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Spatial segregation patterns and association with built environment features in Colombian cities

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ABSTRACT

Spatial segregation is a pressing issue in Latin American cities due to high urbanization, population density, and inequalities. This study examines segregation patterns in 84 middle to large cities in Colombia and their relationship with the spatial configuration of cities using satellite data. The analysis focuses on evenness and isolation metrics of segregation for ethnicity, education level, and employment status. The findings reveal higher segregation in education level and race/ethnicity in terms of evenness dimension, and in education level and employment status in terms of isolation dimension. The study also identifies associations between segregation and built environment metrics. Negative associations are observed between education level and race/ethnicity segregation and fragmentation, as well as between employment status and patches of isolation. Positive associations exist between education level and fragmentation, race/ethnicity and patches of isolation, and a negative association between employment status and street density. These results have implications for public urban policies, particularly in small and medium cities, where there is limited understanding of segregation dynamics. The study highlights the need to consider factors beyond income, such as ethnicity, in addressing spatial segregation in urban planning and policy-making.

1. Introduction

Spatial segregation is a recurrent problem in the design of public policies in cities with different typologies. The importance of spatial segregation has grown as social inequalities have become more prominent in public policy in the 20th and 21st centuries (Dosh et al., 2003). Studies have found a negative relationship between spatial segregation and quality of life, highlighting its importance in shaping people's social circles and access to goods and jobs. In the United States, it has been shown that concentrations of vulnerable populations lead to greater exposure to crime, resulting in high rates of violence and asymmetries among different social groups (Greenstein et al., 2000; Peterson & Krivo, 2005). In Europe, its effects are seen particularly in the migrant population (Benassi et al., 2020; Benassi et al., 2023) and in areas with disparities in access to the labor market (Nielsen et al., n.d.; Arbaci, 2007; Vaughan & Arbaci, 2011), which expose immigrants and multiethnic groups to lower well-being.

Latin America has unique urban characteristics that could shape segregation patterns. The region is dense and highly urbanized (United Nations - Department of Economic and Social Affairs - Population Division, 2014; United Nations Human Settlements Programme, 2010). It is also notoriously unequal, with a Gini coefficient above 0.45 (OECD, 2015; World Bank Group, 2020). Around 80 % of the population lived in urban areas in 2020 (Benassi et al., 2023), and 24 % of the population lives in dense informal settlements (Inostroza, 2017). These informal settlements tend to be located on the cities' peripheries, where access to services is scarce and levels of violence are high. Additionally, unplanned policies exacerbate the appearance of these settlements (dos Santos et al., 2021; Dosh et al., 2003; Greenstein et al., 2000). Lower-income groups tend to occupy these peripheral, homogenous, and poorly serviced areas, while high-income groups cluster in central areas of the cities, with little or no interaction with their counterparts

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(Sabatini, 2006). These central areas usually concentrate financial and working places, where the cost of living is higher, reinforcing segregation patterns (Greenstein et al., 2000). This has been the pattern for most of the 20th century. However, the upper classes are increasingly moving to the peripheries of cities in search of greener spaces and more space. These concentrations end up forming golden ghettos or heavily isolated communities on the peripheries (Álvarez-Rivadulla, 2007; Greenstein et al., 2000; Sabatini, 2006).

Even if there is evidence of segregation patterns in some of the largest cities in Latin America, spatial segregation has not been extensively studied in non-capital cities or large samples of cities (Daude, et al., 2017a; Kaztman & Retamoso, 2007). Large cities recognize segregation as a problem, and studies have analyzed its potential impacts on various economic and social measures. Urbanization processes in small cities can generate the same dynamics as in large cities, so evidence is needed in these smaller cities to diminish the effects of segregation on populations and urban shape through effective policies. Currently, some government policies in Latin America (e.g., in Colombia) are aimed at improving equity in areas where the state has not had a strong presence, including non-capital cities. This is important because, as in the Colombian case, the state budget has been increased to support regions with little state presence in past governments, making this a crucial issue in decision-making and a state policy in itself. Therefore, studying the current social conditions—specifically economic disparity and segregation in small-to-large cities—becomes a primary necessity for emerging countries.

In Colombia, studies regarding spatial segregation are scarce, and previous research has mainly focused on large capital cities, including Bogotá, Cali, and Medellin (Aliaga-Linares & Álvarez-Rivadulla, 2010; Duarte Mayorga et al., 2013). Studies conducted in these cities (Aliaga-Linares & Álvarez-Rivadulla, 2010; Duarte Mayorga et al., 2013) showed high levels of residential segregation patterns related to race and socioeconomic status, partly due to the higher cost of living. Afro-Colombian and indigenous people exhibit the worst quality of life, education, and access to the labor market compared to white and mestizo people. Due to the increase in costs, these populations tend to relocate to unconnected and outskirts areas when migrating from their local communities. Studies have analyzed these cities with data before 2010, suggesting a lack of recent evidence for both capital cities and medium- and small-sized cities (Aliaga-Linares & Álvarez-Rivadulla, 2010; Duarte Mayorga et al., 2013). Additionally, policies in the country aimed at improving poverty have primarily used income status and, in some cases, income segregation as measures of poverty, neglecting the inherent nature of segregation related to race and education (*Desegregating the city: Ghettos, enclaves, and inequality*, 2005; Greenstein et al., 2000; Peterson & Krivo, 2005). Some studies have found that racial segregation is associated with income segregation (Greenstein et al., 2000). Although education has not been extensively studied in the segregation literature, other research has demonstrated a relationship between education level, employment status, and income inequalities (Greenstein et al., 2000; Sabatini, 2006).

This study will measure segregation patterns in medium and large cities in Colombia and explore their relationship with the spatial configuration of these cities, understood as the spatial arrangement of uninterrupted urban development areas. This exploration of the relationship between segregation and the built environment is a key contribution of this paper. Although segregation measures the spatial distribution of populations, spatial features are rarely considered in studies. We hypothesize that social conditions of individuals, especially education level, ethnicity, and employment status, are related to the observed spatial segregation patterns in Colombia. The spatial nature of segregation allows for a paradigm where cities are conceived as highly complex systems, with dynamic interactions between citizens and the built environment leading to changes in social patterns (Barthélemy & Flammini, 2008) embedded in the urban environment (Spielman & Harrison, 2014). This holistic approach could provide evidence on how the effects of spatial segregation influence the configuration and evolution of urban dynamics in cities (Domic et al., 2011; Cortez et al., 2015; Anonymous, 2017a; Anonymous, 2017b; Goles et al., 2020; Daude, et al., 2017b; Spielman & Harrison, 2014). Changes in built environment factors can produce substantial changes in segregation measures, suggesting that built and social environments co-evolve (Spielman & Harrison, 2014). With developments in satellite imagery, it is now possible to estimate better indicators that represent the state of the built environment in cities and associate these with segregation measures.

This study is part of the Urban Health in Latin America (SALURBAL) project, an international collaboration that investigates how urban environments and policies affect the health of city dwellers and environmental sustainability throughout Latin America. A key aim of the project is to quantify the contributions of city-level built environment factors to differences in health and health inequality among and within cities (Quistberg et al., 2019). This study provides an opportunity to examine a large number of small, medium, and large cities from Latin America using satellite data to characterize the built environment. We examined all Colombian cities with >100,000 residents (32 based on census data), encompassing 84 cities. All analyses were conducted at the municipality level (Quistberg et al., 2019). First, we measured the degree of spatial segregation for categories within different demographic characteristics (race/ethnicity, education, and employment status) along two dimensions: spatial evenness and spatial isolation. The spatial evenness dimension measures the extent to which different groups are similarly distributed in residential space. To assess this dimension, we calculated the Wong Dissimilarity Index (WDI) (Reardon & O'Sullivan, 2004; Wong, 1998). The spatial isolation dimension measures the probability of members of a single group encountering members of another group in their local spatial environment. To assess this dimension, we calculated the spatial isolation index (Reardon & O'Sullivan, 2004; Wong, 1998). Second, we examined the association between the two segregation indicators (WDI and spatial isolation index) within each sociodemographic variable (education level, race/ethnicity, and employment status). Third, we evaluated the association between segregation indicators and built environment variables, specifically urban landscape and street design metrics (Quistberg et al., 2019). This analysis can help decision-makers better understand the relationship between the spatial configuration of the built environment and segregation patterns.

2. Literature review

Segregation has been studied as a spatial phenomenon in classic literature. This research has highlighted the importance of the environment or space as the primary means of quantifying segregation (Clark, 1991; Galster, 2012; Massey & Denton, 1988; Quillian, 2012; Schelling, 1971). However, space has usually been considered just one variable in the quantification of segregation, not as a significant factor in the complex social dynamics that lead to the emergence of spatial segregation patterns in cities. Cities naturally foster the creation of asymmetric dynamics that favor the formation of groups with unequal access to resources and other benefits resulting from connectivity with other spaces and groups (McFarlane, 2021; Vaughan & Arbaci, 2011; Yang et al., 2015). Various social dynamics, such as housing, migration, and social cohesion, emerge when urban space characteristics promote these patterns and impact segregation. The state and quality of the environment or urban spaces can manifest in violence (Dosh et al., 2003; Sampson et al., 1997) and mental health impairments or poor health conditions (Galster, 2012; Tampubolon, 2012).

Throughout the years, it has been discussed how this complexity can be associated with different forces, including social interactions, the environment, and the interactions between them, as well as individual actions. This conversation is especially relevant in areas such as South America, Asia, and Africa, regions historically understudied in these topics. These regions represent both an opportunity and a challenge due to their urban and demographic growth. Particularly, theories developed in these regions better explain the formation of informal settlements and the overall configuration of cities, such as the concept of marginalization (McFarlane, 2021). This phenomenon is characterized by rapid urbanization, uneven development, and urban segregation in contexts of economic development. Spatial segregation in Latin America has mostly been studied through this pattern, which differs from high-income countries where segregation is usually related to race or migration (Arbaci, 2007; *Desegregating the city: Ghettos, enclaves, and inequality*, 2005; Greenstein et al., 2000; Hwang & Sampson, 2014; Peterson & Krivo, 2005). In Latin America, segregation is a mixture of many more elements (Borsdorf et al., 2007; Dosh et al., 2003; Sabatini, 2006).

At the intersection of space, economic factors, and inequalities, marginalization can be understood in two primary forms (contingent and systemic) and two derivative forms (collateral and leveraged) (Auyero & Jensen, 2015; Mehretu et al., 2000). The primary forms refer to processes related to economic forces and asymmetric relations that can disadvantage individuals compared to privileged individuals (contingent) or cause them to experience everything differently because of their disadvantage (systemic). Derivative forms refer to the effects that primary forms can have on groups due to their proximity to disadvantaged individuals (collateral) or their disadvantaged position relative to large market players (leveraged). These intersecting forces explain why, in the Latin American context, the interaction of the physical built environment and spatial segregation is relevant to study. Groups socially segregated by multiple forces (contingent and systemic forms) end up differently affecting those who are also spatially segregated (collateral and leveraged forms) by the city's spatial configuration (Auyero, 1999; Auyero & de Lara, 2012; Auyero & Jensen, 2015; Mehretu et al., 2000). Studies conducted in capital cities across Latin America—Argentina (Michelini & Pintos, 2016), Chile (Borsdorf et al., 2007; Espinosa, 2016; Romero et al., 2012; Sabatini & Salcedo, 2007; Scarpaci et al., 1988), Costa Rica (Van Noorloos & Steel, 2016), Ecuador (Van Noorloos & Steel, 2016), Mexico (Pérez-Tamayo et al., 2017), Peru (Fernández de Córdova et al., 2016), and Uruguay (Álvarez-Rivadulla, 2007; Kaztman & Retamoso, 2007)—suggest that this pattern of spatial segregation is partly due to rapid urban growth and expansion towards peripheral areas (Daude, et al., 2017b), evidencing the forms described by Mehretu et al. (2000).

Colombia is a special case in the region due to its exposure to long-term effects related to the armed conflict (Egea Jiménez et al., 2008). The emergence of informal settlements in Colombia has typically been linked to migration caused by violence and armed conflict (Egea Jiménez et al., 2008). Most capital cities in Colombia have experienced waves of migration over the past 80 years due to violence and armed conflict, leading these populations to settle in informal settlements (Egea Jiménez et al., 2008). Given the intersection of spatial segregation patterns common in the Latin American region and a unique historical context influenced by migration and armed conflict, a differential analysis of segregation is required, incorporating the built environment actively. Therefore, we argue for the use of the dimensions of evenness and exposure proposed by Reardon & O'Sullivan (2004) as crucial for characterizing segregation in Latin America and analyzing its relationship with the built environment. This is justified by the particular composition of segregation and its connection to the presence of informal settlements in cities (Sabatini, 2006; Sabatini & Sierralta, 2006), as well as their form resulting from ongoing and accelerated urbanization dynamics (Inostroza, 2017; Inostroza et al., 2013).

3. Methods

3.1. Sample

We used a subsample of 84 Colombian municipalities included in the SALURBAL project. The SALURBAL project included cities of 11 Latin American countries with >100,000 inhabitants as of 2010 at the administrative level (32 for Colombia based on census data) (Diez Roux et al., 2019; Quistberg et al., 2019). The process for identifying SALURBAL cities and their component municipalities is described elsewhere (Quistberg et al., 2019). Several of the SALURBAL cities include more than one municipality. For these analyses, we focused on the municipalities that compose the SALURBAL cities, that is, 84 municipalities (Fig. 1) that we refer to as municipal "cities" for the purpose of this paper.

3.2. Spatial segregation measures

We used the conceptual dimensions of spatial evenness and spatial exposure to measure residential segregation (Reardon & O'Sullivan, 2004). The spatial evenness dimension assesses how homogeneous an individual's local environment is compared to the overall city population (Reardon & O'Sullivan, 2004). On the other hand, the spatial exposure dimension evaluates the extent to which inhabitants of different groups encounter each other in the same spatial environment. While there are several segregation indexes available in the literature (Brown & Chung, 2006; Oka & Wong, 2024; Reardon & O'Sullivan, 2004; Wong, 1993; Wong, 1998; Wong, 2004), we selected the Wong Dissimilarity Index (WDI) for measuring spatial evenness and the spatial isolation index for assessing spatial exposure (Reardon & O'Sullivan, 2004). These indexes were chosen for their ability to incorporate the spatial component into their measurement. A key aspect of our study was including geographic considerations in the segregation calculations to address issues related to the contiguity of geographic areas. We opted to use small to medium-sized areas, which previous studies have shown minimize scale-related effects in Colombian cities (Aliaga-Linares & Álvarez-Rivadulla, 2010; Sabatini & Sierralta, 2006). Additionally, the population within these scales exhibits relatively homogeneous characteristics within each city, reducing variability that could affect calculations. Furthermore, the choice of these indexes ensures interpretability across different scales, equivalence in location, and invariance to population density, making them suitable for the selected variables and facilitating comparability with other studies in the literature.

To estimate indexes, we retrieved data from several sources. We used census data for socioeconomic variables used in the residential segregation metrics and population metrics, GIS data from the census at a "Seccion" scale (an aggrupation of census tracts) as the smallest spatial unit, OpenStreetMap and OSMNx for the street design metrics, and the Global Urban Footprint Dataset derived from TerraSAR-X and TanDEM-X images for the urban landscape metrics (Quistberg et al., 2019). Built environment metrics were selected from previous studies that exhibited a relation with socioeconomic determinants of health (Sarmiento et al., 2021). The total population of the study cities ranged from 2834 to 7,363,782 inhabitants at the municipality level, and the total area ranged from 4.14 to 32,680.53 km^2.

We employed data from the Colombian Census to collect population distribution by sex (male or female), age (ages in groups every five years), school attendance (yes or no), level of education (no studies; primary, secondary, technical, or technological studies; undergraduate studies; or postgraduate studies), employment status (employed, unemployed, or retired), and racial/ethnic self-identification (indigenous, gypsy or Romani, black, mulatto, Afro-descendant or Afro-Colombian, mestizo, or white) for each city. Data were filtered to include only adults older than 24, the most common age corresponding to the conclusion of undergraduate studies in Colombia (Quistberg et al., 2019).

Education is used to measure segregation by socioeconomic level since there is no census information related to income. We constructed four comparisons for education: below secondary, below technical or technological studies, below undergraduate studies, and below postgraduate studies, against the remaining population in each case. These

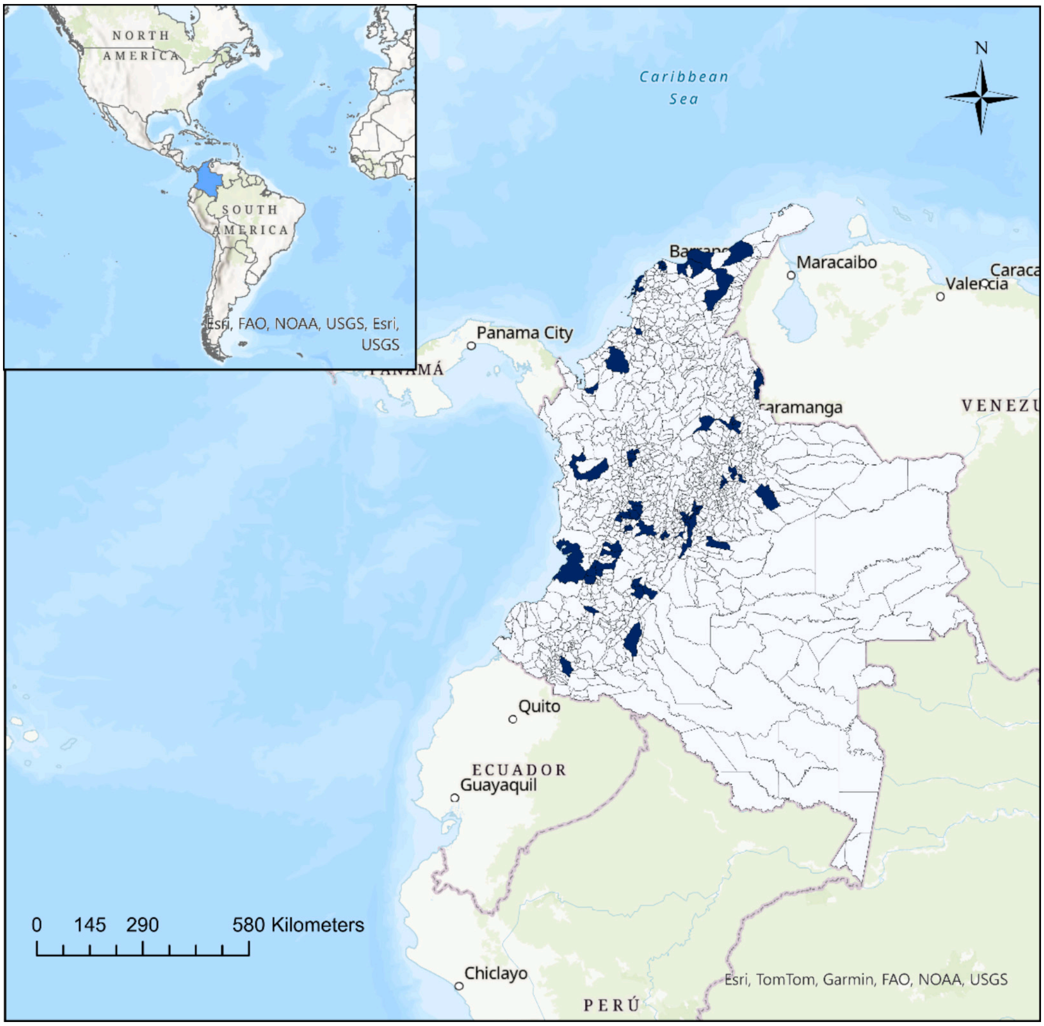

Fig. 1. Distribution at the municipal level of the 1122 municipalities of Colombia and the sample of 84 municipalities with >100 K inhabitants (in blue). Source of geographic data (DANE) and Arcgis. At the left bottom of the graph the location of Colombia within the region (in blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

groupings are adjusted to the educational stages typical in Colombia, unlike other studies in the region. Higher levels of educational specialization correspond to higher entry and graduation rates. For employment status, we compared the employed group with the non-employed based on previous studies (Quistberg et al., 2019). Regarding racial/ethnic self-identification, we created a black group by combining three categories (black, mulatto, Afro-descendant or Afro-Colombian) and compared it with the mestizo and white groups.

The WDI [1] measures the unevenness of a group distribution, including the spatial distribution in contiguous units within the same geographic unit (Wong, 1998). The WDI ranges from 0 to 1 and allows us to identify cities where groups (referring to groups that were created for each of the selected variables) are evenly distributed (WDI = 0) or cities where groups are completely concentrated (WDI = 1) (Wong, 1998). This index is defined by the following formula for a city (Hong et al., 2014; Wong, 1998):

$$[1]\quad WDI = \frac{1}{2}*\sum_{i}^{n}\left|\frac{b_i}{B}-\frac{w_i}{W}\right| - \frac{1}{2}*\sum_{i}^{n}\sum_{j}^{n}\frac{d_{ij}}{\sum_{j}^{n}d_{ij}}*\left|z_j - z_i\right|*\frac{\frac{1}{2}*\left[\frac{P_i}{A_i}+\frac{P_j}{A_j}\right]}{max\left(\frac{P}{A}\right)}$$

where z_i refers to the proportion of the reference group for a particular variable in unit i in the set n of units; d_{ij} is the distance between unit i and the unit j; P_i is the perimeter of the unit i; A_i is the area of unit i; b_i is the total population of the reference group in unit i; w_i is the total population of the rest of the groups in unit i; B is the total population of the reference group in the city; and W is the total population of the rest of the groups in the city. The distance between units is calculated using the centroids of the polygons of each unit and the Euclidean distance. A unit is represented by "Sección," a geographical area defined for the DANE (Departamento Administrativo Nacional de Estadística by its acronym in Spanish) that groups many census blocks.

The spatial isolation index [2] calculates the probability that a member of the reference group encounters members of his own group (Hong et al., 2014; Reardon & O'Sullivan, 2004). This index is defined by the following formula for a city(14):

$$[2]\quad P^{*} = \int_{i\in R}\frac{\tau_{im}}{T_m}*\pi_{im}di$$

where τ_{im} refers to the population density of the group m at the unit i; π_{im} refers to the proportion of the group m at unit i; T_m is the total population of the group m; and R refers to the set of units. The index ranges from 0 to 1, where greater values exhibit higher isolation.

We calculated indexes in both dimensions of residential segregation for education level, employment status, and race/ethnicity (Brown & Chung, 2006). Spatial data from the DANE public information were used for the political-administrative distribution to incorporate the spatial component into the segregation indexes. Census tract polygons were utilized to adjust for the perimeter-to-area ratio in contiguous zones (Tivadar, 2019). To estimate the average statistics of each index for each city in each dimension, we employed resampling using bootstrap techniques with 100 samples (Efron & Tibshirani, 1994; Tivadar, 2019). These indexes were computed using functions available in the OasisR package in R (Tivadar, 2019).

3.3. Built environment measures

We separately analyzed measures of the built environment that encompass the dimensions of urban landscape and street design. The urban landscape dimension assesses the configuration of urban development within each city (Sarmiento et al., 2021). In this domain, we utilized measures such as patch density, area-weighted mean patch size, area-weighted mean Euclidean nearest neighbor distance, and area-weighted mean shape index. These measures are standardized in units of patches, which represent areas of uninterrupted urban development. The size and frequency of these patches are primarily influenced by how settlements have emerged in cities, where planning and urban expansion policies typically dictate the orderly growth of cities.

Patch density is a measure of fragmentation defined as the number of patches divided by the total area of the geographic unit, where larger values reflect higher fragmentation (Irwin & Bockstael, 2007). Area-weighted mean path size is a measure of how large the patches are, where lower values reflect higher fragmentation. Area-weighted mean Euclidean nearest neighbor distance is a measure of how isolated the patches are. This measure is defined as the mean distance (in meters) to the nearest urban patch within the geographic unit weighted by the area of each patch, where higher values reflect higher levels of isolation (Boentje & Blinnikov, 2007). Area-weighted mean shape index is a measure of the shape of the patches. The shape index is a ratio of the actual perimeter of a patch to the minimum perimeter possible for a maximally compact patch of the same size. This index ranges from 1 to infinite, where a value of 1 represents a maximally compact patch and larger values reflect patches with more complex shapes (Irwin & Bockstael, 2007).

For the street design domain, we used the intersection density, street density, and circuity average measures. The intersection density is a measure of street connectivity and is defined as the number of intersections per km^2. The street density is a measure of street connectivity and is defined as the length of the streets (km) per km^2. The circuity average is a measure of directness and is defined as the average ratio of network distances to straight-line distances from every node in the street network to every other node. This indicator ranges from 1 to infinity, where a value of 1 denotes higher directness, and higher values of the indicator reflect less directness (Boeing, 2020).

3.4. Statistical analysis

The statistical analysis proceeded in four phases. First, we compiled and harmonized variables for the cities from census data to construct segregation indexes and built environment measures calculated from the SALURBAL study. Second, descriptive statistics were computed for all variables. Third, Moran's I metric was calculated for each segregation index using sociodemographic characteristics analyzed at the "sección" scale and then rescaled at the municipality level. Moran's I is a measure of spatial autocorrelation that assesses whether the pattern related to a variable is clustered, dispersed, or random among spatial units (Bhattacharji et al., 2000). Moran's I permutations were conducted using Monte Carlo simulation to establish the statistical significance of the observed patterns. The null hypothesis in this test assumes no spatial autocorrelation. Fourth, linear regression models were developed to explore the association between built environment variables and spatial segregation indexes. All models included total area and population as covariates. Statistical analyses were conducted using R (RStudio Team, 2020).

4. Results

4.1. Sociodemographic characteristics

Descriptive characteristics of the study population are presented in Table 1.

Overall, the Colombian population (27,220,271 inhabitants older than 20 years, a typical age of completion of secondary education) is composed of 52.1 % women; more than half of the population is aged between 20 and 60 years (58 %); around 28.4 % are aged <20 years; and 13.5 % are aged >60 years. Regarding ethnicity, only 4.79 % of the population self-identified as black, mulatto, or Afro-descendant or Afro-Colombian. Regarding education level, 73.9 % of the population has not completed higher education (no studies, primary, or secondary); 22.5 % completed undergraduate studies; and only 3.6 % completed postgraduate studies. Regarding employment status, 39.9 % of the population is formally employed, 4.2 % are retired, and 55.9 % are unemployed. This unemployment figure includes people who are informally employed.

When comparing cities by size, the results indicate significant differences in sociodemographic composition across small (fewer than 500,000 inhabitants), medium (500,000 to one million inhabitants), and large cities (more than one million inhabitants). In terms of ethnic distribution, the proportion of minority groups tends to decrease as population size increases. Regarding educational attainment, approximately 14 % of the population in smaller cities hold higher education degrees, whereas in the largest cities, <20 % of the population have attained this level of education. Regarding employment status, the most populated

Table 1
Sociodemographic characteristics of the population cities in the selected sample.

Characteristics	Population size			p-value
	<500 k ($N = 74$)	[500 k–1 M) ($N = 6$)	≥ 1 M ($N = 4$)	
	%	%	%	
Sex				1.00
Male	48.2 %	48.2 %	47.5 %	
Female	51.8 %	51.8 %	52.5 %	
Age				1.00
0–14	21.6 %	22.7 %	18.5 %	
15–19	8.5 %	8.6 %	7.8 %	
20–39	32.8 %	33.5 %	34.7 %	
40–59	23.9 %	23.1 %	24.9 %	
≥ 60	13.3 %	12.1 %	14.2 %	
Ethnic recognition				1.00
Indigenous	1.8 %	0.2 %	0.3 %	
Gypsy	0.0 %	0.0 %	0.0 %	
Black, mulatto, Afro-descendant or Afro-Colombian	5.9 %	5.6 %	3.6 %	
Mestizo or white	92.3 %	94.2 %	96.2 %	
Education level				1.00
No studies	11.0 %	11.1 %	9.4 %	
Primary	41.4 %	40.4 %	34.9 %	
Secondary	24.7 %	26.5 %	25.6 %	
Technical or technological studies	8.8 %	9.5 %	10.2 %	
Undergraduate studies	11.2 %	10.4 %	15.2 %	
Postgraduate studies	2.9 %	2.1 %	4.7 %	
Scholarly assistance				1.00
Yes	26.3 %	25.6 %	24.9 %	
No	73.7 %	74.4 %	75.1 %	
Employment status				1.00
Employed	37.0 %	36.3 %	43.5 %	
Retired	3.7 %	3.0 %	5.0 %	
Unemployed	59.3 %	60.8 %	51.5 %	

The p-value was calculated using a chi-square test. Percentage area was calculated based on the pooled populations.

cities show higher employment rates (43.5 %) compared to less populated cities (37.0 %) (see Table 1).

4.2. Spatial segregation in cities

When measuring the spatial evenness dimension (Table 2) for educational level ($N = 77$ cities), the WDI showed high variability. On average, the WDI was higher (0.2933) for cities where more individuals had completed education below the postgraduate level compared to those with education below the secondary level (0.1639). This indicates that cities tend to exhibit a more even distribution among individuals with lower educational attainment than among those with higher levels of education. For employment status ($N = 78$ cities), the WDI exhibited less variability and a narrower range compared to educational level. On average, the WDI was lower in cities with more employed individuals compared to unemployed individuals, suggesting a more even distribution of employment status across these cities. Regarding race/ethnicity ($N = 79$ cities), the WDI showed high variability. On average, the WDI was higher in cities with a higher proportion of individuals self-identifying as black, mulatto, Afro-descendant, or Afro-Colombian compared to those identifying with other ethnicities. This suggests that cities are more likely to have a homogeneous distribution of individuals self-identifying with the same ethnicity than a heterogeneous distribution. This finding aligns with the underrepresentation of Afro-Colombian populations in certain regions and their concentration in specific cities.

In terms of city size, we find significant differences in the spatial evenness index measured by education level. On average, in larger cities (more than one million inhabitants) the distribution of more educated people and less educated people is less even (0.45) compared with small cities (0.31) and medium cities (0.28). We do not find significant differences for employment status and race/ethnicity by city size. Although not significant differences are seen with global measures, studies in Latin America have shown that this is partly due to the concentration of segregated zones in specific areas in cities that global measures may not be fully capturing (Aliaga-Linares & Álvarez-Rivadulla, 2010).

When measuring the spatial isolation dimension (Table 2) for educational level ($N = 77$ cities), the spatial isolation index exhibited high variability. On average, the index was higher (0.978) for cities with a higher proportion of individuals who completed education below the postgraduate level compared to those below the secondary level (0.566). This indicates that cities tend to have a higher probability of isolating more educated individuals from those with lower educational attainment. For employment status ($N = 78$ cities), the spatial isolation index showed less variability but higher average values. This suggests that, on average, cities are more likely to isolate employed individuals from the unemployed. Regarding ethnicity ($N = 73$ cities), the spatial isolation index displayed the highest variability but lower average values. This suggests that, on average, cities tend to have a higher probability of isolating individuals who self-identify as black, mulatto, Afro-descendant, or Afro-Colombian from those who identify with other ethnicities. In terms of city size, no differences were found in any of the social variables evaluated for the spatial isolation dimension.

4.3. Moran's I estimate

Moran's I metrics were estimated for the WDI regarding educational level (statistic = 0.04, p-value = 0.32), employment (statistic = 0.13, p-value = 0.08), and ethnicity (statistic = 0.21, p-value = 0.03), suggesting that for most social segregation characteristics, there is no significant global spatial autocorrelation with spatial evenness measures. Similarly, Moran's I metrics were calculated for the spatial isolation index regarding educational level (statistic = 0.09, p-value = 0.17), employment status (statistic = 0.11, p-value = 0.11), and ethnicity (statistic = 0.28, p-value = 0.006), indicating that for most of the social variables, there is no significant global spatial autocorrelation with spatial isolation measures. The results of Moran's I suggest that a simple linear model could effectively identify associations between spatial segregation indexes and built environment metrics.

4.4. Urban landscape indicators

Overall, urban landscape indicators varied among cities (Table 3).

The results in the table suggest that there are significant differences by city size in the mean patch size (p-value <0.001) and the mean isolation of patches (p-value = 0.004), where small cities have higher moderate-sized patches and greater isolation compared to the rest of the cities. The urban landscape indicators were slightly lower than the country average for the five most populated cities in the country.

4.5. Street design indicators

Overall, street design indicators varied among cities (Table 3). The results in the table suggest that there are significant differences by city size in the street network connectivity, with an increase in the connectivity as the population size of the cities increases. The street design indicators were higher than the country average for the five most populated cities in the country.

Table 2
Spatial segregation patterns of education, ethnicity, and employment among cities.

Sociodemographic characteristics	Spatial segregation dimensions									
	Spatial evenness					Spatial exposure				
	N	Min	Max	Mean	95 % CI of the mean	N	Min	Max	Mean	95 % CI of the mean
Education level*										
Below secondary	77	0.002	0.305	0.164	[0.147;0.181]	77	0.207	0.566	0.388	[0.373;0.404]
Below technical or technological studies	77	0.000	0.406	0.220	[0.197;0.242]	77	0.436	0.895	0.686	[0.667;0.705]
Below undergraduate studies	77	0.011	0.495	0.267	[0.240;0.293]	77	0.600	0.963	0.804	[0.787;0.822]
Below postgraduate studies	77	0.058	0.522	0.293	[0.267;0.319]	77	0.835	0.978	0.941	[0.934;0.947]
Ethnicity**										
Black, mulatto, Afro-descendant or Afro-Colombian	79	0.078	0.769	0.306	[0.276;0.336]	73	0.002	0.966	0.053	[0.016;0.090]
Employment status***										
Employed	78	0.002	0.155	0.053	[0.047;0.058]	78	0.415	0.713	0.594	[0.581;0.606]

The 95 % confidence intervals of the mean from bootstrap sample are shown in square brackets. N is <84 due to differences in geographic scale that do not allow performing metrics for all units.

* The comparison group for each category is calculated with the remaining population in the other categories.

** The comparison groups are white, mestizos, and indigenous.

*** The comparison groups are unemployed.

Table 3
Descriptive statistics for built environment metrics for selected Colombian cities by population size.

Characteristics	Population size					
	<500 K ($N = 72$)		[500 K–1 M) ($N =$ 8)		≥ 1 M ($N = 4$)	
	Mean	SD	Mean	SD	Mean	SD
Population metrics						
Population density	3152	2930	840	1667	5559	1613
Urban landscape metrics						
Total area (km^2)	860.1	631.1	2056.5	1142.2	7103.7	6388.8
Patch density (patches/km^2)	0.59	0.64	0.43	0.19	0.52	0.22
Area-weighted mean path size (km^2/patches)	1.84	0.89	0.52	0.51	13.26	10.51
Area weighted mean Euclidean nearest neighbor distance (m)	145.16	238.56	97.72	63.01	64.63	2.44
Area weighted mean shape index	3.59	1.03	4.52	0.98	4.97	1.16
Street design metrics						
Intersection density (intersections/km^2)	7.00	9.51	22.56	29.72	41.50	12.79
Street density (m/km^2)	1524.1	1551.7	3289.8	3115.8	6533.2	2299.3
Circuity average	1.1318	0.0861	1.1054	0.0585	1.0595	0.0376

4.6. Association between segregation patterns and built environment metrics

In the spatial evenness dimension, we observed a negative association between segregation patterns based on education level (individuals who completed studies below the postgraduate level or those with the highest education) and race/ethnicity with higher fragmentation (−0.04 for patch). This suggests that the spatial distribution of groups tends to be more diverse (values closer to 0 for the index) or less segregated in cities that are more fragmented. This pattern aligns with the distribution seen in smaller cities, which generally exhibit lower fragmentation compared to larger cities (Sarmiento et al., 2021). For spatial evenness measured by employment status, we found a negative association with the area-weighted mean Euclidean nearest neighbor distance (−0.0006). This indicates that the spatial distribution of groups tends to be more diverse (values closer to 0 for the index) when the isolation of patches is higher. No significant associations were found with the street design metrics (Table 4).

In the spatial isolation dimension, we observed a positive association between segregation measured by education level and fragmentation (0.03). This suggests that in cities with higher fragmentation, there is a greater likelihood of finding a higher proportion of educated individuals compared to those with lower education. This implies that individuals with higher education levels tend to concentrate in specific, more geographically isolated areas from the rest of the population. For employment status, we found associations between the index and intersection (−0.03) and street density (0.04). This indicates that there is a complex relationship where higher intersection density and lower street density tend to be associated with higher levels of employment segregation. Lastly, we identified a positive association between the index measured by race/ethnicity and area-weighted mean Euclidean nearest neighbor distance (0.28). This suggests that when the isolation of patches is higher, there is a greater likelihood of encountering mestizo

Table 4
Linear model estimates for segregation indexes including built environment measures as covariates.

Segregation dimension	Sociodemoghrapic variable	Estimates [CI95%]								
		Patch density (patches/km2)	Area-weighted mean patch size	Area-weighted mean shape index	Area-weighted mean euclidean nearest neighbor distance (meters)	Intersection density (intersections/km2)	Street density (m/km2)	Circuity average	Total urban area	Total population
Spatial evenness	Education level	−0.04 [−0.07;-0.01]	0.04 [−0.11;0.18]	0.02 [−0.01;0.05]	−0.02 [−0.04;0.005]	−0.01 [−0.11;0.08]	0.008 [−0.10;0.12]	−0.01 [−0.03;0.01]	0.006 [−0.03;0.04]	0.03 [−0.11;0.17]
	Employability status	−0.005 [−0.01;0.002]	−0.02 [−0.05;0.02]	0.002 [−0.005;0.009]	−0.006 [−0.01;-0.0002]	−0.006 [−0.03;0.02]	0.01 [−0.01;0.03]	−0.005 [−0.01;0.0008]	−0.0002 [−0.009;0.008]	0.02 [−0.01;0.05]
	Ethnicity	−0.05 [−0.09;-0.01]	0.11 [−0.08;0.30]	0.005 [−0.03;0.04]	−0.005 [−0.03;0.04]	−0.01 [−0.14;0.11]	0.05 [−0.08;0.19]	0.01 [−0.02;0.04]	−0.007 [−0.05;0.04]	−0.12 [−0.31;0.07]
Spatial exposure	Education level	0.03 [0.01;0.04]	−0.01 [−0.08;0.06]	−0.01 [−0.02;0.0005]	0.01 [−0.001;0.02]	−0.006 [−0.05;0.05]	0.00 [−0.05;0.05]	−0.002 [−0.01;0.009]	−0.004 [−0.02;0.01]	0.02 [−0.04;0.09]
	Employability status	−0.004 [−0.01;0.004]	0.01 [−0.02;0.05]	−0.003 [−0.01;0.005]	0.0005 [−0.006;0.007]	0.03 [0.005;0.06]	−0.04 [−0.07;-0.01]	0.002 [−0.005;0.009]	−0.006 [−0.01;0.004]	−0.005 [−0.04;0.03]
	Ethnicity	0.005 [−0.03;0.04]	−0.004 [−0.17;0.16]	0.01 [−0.02;0.05]	0.28 [0.14;0.41]	−0.03 [−0.14;0.08]	0.06 [−0.06;0.18]	−0.02 [−0.05;0.01]	0.12 [0.07;0.16]	−0.01 [−0.18;0.15]

All models were adjusted by urban total area and total population.

people compared to white people. This association may be linked to the historical and spatial concentration of these racial and ethnic groups in specific areas within large cities.

5. Discussion and conclusions

This study enhances our understanding of spatial segregation phenomena by analyzing not only large cities but also low- to middle-sized cities and their association with the built environment in Colombia. We identified higher segregation in the spatial evenness dimension for education level and race/ethnicity, and in the spatial isolation dimension for education level and employment status. Regarding city size, significant differences were found in the spatial evenness index measured by education level, while no differences were observed in the spatial isolation index. In terms of the associations between segregation indexes and built environment metrics, we found negative associations between the spatial evenness dimension for education level and race/ethnicity and fragmentation. Similarly, the index measured by employment status showed negative associations with patches of isolation. In the spatial isolation dimension, we found positive associations between education level and fragmentation, and between race/ethnicity and patches of isolation. Additionally, there was a negative association between employment status and street density. To our knowledge, this is the first study to attempt to measure segregation patterns in cities of various sizes and populations within a low–middle-income country, using the most updated available sources and spatial data.

According to the spatial evenness dimension, the highest segregation was found, on average, for race/ethnicity (0.306). We observed that the spatial distribution of the most educated individuals in cities tends to be less diverse (0.293) compared to those with a lower education level (ranging from 0.267 to 0.164). These findings suggest that individuals with higher socioeconomic status (measured by higher education levels) are more likely to be located in less diverse environments, contrasting with those with lower socioeconomic status. This pattern aligns with the socioeconomic disparities observed across cities, where higher-income groups tend to reside in more isolated areas from lower-income groups. We found a highly diverse spatial distribution of groups when measured by employment status. According to the spatial isolation dimension, the highest segregation was observed, on average, for education level. Despite differences in the proportions of highly educated individuals across cities, the spatial distribution of groups based on this social variable exhibited higher levels of isolation (ranging from 0.388 for below secondary education to 0.941 for postgraduate studies). This suggests that individuals with higher educational attainment are more likely to be isolated from those with lower educational levels within cities. We found moderate average levels of isolation (0.594) by employment status, indicating that employed individuals are more likely to encounter other employed individuals in the same local environment. In terms of ethnicity, we found lower average isolation levels (0.053), suggesting that the probability of encountering members of the same or different ethnic groups in the same local environment is similar.

Our findings indicate that the distribution of highly educated individuals in cities is uneven, and this unevenness is more pronounced in cities with greater spatial fragmentation. These patterns of uneven distribution are predominantly observed in large cities, where access to quality (Greenstein et al., 2000) basic and higher education is often challenging and where students from different social classes or ethnic backgrounds are disproportionately distributed among schools (Collet-Sabé, 2019; Dosh et al., 2003; Greenstein et al., 2000). These observed patterns reinforce recent studies that have highlighted the link between the built environment and social determinants of health. Such studies have shown that less fragmented cities, particularly small to medium-sized ones, are associated with higher population density, limited access to piped water, and lower educational attainment among individuals aged 24 years and older (Sarmiento et al., 2021). These health determinants are closely tied to aspects of quality of life that are often lacking in more segregated environments (Velazquez, 2016). Typically, individuals with higher levels of socioeconomic segregation tend to reside in isolated areas on the outskirts of cities, where infrastructure for basic services and transportation is more precarious (Greenstein et al., 2000; Sabatini, 2006). This situation results in reduced exposure of individuals in more segregated environments to the benefits of high-quality infrastructure and better connectivity.

Regarding the distribution of employment status, we identified a correlation between high concentrations of employed individuals and greater urban fragmentation. Concentrated employment patterns in specific areas with higher fragmentation can exacerbate income inequalities (Álvarez & Orozco, 2015; Duarte Mayorga et al., 2013) and contribute to the emergence of segregation across various sociodemographic dimensions. Additionally, we observed that spatial isolation, as measured by employment status, shows a negative association with street density. This trend is particularly noticeable in localized urban areas where concentrations of unemployed individuals, often situated in informal settlements, are isolated from the economic hubs of cities. This isolation aggravates living conditions for these individuals, exposing them to higher levels of congestion, especially in larger cities (Sarmiento et al., 2021). This situation is exacerbated in countries where informal employment is prevalent, often reported as work but lacking access to social security and formal employment benefits.

Regarding the race/ethnicity distribution, we found associations with lower fragmentation, the same pattern identified previously for education. These configurations are mostly present in small and larger cities, where ethnic populations are concentrated, or in the case of larger cities, where migrations tend to concentrate black populations in marginal areas of cities. These concentrations are related in part to the massive migrations during the last 80 years because of violence and armed conflict (Egea Jiménez et al., 2008).

Regarding the multidimensional nature of the metrics assessed in this study, previous research has demonstrated that segregation in cities arises from multiple dimensions. It has been concluded that the built environment significantly influences the formation of segregation patterns within urban areas (Salazar Miranda, 2020; Schindler, 2015; Spielman & Harrison, 2014). We observed that city size plays a role in determining the levels of segregation present. Given the high rates of urbanization in the region and particularly in Colombia, smaller and medium-sized cities are expected to experience growth comparable to that of larger cities over time. Insights gained from studying large cities can provide valuable lessons for smaller and medium-sized cities, emphasizing the importance of well-organized urban planning. This approach can help mitigate the emergence of informal settlements and urban configurations that contribute to higher levels of segregation.

The relationship between segregation and the built environment can be linked to changes in housing distribution (Spielman & Harrison, 2014), block-level built environment features (Salazar Miranda, 2020), and overall physical characteristics within cities (Schindler, 2015). Our study aligns with these findings, highlighting the significant role of the urban landscape in shaping patterns of segregation. The built environment not only influences segregation but also plays a crucial role in the provision of service infrastructures. Well-planned urban environments typically receive better infrastructure compared to informal settlements that develop haphazardly and often receive infrastructure upgrades belatedly (Danziger & Haveman, 2001; Dosh et al., 2003; Greenstein et al., 2000; Velazquez, 2016). Research indicates that infrastructure tends to be initially concentrated in economically developed areas of Latin American cities where wealthier populations reside (Dosh et al., 2003; Greenstein et al., 2000). Despite efforts to mitigate the impacts of rapid urbanization, persistent economic forces continue to contribute to the creation and perpetuation of areas characterized by high poverty concentrations and segregation.

Our findings should be interpreted in light of several limitations. First, while we utilized the most current satellite data and advanced spatial mapping techniques, variations in our metrics may arise depending on the administrative levels utilized (Quistberg et al., 2019). Second, due to data constraints, we were unable to include additional built environment variables such as mixed land use and informal settlements, which are crucial for a comprehensive understanding of urban dynamics across small to medium-sized cities. This limits the generalizability of our findings, which primarily focused on larger cities and capitals. Third, our segregation metrics represent a specific approach and may not capture all dimensions of segregation. Alternative methods could offer complementary insights and should be explored in future research to enhance our understanding of segregation patterns in real time (Oka & Wong, 2024; Reardon & O'Sullivan, 2004; Wong, 2004). Moreover, self-reported data on race/ethnicity introduces potential biases, although it remains the most feasible method for achieving national comparability. Moving forward, researchers should develop and implement real-time measurement strategies to monitor segregation changes and trends more dynamically. Despite these limitations, our study constitutes a significant advancement in comprehending spatial segregation patterns within Colombia's middle- to low-size cities. Future studies could build upon our findings by integrating mobility data and adopting census-independent approaches to further enrich the spatial analysis of segregation.

To conclude, the spatial configuration of cities significantly influences segregation patterns. This study illustrates the diverse segregation patterns across middle- to large-size cities in Colombia, highlighting their relationship with spatial configuration. Accelerated urbanization processes have adversely impacted city growth, necessitating focused public policies to mitigate these effects and enhance built environment spaces while ensuring equitable provision of public services. The multidimensional approach used to measure segregation expands our understanding of these patterns in Latin American cities. The identified associations can inform spatial interventions that promote diversity within local environments, serving as a foundational step to better locate and characterize these groups across the city. This understanding is crucial for guiding effective place-based policies and interventions aimed at addressing inequality and poverty, particularly in marginalized urban sectors. Given the ongoing urbanization of small- and medium-size cities, which are poised to grow into large cities, it is imperative to grasp the development of segregation patterns early to prevent them from becoming entrenched, especially in informal settlements.

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Andrés F. Useche: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Olga L. Sarmiento:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization. **María José Álvarez-Rivadulla:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Pablo Medina:** Writing – review & editing, Writing – original draft, Formal analysis. **Diana Higuera-Mendieta:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Felipe Montes:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Conceptualization.

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During the preparation of this work the author(s) used ChatGPT in order to improve the wording and style of the document language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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