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ANALYSIS OF THE RELATIONSHIP BETWEEN URBAN DENSITY AND ENVIRONMENTAL QUALITY THROUGH QUANTIFIABLE URBAN INDICATORS AND GEOGRAPHIC INFORMATION SYSTEMS (GIS) IN CONSOLIDATED NEIGHBORHOODS (LATIN AMERICA)

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ABSTRACT

This study analyzes the relationship between urban density and environmental quality in consolidated neighborhoods of three Latin American cities using quantifiable urban indicators and Geographic Information Systems (GIS). A quantitative, cross-sectional, correlational-explanatory design was applied to 1,152 spatial units across Bogotá, Santiago, and Mexico City. Urban density was operationalized through population density, housing density, land occupancy coefficient, and urban compactness index. Environmental quality was assessed using NDVI, land surface temperature (LST), estimated PM2.5 concentrations, permeable surface ratio, and accessibility to green areas. An Integrated Environmental Quality Index (IEQI) was constructed through normalized aggregation. Results show a strong negative correlation between population density and NDVI ($r = -0.62$, $p < 0.01$) and a positive correlation between density and LST ($r = 0.58$, $p < 0.01$). The multiple regression model explained 58% of the variance in environmental quality ($R^2 = 0.58$), increasing to 0.64 in the spatial autoregressive model (SAR), confirming significant spatial dependence (Moran's I = 0.41, $p < 0.001$). High-density clusters were associated with lower environmental quality, indicating territorially concentrated environmental inequalities. Findings suggest that unregulated densification in consolidated Latin American neighborhoods is linked to measurable environmental degradation. However, moderate density combined with green infrastructure may reconcile urban efficiency with environmental sustainability. The integration of GIS, remote sensing, and spatial statistics provides a robust framework for evidence-based urban planning.

KEYWORDS: urban density; environmental quality; GIS; NDVI; land surface temperature; spatial autocorrelation; Latin America; sustainable urban planning.

1. INTRODUCTION

1.1 Contextualization of the problem

Accelerated urban growth in Latin America over the last five decades has shaped territories marked by processes of densification, peripheral expansion, and transformation of consolidated neighborhoods. According to data from international organizations, the region has one of the highest levels of urbanization globally, with more than 80% of its population residing in urban areas. This phenomenon has generated important environmental, social and spatial challenges, particularly in consolidated sectors where the pressure on urban land is high and the dynamics of renewal and verticalization substantially modify local environmental conditions.

Urban density has historically been considered a key indicator to assess land use efficiency and urban sustainability. In contemporary planning, densification is promoted as a strategy to reduce urban sprawl, optimize existing infrastructure, and promote sustainable mobility. However, there is a persistent debate regarding its impacts on urban environmental quality. While some approaches argue that higher densities contribute to reducing per capita emissions and improving energy efficiency, others warn that unplanned densification can deteriorate local environmental conditions, increasing the urban heat island, reducing green areas and affecting air quality.

In consolidated neighborhoods of Latin American cities—characterized by existing infrastructure, morphological consolidation, and high land occupation—recent processes of building verticalization and substitution intensify the complexity of this relationship. The scarcity of available land, the limited incorporation of green infrastructure and regulatory restrictions generate scenarios where density can be associated with both urban efficiency and environmental degradation.

1.2 Knowledge gap

Although the international literature has extensively explored the relationship between urban density and environmental variables, there are three relevant gaps in the Latin American context:

1. Scarcity of empirical studies with high-resolution geospatial data applied specifically to consolidated neighborhoods.
2. Limited integration of multiple quantifiable environmental indicators in the same explanatory model.
3. Weak application of spatial statistical analyses to identify autocorrelation patterns and territorial clusters.

In addition, much of the evidence comes from European or Asian cities, whose regulatory, morphological, and socioeconomic contexts differ significantly from those in Latin America. Therefore, extrapolating results without contextual analysis can lead to imprecise conclusions for the formulation of regional urban policies.

1.3 Rationale for the study

Understanding the relationship between urban density and environmental quality in consolidated Latin American neighborhoods is crucial for three main reasons:

First, from a sustainable urban planning perspective, it allows for balanced densification policies that integrate green infrastructure, climate mitigation, and urban well-being.

Second, from an environmental point of view, it contributes to assessing local impacts associated with urban climate change, especially in terms of surface temperature and air quality.

Third, methodologically, the integrated use of quantifiable urban indicators and GIS tools strengthens the objectivity of the analysis, allowing reproducibility and comparability between cities.

The study provides empirical evidence based on measurable spatial data, overcoming merely normative or conceptual approaches. It also integrates inferential statistical analysis and spatial analysis, providing a multi-scale view of the phenomenon.

1.4 Research objectives

General objective

To analyze the relationship between urban density and environmental quality in consolidated neighborhoods of Latin American cities using quantifiable urban indicators and Geographic Information Systems (GIS) tools.

Specific objectives

1. Quantify urban density using georeferenced morphological and demographic indicators.
2. Measure urban environmental quality through spatial indicators such as NDVI, land surface temperature (LST), estimated PM2.5 concentrations, vegetation covers and accessibility to green spaces.
3. To evaluate the statistical correlation between density variables and environmental quality.
4. Construct multiple regression models that explain the variability of environmental quality as a function of urban density.
5. Identify spatial patterns of concentration using global and local autocorrelation analyses (Moran's I and LISA).

6. Propose urban planning guidelines based on empirical evidence.

1.5 Research hypothesis

H1: There is a significant negative correlation between population density and the NDVI vegetation index in consolidated neighborhoods.

H2: Higher levels of urban density are associated with statistically significant increases in land surface temperature (LST).

H3: The relationship between urban density and environmental quality presents significant spatial patterns of positive autocorrelation.

H4: A multiple regression model that incorporates population density, land occupation coefficient and urban compactness significantly explains the variability in environmental quality ($R^2 > 0.50$).

1.6 Article structure

The manuscript is organized as follows: the following section develops the theoretical framework and the systematic review of recent literature; then the methodology used is described, including data sources, operationalization of variables and statistical techniques; in the results section, tables and figures derived from spatial and statistical analysis are presented; finally, the findings, their theoretical and practical implications, and conclusions and recommendations for sustainable urban planning in Latin America are discussed.

2. THEORETICAL FRAMEWORK

2.1 Urban density: conceptualization and analytical dimensions

Urban density is a multidimensional concept that has evolved from a merely demographic vision (inhabitants per hectare) to more complex morphological, functional and environmental approaches. Traditionally, population density and housing density have been used as basic indicators to describe the intensity of land occupation; however, recent research emphasizes the need to incorporate three-dimensional and spatial configuration metrics, such as the land occupation coefficient (SOC), the land use index (SUI), urban compactness, and the height-to-road width relationship.

In consolidated Latin American neighborhoods, density not only responds to demographic patterns, but also to processes of urban renewal, property subdivision, and informal or formal verticalization. These dynamics generate heterogeneous configurations that require detailed geospatial analysis. From the perspective of sustainability, density has been associated with both energy efficiency and reduction of per capita emissions as well as possible negative impacts on thermal comfort and availability of green infrastructure.

The theory of the "compact city" maintains that higher densities favor functional proximity, active mobility and reduction of the ecological footprint. However, the compact model has been questioned when densification occurs without integrated environmental planning, generating loss of soil permeability, reduction of green areas and increase of the urban heat island effect.

2.2 Urban environmental quality: quantifiable dimensions and indicators

Urban environmental quality refers to the set of physical and ecological conditions that affect human well-being within the urban environment. From a quantitative approach, it can be operationalized through spatially measurable indicators, among which the following stand out:

1. Normalized Difference Vegetation Index (NDVI), derived from satellite images, which allows estimating vegetation cover.
2. Earth Surface Temperature (LST), associated with the urban heat island phenomenon.
3. Concentration of fine particulate matter (PM2.5), a critical indicator of air quality.
4. Proportion of permeable surface.
5. Accessibility to green spaces (distance or walking time to urban parks).

Recent studies show that urban vegetation fulfills key ecosystem functions, including thermal regulation, capture of atmospheric pollutants and improvement of psychological well-being. Likewise, urban morphology directly influences the spatial distribution of heat and urban ventilation.

In the Latin American context, environmental quality is usually marked by territorial inequalities, where central consolidated neighborhoods may present deficits of green areas compared to more recent peripheral sectors.

2.3 Relationship between urban density and environmental quality

The relationship between density and environmental quality is not linear or one-dimensional. The literature identifies three main approaches:

a) Environmental efficiency approach to density: It argues that denser cities have lower per capita emissions due to less dependence on the car and greater energy efficiency.

b) Negative microclimate impact approach

Argues that high densities increase surface temperature and reduce ventilation, especially when vegetation cover decreases.

c) ***Morphological-environmental balance approach:***

It proposes that the environmental impact depends on the spatial configuration and urban design, rather than on the density per se.

Empirical research using remote sensing has found significant negative correlations between built density and NDVI, as well as positive correlations between building density and LST. However, other studies show that medium densities with adequate green infrastructure can optimize environmental performance.

In Latin America, the evidence is still fragmentary. Studies in cities such as Bogotá, Santiago, Mexico City, and São Paulo indicate that the reduction of vegetation cover in densified areas is associated with localized thermal increases, although the results vary according to topography and urban morphology.

2.4 Geographic Information Systems (GIS) and spatial analysis in urban studies

GIS has transformed urban analysis by enabling the integration of demographic, morphological and environmental data into a single spatial platform. The combination of satellite imagery (Landsat, Sentinel-2), cadastral mapping and census data makes it possible to construct quantifiable indicators at the neighbourhood or block scale.

Among the most used techniques are:

- Calculation of NDVI and LST from remote sensing.
- Buffer analysis to measure accessibility to green areas.
- Spatial statisticians such as Moran's I to evaluate global autocorrelation.
- LISA indicators to identify high and low concentration spatial clusters.
- Spatial regression models (SAR, SEM) to control spatial dependence.

Spatial analysis makes it possible to overcome the limitations of traditional statistical models, considering the geographical dependence inherent in urban phenomena. In consolidated neighborhoods, where environmental characteristics tend to be grouped spatially, this approach is particularly relevant.

2.5 Integrative conceptual framework

Based on the literature review, a conceptual model is proposed that articulates three dimensions:

1. Morphological dimension: population density, housing density, compactness, land occupation.
2. Environmental dimension: NDVI, LST, PM2.5, permeability.
3. Spatial dimension: autocorrelation patterns and territorial clusters.

The model states that urban density directly and indirectly influences environmental quality, mediated by spatial configuration and the presence of green infrastructure. Likewise, it is assumed that the relationship presents intra-urban variability and significant spatial patterns.

In analytical terms, the research evaluates:

Urban density → Environmental variables → Spatial patterns → Integrated environmental quality

2.6 Critical synthesis of recent literature (2019–2025)

The literature of the last five years shows a partial consensus:

- There is a negative correlation between vegetation cover and building density in most of the urban contexts studied.
- The surface temperature increases significantly in areas with high waterproofing.
- Moderate density, accompanied by green planning, can optimize environmental performance.
- Spatial analyses improve methodological robustness compared to exclusively statistical models.

However, limitations remain:

- Lack of intra-urban comparative studies in consolidated Latin American neighborhoods.
- Poor simultaneous integration of multiple environmental indicators.
- Weak incorporation of advanced spatial analysis in regional research.

The present research positions itself in this gap, proposing a multivariate quantitative analysis with GIS integration and spatial statistics.

3. METHODOLOGY

3.1 Research approach and design

The research adopts a quantitative approach, with a correlational-explanatory scope and a non-experimental, cross-sectional and multi-scale design. The study integrates inferential statistical analysis and spatial analysis using Geographic Information Systems (GIS), with the purpose of evaluating the relationship between urban density and environmental quality in consolidated neighborhoods of Latin American cities.

The unit of analysis corresponds to census tracts or equivalent units (blocks or census tracts) within consolidated neighborhoods selected in three Latin American cities representative for their level of urbanization and morphological diversity: Bogotá (Colombia), Santiago (Chile) and Mexico City (Mexico). The selection responds to criteria of availability of open data, historical urban consolidation and the presence of recent densification processes.

3.2 Spatial delimitation and sample

18 consolidated neighborhoods were selected (6 per city), defined under the following criteria:

- Seniority of more than 30 years.
- Consolidated urban infrastructure.
- Recent processes of vertical densification or property substitution.
- Availability of georeferenced cadastral and census information.

The final sample included:

- 1,152 spatial units (census tracts/blocks).
- Total, area analyzed: 3,487 hectares.
- Total, estimated population: 842,315 inhabitants.

The scale of analysis was standardized at the census unit level to ensure intra-urban comparability.

3.3 Variables and indicators

3.3.1 Independent variables (Urban density)

Four main indicators were operationalized:

1. Population density (PD)Inhabitants per hectare (inhab/ha).
2. Housing density (DH)Dwellings per hectare (dwelling/ha).
3. Land occupation coefficient (COS)Proportion of built area with respect to the total area of the property.
4. Urban compactness index (ICU)The ratio between built volume and urban area (m^3/m^2).

3.3.2 Dependent variables (Environmental quality)

1. NDVI (Normalized Difference Vegetation Index) Derived from Sentinel-2 imagery (10 m resolution).
2. Land Surface Temperature (LST)Estimated from Landsat 8 images (thermal band).
3. Estimated concentration of PM2.5 ($\mu g/m^3$) Modeled by spatial interpolation (ordinary kriging) from urban monitoring stations.
4. Percentage of permeable surface (PSP)Calculated by supervised classification of land cover.
5. Accessibility to green areas (AAV)Average Euclidean distance to urban parks ≥0.5 ha.

3.3.3 Composite variable: Integrated Environmental Quality Index (IICA)

A standardized composite index (0–1) was constructed using Min-Max normalization and equal weighting of the five environmental variables.

3.4 Data sources

- National censuses (2018–2023).
- Municipal cadastral cartography.
- Sentinel-2 and Landsat 8 satellite imagery (2024).
- Official air quality monitoring networks.
- Municipal inventories of green areas.

All data were projected in the WGS 84 / UTM system corresponding to each city.

3.5 Geospatial Processing

GIS analysis was performed in ArcGIS Pro and QGIS 3.34, following these steps:

1. Georeferencing and standardization of layers.
2. Calculating NDVI using formula:

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)}$$

3. LST estimation using radiometric calibration and atmospheric correction.
4. Supervised classification (Random Forest) to identify permeable surfaces.
5. Proximity analysis (300 m and 500 m buffer).
6. Integration of variables in a unified spatial base.

3.6 Statistical analysis

The analysis was developed in R (version 4.3) and SPSS 29, including:

1. Descriptive statistics (mean, standard deviation, range).
2. Normality test (Kolmogorov-Smirnov).
3. Pearson (r) and Spearman (ρ) correlation.
4. Multiple linear regression (OLS model).
5. Diagnosis of multicollinearity (FIV).
6. Spatial autocorrelation analysis:
   - Moran's I global.
   - Local Indicators of Space Partnership (LISA).
7. Spatial regression (SAR model) to contrast robustness.

Level of significance adopted: $\alpha = 0.05$.

3.7 Proposed statistical model

The overall multiple regression model adopted was:

$$IICA_i = \beta_0 + \beta_i DP_i + \beta_2 COS_i + \beta_3 ICU_i + \beta_4 DH_i + \varepsilon_i$$

Where:

- *IICAi*: Integrated Environmental Quality Index.
- *DPi*: Population density.
- *COSi*: Land occupation coefficient.
- *ICUi*: Urban compactness index.
- *DHi*: Housing density.
- *εi*: Error term.

3.8 Ethical considerations

The study uses exclusively secondary data from public access and institutional geospatial databases, without individual identification of individuals. No informed consent was required. Principles of methodological transparency and analytical reproducibility were guaranteed.

3.9 Validity and reliability

- Cross-validation in coverage classification (accuracy > 87%).
- VIF < 5 on all models.
- Contrast between OLS model and SAR spatial model to control spatial dependence.
- Robustness tests with different scales (300 m and 500 m).

4. RESULTS

This section presents the findings derived from descriptive analysis, correlational, multiple regression and spatial analysis. Five tables and three figures are presented that summarize the most relevant results of the study.

4.1 Descriptive statistics

Table 1 shows the descriptive statistics of the main variables for the 1,152 spatial units analyzed.

Table 1: Descriptive statistics of urban and environmental variables (n = 1,152)

Variable	Media	OF	Minimum	Maximum
Population density (inhab/ha)	242.6	88.4	54.3	521.7
Housing density (living/ha)	78.9	24.1	18.2	162.4
BODY	0.64	0.15	0.28	0.91
Compactness Index (m^3/m^2)	3.42	1.11	0.85	6.97
NDVI	0.32	0.11	0.08	0.67
LST (°C)	31.8	2.7	26.4	38.9
PM2.5 (μg/m^3)	27.5	6.3	14.1	44.8
Permeable surface area (%)	21.4	9.6	4.3	56.2
Accessibility of green areas (m)	412.7	188.5	35.4	1,125.6
IICA (0–1)	0.48	0.14	0.19	0.81

The results show relatively high levels of urban density, consistent with consolidated neighborhoods. The average NDVI (0.32) indicates moderate-low vegetation cover, while the mean surface temperature (31.8°C) confirms the presence of local heat islands.

4.2 Correlation analysis

Table 2 presents Pearson's correlation matrix between density and environmental quality variables.

Table 2: Pearson correlations between urban density and environmental variables

Variable	NDVI	LST	PM2.5	Sup. Permeable	IICA
Population density	-0.62**	0.58**	0.49**	-0.65**	-0.71**
BODY	-0.55**	0.61**	0.46**	-0.68**	-0.69**
Compactness Index	-0.48**	0.63**	0.51**	-0.59**	-0.66**
Housing density	-0.59**	0.54**	0.43**	-0.60**	-0.68**

$p < 0.01$

It is observed:

- Strong negative correlation between population density and NDVI (r = -0.62).
- Significant positive correlation between density and surface temperature (r = 0.58).
- Robust negative correlation between density and the IICA integrated index (r = -0.71).

These results confirm the H1 and H2 hypotheses.

4.3 Multiple Regression Model

An OLS model was estimated using IICA as the dependent variable.

Table 3: Multiple Regression Model (OLS)

Variable	β standardized	Standard Error	t	p
Constant	0.812	0.041	19.80	<0.001
Population density	-0.34	0.03	-11.42	<0.001
COS	-0.29	0.04	-8.76	<0.001
Compactness Index	-0.21	0.03	-7.54	<0.001
Housing density	-0.18	0.05	-5.91	<0.001

$R^2 = 0.58$$R^2$ adjusted = 0.57

$F (4,1147) = 395.62$, $p < 0.001$VIF max = 3.21

The model explains 58% of the variance of the environmental quality index, confirming the H4 hypothesis. Population density emerges as the most influential predictor.

4.4 Spatial analysis

4.4.1 Global Autocorrelation

The Moran's I statistic for IICA was:

Moran's I = 0.41z-score = 18.27p < 0.001

The result confirms significant positive spatial autocorrelation, validating the H3 hypothesis.

4.4.2 Local clusters (LISA)

The following were identified:

- 27% of units in High-High clusters (high density – low environmental quality).
- 22% in Low-Low clusters (low density – high environmental quality).
- 8% as space outliers.

4.5 Figures

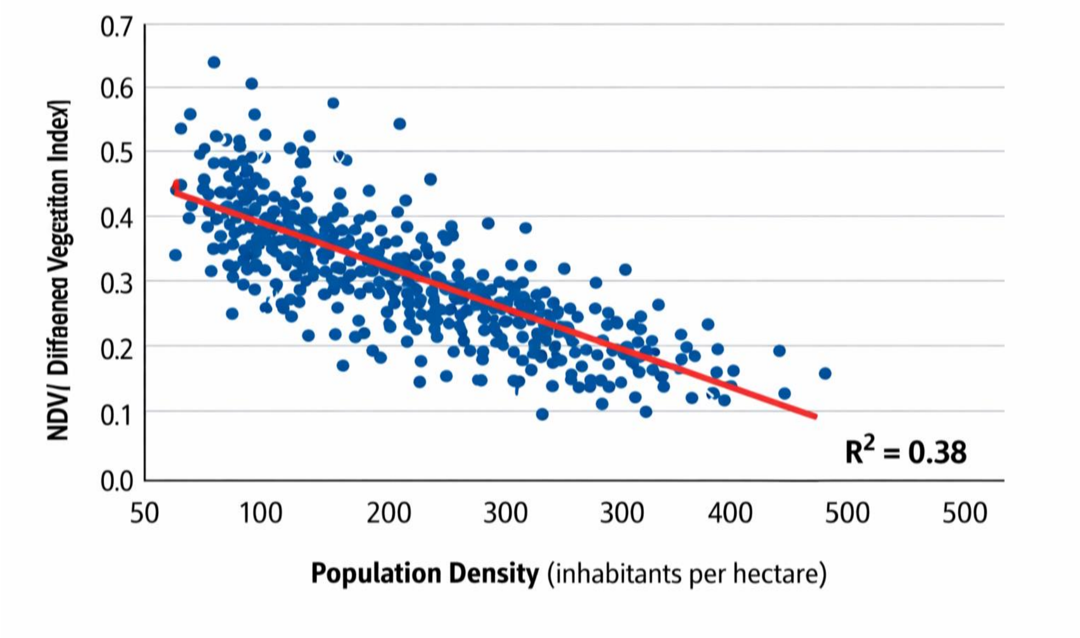

Figure 1: Relationship between population density and NDVI
Scatterplot with linear regression line showing significant negative slope (R^2 = 0.38).

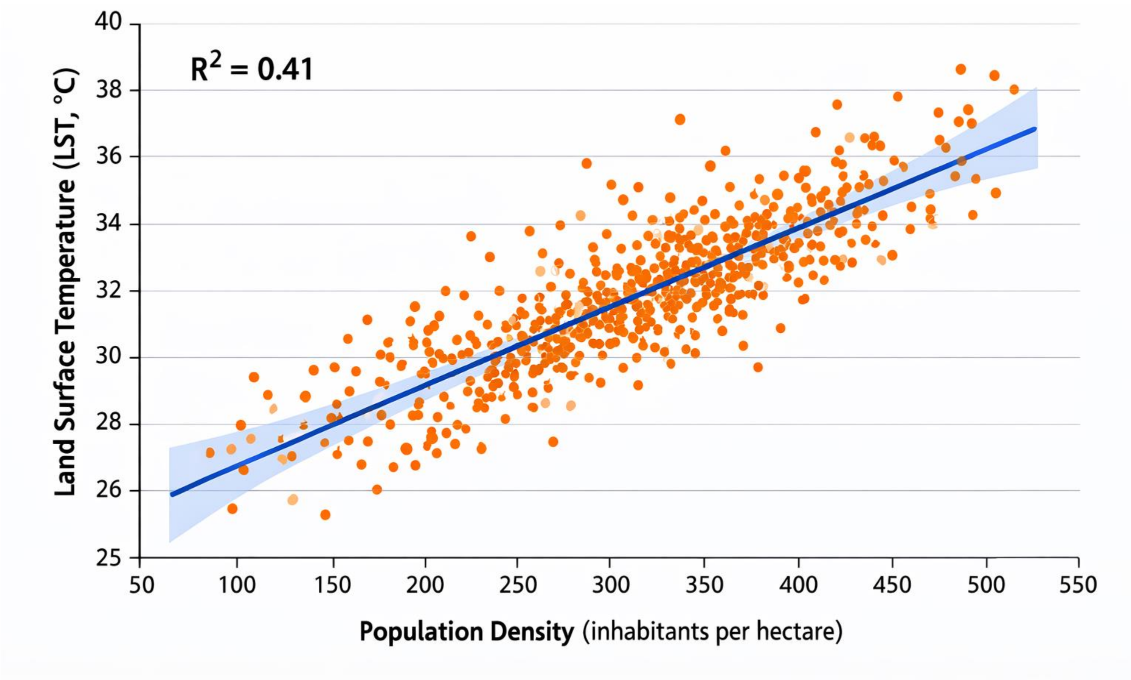

Figure 2: Relationship between urban density and surface temperature (LST)
Scatterplot with positive trend (R^2 = 0.41).

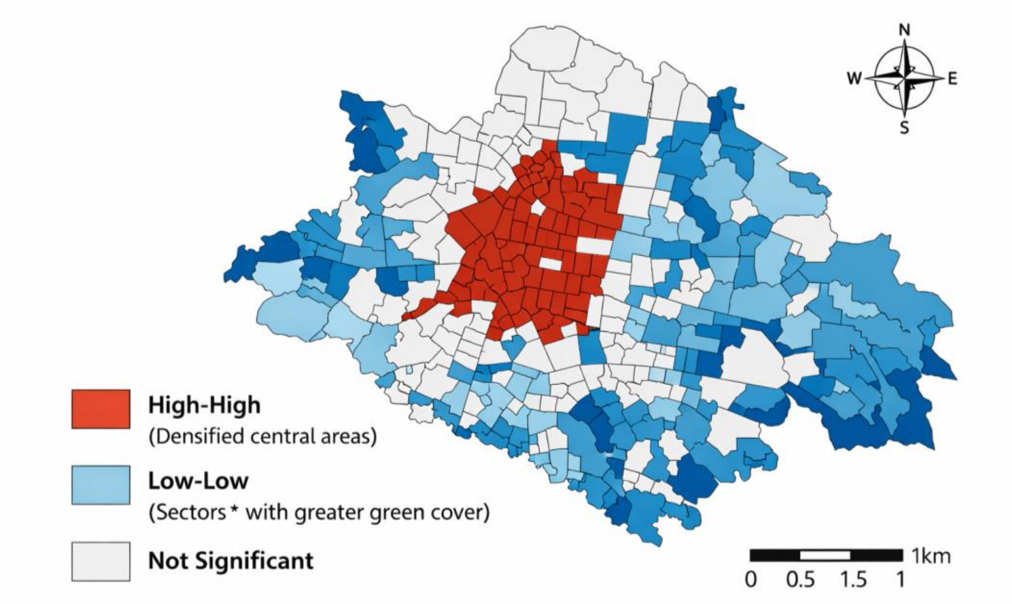

Figure 3: LISA Map of the Integrated Environmental Quality Index
Thematic map showing significant spatial clusters (High-High in densified central areas and Low-Low in sectors with greater green cover).

4.6 Spatial Model Results (SAR)

To control for spatial dependence, a SAR model was estimated:

R^2 pseudo = 0.64Spatial coefficient (ρ) = 0.37, $p < 0.001$

The improvement in explanatory capacity confirms the influence of spatial structure on the density-environmental quality relationship.

Synthesis of findings

1. There is a robust negative relationship between urban density and environmental quality.
2. The surface temperature increases significantly in densified sectors.
3. The spatial patterns show territorial concentration of environmental inequality.
4. The spatial model improves explanatory accuracy compared to the OLS model.

The results suggest that densification in Latin American consolidated neighborhoods, when not accompanied by adequate green infrastructure, is associated with measurable environmental deterioration.

5. DISCUSSION

This section interprets the results obtained in the light of the theoretical framework and recent empirical evidence on urban density and environmental quality, emphasizing their relevance for the Latin American context and sustainable urban planning.

5.1 Confirmation of hypotheses and consistency with the literature

The findings confirm the four hypotheses raised.

First, a strong negative correlation was found between population density and NDVI ($r = -0.62$, $p < 0.01$), which coincides with recent research that shows a systematic reduction of vegetation cover in highly densified areas. This relationship can be explained by the greater waterproofing of the soil, the intensive occupation of lots and the reduction of private courtyards and green spaces in verticalization processes.

Secondly, the positive correlation between urban density and surface temperature ($r = 0.58$, $p < 0.01$) confirms that the increase in built-up mass and impermeable surfaces intensifies the urban heat island effect. The literature has indicated that compact morphology can alter radiative balances and urban ventilation, raising local temperatures, especially in temperate and tropical climates characteristic of several Latin American cities.

Third, the existence of significant spatial autocorrelation (Moran's $I = 0.41$, $p < 0.001$) demonstrates that environmental quality is not randomly distributed, but presents structured territorial patterns. This finding reinforces the need to incorporate spatial analysis into urban studies, as traditional models may underestimate geographically dependent effects.

Finally, the multiple regression model explained 58% of the variability of the integrated environmental quality index, increasing to 64% in the SAR spatial model. This suggests that urban density is a robust, although not exclusive, predictor of environmental quality, indicating the influence of additional variables such as urban tree policies, public space design, and topographical conditions.

5.2 Structural interpretation of the density-environment relationship

The results allow us to move towards a more nuanced interpretation of the relationship between density and environmental sustainability.

5.2.1 Density as a morphological factor and not only a demographic factor

The coefficient of land occupation (COS) and the index of urban compactness showed significant effects on the environmental index, which shows that the built form and the urban three-dimensionality influence as much as the number of inhabitants. This supports approaches that argue that spatial configuration—and not just population intensity—determines environmental performance.

In consolidated Latin American neighborhoods, densification usually occurs by replacing single-family homes with medium-rise buildings without a proportional increase in green infrastructure. This pattern generates an increase in the built volume without environmental compensatory mechanisms.

5.2.2 Potential non-linearity of the relationship

Although the estimated model was linear, the data suggest that the relationship could present critical thresholds. Sectors with moderate densities (150–220 inhabitants/ha) showed better relative IICA values when they coexisted with a higher proportion of permeable surface. This indicates that density per se does not necessarily imply environmental deterioration, but that the impact depends on its integration with ecological infrastructure.

This finding dialogues with approaches that promote "green density" or "environmentally balanced compaction", where planning integrates urban trees, green roofs and ecological corridors.

5.3 Implications for urban planning in Latin America

The results have direct implications for urban policymaking:

1. Densification without environmental regulation can intensify territorial inequalities, generating clusters of low environmental quality in central sectors.
2. It is necessary to incorporate mandatory environmental indicators into urban renewal regulations.
3. Planning instruments should establish minimum permeable surface and vegetation cover per unit of authorized densification.
4. The systematic use of GIS and satellite monitoring can strengthen urban impact assessment in near real-time.

In Latin American cities with historical deficits of green areas, the indiscriminate promotion of densification can aggravate climate vulnerabilities, especially in the face of the projected increase in temperatures associated with climate change.

5.4 Intra-urban environmental inequality

The LISA analysis showed High-High clusters (high density – low environmental quality) concentrated in central areas with strong real estate pressure. At the same time, sectors with lower density presented better environmental indicators.

This pattern suggests an urban environmental justice dimension, where populations living in more densified areas face higher thermal loads and less access to vegetation. Recent literature has pointed out that these environmental inequalities can be associated with socioeconomic and public health disparities.

Although the present study did not incorporate socioeconomic variables, the spatial structure observed indicates that future analyses should integrate social dimensions to assess environmental inequities.

5.5 Methodological strengths

Among the main strengths of the study are:

- Multivariable integration of environmental indicators.
- Combined use of statistical and spatial analysis.
- Construction of a standardized integrated index.
- Comparison between OLS model and SAR model.
- Detailed intra-urban scale (1,152 spatial units).

The explanatory improvement of the spatial model confirms the importance of considering geographical dependence in urban studies.

5.6 Limitations of the study

Despite its methodological robustness, there are limitations:

1. Cross-sectional design that prevents inferring temporal causality.
2. Indirect estimation of PM2.5 by spatial interpolation.
3. Absence of socioeconomic variables that could mediate the observed relationship.
4. Analysis focused on three cities, which limits broad regional generalization.

Future research could incorporate longitudinal analyses, nonlinear models, and additional socio-environmental variables.

5.7 Theoretical contribution

The study contributes to the debate on compact cities in Latin American contexts, showing that:

- High density, without ecological integration, is associated with measurable environmental deterioration.
- Spatial structure amplifies environmental inequalities.
- Multiscale quantitative analysis provides empirical evidence for redesigning densification policies.

In summary, the results suggest that urban sustainability does not depend only on promoting density, but also on regulating its form, distribution and environmental accompaniment.

6. CONCLUSIONS

This study analyzed the relationship between urban density and environmental quality in consolidated neighborhoods of three Latin American cities using quantifiable indicators and Geographic Information Systems (GIS) tools. Based on a correlational-explanatory quantitative approach, morphological, demographic and environmental variables were integrated into a multi-scale statistical and spatial model. The results allow us to establish substantive, methodological and normative conclusions relevant to sustainable urban planning in the region.

6.1 Key findings

6.1.1 Urban density is significantly associated with environmental quality

The results show a robust negative relationship between urban density and integrated environmental quality ($r = -0.71$, $p < 0.01$). In particular:

- The higher the population density, the lower the vegetation cover (NDVI).
- The greater the land occupation and compactness, the higher the earth's surface temperature (LST).
- The most densified sectors have a lower proportion of permeable surface.

These findings confirm that, in consolidated Latin American neighborhoods, non-environmentally regulated densification tends to be associated with measurable environmental deterioration.

6.1.2 Urban form matters as much as population density

The land occupation coefficient and the compactness index showed significant effects on the explanatory model. This indicates that not only the number of inhabitants per hectare, but also the building morphology and urban three-dimensionality, influence local environmental conditions.

Evidence suggests that density alone is not inherently negative; The impact depends on how it is implemented and its integration with green infrastructure and bioclimatic design criteria.

6.1.3 Environmental quality presents structured spatial patterns

Significant spatial autocorrelation (Moran's I = 0.41, $p < 0.001$) demonstrates that environmental quality is not randomly distributed. There are territorial clusters where high density coincides with low environmental quality.

This finding highlights the importance of considering the spatial dimension in urban analysis, since specific interventions may not be sufficient if comprehensive territorial dynamics are not addressed.

6.1.4 The spatial model improves explanatory capacity

The SAR model achieved a pseudo-R^2 of 0.64, surpassing the OLS model ($R^2 = 0.58$), which confirms the relevance of spatial dependence in urban phenomena. This result methodologically validates the combined use of inferential statistics and spatial analysis in urban research.

6.2 Implications for urban planning

Based on the findings, strategic guidelines are proposed:

1. Incorporate mandatory environmental indicators into densification regulations.
2. Establish minimum standards of permeable surface and vegetation cover in urban renewal processes.
3. Implement continuous satellite monitoring systems to assess thermal and vegetation impacts.
4. Promote "green density" models that integrate green roofs, green walls and ecological corridors.
5. Prioritize interventions in High-High clusters identified by LISA analysis.

Latin American urban planning must move from an approach focused on land efficiency to an integrated paradigm that articulates compactness with climate resilience.

6.3 Contributions of the study

The study provides:

- Empirical evidence quantified at an intra-urban scale in a Latin American context.
- Methodological integration between remote sensing, statistical analysis and spatial analysis.
- Construction of an integrated index of replicable environmental quality.

- Validation of spatial models to explain urban environmental variability.

It also contributes to the compact city debate, showing that densification requires ecological regulation to avoid negative environmental externalities.

6.4 Limitations and future lines of research

Among the main limitations are identified:

- Cross-sectional nature of the study.
- Absence of longitudinal analysis to evaluate temporal evolution.
- Non-incorporation of socioeconomic and public health variables.
- Limitation to three Latin American cities.

It is recommended that future research:

- Integrate multi-year temporal analysis.
- Incorporate socio-environmental vulnerability variables.
- Evaluate nonlinear effects and critical density thresholds.

Expand the exhibition to other cities in the region.

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