Factors associated with the spatial distribution of leprosy: a systematic review of the published literature

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Abstract

This systematic review aimed to identify factors related to the spatial distribution of leprosy through studies utilising geographic information systems (GIS) techniques. PRISMA 2020 guidelines were adopted and the Population, Concept, Context (PCC) strategy employed to formulate the research question and define its scope: *what factors associated with the spatial context of leprosy have been identified in studies utilising GIS techniques, and what are the key contributions of GIS in understanding the disease?* The bibliographic databases consulted included PubMed, LILACS, EMBASE and Scopus. Only full original research articles in English, Spanish or Portuguese were included. Of the identified articles, 35 (23.8%) met the inclusion criteria, with the majority addressing socioeconomic factors (60.0%), followed by health indicators (17.1%). A smaller proportion of studies focused on logistics/distance (8.6%) or environmental aspects (2.9%). Although numerous studies utilise GIS techniques for understanding leprosy, few adopt robust methodologies to investigate the factors influencing its spatial features. There is a scarcity of studies employing GIS to examine environmental and logistical aspects related to the spatial distribution of leprosy. Addressing these gaps requires broader dissemination of the potential advantages of GIS in leprosy; the provision of reliable public data; and the capacity-building of professionals committed to combating and controlling leprosy in endemic areas.

Introduction

Geographic Information Systems (GIS) represent a set of technological tools facilitating storage, analysis and visualisation of georeferenced data, that is, information associated with specific geographic locations. These systems integrate digital maps with databases, enabling spatial analysis of events and the identification of patterns and geographical relationships (Chang, 2019a; Chang, 2019b). In public health, GIS have become almost indispensable and have witnessed significant growth, particularly in identifying priority areas for interventions, where mapping is crucial for planning disease control and prevention strategies (Fradelos *et al.*, 2014).

Leprosy is one of the Neglected Tropical Diseases (NTDs) listed by the World Health Organization (WHO). This disease affected 182,815 people worldwide in 2023, including 10,322 children and has been reported in 127 countries, with 80% of cases concentrated in India, Brazil, and Indonesia (WHO, 2024). The disease is caused by *Mycobacterium leprae* or *Mycobacterium lepromatosis* (Han *et al.*, 2008), both of which attack peripheral nerves. Consequently, when diagnosed late, and particularly when sensory nerve damage occurs, the infection leads to permanent physical deformities, compromising the quality of life and work capacity of those affected (MS, 2020). Thus, leprosy remains a significant public health concern, particularly in developing countries. Currently, the use of GIS has significantly enhanced the understanding of geographical distribution and mapping of the NTDs when applied in control programmes to map high-prevalence areas, enabling the more efficient allocation of often scarce resources to the most critical locations. Furthermore, GIS spatial analyses facilitate the estimation of at-risk populations, providing essential data for programme managers in the fight against the NTDs (Brooker & Smith, 2013; Chimfwembe *et al.*, 2024). The use of GIS in understanding leprosy is essential due to the heterogeneous distribution of the disease in endemic regions, which is influenced by socioeconomic, environmental, and healthcare access factors. GIS techniques enable the identification of geographical patterns of leprosy, assisting in the prioritisation of critical areas for interventions and the more efficient allocation of resources for disease control and elimination (Dias *et al.*, 2007; Silva *et al.*, 2017). The WHO recognises and recommends the use of these tools to strengthen surveillance and monitoring in leprosy elimination programmes at national, regional, and sub-regional levels (WHO, 2025). By disrupting essential services such as diagnosis, treatment, and patient follow-up, the COVID-19 pandemic has had a profound impact on the NTDs (Butala *et al.,* 2024), including leprosy (Paz *et al.,* 2022). WHO recommendations led to the postponement of community-based research, the suspension of active case detection efforts, and the interruption of mass treatment campaigns, affecting early detection and disease control until new guidelines were established. In the post-pandemic context, restructuring epidemiological surveillance systems and adopting more effective strategies to map and support vulnerable populations have become urgent priorities (WHO, 2023).

GIS has proven to be an effective tool, particularly during the COVID pandemic and has been strongly recommended to enhance public health responses. However, in the field of leprosy, its practical application remains underestimated (Bakker *et al*., 2009), with few consolidated studies, underutilisation of available tools and a lack of systematisation regarding the factors influencing its implementation. Given the need to improve the use of these technologies during a period of reconstruction in public health systems, a bibliographic review of GIS and leprosy would therefore be particularly timely. To achieve this, it is essential to identify their potential applications and limitations, challenges, and the variables with which these tools have been employed in the leprosy context. Thus, this aim of this review was to address the gaps mentioned by compiling and analysing studies that have explored factors associated with the spatial context of leprosy using GIS techniques, highlighting their main contributions to understanding disease distribution and providing valuable insights for planning more effective surveillance and control strategies.

Materials and Methods

This review followed the guidelines of the Preferred Reporting Items for Systematic Reviews (PRISMA) 2020 (Page *et al.*, 2021). Initially, we applied the Population, Concept, Context (PCC) strategy (Peters *et al.*, 2020) to formulate and structure the research question, defining the scope of the review, as presented in Table 1. Based on this framework, we developed the following guiding question: *what factors associated with the spatial context of leprosy have been identified in studies using GIS techniques, and what are the key contributions provided by GIS in understanding the disease?*

Eligibility criteria

The primary eligibility criterion for this review was the inclusion of full original research articles published at any time and written in English, Spanish or Portuguese and focused on the investigation of leprosy using GIS techniques. These studies were required to report the factors examined or identified in their analyses within the spatial context of the disease, whether descriptive, observational or geostatistical.

Information sources and search strategy

Initially, a survey of potential descriptors was conducted using both Medical Subject Headings (MeSH) (National Library of Medicine, 2024) and Health Sciences Descriptors (DeCS) (Biblioteca Virtual em Saúde, 2024). After refining the terms, searches were performed in representative health-related databases in English, Spanish and Portuguese. The bibliographic databases consulted included Public/Publisher MEDLINE (PubMed), Latin American and Caribbean Literature in Health Sciences (LILACS), Excerpta Medica Database (EMBASE) and Scopus.

Selection process

A search was carried out to identify health-related descriptors that corresponded to the objective of the review. Thus, using the controlled vocabularies of MeSH and DeCS, the following descriptors were selected: “Leprosy,” “Topography, Medical,” “Geography, Medical,” “Geographic Information Systems,” “Geographic Mapping,” and “Remote Sensing Technology.”

To broaden the search results, synonyms or free terms for each of the descriptors were also collected, with the search field was limited to title and abstract, ensuring precision and recall in the results. The search strategies were constructed using a method composed of terms, Boolean operators, and special characters, following combination rules that would allow the retrieval of relevant information in the databases, taking into account the specific characteristics of each database and their indexing languages (English, Spanish and Portuguese).

Thus, for each database used, the search strategy was adapted to its specific language. The following bibliographic databases

Table 1. The Population, Concept, Context' strategy used to define the research question.

Population	Concept	Context
Who are the participants or patients involved?	*What is the concept or phenomenon of interest?*	*In what environment or setting is the research taking place?*
Individuals affected by leprosy, their contacts and members of the general community.	Factors related to the spatial context of the disease in studies using GIS techniques for leprosy.	Any geographical region.

were selected: PubMed, LILACS), EMBASE and Scopus. This set of databases was felt to be justified by its thematic scope, geographical coverage, indexing quality and relevance to the field of public health and the NTDs, particularly leprosy. A detailed description of each search strategy is presented in Table 2.

Screening, abstract reading, article selection and data collection were conducted collaboratively, with the one reviewer (NGO) initially responsible. Reviewer BEB verified and validated the accuracy and consistency of the information and reviewer IMFDB, with expertise in leprosy, conducted the final verification and validation of the epidemiological, clinical and operational data extracted from the articles. The detailed selection process, including exclusion and inclusion criteria, is described in Figure 1.

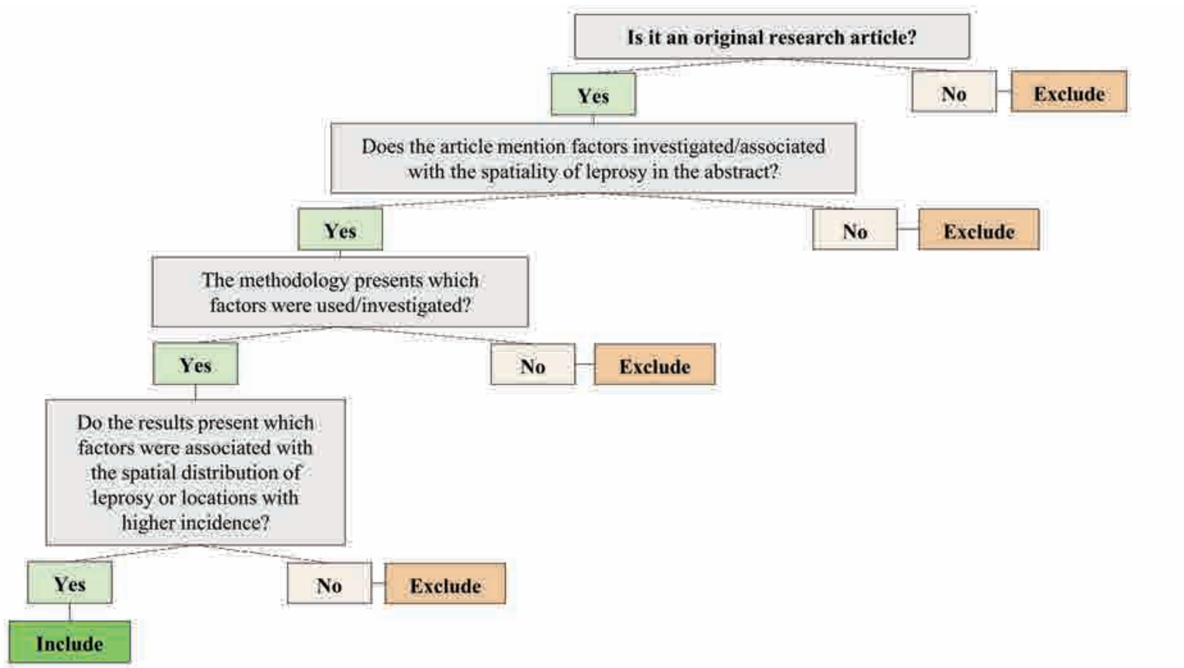

Figure 1. Guiding flowchart of the criteria for the inclusion and exclusion of articles.

Table 2. Article search strategies used to carry out review on factors associated with the spatial distribution of leprosy

Database	Vocabulary found/free vocabulary
PUBMED	((Leprosy[MH] OR Leprosy[TI] OR "Hansen Disease"[TI] OR "Hansen's Disease"[TI] OR "Mycobacterium leprae"[MH] OR "Mycobacterium leprae"[TI]) AND ("Topography, Medical"[MH] OR "Medical Topography"[TI] OR "Dasymetric Mapping"[TI] OR "Choropleth Mapping"[TI] OR Georeferencing[TI] OR Geocoding[TI] OR "Geography, Medical"[MH] OR Geomedicine[TI] OR "Medical Geography"[TI] OR Nosogeography[TI] OR "Spatial Analysis"[MH] OR "Spatial Analyses"[TI] OR "Spacial Analysis"[TI] OR "Geographic Information Systems"[MH] OR "Geographic Information Systems"[TI] OR "Geographic Mapping"[MH] OR "Geographic Mapping"[TI] OR "Geographic Cartography"[TI] OR "Remote Sensing Technology"[MH] OR "Remote Sensing Technology"[TI] OR "Spatial Modeling"[TI] OR "Digital Cartography"[TI] OR "Geoprocessing"[TI]))
LILACS	((mh:Leprosy OR ti:Leprosy OR ti:Hanseníase OR ti:Lepra OR ti:"Doença de Hansen" OR ti:"Hansen Disease" OR ti:"Hansens Disease" OR mh:"Mycobacterium leprae" OR ti:"Mycobacterium leprae" OR ti:"Bacilo da Hanseníase" OR ti:"Bacilo de Hansen") AND (mh:"Topography Medical" OR ti:"Medical Topography" OR ti:"Topografía Médica" OR ti:"Choropleth Mapping" OR ti:Georeferencing OR ti:Georreferenciamento OR ti:Geocoding OR mh:"Geography Medical" OR ti:"Geografía Médica" OR ti:Geomedicine OR ti:"Medical Geography" OR ti:Nosogeography OR mh:"Spatial Analysis" OR ti:"Análisis Espacial" OR ti:"Spatial Analyses" OR ti:"Análisis Espacial" OR ti:"Spacial Analysis" OR mh:"Geographic Information Systems" OR ti:"Sistemas de Informação Geográfica" OR ti:"Geographic Information Systems" OR ti:"Sistemas de Información Geográfica" OR mh:"Geographic Mapping" OR ti:"Dasymetric Mapping" OR ti:"Mapeamento Geográfico" OR ti:"Mapeo Geográfico" OR ti:"Geographic Cartography" OR mh:"Remote Sensing Technology" OR ti:"Remote Sensing Technology" OR ti:"Tecnologia de Sensoriamento Remoto" OR ti:"Tecnología de Sensores Remotos" OR ti:"Spatial Modeling" OR ti:"Modeloespacial" OR ti:"Digital Cartography" OR ti:"Cartografía digital" OR ti:"Geoprocessing" OR ti:Geoprocessamento))
Scopus	TITLE ((leprosy OR "Mycobacterium leprae" OR "Mycobacterium lepromatosis" OR "Hansen Disease" OR "Hansens Disease" AND ("Spatial Analysis" OR "Geographic Information System" OR demography OR "Geographic Mapping" OR "Remote Sensing Technology" OR "Spatial Modeling" OR "Digital Cartography" OR geoprocessing OR kriging OR "Density Estimations Kernel" OR "Geographical Information System" OR "Global Positioning System" OR "Information System Geographical" OR "Accounting Demographic" OR "Distribution Population" OR "Cartography Geographic" OR "Choropleth Mapping" OR georeferencing OR "Nautical Chart" OR "Technology Remote Sensing"))

Data collection process and data items

The Zotero software (Corporation for Digital Scholarship, 2025) was used for the initial processing of the articles, excluding duplicates and texts that were not complete original research articles. Subsequently, a database was created in Microsoft Excel® format to systematically collect information from the selected studies. The database, available in the public GitHub repository (https://github.com/BiomedNathanOliveira/OriginalFragments) provided a detailed overview of the collected information. In summary, the database allowed for the extraction of: i) general information such as authors, year and country of publication; ii) study objectives and design; iii) investigated population; iv) epidemiological measures used; v) details of the analysis, including the geostatistical and data visualisation techniques employed; and vi) main conclusions, encompassing possible associations between factors and the spatial aspects of leprosy, including the authors' perceptions where available, regarding the use of GIS in the study of the disease.

Effect measures

The reported leprosy case rates from the studies were compiled and analysed. As many studies reported rates for different subpopulations or distinct periods, the mean of all reported values was calculated. The multiplication factor also varied among studies, so the values were standardised to the most common factor for each spatial level: 100,000 for administrative regions or municipalities and 10,000 for neighbourhoods and census tracts. The values for each territorial level were structured and converted into a data frame using R software (R Core Team, 2023). A Shapiro-Wilk test was conducted to assess normality, after which a Kruskal-Wallis test was performed using the 'companion to applied regression (car)' package as described by Fox & Weisberg (2023) to determine whether there were statistically significant distribution differences across the categories. The results were visualised using the 'ggplot2' package and illustrated in Microsoft PowerPoint®.

Synthesis methods

To collect citation indicators for the articles, a search was conducted in the Scopus database using digital object identifiers (DOI) and PubMed IDs (PMID). All information was then organised into a Microsoft Excel spreadsheet. Using the 'ggplot2' (Wickham, 2016),'dplyr'(Wickham, 2025) and 'networkD3' packages in R software (R Core Team, 2023), exploratory analyses were performed to guide the narrative review of the articles. Additionally, summary tables (*Supplementary Tables 3 and 4*) were constructed, highlighting key information, focusing on authorship characteristics, study objectives, geostatistical methods, associated factors and the main conclusions of the studies.

A word-cloud was created to highlight the key themes and concepts emphasised by the authors in their conclusions regarding the

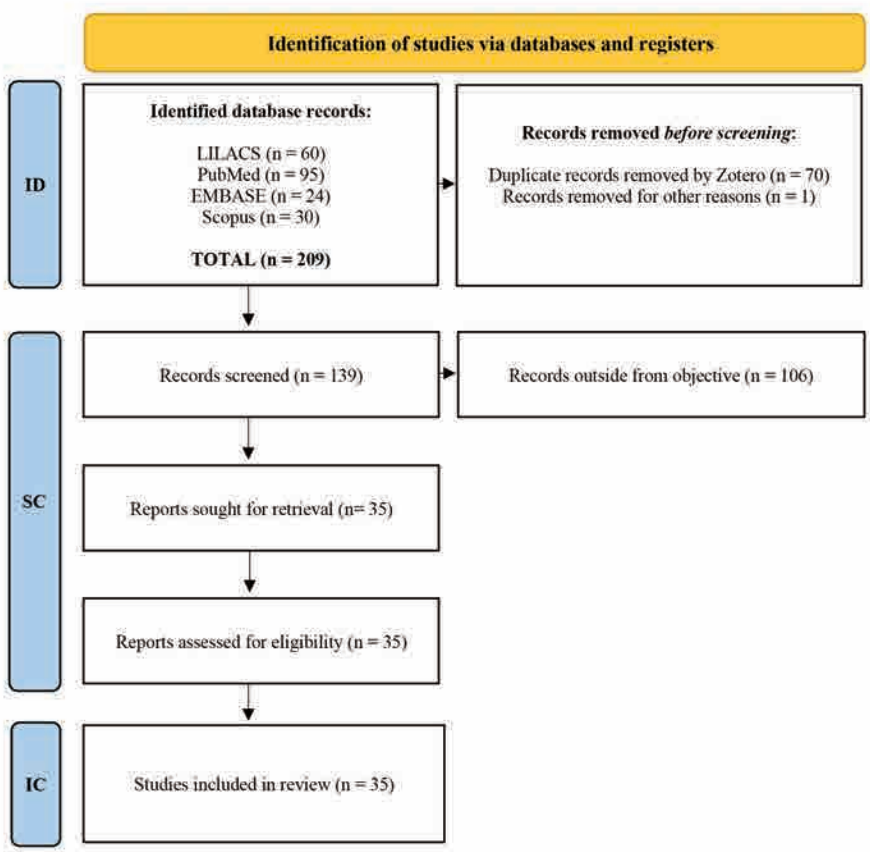

Figure 2. Selection process for the systemic review according to PRISMA. ID, Identification; SC, Screening; IC, Included. *Source: Page MJ, et al. BMJ 2021;372: n71. doi: 10.1136/bmj.n71. This work is licensed under CC BY 4.0. To view a copy of this license, visit https://creativecommons.org/licenses/by/4.0/*

spatial analysis of leprosy. This method identified semantic patterns, revealing the most frequently occurring terms and the aspects considered most relevant (Vilela *et al.,* 2020) related to the use of GIS for studying the disease. The word-cloud was developed based on the authors' insights extracted from the conclusions of the analysed articles. The texts underwent preprocessing in R, including cleaning, removal of irrelevant words and creation of a term matrix to calculate word frequency. The visualisation was generated using the 'wordcloud' package (Fellows, 2022) displaying the most frequent terms with sizes proportional to their prevalence in the dataset.

Results

Study selection

As shown in Figure 2, the search strategies resulted in the identification of 209 articles. Of these, 70 (33.4%) were identified as duplicates, and one was retracted, according to the Zotero software, leaving 139 (66.5%) articles for abstract screening. Among these, 106 (76.2%) were excluded for not presenting factors associated with the spatial distribution of leprosy or for not being original research articles. The remaining 35 (23.8%) articles had their methodologies reviewed to verify whether they met the inclusion criteria. All were within the scope of the review and were deemed relevant, thus being read in full and included.

Study characteristics

The selected articles were published between 2001 and 2023, with 2020 accounting for the highest number of publications (6-6.7%). Twenty-six (82.2%) articles were indexed in the Scopus database, with an average citation count of 14.82, while the general literature on leprosy had an average citation count of 17.29 (Supplementary Table 2). As shown in Figure 3, the majority of the articles were conducted in Brazil (31-88.6%), followed by India with two studies (5.7%). Madagascar, Comoros and Ethiopia were other study locations, each with one article (3.1%).

The results in the Sankey diagram show a diverse relationship between the impact factor of the journals and the number of citations of the articles. It is observed that some highly cited articles were published in low-impact journals, while others with fewer citations appeared in higher-impact journals. Specifically, in Brazilian articles, an average of 15.1 citations was observed, with the majority published in national journals (25-40.0%) (Figure 3). *Supplementary Table 3* summarises the main quantitative information from the studies, including epidemiological measures of leprosy, cases per number of inhabitants, and types of variables. In it, it is possible to verify the references of the articles and the respective information. In summary, the objectives of the included stud-

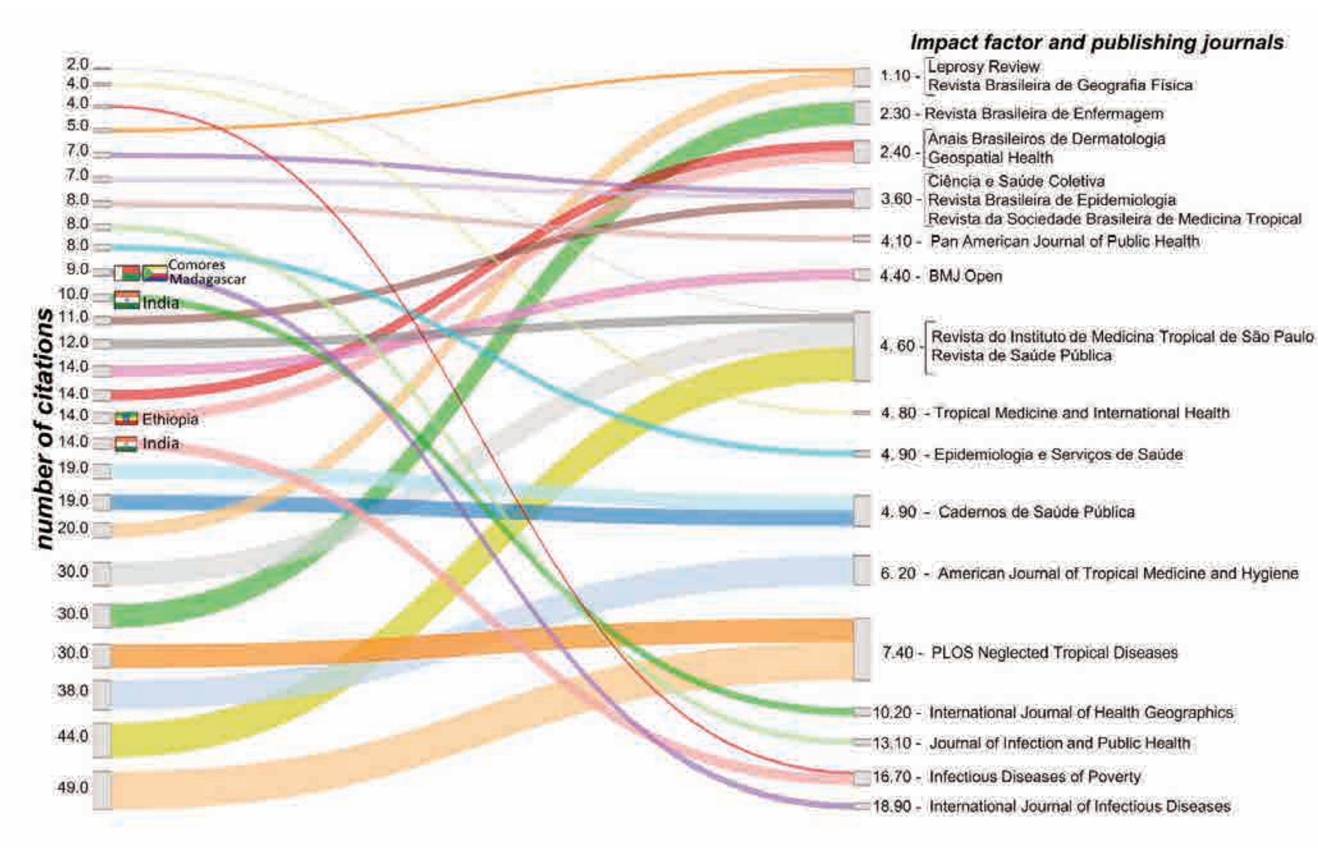

Figure 3. Sankey diagram illustrating the relationship between the impact factor of the selected articles in the SCOPUS database. Number of citations, and the countries where the studies were conducted. Connections without country identification indicate that the research presented in the articles had been conducted in Brazil.

ies were to investigate factors that were present or influenced the epidemiological measures of leprosy in the investigated territories. The epidemiological measures used in the studies (32-91.4%) were predominantly coefficients, found in 21 studies (65.6%). Incidence was addressed in 8 studies (25.0%), while prevalence was mentioned in 3 studies (9.4%).

The factors investigated were predominantly socio-economic (21–60.0%), followed by those using health indicators (6–17.1%). Four studies (11.4%) investigated both socio-economic factors and health indicators (11.1%). Three studies (8.6%) investigated factors related to logistics/distance (8.3%), and one (2.9%) study investigated environmental aspects.

To achieve these objectives, the studies adopted an ecological design using various geospatial methods, applied either concurrently or complementarily based on the research question. These methods can be organised into two main groups: the first group included studies that used spatial modelling techniques such as Markov Chain Monte Carlo (MCMC); Simulation; Ecological Niche-Modelling; Genetic Algorithm for Rule set Production (GARP); Spatial Error Model (SEM); Spatial Lag Model (SLM); Generalized Linear Models (GLMs); Empirical Bayesian Model; and Multivariate Linear Regression (backward method). The second group referred to approaches that applied techniques for cluster analysis and spatial pattern detection, such as Kernel Density (KD); Spatial Scan Statistics; Global Moran's I, Local Moran's I; Voronoi Diagram (Thiessen Polygon); and Kriging. Complementary biostatistical techniques were also employed, including Principal Component Analysis (PCA) with Varimax Rotation; Spearman's Correlation Coefficient; Poisson Regression Model; as well as model assessment and comparison tests: Akaike Information Criterion (AIC); Bayesian Information Criterion (BIC); and Log-Likelihood Ratio (LLR).

Figure 4 presents the leprosy detection rate across different territorial levels, as reported in the studies. The territorial levels investigated by the studies were municipalities (12-34.3%), census tracts (10-28,6%), neighbourhoods (4-11.4%) and villages (2-5.7%). Seven (20.0%) studies were conducted in administrative regions, with two of them specifically focused on health. The studies focusing on municipalities and specifically census tracts or neighbourhoods were conducted in urban areas, with only one study investigating the rural perimeter. The lowest average rate was observed in neighbourhoods (5.1/10,000 inhabitants) followed by census tracts (12.0/10,000 inhabitants) and municipalities (21.8/100,000 inhabitants). Administrative regions recorded the highest detection rate (36.5/100,000 inhabitants). The Kruskal-Wallis test did not reveal a statistically significant difference among territorial levels (*p*=0.2079).

Synthesis

Socio-demographic variables

As previously mentioned, socio-demographic factors were the most investigated in relation to the spatial distribution of leprosy. The articles addressed a wide variety of variables related to development, inequality, and social vulnerability, living conditions, infrastructure, and sanitation, which could be organised into at least four different dimensions according to the topics covered (*Supplementary Table 4*). The first dimension referred to variables related to development and inequality indicators; the second to grouping of indicators of social vulnerability and living conditions focusing on urban infrastructure, human capital, and social deprivations; the third on indicators of infrastructure and sanitation referred to conditions of sanitation and urban infrastructure; and the fourth on socioeconomic indicators, such as economic, educational, and demographic aspects.

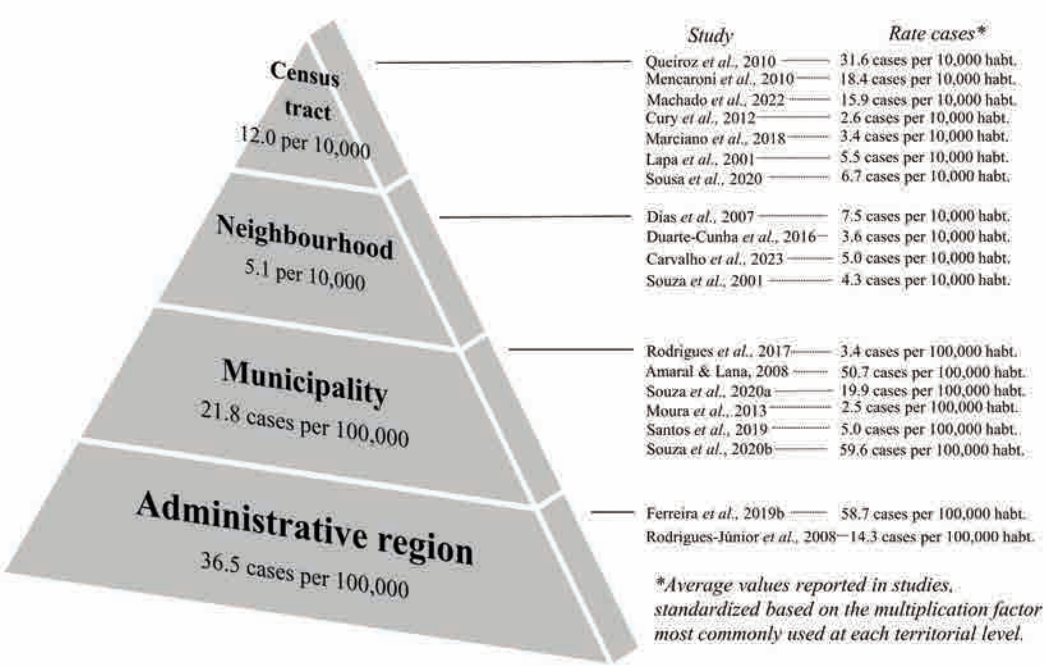

Figure 4. Leprosy rates reported in the studies in relation to the territorial levels studied.

Variables of health

The health-related variables in the studies encompassed various clinical, epidemiological, and operational aspects of healthcare services. The health vulnerability index (IVSA), which integrates several covariates to assess disease susceptibility within a population, was employed in the studies by Rodrigues *et al.* (2017) and Amaral & Lana (2008). In both studies, the territories investigated (census tracts and municipalities, respectively), which exhibited a higher IVSA, showed a significant correlation with areas of greater disease endemicity.

Three studies focused on clinical-epidemiological variables. Duarte-Cunha *et al.* (2016) considered the proportion of different operational classifications, clinical stages, and the degree of physical disability (degree II), and identified that the proportion of cases with an indeterminate clinical form was positively associated with a higher detection rate in the southern region of the study area.

The rate of cases in individuals under 15 years old was assessed in the studies by Souza *et al.* (2020b) and Santos *et al*. (2019), and in both studies, this population indicated regions where disease transmission was active and required healthcare operational interventions. Santos *et al*. (2019) also included the presence of physical disability, as did Franca *et al.,* (2023), which helped to identify areas with weaknesses in early diagnosis.

The study by Souza *et al.* (2020) discussed the prevalence of anti-PGL-I (Phenolic Glycolipid-I) antibodies to analyse geographic patterns of infection and the dynamics of *M. leprae* dissemination across different populations. The authors highlighted that the rapid test for detecting these was essential for identifying asymptomatic individuals in high-endemicity areas, particularly among contacts of index cases within census tracts with higher transmission intensity. The health service operational variables were used in three studies. Borba *et al.* (2021) investigated the coverage of the Family Health Strategy Program and conditions sensitive to primary care, which were significant explanatory variables ($p<0.01$) in relation to the number of new leprosy cases. According to the authors, these data allowed for the identification of spatial vulnerability patterns of the disease in the studied territory and may contribute to the development of contingency strategies. On the other hand, Dias *et al.* (2007) demonstrated that areas that received active search campaigns identified severe cases of the disease, including those in individuals under 15 years old, which could have gone unnoticed by health services. It is noteworthy that the authors also highlighted that the combination of GIS techniques with active search strategies not only increased case detection but also resulted in a significant reduction in costs compared to previous annual campaigns. Finally, the study by Franca *et al.* (2023) assessed the area of influence of the Basic Health Units, delineating the impact of these units on new cases with physical disabilities. The study found a correlation between the absolute number of cases with physical disabilities and the health units with lower efficiency in performing early diagnosis.

Environmental variables

The study by Argaw *et al.* (2006) was the only one to investigate environmental factors potentially associated with the spatial distribution of leprosy. In the study, the authors correlated leprosy prevalence with long-term climatic data (temperature and moisture

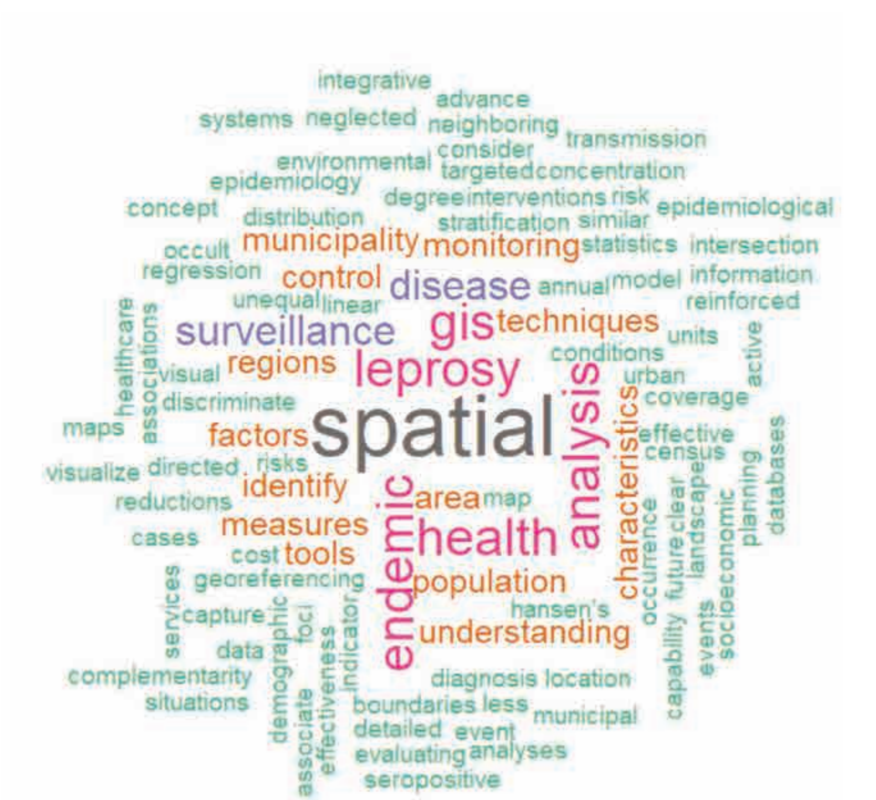

Figure 5. Word-cloud of the perceptions of the authors of the selected articles regarding the contributions of GIS techniques in leprosy.

balance), the normalised difference vegetation index (NDVI) and the maximum daytime surface temperature (Tmax) using GARP based on these data. The study concluded that the viability of *M. leprae* outside the human body, and consequently its transmission, is linked to the thermal-hydrological regime of the environment.

Logistic variables

Three studies investigated logistical factors potentially associated with the spatial distribution of leprosy. Ortuño-Gutiérrez *et al.* (2021) stratified the population of the studied territory into six categories, organised based on varying distances between household contacts, nearby neighbours (<25 m), and other general contact measures (25–<50 m; 50–<75 m; 75–<100 m). The authors identified that 10% of the total leprosy population resided ≤25 metres from another leprosy patient. Compared to those living more than 100 metres away, it was found that the shorter the distance, the higher the risk of disease transmission.

Ribeiro *et al.* (2019) evaluated the spatiotemporal relationship between infection and illness caused by *M. leprae*, comparing historical and clinical aspects between two groups (G1 = cases + contacts; G2 = schoolchildren). The study identified a spatiotemporal relationship between diagnosed cases with a three-year difference, residing within a 100-metre radius ($p = 0.010$). On the other hand, Amaral *et al.* (2020) created maps that associated key characteristics of school-age individuals with the leprosy rate in adults, using linear distance and proximity matrices. The presence of leprosy cases within the family, at a distance of up to 10 km, was associated with schoolchildren who were assessed at school and showed leprosy patches on their skin.

Contributions of GIS on leprosy

Some studies highlighted the key contributions of GIS in understanding and controlling leprosy. As mentioned by Queiroz *et al*. (2010), the use of GIS has been crucial for a better understanding of the epidemiology of the disease. Four studies emphasised the use of GIS for the effective mapping of risk areas, such as Mencaroni *et al.* (2004) and Duarte-Cunha *et al.* (2016), who highlighted that GIS allows for the identification of unequal risks for the occurrence of the disease endemic. Marciano *et al.* (2018) emphasised the importance of annual spatial monitoring to identify transmission hotspots in high-endemic territories.

Two studies highlighted the effectiveness of GIS in leprosy interventions and cost reduction. Dias *et al*. (2007) observed that the use of GIS in leprosy diagnosis enables targeted interventions and significant cost reductions. Cury *et al*. (2012) also pointed out that the use of GIS and spatial analysis are crucial tools in the planning and monitoring of disease control measures.

Finally, two studies highlighted the role of GIS in understanding the relationships between healthcare coverage, diagnosis, and surveillance. Ribeiro *et al*. (2019) indicated that the use of GIS revealed active transmission chains and areas of hidden endemicity. Lapa *et al*. (2001) stated that GIS enables the association of information from various databases and the visualisation of risk situations due to its integrative capacity, significantly contributing to the advancement of spatial analyses in health surveillance systems. Figure 5 presents a word-cloud developed from the perceptions of the authors of the selected articles regarding the contributions of GIS techniques in leprosy. The word "spatial" is central, reflecting the main focus of this study and the reviewed articles. The importance of "spatial" analyses in the disease is followed by terms related to the objectives of the studies, such as understanding the "endemicity" of "leprosy" and "health" of the population through "analyses" using "GIS" techniques. Next, words like "understanding", "regions", "municipalities", "population", "factors", "characteristics", "monitoring", and "control" emerge, highlighting the role of GIS in the development of intervention and prevention strategies through spatial understanding of the disease in the studied territories. The remaining terms were less frequent and appeared at the word cloud's edges. These terms are related to specific approaches used in the studies (e.g., "georeferencing", "indicator", "morbidity", "stratification", "integrative", and "risks") or the effectiveness of its use ("cost", "diagnosis", "future", and "effective").

Discussion

Initially, a larger number of articles was expected to be included in this review. However, out of the 209 studies, only 35 met the inclusion criteria. This is due to the fact that most of the studies focused on exploratory and descriptive analyses, such as the spatial distribution of cases and the endemic situation of the territories, without addressing the relationship between the spatial distribution of leprosy and socio-demographic, environmental, or operational health variables. Although these descriptive analyses are important, the absence of approaches that integrate multiple dimensions limits the understanding of the factors influencing the distribution of leprosy in a more comprehensive and accurate manner.

Although descriptive analyses are valuable, the lack of approaches integrating multiple dimensions limits a comprehensive understanding of the factors influencing leprosy distribution.

Notably, the impact factor of journals did not necessarily correlate with the number of citations, reinforcing that the scientific value of a study extends beyond journal rankings. In GIS-based studies, applicability plays a critical role in supporting research, particularly in epidemiological contextualisation. Regarding leprosy, the WHO recognises GIS as a key tool for monitoring treatment coverage and managing disease elimination programmes at national, regional, and sub-regional levels (WHO, 2025; Bakker *et al*., 2009). The majority of the studies included were conducted in Brazil, a country notable for its wide availability of high-quality public data and a progressive approach to using such information for research and public policy formulation (Ali *et al.,* 2019). However, this scientific output does not uniformly reflect the distribution of the disease burden. Although the Northern and Central-Western regions are the most affected by leprosy, a significant number of studies were carried out in the Southeast, revealing a discrepancy between disease occurrence and the focus of research efforts (Silva *et al*., 2007). Moreover, the importance of using integrated databases, such as Brazil's Information System for Notifiable Diseases (SINAN) and the Brazilian Census, is underscored by Lapa *et al*. (2004), who highlight the relevance of intersectoral actions in improving data quality and ensuring effective planning of control measures.

However, beyond social issues, it is crucial to discuss access to cities, that is, how people in this context have access to basic services such as healthcare, education, and leisure. It is a fact that low-income families, the elderly, people with disabilities, women and ethnic minorities, commonly present in peripheral and rural areas, face disproportionate disadvantages in terms of accessibility due to the lack of suitable options, financial costs, environmental issues and safety. These barriers can also result in the loss of early diagnosis and treatment (Preston & Rajé, 2007; Lucas *et al*., 2016;

Pereira *et al.*, 2020; Tomasiello *et al.*, 2023). Further, Amaral & Lanna (2008) highlighted that the structure and organisation of healthcare services had a greater influence on the epidemiological situation of leprosy in their study than socioeconomic factors. Based on the results obtained using GIS in the study, the authors concluded that there is a need to reformulate the healthcare assistance model, making it more efficient, agile, and accessible for individuals with leprosy. This change should be supported by public policies that ensure the economic, political, and social sustainability of the Leprosy Control Programme, as well as providing financial resources for advancing research in the field.

Climate change will have a profound impact on the epidemiology of many NTDs, in addition to threatening healthcare infrastructure and workforce, and altering fundamental determinants of human health. Recent epidemics, such as those of the Ebola virus, COVID-19 and Mpox, exemplify this scenario (Klepac *et al*., 2024). However, in the case of leprosy, investigations into environmental effects are limited and should be expanded. Recently, a study published after the search strategy of this review was concluded analysed the impact of deforestation and 'anthropisation' in the Legal Amazon, suggesting a correlation between these environmental changes and the increase in leprosy incidence in the region (Valois *et al.*, 2024).

Logistical factors, such as population migration, significantly impact the distribution of leprosy, particularly in endemic regions such as the Brazilian Amazon. The migratory phenomenon affects social organisation and public infrastructure, hindering access to diagnosis and treatment, while also increasing the risk of transmission by exposing non-immune populations to endemic areas (Silva *et al.,* 2010; Urban *et al*., 2021). Thus, continued investigation into environmental and logistical aspects is essential for a deeper understanding of leprosy challenges and for refining public health strategies. For the authors of the studies included, GIS techniques provide valuable contributions to leprosy control, such as annual spatial monitoring and support for diagnosis, enabling more precise interventions and cost reduction. These tools also help in understanding the interactions between healthcare coverage, diagnosis, and surveillance. However, as pointed out by Bakker *et al.* (2009), the added value of GIS in leprosy control programmes is still not widely recognised. Some professionals involved in the control of the disease maintain a critical stance regarding its implementation, pointing out limitations and questioning its benefits. This highlights the need for greater awareness and training about the potential of GIS to optimise strategies for combating leprosy.

Limitations

Although useful, the application of GIS still faces significant limitations, such as inconsistencies and gaps in secondary datasets, which affect the reliability of results. Temporal mismatches between datasets hinder precise analyses, as many indicators and censuses are outdated. The integration of these databases also presents challenges, as territorial discrepancies, variations in sources and formats compromise the consistency of spatial analyses. To overcome these obstacles, investment in standardisation, enhancement of data infrastructure, and capacity-building in spatial analysis is crucial to ensure greater accuracy and reproducibility of information. A potential limitation of this study is its review process, which was restricted to scientific articles indexed in databases, excluding theses, epidemiological bulletins, and conference papers. While incorporating these sources could have broadened the review's scope, the decision aimed to maintain methodological rigour and reproducibility. However, this approach may have overlooked valuable contributions on specific aspects of leprosy and its spatial epidemiology in local contexts. Moreover, although the diversity of spatial methods, approaches, and territorial levels used highlights the versatility of GIS in understanding the spatial dynamics of leprosy, this heterogeneity also presents challenges that hinder more robust analyses of comparability and evaluation of the quality of the studies included. Additionally, the ecological nature of the studies themselves imposes difficulties in interpreting the results, as inferences about individuals from aggregated data can undermine the validity of the conclusions (the ecological fallacy).

Conclusions

The findings of this review underscore the crucial role of GIS techniques in identifying areas with high disease prevalence and reveals additional factors influencing its distribution, thereby supporting more precise public health strategies. To maximise the potential of GIS in leprosy, it will be essential to conduct studies that systematically integrate environmental variables, logistics and operational aspects of healthcare services. Although these factors still appear to be underestimated, they are sufficiently capable of hindering progress and reducing the effectiveness of efforts to combat and control the disease in endemic regions.

In the future, it will be essential to discuss and explore emerging topics in the GIS context that have been addressed in recent research. Among these, the importance of standardised indicators for urban monitoring and sustainable development stands out (Ekmen & Kocaman, 2023). Furthermore, the combined application of GIS and remote sensing can drive sustainable development strategies and enhance community participation (Ramaano, 2024). Participatory GIS also deserves special attention, as recent studies highlight its potential in socio-environmental justice initiatives and community development, using real-world cases as reference (Malakar & Roy, 2024).

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Online supplementary materials

Supplementary Table 1. Fragments of the key information from the 35 articles included in the study.

Supplementary Table 2. Article search strategies used to carry out review on factors associated with the spatial distribution of leprosy.

Supplementary Table 3. Presentation of the main quantitative methodological information on the 35 study articles on leprosy.

Supplementary Table 4. Main examples of the investigated variables that formed the four socio-demographic dimensions associated with the spatial distribution of leprosy.