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Spatial clustering and population density-related patterns of tuberculosis incidence in Semarang City, Indonesia (2016-2022)

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Abstract

Spatial heterogeneity and population density are critical determinants of Tuberculosis (TB) transmission, yet their combined spatial-temporal dynamics are not well understood. This study aimed to examine spatial clustering and population density-related patterns of TB incidence in Semarang from 2016 to 2022. This ecological spatial study used district-level TB surveillance and population data. Spatial patterns were examined to assess the distribution and temporal trends of TB incidence. Global Moran's I and Local Indicators of Spatial Association (LISA) analyses were performed using a first-order Queen contiguity spatial weights matrix to evaluate global and local spatial autocorrelation. Bivariate Moran's I and LISA were applied to examine the spatial relationship between TB incidence and population density. Statistical significance was assessed using 999 Monte Carlo permutations, with $p < 0.05$ considered statistically significant. Spatial distribution of TB in Semarang remained heterogeneous, with consistently higher incidence in northern and central districts and lower rates in southern areas. Significant positive global spatial autocorrelation was observed in most study years (Moran's I = 0.278–0.377; all p-values < 0.05), indicating non-random spatial clustering of TB incidence. Persistent high–high clusters were identified in northern districts, whereas low-low clusters were concentrated in southern areas. The bivariate analysis also demonstrated significant positive spatial associations between population density and TB incidence during 2020–2022 (Moran's I = 0.403, 0.421, and 0.279; all p-values < 0.05). TB incidence in Semarang City exhibited persistent spatial clustering and a positive spatial association with population density. Given the exploratory ecological design of this study, these findings should be interpreted as spatial associations rather than evidence of a causal relationship. The identification of persistent TB hotspots provides evidence to support geographically targeted TB surveillance, active case finding, and resilient TB control strategies in high-risk urban areas.

Key words: tuberculosis, spatial clustering, urban health, population density, Indonesia.

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Introduction

Tuberculosis (TB) remains a major global public health concern and continues to be one of the leading causes of morbidity and mortality from infectious diseases worldwide, with an estimated 10.7 million people developing TB and about 1.23 million deaths in 2024 (World Health Organization, 2025). Despite decades of control efforts, TB persists as a complex and multifactorial disease influenced by biological, social, economic, and environmental determinants making transmission highly sensitive to population dynamics and living conditions (Deng *et al*., 2024; Kussainova *et al*., 2026; Najafizada *et al*., 2021; Shaluhiyah *et al*., 2025). Consequently, progress in TB control remains uneven, with the majority of cases concentrated in low- and middle-income countries where structural and resource constraints continue to limit effective prevention and care (World Health Organization, 2025).

Indonesia has consistently ranked as the second-highest contributor to the global tuberculosis burden in recent years (World Health Organization, 2025). Despite this, the country has made substantial progress in TB control through national strategies aligned with global targets, including improved case detection, expanded treatment coverage, and strengthened surveillance systems (Lestari *et al*., 2023). However, TB incidence remains high, which indicates ongoing transmission and persistent gaps in prevention and control efforts. The burden of TB in Indonesia is not evenly distributed, with urban areas contributing significantly to the overall incidence (Farkhan *et al*., 2026). Rapid urban growth has created environments that facilitate TB transmission by increasing population density and intensifying the risk of infection (Wang *et al*., 2025). High-density settings are characterised by overcrowded housing, poor ventilation, and frequent close interpersonal contact, all of which facilitate TB transmission (Lee *et al*., 2022). Furthermore, informal settlements commonly found in urban areas further exacerbate vulnerability and sustain transmission (Iravatham *et al*., 2019; Noykhovich *et al*., 2019). Nevertheless, population density alone does not fully explain the spatial distribution of TB. Previous studies have shown that socioeconomic deprivation, poor housing conditions, urban slums, population mobility and migration, limited access to healthcare services, and environmental conditions such as air pollution, humidity, and flooding interact to shape local TB transmission dynamics. These determinants may modify the relationship between population density and TB incidence and contribute to spatial heterogeneity across urban settings (Deng *et al*., 2024;

Peptenatu *et al*., 2024; Shaluhiyah *et al*., 2025; Wang *et al*., 2025).

Spatial heterogeneity is a well-established characteristic of TB distribution, with cases often unevenly distributed across geographic areas, forming clusters or hotspots where transmission is more intense. Evidence from spatial epidemiological studies has consistently demonstrated significant clustering of TB across diverse settings, including associations with environmental exposures such as air pollution, socioeconomic disparities, and geographic accessibility to care (Peptenatu *et al*., 2024; J. Wang *et al*., 2023). Studies conducted in Indonesia have similarly identified persistent TB hotspots at subnational levels, indicating localised transmission dynamics that vary across districts and over time (Fahdhienie *et al*., 2024).

Despite these advances, existing studies have largely focused on cross-sectional analyses or specific regions, with relatively limited integration of temporal dynamics and population density factors in rapidly urbanizing settings. Consequently, a comprehensive understanding of how TB transmission evolves spatially and temporally within dense urban environments remains limited. This study therefore examined the period from 2016 to 2022 because complete district-level TB surveillance and population data were consistently available during these years. In addition, this timeframe encompasses the period before, during, and after the COVID-19 pandemic, allowing changes in the spatial distribution of TB incidence to be observed across different phases of health system disruption and recovery. The selected period is also relevant to Indonesia's national TB elimination strategy, which emphasizes strengthening surveillance and targeted interventions in high-burden urban areas. Addressing this gap is critical for informing targeted, place-based interventions. Therefore, this study aims to analyse the spatial clustering and population density-related patterns of TB incidence in Semarang City, Indonesia, over the period 2016-2022. By integrating seven years of district-level surveillance data with descriptive spatial mapping, Global Moran's I, Local Indicators of Spatial Association (LISA), and bivariate spatial analyses, this study identifies persistent TB hotspots and examines their spatial association with population density before, during, and after the COVID-19 pandemic. These findings provide evidence to support geographically targeted TB surveillance and intervention strategies in high-burden urban settings.

Materials and Methods

Study setting

This study was conducted in Semarang City, the capital of Central Java Province, Indonesia. Semarang is a coastal metropolitan city located on the northern coast of Java and serves as an important administrative, economic, and transport hub within the province. According to the Semarang City Statistics Bureau, during 2016-2022, the population increased from approximately 1.6 to 1.66 million inhabitants. Population density varied considerably across districts, ranging from approximately 1176 to 12067 persons/km², reflecting substantial heterogeneity in urban development. Administratively, the city is divided into 16 districts (Figure 1) (BPS-Statistics Indonesia Semarang Municipality, 2022). Semarang was selected as the study area because of its persistently high TB burden and its complex urban characteristics, particularly in the northern coastal districts, which are affected by tidal flooding, overcrowded housing, and poor ventilation, which may contribute to heterogeneous TB transmission (Shaluhiyah *et al*., 2025). The observation period (2016-2022) was selected because complete district-level surveillance and population data were consistently available throughout these years. Furthermore, this period encompassed the epidemiological phases before, during, and after the COVID-19 pandemic, enabling a robust assessment of temporal changes in the spatial distribution of TB incidence.

Study data sources and analysis

Annual district-level TB surveillance data were obtained from the Indonesian National Tuberculosis Surveillance System and included all notified TB cases reported in Semarang City between 2016 and 2022. The dataset comprised all forms of TB, including pulmonary and extrapulmonary TB, and covered both clinically diagnosed and bacteriologically confirmed drug-sensitive TB

Table 1. Full IR rate per district 2016-2022.

No	Districts	IR 2016	IR 2017	IR 2018	IR 2019	IR 2020	IR 2021	IR 2022
1	Tugu	162.29	291.24	255.96	270.00	67.03	169.96	160.22
2	Mijen	121.55	207.37	245.78	156.50	65.51	76.81	101.38
3	Gunung Pati	168.78	139.72	116.31	91.78	81.61	96.60	67.90
4	Ngaliyan	149.13	205.83	185.71	184.05	97.37	123.13	119.25
5	Genuk	212.04	157.39	173.25	224.35	118.40	168.30	127.43
6	Banyumanik	111.62	119.95	145.93	143.07	78.13	100.22	61.56
7	Tembalang	144.59	196.89	187.13	171.83	96.48	140.95	107.50
8	Gajah Mungkur	155.26	172.64	214.25	146.67	136.93	134.27	82.90
9	Semarang Barat	158.04	254.50	227.69	172.68	105.45	145.38	124.56
10	Pedurungan	157.46	175.24	180.25	203.55	145.48	154.30	102.01
11	Semarang Utara	205.30	213.39	255.52	280.83	176.86	199.45	165.44
12	Semarang Selatan	161.69	170.85	198.75	190.01	111.24	167.16	137.23
13	Semarang Tengah	170.70	216.13	246.02	217.67	183.42	168.20	149.07
14	Gayamsari	210.46	220.43	247.08	208.34	111.01	151.88	141.34
15	Candisari	167.38	154.11	225.98	223.79	157.71	172.11	169.22
16	Semarang Timur	181.44	178.60	265.44	266.62	179.48	280.90	174.24

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cases. Records lacking complete district-level geographic identifiers were excluded because they could not be spatially assigned. A total of 4159 cases (17%) were excluded for this reason. Although these exclusions reduced the number of cases included in the spatial analyses, retaining only records with complete geographic information was necessary to ensure the validity of the district-level Moran's I and LISA analyses. The potential for spatial selection bias resulting from the excluded records is acknowledged and discussed in the study limitations.

Annual district-level population and population density data were obtained from the Semarang City Statistics Bureau (https://semarangkota.bps.go.id/id). District-specific TB incidence rates were calculated for each year of observation and standardised per 100,000 population (Zainuddin *et al*., 2022). The incidence rate was calculated as follows:

$$\text{TB incidence rate} = \frac{Number\ of\ TB\ cases\ each\ district}{Total\ Population\ each\ district} x\ 100{,}000$$

The data were analysed using a two-stage spatial analytical approach. First, descriptive and exploratory spatial analyses were conducted, including district-level choropleth mapping, kernel density estimation (heatmap) visualization, and spatio-temporal mapping, to examine the spatial distribution and temporal persistence of TB incidence across districts in Semarang City from 2016 to 2022. Kernel density estimation was conducted using the default bandwidth implemented in QGIS to provide a smoothed visualisation of areas with relatively higher concentrations of TB cases. The heatmap was used solely for descriptive visualization rather than statistical inference.

Second, inferential spatial analyses were performed to formally assess spatial dependence and spatial association. Spatial relationships between districts were defined using a first-order Queen contiguity spatial weights matrix, in which districts sharing either a common boundary or a vertex were considered neighbours. Queen contiguity was selected because it captures both edge and corner adjacency and is widely recommended for areal epidemiological analyses involving administrative boundaries. Global Moran's I statistics were used to evaluate overall spatial autocorrelation of TB incidence and its bivariate association with population density, while Local Indicators of Spatial Association (LISA) were applied to identify local clustering patterns (High-High, Low-Low, High-Low, and Low-High). Statistical significance for Moran's I and LISA was assessed using Monte Carlo permutation tests with 999 random permutations, and results were considered statistically significant at $p<0.05$. To compare local spatial clustering before and after the COVID-19 pandemic, mean annual TB incidence was calculated separately for the pre-pandemic period (2016-2019) and the post-pandemic period (2020-2022). Separate univariate LISA analyses were then performed for each period using a first-order Queen contiguity spatial weights matrix and 999 Monte Carlo permutations. The resulting LISA cluster maps were compared descriptively to examine changes in local spatial clustering between the two periods.

Spatial analyses were conducted using GeoDa 1.22.0.21 (Luc Anselin Center for Spatial Data Science, University of Chicago), while thematic maps and heatmaps were produced using QGIS version 3.99. Data management and descriptive statistics were performed using Microsoft Excel. This study analysed aggregated secondary surveillance data without personal identifiers. Ethical approval was therefore exempted by the Health Research Ethics Committee, Faculty of Public Health, Diponegoro University (No.172/EA/KEPK-FKM/2025), as no individual participant information was accessed.

Results

The TB incidence rate in Semarang City showed a dynamic trend during the period from 2016 to 2022 (Table 1). As indicated in Table 2, the citywide incidence rate increased consistently from 164.86 per 100,000 population in 2016 to 196.99 per 100,000 in 2019. However, in 2020, a significant decline in the citywide incidence rate was observed, decreasing to 119.51 per 100,000 population. This substantial reduction was evident across nearly all districts and coincided with the onset of the COVID-19 pandemic, likely indicating considerable disruptions to TB services. Following the COVID-19 pandemic, the incidence rate significantly increased to 153.10 per 100,000 population in 2021. Several districts consistently exhibited high incidence rates, particularly Semarang Utara and Semarang Timur.

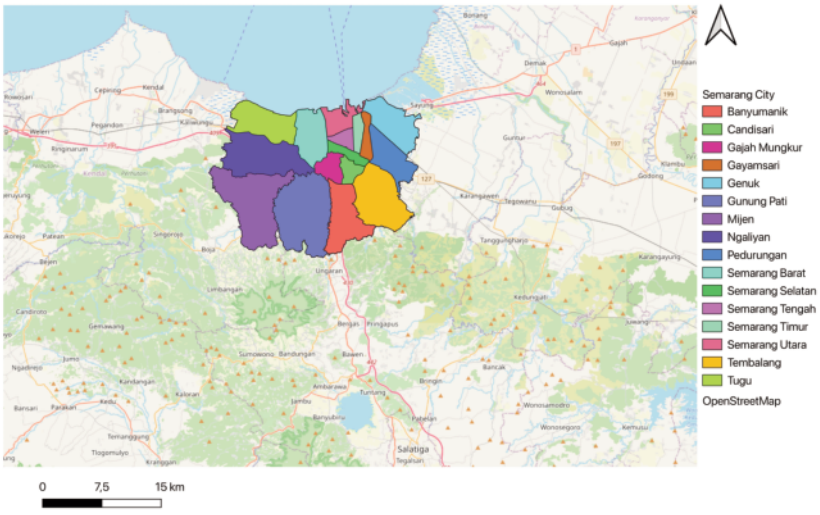


Figure 1. Study area.

Descriptive spatial distribution of TB incidence rate 2016-2022

The district-level distribution of TB incidence rates from 2016 to 2022 showed marked spatial heterogeneity (Figure 2). Throughout the study period, TB incidence was unevenly distributed across districts, indicating persistent geographic disparities in disease burden. During 2016-2018, higher incidence rates were predominantly observed in northern and parts of central districts, while southern districts consistently exhibited lower levels. Although spatial patterns fluctuated over time, recurring high-incidence clusters were observed in northern areas, particularly before 2020. In 2020, incidence rates declined substantially across most districts, resulting in a more uniform and generally lower spatial pattern. This pattern likely indicates disruptions in TB case detection and reporting during the COVID-19 pandemic, including reduced health service utilization and surveillance capacity. These disruptions may have contributed to underdiagnosis and delays in notification rather than a true reduction in TB transmission. In 2021-2022, as health services began to recover from pandemic-related disruptions, localised increases reappeared in selected northern and central districts, while southern districts largely remained in the lowest incidence categories.

Figure 3 further illustrates the spatial distribution of TB incidence from 2020 to 2022, revealing pronounced geographic heterogeneity across districts. The heatmap demonstrates that TB cases are not evenly distributed but are strongly clustered in specific areas, with the most intense hotspots consistently located in the northern and north-eastern parts of the study area. These high-incidence clusters indicate persistent transmission zones that remain affected over time rather than indicating short-term or isolated outbreaks. In contrast, southern districts generally exhibit lower intensity, indicating a comparatively lower TB burden and highlighting clear and stable spatial disparities in disease risk. The aggregation of cases over the 2020-2022 period further reinforces these long-term spatial patterns, which may indicate underlying structural determinants such as population density, socioeconomic conditions, housing quality, and access to health services.

Global spatial autocorrelation, local clusters, and hotspots of TB incidence rate per 100,000 population

The analysis of global spatial autocorrelation through Moran's I confirmed a non-random spatial distribution of TB incidence rates across districts (Figure 4a). The Moran's I values demonstrated that districts with comparable TB incidence rates tended to cluster geographically. In 2016, a moderate positive spatial autocorrelation was observed (Moran's I: 0.313, z: 2.6360, p-value:0.011), which continued into 2017 (Moran's I: 0.325, z: 2.7963, p-value:

Table 2. Semarang City and the five districts with the highest tuberculosis incidence rate per year, 2016–2022.

Districts	IR per 100,000 population						
	2016	2017	2018	2019	2020	2021	2022
Semarang City	164.86	192.14	210.69	196.99	119.51	153.10	124.45
Genuk	212.04	-	-	224.35	-	168.30	-
Gayamsari	210.46	220.43	247.08	-	-	-	-
Semarang Utara	205.30	213.39	255.52	280.83	176.86	199.45	165.44
Semarang Timur	181.44	-	265.44	266.62	179.48	280.90	174.24
Semarang Tengah	170.70	216.13	246.02	-	183.42	-	149.07
Tugu	-	291.24	255.96	270	-	169.96	160.22
Semarang Barat	-	254.50	-	-	-	-	-
Candisari	-	-	-	223.79	157.71	172.11	169.22
Pedurungan	-	-	-	-	145.58	-	-

Note: IR, incidence rate per 100,000 population. The table presents Semarang City and the five districts with the highest TB incidence rate in each respective year. The symbol "–" indicates that the district was not among the five highest incidence-rate districts in that year. Complete annual TB incidence rates for all 16 districts are provided in Supplementary Table S1.

Table 3. Number of statistically significant LISA clusters by study year, Semarang City, 2016–2022.

Study year	Clusters High-High	Low-Low	High-Low	Low-High
2016	4 (Genuk, Gayamsari, Semarang Timur, Semarang Utara)	0	2 (Candisari, Gunungpati)	0
2017	2 (Tugu, Semarang Barat)	1 (Banyumanik)	0	0
2018	0	0	2 (Mijen, Gajahmungkur)	0
2019	3 (Genuk, Gayamsari, Semarang Timur)	3 (Banyumanik, Gunungpati, Gajahmungkur)	0	0
2020	3 (Semarang Utara, Semarang Tengah, Semarang Timur)	2 (Genuk, Semarang Selatan)	0	2 (Ngaliyan, Gunungpati)
2021	4 (Semarang Utara, Semarang Tengah, Semarang Timur, Genuk)	3 (Ngaliyan, Gunungpati, Mijen)	0	1 (Gayamsari)
2022	3 (Semarang Utara, Semarang Tengah, Semarang Timur)	1 (Gunungpati)	0	0

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0.006), indicating a clustering trend during these years. In 2018, the Moran's I values decreased (Moran's I: 0.081, z: 1.0785, p-value: 0.134), indicating a temporary reduction in spatial dependence. However, from 2019 onwards, spatial autocorrelation strengthened again, with moderate positive Moran's I values recorded in 2019 (Moran's I: 0.349, z: 2.9476, p-value: 0.005), 2020 (Moran's I: 0.278, z: 2.3226, p-value: 0.022), 2021 (Moran's I: 0.377, z;3.5639, p-value: 0.001), and 2022 (Moran's I: 0.300, z:2.4925, p-value: 0.018). This pattern suggests that TB incidence maintained a persistent spatial dependence over time, despite short-term temporal variations.

LISA analysis identified statistically significant local clusters of TB incidence (Table 3), thereby enhancing the understanding of the spatial distribution of the disease (Figure 4b and c). Persistent High-High clusters were repeatedly observed in the northern districts, particularly Semarang Timur and Semarang Utara, which appeared in multiple years, indicating sustained TB hotspots. Semarang Tengah emerged as a High-High cluster during 2020-2022, while Gayamsari and Genuk were identified as High-High clusters in several earlier years. In contrast, Low-Low clusters were relatively uncommon and were identified only in Semarang Selatan and Genuk in 2020 and Gayamsari in 2021. Low-High clusters occurred intermittently, primarily in Gunungpati, Ngaliyan, Mijen, Banyumanik, and Gajah Mungkur, indicating districts with relatively low TB incidence surrounded by neighbouring districts with higher incidence. High-Low clusters were detected only sporadically, occurring in Candisari and Gunungpati in 2016 and Gajah Mungkur and Mijen in 2018. Overall, these findings demonstrate that TB hotspots persisted predominantly in the northern districts of Semarang City, whereas southern districts generally exhibited weaker or more transitional spatial clustering patterns.

Comparison of local spatial clustering of TB incidence pre and post pandemic

Figure 5 compares the local spatial clustering of TB incidence between the pre-pandemic (2016-2019) and post-pandemic (2020-2022) periods. During the pre-pandemic period, three statistically significant High-High clusters, three Low-Low clusters, and one High-Low spatial outlier were identified. In contrast, during the post-pandemic period, the number of High-High clusters increased to six, while three Low-Low clusters remained and no spatial outliers were observed. These findings suggest that local spatial clustering of TB incidence became more consolidated in the northern districts during the post-pandemic period, whereas southern districts continued to exhibit relatively low TB incidence.

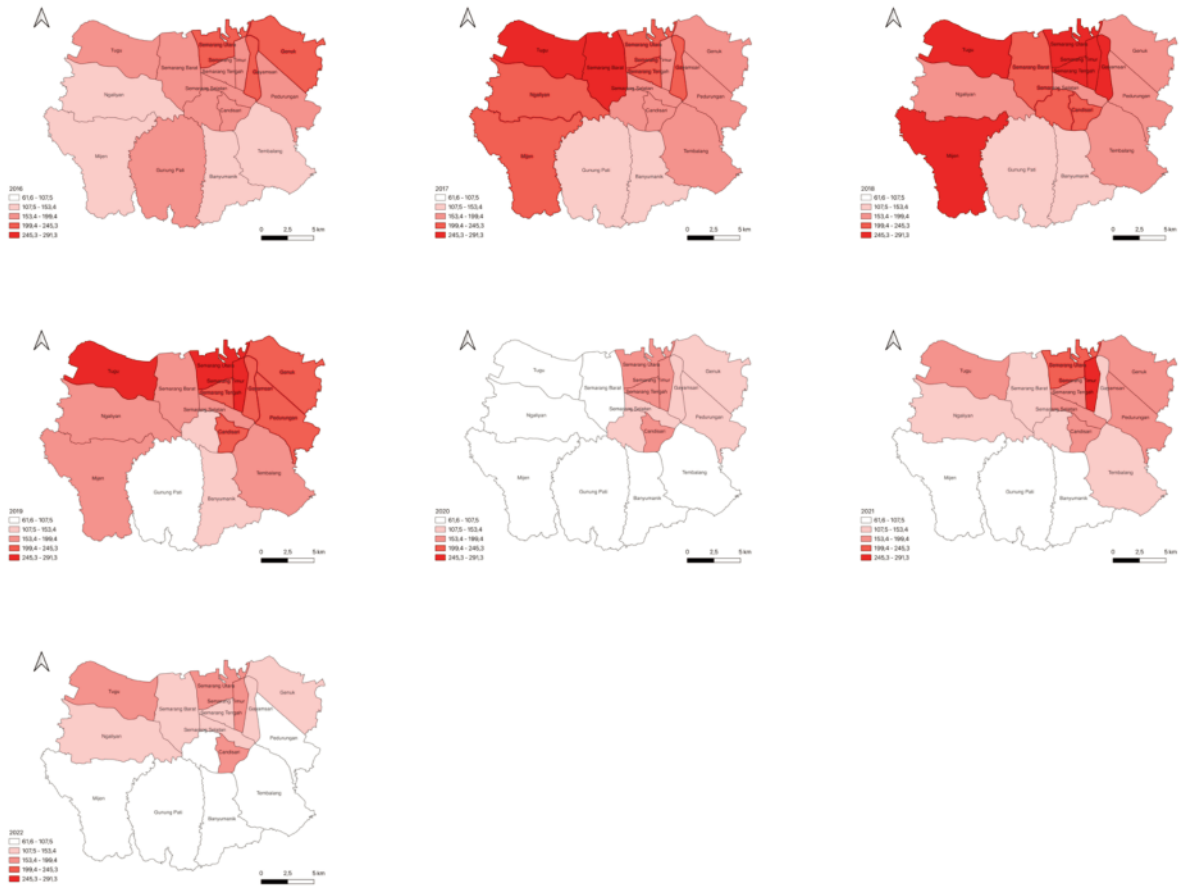


Figure 2. Spatial distribution of TB incidence rates at the district level from 2016 to 2022.

Spatial association between population density and TB incidence rate per 100,000 population

Figure 6 presents the bivariate spatial association between population density and tuberculosis (TB) incidence in Semarang City from 2016 to 2022 using Global Moran's I and bivariate LISA. The Global Moran's I results indicate a predominantly positive spatial autocorrelation between TB incidence and population density across the study period, although the magnitude of association varied over time. A moderate positive spatial association was observed in 2016 (Moran's I = 0.325, z: 2.9152, p-value: 0.004), followed by a near-random spatial pattern in 2017 (Moran's I = −0.039, z: -0.4612, p-value: 0.300). From 2018 onward, the spatial association strengthened again, with Moran's I values of 0.111 (z: 1.1871, p-value: 0.133) in 2018 and 0.281(z: 2.6132, p-value: 0.009) in 2019. The strongest spatial autocorrelation was observed during 2020-2022, with Moran's I values of 0.403 (z: 3.1924, p-value: 0.006), 0.421 (z: 3.6557, p-value: 0.001), and 0.279 (z: 2.5239, p-value: 0.011), respectively, indicating persistent spatial clustering of TB incidence in relation to population density in the later years of the study period.

The bivariate LISA cluster maps further demonstrate substantial spatial heterogeneity in the local relationship between TB incidence and population density. Across multiple years, high-high clusters were consistently identified, indicating districts with high TB incidence surrounded by districts with high population density. Conversely, low-low clusters were observed in districts with comparatively lower TB incidence and lower surrounding population density. Spatial outliers were identified intermittently, indicating localised deviations from broader spatial patterns. Overall, these findings demonstrate that the spatial distribution of TB incidence in Semarang City is non-random and context-dependent, with persistent localised clustering associated with population density.

Discussion

This study demonstrates that TB incidence in Semarang City is spatially structured, with persistent clustering and clear intra-urban disparities, which indicate that transmission is strongly shaped by localised environmental and demographic conditions. The temporal trend shows a steady increase in TB incidence from 2016 to 2019, followed by a sharp decline in 2020 and a partial rebound thereafter. The observed decline in 2020 may indicate disruptions in TB case detection and reporting during the COVID-19 pandemic rather than a true reduction in TB transmission. Similar declines have been reported globally, where restricted mobility, overwhelmed health systems, and reduced healthcare-seeking behaviour led to underdiagnosis of TB (Falzon *et al*., 2023; Surendra *et al*., 2023). Studies from Indonesia have likewise documented substantial declines in TB notifications during the COVID-19 pandemic, suggesting that reduced case detection may have contributed to the observed temporal pattern (Lestari *et al*., 2023; Surendra *et al*., 2023). The subsequent increase in 2021 may indicate the gradual recovery of TB services and surveillance activities, although this study did not directly evaluate health service utilization or reporting completeness. The decline observed in 2022 should therefore be interpreted cautiously, as it may also have been influenced by changes in case detection and reporting practices. Modelling studies have suggested that disruptions to TB services during the pandemic could result in an accumulation of undetected cases, potentially sustaining community transmission even after health systems begin to recover (Bui *et al*., 2025; Winglee *et al*., 2022). The persistent spatial inequality in TB distribution showed that northern and central districts consistently exhibited higher incidence rates, while southern districts remained relatively low. This stable spatial configuration suggests that TB risk is not randomly distributed but embedded within underlying socio-environmental and structural conditions. The concentration of TB in northern coastal areas, often characterized by higher population density, informal settlements, and limited living space, highlights the role of overcrowding, poor ventilation, and socioeconomic vulnerability in sustaining transmission (Saparina *et al*., 2024; Shaluhiyah *et al*., 2025). Environmental stressors such as flooding, poor sanitation, and substandard infrastructure are also commonly observed in coastal and low-lying urban settlements that further exacerbate health risks by weakening overall living conditions and reducing the capacity for effective disease prevention (Tariq *et al*., 2026). In contrast, southern districts, which tend to have lower population density, better housing quality, and improved urban infrastructure, consistently demonstrate lower TB incidence, indicating a more protective environment (Findayani *et al*., 2024, 2019).

The spatial statistical analysis further demonstrates that TB incidence is significantly clustered. The stronger spatial autocorrelation observed during 2020-2022 may indicate that TB incidence became more spatially concentrated during and after the COVID-19 pandemic. However, because this study did not directly assess changes in healthcare access or surveillance performance, these findings should be interpreted as spatial patterns rather than evidence that the pandemic itself caused the observed clustering. Similar spatial clustering has been reported in China, where TB incidence demonstrated significant positive spatial autocorrelation across multiple years (Wang *et al*., 2012). Likewise, a study in Fujian Province identified persistent High-High and Low-Low clusters over time, suggesting that TB hotspots are associated with long-standing socioeconomic and environmental conditions rather than short-term fluctuations (Yu *et al*., 2024). These findings suggest that TB hotspots are not transient phenomena but are sustained by underlying socioeconomic and environmental conditions.

Another important finding was the significant spatial association between TB incidence and population density. The stronger association observed during 2020-2022 suggests that districts with higher population density tended to be spatially associated with neighbouring districts experiencing higher TB incidence.

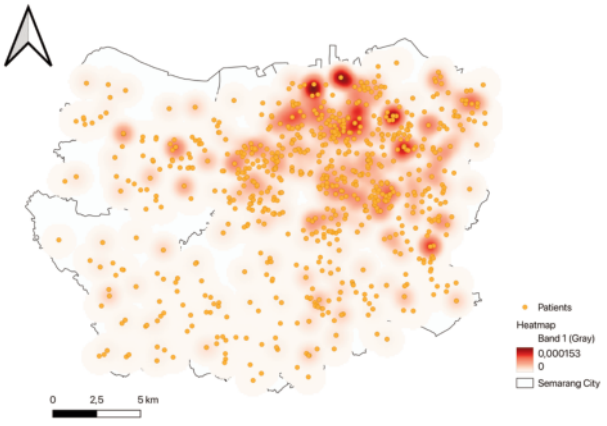


Figure 3. Heatmap of TB incidence 2020-2022.

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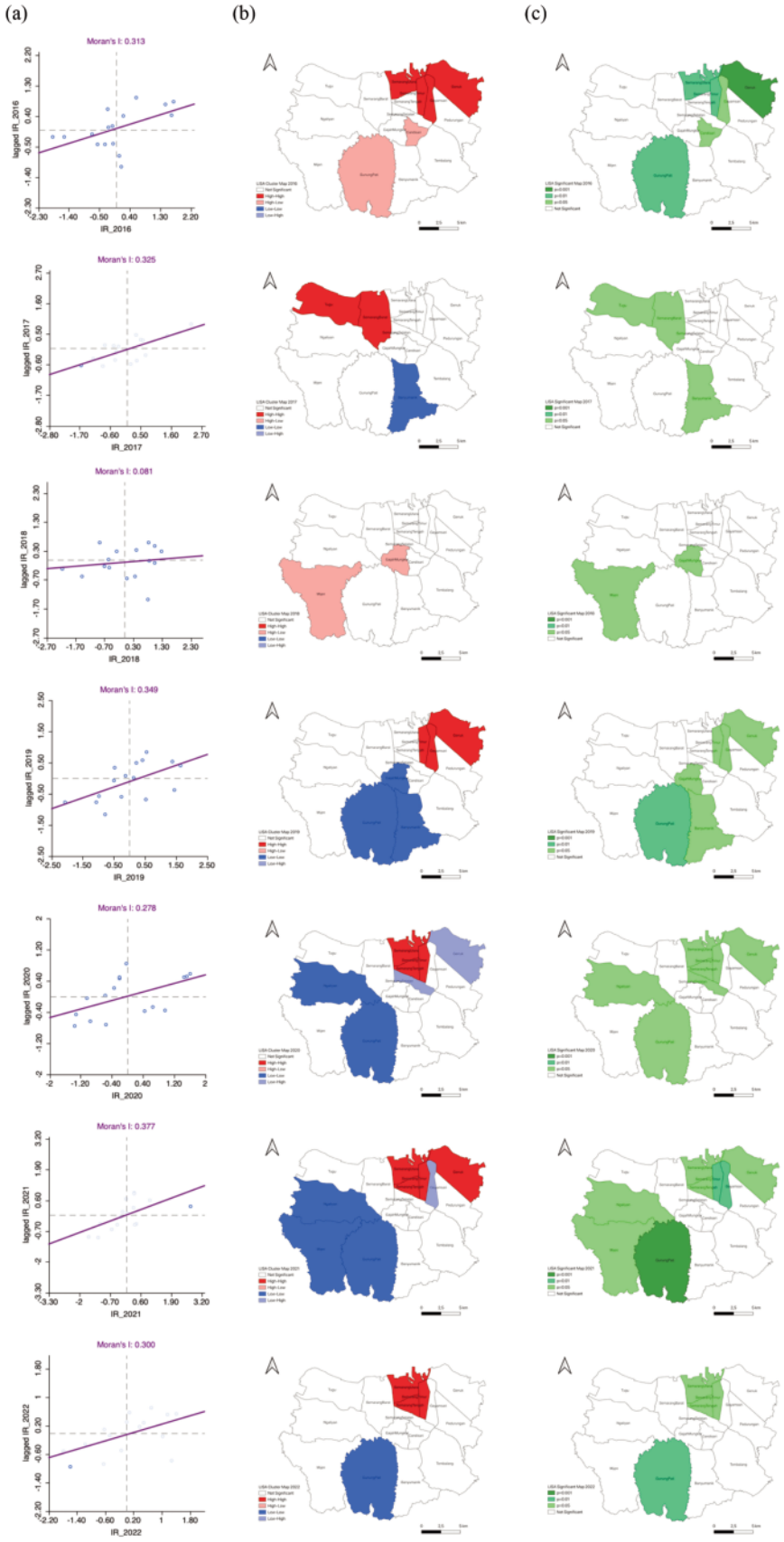


Figure 4. Variation of TB incidence per 100,000 population in Semarang 2016-2022 (**a**) Moran's I scatterplot matrix; (**b**) LISA cluster map (univariate); (**c**) LISA significant map (univariate).

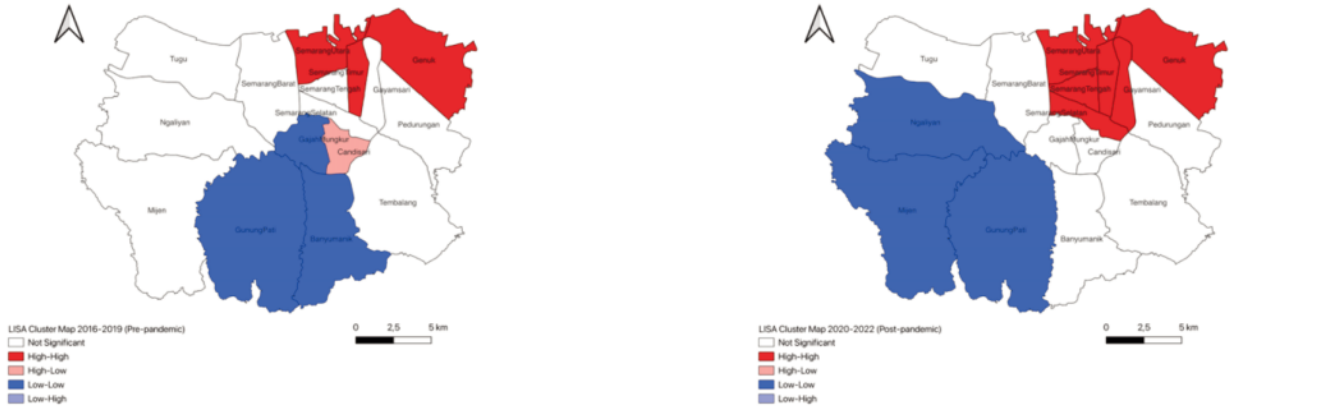


Figure 5. Comparison of Local Spatial Clustering (LISA) of tuberculosis incidence between the pre-pandemic (2016-2019) and post-pandemic (2020-2022) periods.

However, this association should not be interpreted as evidence of a causal relationship. Population density was the only explanatory variable included in the bivariate spatial analysis, whereas TB transmission is influenced by multiple interacting determinants, including socioeconomic deprivation, housing quality, migration, healthcare accessibility, environmental conditions, and behavioural factors. Consequently, the observed spatial association may partially indicate the influence of these unmeasured factors rather than the independent effect of population density alone. Nevertheless, previous studies have reported that high-density urban environments facilitate prolonged close interpersonal contact, increasing opportunities for airborne transmission (Hu *et al*., 2023; Peng *et al*., 2022; Prapinsri *et al*., 2025). The identification of consistent High-High clusters in densely populated districts suggests that interventions targeting these areas, such as active case finding, improved housing conditions, and community-based screening, could yield a substantial impact.

These highlight the need for spatially targeted TB control strategies in Semarang. Interventions should prioritize northern high-incidence districts, particularly those with high population density, through enhanced surveillance, community engagement, and tailored public health responses. Because the present study was exploratory and ecological in nature, future research should incorporate multivariable spatial regression models that include socioeconomic, environmental, and healthcare-related factors to better understand the determinants of TB spatial distribution and quantify their relative contributions. Additionally, strengthening the resilience of TB services during public health emergencies is critical to prevent future disruptions similar to those observed during the COVID-19 pandemic.

Strength and Limitation

This study has several strengths. It provides one of the first longitudinal assessments of the spatial distribution of TB incidence in Semarang City over a seven-year period, integrating descriptive spatial mapping with global and local spatial autocorrelation analyses to identify persistent TB hotspots and their spatial association with population density. The use of routinely collected surveillance data enabled the assessment of long-term spatial patterns that are directly relevant for local TB control planning.

Nevertheless, this study has several limitations that should be acknowledged. First, this was an ecological study conducted at the district level; therefore, the observed spatial associations may not necessarily indicate relationships at the individual level and are subject to ecological fallacy. Second, the analysis included only 16 administrative districts, which may reduce the statistical stability of Moran's I and LISA estimates and increase their sensitivity to neighbourhood definitions and the Modifiable Areal Unit Problem (MAUP). Third, the study relied on routinely reported TB surveillance data, which may be affected by underreporting, delayed case notification, and changes in reporting practices, particularly during the COVID-19 pandemic. In addition, approximately 17% of notified TB cases were excluded because district-level geographic identifiers were unavailable. Although exclusion of these records was necessary for valid spatial analysis, if the missing geographic information was not randomly distributed, some degree of spatial selection bias may have occurred. Fourth, population density was the only explanatory variable included in the bivariate spatial analysis. Other determinants of TB transmission, including socioeconomic deprivation, housing quality, informal settlements, migration, healthcare accessibility, environmental conditions, and behavioural factors, were not examined and may have contributed to the observed spatial patterns. Finally, because this study employed an exploratory ecological design, the identified spatial association between population density and TB incidence should not be interpreted as evidence of a causal relationship. Future studies should incorporate multivariable spatial regression approaches, such as Spatial Lag Models, Spatial Error Models, or Geographically Weighted Regression, to better quantify the independent contributions of multiple determinants to TB spatial distribution.

Conclusions

TB incidence in Semarang City exhibited dynamic temporal changes and persistent spatial heterogeneity throughout the study period. The decline in reported TB incidence in 2020, followed by an increase in 2021 and a subsequent decrease in 2022, may reflect disruptions in TB case detection and reporting during the COVID-19 pandemic, although this study did not directly assess health service performance. Spatial analyses identified significant spatial clustering of TB incidence, with persistent hotspots in northern districts and lower-incidence clusters in southern districts.

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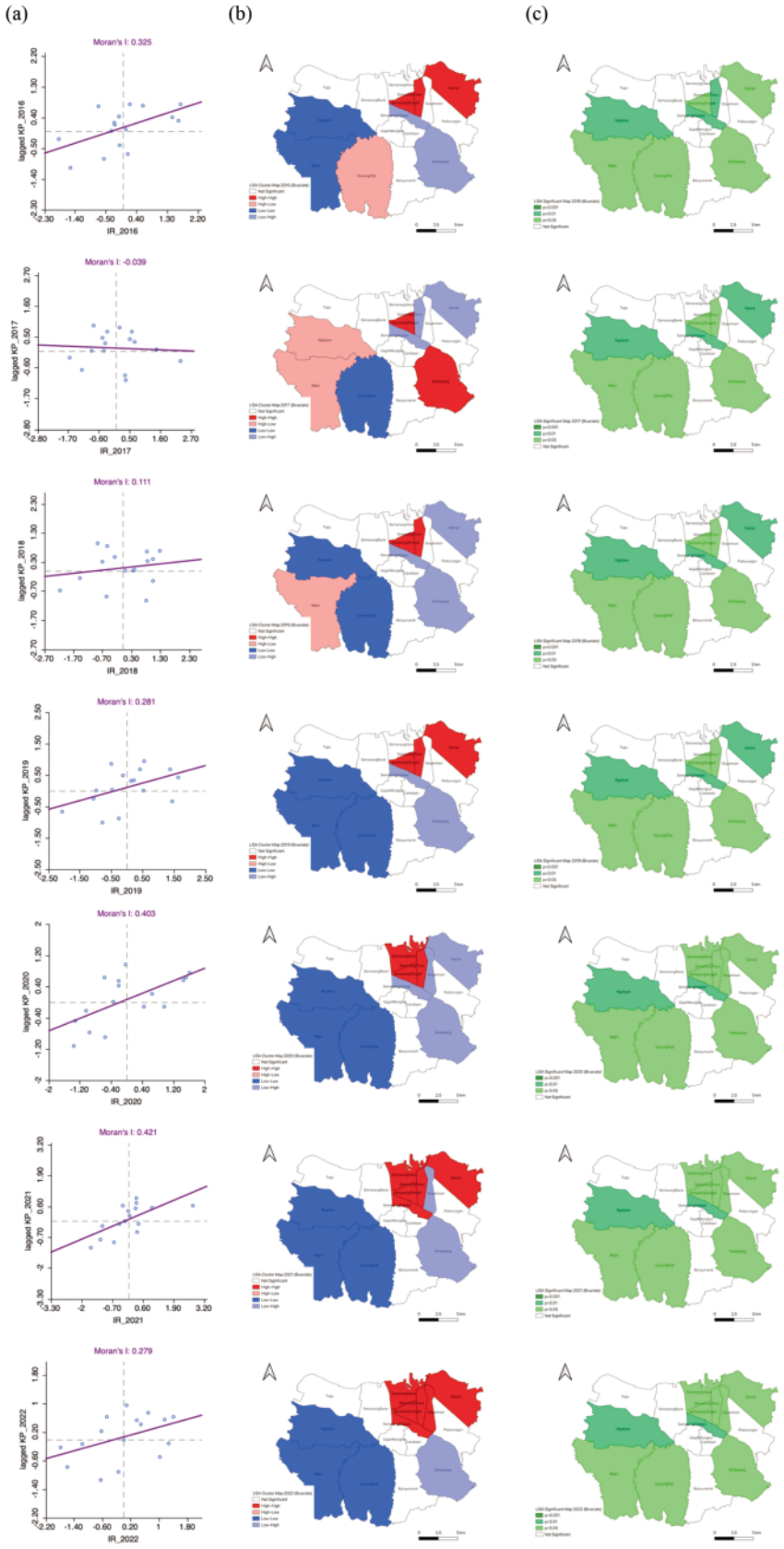


Figure 6. Correlation of population density and TB incidence rate per 100,000 population in Semarang 2016-2022. (**a**) Moran's I scatterplot matrix; (**b**) LISA cluster map (bivariate); (**c**) LISA significant map (bivariate).

Bivariate spatial analysis further identified a positive spatial association between population density and TB incidence; however, given the exploratory ecological design and the inclusion of population density as the only explanatory variable, these findings should not be interpreted as evidence of a causal relationship. Other socioeconomic, environmental, housing, and healthcare-related factors may also contribute to the observed spatial patterns. Nevertheless, the identification of persistent TB hotspots provides valuable evidence for prioritizing geographically targeted TB surveillance, active case finding, and community-based interventions, while highlighting the importance of strengthening resilient TB services to minimize disruptions during future public health emergencies.

References

BPS-Statistics Indonesia Semarang Municipality, 2022. Semarang Municipality Population. BPS-Statistics Indonesia, Semarang Municipality.

Bui VL, Ragonnet R, Hughes A, Shipman DS, McBryde ES, Nguyen BH, Do HN, Ha TS, Fox GJ, Trauer JM, 2025. Impact of case detection and COVID-19-related disruptions on tuberculosis in Vietnam: a modeling analysis. J Infect Dis 232:e682-e690.

Deng L, Zhao F, Li ZW, Zhang WW, He GX, Ren X, 2024. Epidemiological characteristics of tuberculosis incidence and its macro-influence factors in Chinese mainland during 2014-2021. Infect Dis Poverty 13:34.

Fahdhienie F, Sitepu FY, Depari EB, 2024. Tuberculosis in Aceh Province, Indonesia: a spatial epidemiological study covering the period 2019-2021. Geospat Health 19:1318.

Falzon D, Zignol M, Bastard M, Floyd K, Kasaeva T, 2023. The impact of the COVID-19 pandemic on the global tuberculosis epidemic. Front Immunol 14:1234785.

Farkhan A, Lawpoolsri S, Soonthornworasiri N, Pakasi TT, Sulistyo S, Salsabila A, Maude RJ, Surendra H, Rotejanaprasert C, 2026. Spatiotemporal epidemiology, geographic hotspots, and risk factor associations of drug-resistant tuberculosis incidence in Indonesia: a Bayesian hierarchical modelling approach. Infect Dis Poverty 15:23.

Findayani A, Aji A, Indrayati A, 2019. Semarang City food risk disaster mapping based on geographic information system. Adv Soc Sci Educ Human Res 313:74.

Findayani A, Hayati R, Amrullah MF, Rahman AU, 2024. Towards a resilient city: analyzing Semarang preparedness in facing disaster related to climate change, Indonesia. Jambura Go Educ 5:54-66.

Hu Y, Lin Z, Jiao S, Zhang R, 2023. High-density communities and infectious disease vulnerability: a built environment perspective for sustainable health development. Buildings 14:103.

Iravatham CC, Kumar VS, Valluri VL, 2019. Identifying and mapping TB hot spots in an urban slum by integrating Geographic Positioning System and the local postman - A pilot study. Indian J Tuberc 66:203-8.

Kussainova A, Kassym L, Kussainov A, Orazalina A, Smail Y, Derbissalina G, Bekbergenova Z, Kozhakhmetova U, Aitenova E, Semenova Y, 2026. Impact of Social Determinants of Health on the Incidence of Tuberculosis in Central Asia. Int J Environ Res Public Health 23:68.

Lee JY, Kwon N, Goo G, Cho S, 2022. Inadequate housing and pulmonary tuberculosis: a systematic review. BMC Public Health 22:622.

Lestari T, Fuady A, Yani FF, Putra IWGAE, Pradipta IS, Chaidir L, Handayani D, Fitriangga A, Loprang MR, Pambudi I, Ruslami R, Probandari A, 2023. The development of the national tuberculosis research priority in Indonesia: A comprehensive mixed-method approach. PLoS One 18:e0281591.

Najafizada M, Rahman A, Taufique Q, Sarkar A, 2021. Social determinants of multidrug-resistant tuberculosis: A scoping review and research gaps. Indian J Tuberc 68:99-105.

Noykhovich E, Mookherji S, Roess A, 2019. The risk of tuberculosis among populations living in slum settings: a systematic review and meta-analysis. J Urban Health 96:262-75.

Peng Z, Rojas ALP, Kropff E, Bahnfleth W, Buonanno G, Dancer SJ, Kurnitski J, Li Y, Loomans MGLC, Marr LC, Morawska L, Nazaroff W, Noakes C, Querol X, Sekhar C, Tellier R, Greenhalgh T, Bourouiba L, Boerstra A, Tang JW, Miller SL, Jimenez JL, 2022. Practical indicators for risk of airborne transmission in shared indoor environments and their application to COVID-19 outbreaks. Environ Sci Technol 56:1125-37.

Peptenatu D, Băloi AM, Andronic O, Bolocan A, Cioran N, Gruia AK, Grecu A, Panciu TC, Georgescu L, Munteanu I, Pistol A, Furtunescu F, Strâmbu IR, Ibrahim E, Băiceanu D, Popescu GG, Păduraru D, Jinga V, Mahler B, 2024. Spatio□temporal pattern of tuberculosis distribution in Romania and particulate matter pollution associated with risk of infection. Geohealth 8:e2023GH000972.

Prapinsri P, Boonyasuppayakorn S, Salakij S, 2025. Managing occupancy density and ventilation strategies for mitigating airborne transmission during pandemics by using infection risk model. Build Environ 280:113168.

Saparina LT, Akbar MI, Tasnim T, Mulyani S, Noviati N, 2024. Determinants of tuberculosis disease in the coastal area of Kulisusu Sub District, Indonesia. Public Health of Indonesia 10:93-103.

Shaluhiyah Z, Handayani S, Sriatmi A, Agushybana F, Rimawati E, 2025. Understanding tuberculosis as a wicked problem: a qualitative study in coastal urban settlements of Indonesia. Front Commun 10:1719819.

Surendra H, Elyazar IRF, Puspaningrum E, Darmawan D, Pakasi TT, Lukitosari E, Sulistyo S, Deviernur SM, Fuady A, Thwaites G, Crevel VR, Shankar AH, Baird JK, Hamers RL, 2023. Impact of the COVID-19 pandemic on tuberculosis control in Indonesia: a nationwide longitudinal analysis of programme data. Lancet Glob Health 11:e1412-e1421.

Tariq H, Alamgir A, Punar Z, Fatima N, Minaz A, 2026. Climate variability and infectious disease burden in Coastal Sindh, Pakistan: A trend analysis (2019-2022). Int J Infect Dis 163:108225.

Wang J, Liu X, Jing Z, Yang J, 2023. Spatial and temporal clustering analysis of pulmonary tuberculosis and its associated risk factors in southwest China. Geospat Health 18:1169.

Wang T, Xue F, Chen Y, Ma Y, Liu Y, 2012. The spatial epidemiology of tuberculosis in Linyi City, China, 2005-2010. BMC Public Health 12:885.

Wang Y, Liu X, Li Y, Liu M, Wang Y, Zhang H, Liu J, Zhao Y, 2025. Association of urbanization-related factors with tuberculosis incidence among 1992 counties in China from 2005 to 2019: a nationwide observational study. Infect Dis Poverty 14:30.

Winglee K, Hill AN, Langer AJ, Self JL, 2022. Decrease in tuberculosis cases during COVID-19 pandemic as reflected by outpatient pharmacy data, United States, 2020. Emerg Infect Dis 28:820-27.

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World Health Organization, 2025. Tuberculosis Global Report.
Yu S, Zhan M, Li K, Chen Q, Liu Q, Gavotte L, Frutos R, Chen T, 2024. Analysis of tuberculosis epidemiological distribution characteristics in Fujian Province, China, 2005-2021: spatial-temporal analysis study. JMIR Public Health Surveill 10:e49123-e49123.
Zainuddin AA, Soma AS, Kasim MF, Ramadany S, Djaharuddin I, 2022. Spatial distribution of drug-resistant tuberculosis in Makassar City, South Sulawesi Province, Indonesia. Jurnal Kesehatan Masyarakat 18:296-302.

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Conflict of interest: the authors declare that they have no competing interests.

Ethical considerations: This study used anonymised secondary tuberculosis surveillance data, including geospatial coordinates, obtained from the relevant health authority. No identifiable personal information was included in the analysis or reporting. Ethical approval was obtained from the Health Research Ethics Committee, Faculty of Public Health, Diponegoro University.

Availability of data and materials: all data generated or analyzed during this study are included in this published article.

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