**Sustainability**
Population	1.000	0.332	0.919	0.316	0.803	0.250
Growth	0.332	1.000	0.596	0.356	0.507	0.192
UPI	0.919	0.596	1.000	0.307	0.793	0.275
QOL	0.316	0.356	0.307	1.000	0.448	0.388
Economic	0.803	0.507	0.793	0.448	1.000	0.271
Sustainability	0.250	0.192	0.275	0.388	0.271	1.000

Note: Pairwise N=31. Correlations are Descriptive; Statistical Significance is Not Used as a Substitute for Effect Size and Model Diagnostics.

Figure 2

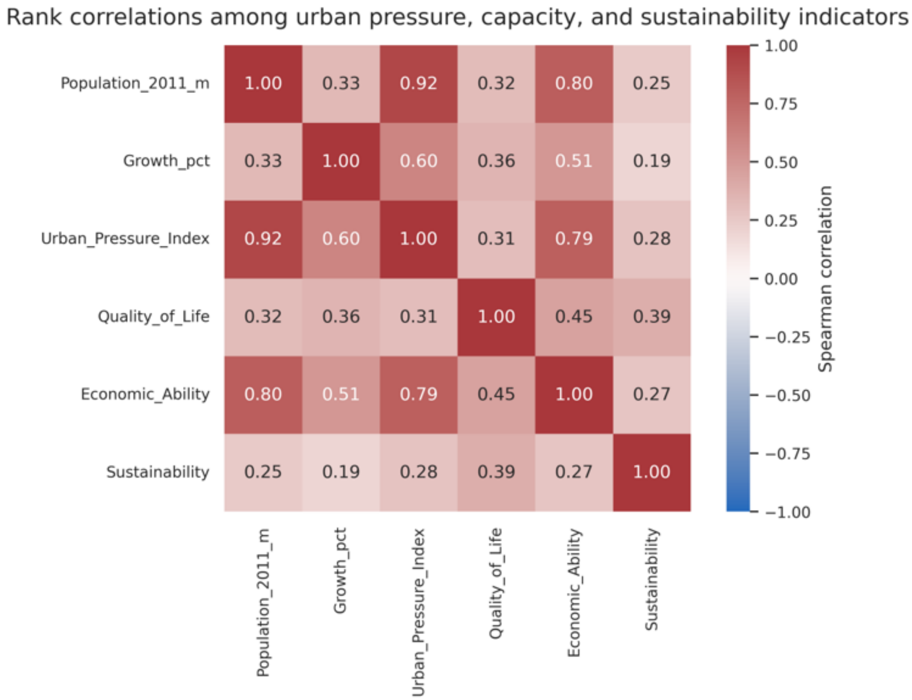

Figure 2 Rank-Correlation Structure of Demographic Pressure and EoLI Dimensions
Note: Cells Report Spearman Coefficients. Darker Colors Indicate Stronger Absolute Association.

Table 5

Table 5 OLS Estimates of City Sustainability with HC3 Robust Inference

Model	Term	Coefficient	HC3 SE	p-value	95% CI
M1	Intercept	54.645	-1.386	0	[51.810, 57.481]
M1	Urban Pressure Index	0.081	-0.039	0.047	[0.001, 0.160]
M1	Model fit	$R^2 = 0.106$	Adj. $R^2 = 0.075$	N = 31	
M2	Intercept	53.866	-2.065	0	[49.636, 58.095]
M2	ln population (2011)	1.985	-1.15	0.095	[-0.370, 4.340]
M2	Population growth (%)	0.049	-0.07	0.487	[-0.093, 0.191]
M2	Model fit	$R^2 = 0.106$	Adj. $R^2 = 0.043$	N = 31	
M3	Intercept	39.347	-8.764	0	[21.332, 57.362]
M3	ln population (2011)	0.74	-1.775	0.68	[-2.909, 4.388]
M3	Population growth (%)	-0.015	-0.081	0.851	[-0.183, 0.152]
M3	Quality of Life	0.307	-0.173	0.088	[-0.049, 0.664]
M3	Economic Ability	0.06	-0.117	0.613	[-0.180, 0.300]
M3	Model fit	R^2=0.197	Adj. $R^2 = 0.073$	N = 31	

Note: Dependent variable: EoLI Sustainability score. Two-sided t tests use residual degrees of freedom. M3 includes log population, growth, Quality of Life and Economic Ability. The 5,000-pairs-bootstrap median for M3 growth is −0.009 with 95% percentile interval [−0.204, 0.117].

Figure 3

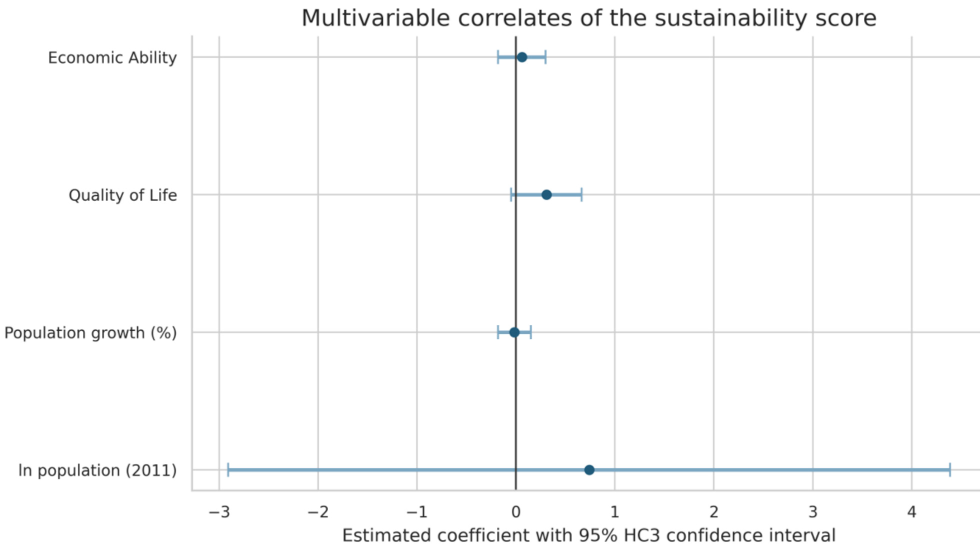

Figure 3 Coefficient Estimates and HC3 95% Confidence Intervals

Note: Points are OLS Coefficients; Horizontal Lines Are HC3 Intervals. Coefficients use Their Original Units and Should Not Be Compared as Standardized Magnitudes.

M1 produces a positive UPI coefficient of 0.081 ($p=0.047$), explaining only 10.6% of cross-city variation. In M2, neither log population nor growth is significant at the 5% level. In M3, growth changes sign and remains close to zero (−0.015, $p=0.851$). Quality of Life has the largest positive partial coefficient (0.307, $p=0.088$), although its confidence interval also includes zero. The evidence rejects a simple interpretation of H1 and is consistent with H2: the demographic association attenuates when capacity dimensions are included.

COUPLED-STRESS DIAGNOSIS

Table 6

Table 6 Cities with the Highest Coupled Pressure–Sustainability Stress

Rank	City	UPI	Sustainability gap	CSI
1	Delhi	76.3	44	57.9
2	Bengaluru	72.7	40	53.9
3	Chennai	65.3	43	53
4	Greater Mumbai	70.7	39.3	52.7
5	Hyderabad	65.1	41.3	51.9
6	Surat	65.4	37.6	49.6
7	Ahmedabad	60.3	35.8	46.5
8	Coimbatore	37.8	51.8	44.2
9	Jaipur	37.5	48.4	42.6
10	Lucknow	33.5	45.2	38.9

Note: The CSI is a Prioritization Metric, Not A Causal Estimate. a High Value Requires Both High Demographic Pressure and A Large Gap from the Maximum Sustainability Score.

Figure 4

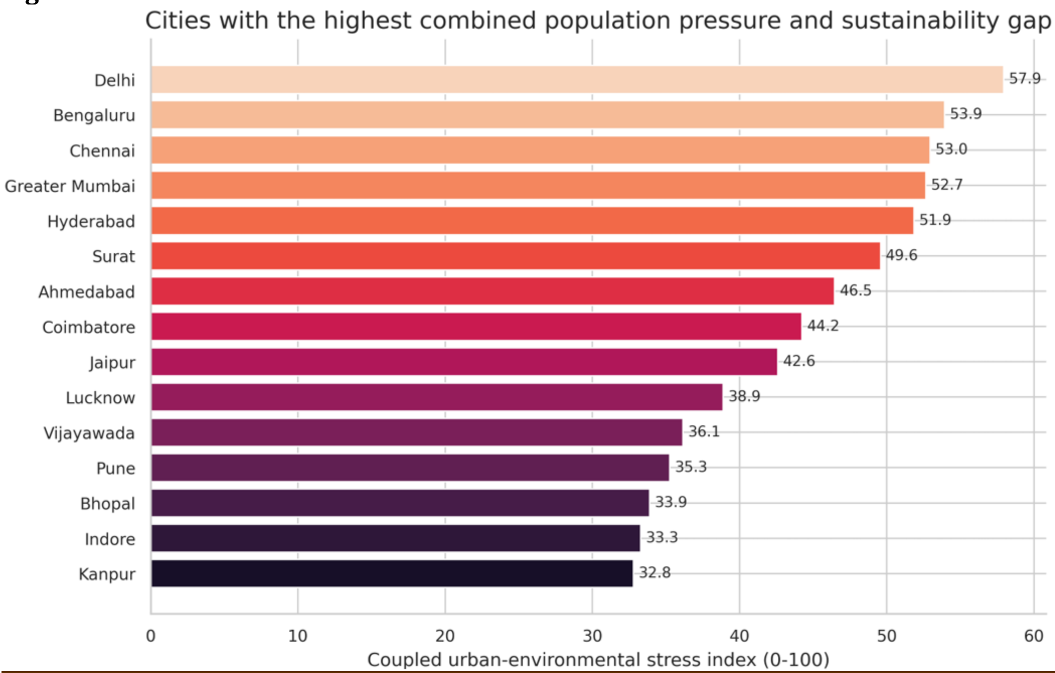

Figure 4 Cities Ranked by Coupled Demographic and Sustainability Stress

Note: Bars Show the Geometric-Mean CSI. The Index Penalizes Imbalance and Remains Low When Either Pressure or the Sustainability Gap is Low.

DISCUSSION

The positive bivariate slope is the study's most important warning. A composite sustainability score captures installed infrastructure, municipal performance and service outcomes as well as environmental burdens. Large cities may score better on selected systems because density supports networks, monitoring and specialized administration, even while residents face congestion, heat or pollution. This capacity channel can reverse an unconditional pressure–sustainability correlation. It would therefore be erroneous to state that population growth improves environmental conditions.

The weak partial effect of growth suggests that demographic momentum by itself is an incomplete policy signal. Where growth is anticipated and serviced, marginal residents can be absorbed through compact development and efficient networks. Where land conversion and service extension lag, equivalent growth can produce informal expansion, longer trips, groundwater depletion and waste leakage. The relevant unit of diagnosis is the pressure–capacity mismatch, not population alone.

The CSI operationalizes this proposition without concealing the two underlying components. Delhi combines the highest pressure with a sizeable sustainability gap, while Bengaluru's rapid growth lifts its pressure score despite stronger economic ability. Mumbai's extreme scale and Chennai's pressure–gap combination place them near the top. These are screening results: city-specific policy must still examine indicator components, spatial distribution and exposure inequalities.

POLICY IMPLICATIONS

First, urban investment formulas should account for both stock and flow: existing metropolitan population and recent growth. Second, capital projects should be appraised as integrated systems. Transit-oriented development without affordable housing may displace lower-income households; drainage without watershed protection can shift rather than remove flood risk; and tree planting without heat-vulnerability targeting may reproduce environmental inequality. Third, city dashboards should publish boundary-consistent, annual data on emissions, air quality, water balance, waste recovery, green cover and climate risk.

For high-CSI cities, immediate priorities are demand management, infrastructure maintenance and spatially targeted risk reduction. Medium-CSI cities need early investment before path dependence raises retrofitting costs. Lower-CSI cities should preserve their advantage through land-use controls and reliable service finance. Benchmarking should be used for learning rather than punitive ranking because indicator systems remain sensitive to definitions and measurement capacity.

LIMITATIONS AND RESEARCH AGENDA

The analysis is constrained by a small cross-section, one sustainability vintage, an older population interval and boundary mismatch between urban agglomerations and municipal jurisdictions. The EoLI sustainability dimension is a policy index rather than a direct physical inventory of emissions or ecosystem condition. Economic Ability and Quality of Life may themselves be jointly determined with sustainability, so M3 is descriptive rather than structural. Spatial dependence, state-level institutions and climate zones are not modeled because the available sample cannot support a rich specification without overfitting.

Future work should construct a panel with harmonized boundaries, satellite-derived land cover and heat, monitored air quality, municipal finance, commuting structure and service reliability. Quasi-experimental changes in governance or infrastructure could identify causal effects. Distributional analysis should also separate citywide averages from neighborhood exposure and access.

CONCLUSION

Across 31 Indian million-plus cities, demographic pressure is not a stable negative predictor of the official sustainability score. Its small positive bivariate association disappears after capacity controls, and the growth coefficient is close to zero with a wide bootstrap interval. The finding does not absolve population pressure; it shows that scale, infrastructure and governance operate together. A coupled-stress framework identifies Delhi, Bengaluru, Chennai, Greater Mumbai and Hyderabad as priority cases and provides a more defensible basis for differentiated urban policy than city size alone.

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