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SPATIAL ANALYSIS OF POPULATION DENSITY, ALTITUDE, HUMIDITY, AND WIND SPEED WITH THE INCIDENCE OF PULMONARY TUBERCULOSIS

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ABSTRACT

Globally, 89% of the population is infected with *Mycobacterium tuberculosis*. In East Java Province, there were 42,922 reported cases, with a treatment success rate of 44.7%, far below the minimum target of 80%. In Madiun District, the treatment success rate in 2022 was 73.31%, with a target of 85.66%. The number of tuberculosis cases in Madiun increased from 547 cases in 2021 to 995 in 2022, then slightly decreased to 968 in 2023. This study aims to analyze the spatial autocorrelation between environmental risk factors and the incidence of pulmonary tuberculosis in Madiun District. This is a quantitative study using an ecological spatial design and secondary data processed through the GeoDa Geographic Information System software. The study sample included pulmonary tuberculosis cases recorded in 15 sub-districts in Madiun District in 2022. The variables analyzed were population density, altitude, humidity, and wind speed. Based on the global univariate analysis using Moran's Index, the total number of tuberculosis cases in 2022 showed no spatial autocorrelation, as indicated by a p-value of 0.475 (>0.05) and a negative Moran's Index of -0.1024, reflecting a dispersed or negative spatial pattern. The Local Indicators of Spatial Autocorrelation (LISA) analysis identified Kebonsari Sub-district as a hot spot area (quadrant I, high-high cluster). Bivariate LISA results showed significant local spatial autocorrelation (p-value < 0.05) between the incidence of pulmonary tuberculosis and the variables of population density, altitude, humidity, and wind speed. Among these, wind speed was the most strongly associated factor, with five sub-districts showing spatial autocorrelation. Kebonsari Sub-district, identified in the high-high cluster, is particularly vulnerable to tuberculosis transmission. It is recommended that pulmonary tuberculosis eradication and control programs be intensified, with priority focus on identified hot spot areas.

Kata Kunci:
Autokorelasi;
Tuberkulosis Paru;
Kepadatan penduduk

ABSTRAK

Populasi dunia yang terinfeksi Mycobacterium tuberculosis mencapai 89%, dengan 42. 922 kasus di Provinsi Jawa Timur dan tingkat pengobatan 44,7%, padahal target minimal adalah 80%. Di Kabupaten Madiun, jumlah pasien yang sembuh pada tahun 2022 adalah 73,31%, dengan target keberhasilan 85,66%. Prevalensi kasus di Madiun meningkat dari 547 pada tahun 2021 menjadi 995 di tahun 2022, tetapi turun menjadi 968 pada tahun 2023. Penelitian ini bertujuan untuk menemukan autokorelasi spasial antara faktor risiko dengan jumlah kasus Tuberkulosis di Kabupaten Madiun. Desain penelitian ini menggunakan metode kuantitatif dengan pendekatan spasial studi ekologi dan menggunakan data sekunder yang diolah melalui perangkat lunak Sistem Informasi Geografis Geoda. Jumlah sampel dalam penelitian ini adalah kasus tuberkulosis paru yang terdeteksi di 15 kecamatan di Kabupaten Madiun dan telah terdata di Dinas Kesehatan Kabupaten Madiun pada tahun 2022. Variabel yang diteliti adalah kepadatan penduduk, ketinggian wilayah, kelembaban udara dan kecepatan angin. Berdasarkan analisis univariat menggunakan *indeks Moran's* secara global diperoleh hasil bahwa jumlah seluruh kasus tuberkulosis pada tahun 2022 tidak terdapat autokorelasi spasial karena p-value of 0.475> 0.05 dan terdapat pola persebaran yang menyebar atau negative sebab nilai moran adalah negative yaitu -0. 1024. Hasil analisis *Local Indicators Of Spatial Autocorrelation* pada tahun 2022 untuk peta klaster pengamatan daerah *Hot Spot* atau pada kuadran I *high-high* berada di Kecamatan Kebonsari. Berdasarkan hasil bivariat *Local Indicators Of Spatial Autocorrelation*, dikatakan terdapat autokorelasi spasial jika nilai *p-value* < 0,05, dan terdapat autokorelasi spasial lokal antara kejadian tuberkulosis paru dengan kepadatan penduduk, ketinggian wilayah, kelembaban udara, dan kecepatan angin. Kesimpulan dari penelitian ini adalah variabel yang paling banyak memiliki autokorelasi antar kecamatan adalah kecepatan angin, terdapat lima kecamatan yang memiliki autokorelasi spasial dan Kecamatan Kebonsari yang menempati *cluster high-high* sangat rawan menularkan penyakit tuberkulosis. Perlu adanya peningkatan program pemberantasan dan pengendalian penyakit tuberkulosis paru yang diprioritaskan atau difokuskan pada daerah *Hot Spot.*

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INTRODUCTION

Tuberculosis is an infectious disease caused by the bacterium *Mycobacterium tuberculosis*, which is transmitted through the air by individuals who are infected. This pathogen primarily attacks the lungs but may also affect organs outside the pulmonary system (Indonesia Ministry of Health 2022). In East Java Province, 43,247 tuberculosis cases were detected in 2021, and this number increased significantly to 78,799 cases in 2022 (73.3%) ('East Java Health Profile', 2022).

In 2021, the overall tuberculosis treatment success rate was only 34.16%. Specifically, in Madiun Regency, the treatment success rate for new BTA+ TB cases was 89.26% in 2021. However, by 2022, the recovery rate dropped to 73.31%. This figure is still below the targeted success rate of 85.66%, indicating that additional efforts are needed, particularly in mobilizing communities and increasing public awareness. According to data from the Madiun District Health Office, the prevalence of tuberculosis cases in the region was 547 in 2021. In 2022, the number of adult TB cases rose to 995, with an additional 85 cases in children aged 0–14 years. In 2023, the number slightly declined to 968 cases (Madiun District Health Service 2022).

Research by Achmad Rizki Azhari, Agustin Kusumayati, and Ema Hermawati shows a significant relationship between humidity and the number of new TB cases, particularly when humidity levels exceed 70% (Azhari et al., 2022). Another climatic factor, wind speed, also influences TB incidence through its role in dispersing droplets containing disease agents and airborne pollutants (Azhari et al., 2022). Beyond climatic factors, demographic aspects such as population density are also recognized as risk factors for pulmonary tuberculosis, as they can facilitate person-to-person transmission (Lestar et al.,2021). The highest population density in Madiun is found in Geger Sub-district, with 1,856 people per km² (Central Statistics Agency Madiun District 2023).

Geographical factors, especially altitude, are also associated with tuberculosis incidence. Low-lying areas have a 3.28-fold greater risk of TB due to environmental influences on temperature, humidity, oxygen levels, and UV exposure—all of which affect the survival of tuberculosis bacteria (Hartanto et al., 2019).

To address these challenges, spatial analysis can be used to explore the relationships between environmental and demographic risk factors and the incidence of TB. In the health sector, Geographic Information Systems (GIS) are utilized to visualize disease patterns and assess spatial correlations during outbreaks. A spatial approach in this study was conducted using the GeoDa software application (Mastuti et al., 2019), with spatial data analyzed using Global Moran's I and Local Moran's I autocorrelation tests (Zachrany, 2023).

Although spatial research on TB has been conducted in several regions, similar studies have not been conducted in Madiun Regency. As a result, the spatial pattern of TB cases in this area remains unclear. Therefore, this study aims to analyze tuberculosis cases in Madiun District, East Java, Indonesia, using spatial analysis based on 2022 data from the Madiun District Health Office.

METHOD

Type of Research

This research employs a quantitative method with an ecological study design. The data were processed using Geographic Information System (GIS) tools, specifically the GeoDa software. The data used in this study are secondary data sourced from the 2022 Madiun Regency Health Profile, the Madiun Regency Statistics Agency, digital maps of East Java Province provided by the Geospatial Information Agency, and climate data from the NASA Earth Science website. To obtain the NASA data, users can access the website https://science.nasa.gov/earth-science/ then select the desired location (e.g., Madiun District) and the required variable (e.g., humidity or air temperature). The selected data will be available for download in document format.

Place and Time of Research

This study was conducted in fifteen sub-districts within Madiun District, East Java Province, from March to June 2024.

Population and Sample

The population in this study consists of all annual reports of pulmonary tuberculosis cases recorded in fifteen sub-districts of Madiun Regency in 2022 by the Madiun District Health Office, East Java Province. The sample includes all confirmed cases of pulmonary tuberculosis documented by the same agency. The study used secondary data comprising 995 cases in adults and 85 cases in children aged 0–14 years.

Data Collection

Data for each variable were collected from various official sources, and ethical clearance for the study was granted under Research Ethics Code No. 011/E-KEPK/STIKES/BHM/VI/2024. Data on pulmonary tuberculosis incidence were obtained from secondary sources provided by the Madiun District Health Office. Weather-related variables, including average humidity and wind speed for the year 2022, were retrieved from the NASA Earth Science website. Data on population density and altitude were sourced from the Madiun Regency Statistical Center. The administrative map of Madiun Regency was obtained by downloading the shapefile format (.shp) map of East Java Province from the Ina-Geoportal website.

Data Analysis and Processing

Univariate spatial autocorrelation analysis was performed using the Global Moran's I test to evaluate the presence of spatial autocorrelation in the incidence of tuberculosis in Madiun Regency in 2022. Spatial weighting was applied using the Queen Contiguity method. The range of Moran's Index values, under a standardized spatial weighting matrix, is $-1 \leq I \leq 1$. A value of $-1 \leq I < 0$ indicates negative spatial autocorrelation, while a value of $0 < I \leq 1$ indicates positive spatial autocorrelation. A value of zero indicates no clustering.

Bivariate spatial autocorrelation analysis was conducted using the Bivariate Local Moran's I test. This analysis assesses whether the value of TB incidence in one location is spatially correlated with different variables in neighboring locations. Bivariate spatial autocorrelation was measured between TB incidence and each of the following variables: population density, humidity, altitude, and wind speed. The analysis was carried out using GeoDa software, and a significance level of 5% ($p < 0.05$) was used to evaluate the alternative hypotheses.

RESULT

Univariate Analysis

Table 1 Moran's Index of Tuberculosis Cases in Madiun District in 2022

Moran's Index	E(I)	P-Value	Scatter Pattern
-0.1024	-0.0714	0.475	*dispersed*

Figure 1 Map of Tuberculosis Case Distribution in Madiun District in 2022

The result of the global Moran's Index analysis shows a p-value of 0.475 (> 0.05), which indicates no spatial autocorrelation. This means that the distribution of tuberculosis cases in Madiun District in 2022 does not exhibit a statistically significant spatial pattern. The Moran's Index value was negative, at -0.1024, falling within the range of -1 < I < 0, which suggests negative spatial autocorrelation. This implies that the pattern of TB cases in one area tends to differ from that of its neighboring areas, or in other words, the distribution is dispersed. Consequently, there is no spatial relationship between the number of TB cases among sub-districts in Madiun District.

Bivariate Analysis

Table 2 Bivariate Autocorrelation Results of Population Density LISA with Pulmonary Tuberculosis Cases Based on Subdistricts

District	Lisa_I	Lisa_P	Lisa_CL
Kebonsari	0.831337	0.037*	1
Geger	-0.051777	0.121	0
Dolopo	-0.058132	0.098	0
Dagangan	-0.121509	0.234	0
Wungu	-0.009640	0.479	0
Kare	0.229165	0.169	0
Gemarang	1.155713	0.017*	3
Saradan	-2.208154	0.046*	4
Pilangkenceng	0.038706	0.158	0
Mejayan	-0.536621	0.003*	4
Wonoasri	0.281046	0.083	0
Balerejo	-0.031013	0.432	0
Madiun	0.116368	0.371	0
Sawahan	-0.834055	0.103	0
Jiwan	-0.009640	0.479	0

Description : Lisa P : * autocorelasi, Lisa CL :

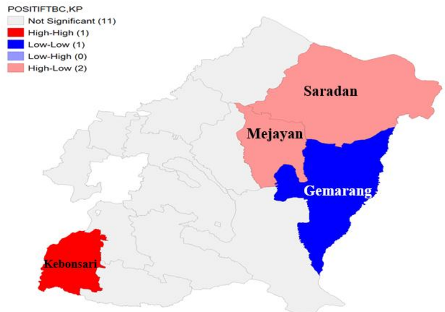

Figure 2 Cluster Map of Population Density Variables with Pulmonary TB Incidence in Madiun District in 2022

Kebonsari Sub-district is located in quadrant I (High-High), categorized as a hot spot area, meaning that it has a high number of TB cases and is adjacent to areas with similarly high cases. Kebonsari, with a population density of 1,296 people/km² and 45 TB cases, borders Dolopo Sub-district, which has a density of 1,275 people/km² and 29 TB cases. The high incidence of pulmonary TB in high-density areas suggests a spatial relationship between population density and TB incidence in and around Kebonsari.

Gemarang Sub-district had a p-value of 0.017 (< 0.05), indicating significant spatial autocorrelation due to inter-regional interaction or spatial proximity. Located in quadrant III (Low-

Low), Gemarang is considered a cold spot, where low case numbers cluster together. With only 9 TB cases and a population density of 343 people/km², its neighboring areas also exhibit low incidence, reinforcing the spatial correlation between low density and low TB cases.

District	Lisa_I	Lisa_P	Lisa_CL
Kebonsari	-0.072700	0.449	0
Geger	-0.022891	0.327	0
Dolopo	-0.001709	0.333	0
Dagangan	-0.263569	0.027*	3
Wungu	-0.117105	0.078	0
Kare	0.014064	0.080	0
Gemarang	-0.962260	0.109	0
Saradan	-0.246479	0.430	0
Pilangkenceng	0.040142	0.095	0
Mejayan	0.328620	0.089	0
Wonoasri	-0.083968	0.387	0
Balerejo	-0.141151	0.040*	4
Madiun	-0.215404	0.307	0
Sawahan	0.597136	0.015*	2
Jiwan	-0.489489	0.060	0

Saradan and Mejayan Sub-districts fall into quadrant IV (High-Low or outlier areas), where high TB incidence occurs next to areas with low incidence. Saradan, with a population density of 469 people/km², recorded 86 TB cases, and is adjacent to Gemarang (9 cases). Mejayan, with a population density of 849 people/km² and 42 cases, neighbors Kare, which only recorded 6 cases. These conditions indicate a potential risk for TB spread and position both Saradan and Mejayan as potential future hot spots over time.

Table 3 Autocorrelation of Regional Altitude with Pulmonary Tuberculosis Cases Based on 15 Subdistricts in Madiun Regency

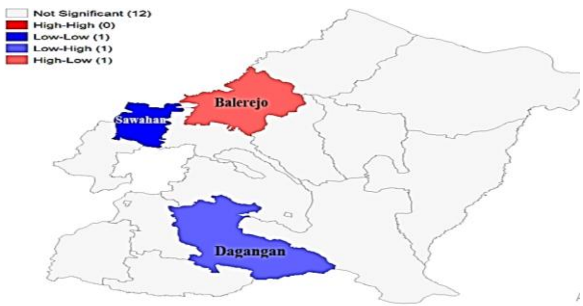

Figure 3 Cluster Map of Regional Altitude Variables with Tuberculosis Cases in Madiun District in 2022

The bivariate LISA test showed that Dagangan Sub-district had a significant spatial autocorrelation with a p-value of 0.037 (< 0.05), and an Ii value of less than 0, indicating a negative spatial pattern. This means that adjacent areas tend to have different values, forming a dispersed distribution. Dagangan, which is located at an altitude of 247 meters above sea level, recorded 24 cases of pulmonary tuberculosis in 2022. Based on the analysis, this sub-district belongs to the Low-Low (LL) cluster, indicating that areas with low tuberculosis incidence are surrounded by other areas with similarly low case numbers. The spatial pattern in Dagangan shows that at a relatively moderate altitude, there is a spatial relationship with lower TB incidence in its neighboring areas. The neighboring sub-districts of Dagangan—namely Dolopo (164 m, 29 cases), Geger (98 m, 28 cases), Wungu (150 m, 34 cases), and Kare (543 m, 6 cases)—display varying altitudes and case counts.

These differences in values between Dagangan and its surrounding sub-districts support the finding of negative spatial autocorrelation. Despite the heterogeneity in elevation and case distribution, there is a spatial interaction observed in Dagangan, suggesting that environmental factors such as altitude may contribute to the dispersion pattern of TB incidence.

Meanwhile, Balerejo and Sawahan Sub-districts also demonstrated p-values below 0.05, indicating significant spatial autocorrelation. In Balerejo Sub-district, with an altitude of 61 meters above sea level and 36 TB cases, the Ii value is negative (Ii < 0), indicating negative spatial autocorrelation, or differing case patterns between the area and its neighbors. In contrast, Sawahan Sub-district, with an altitude of 58 meters and 13 TB cases, has a positive Ii value (Ii > 0), indicating positive spatial autocorrelation, where adjacent areas tend to have similar case values. Both sub-districts fall into the High-Low (HL) cluster category, meaning that high-incidence areas are adjacent to areas with low incidence. This clustering suggests a spread pattern, where altitude-related environmental differences might impact TB transmission. Although Balerejo and Sawahan have similar altitudes, they exhibit distinct autocorrelation patterns. In both cases, the lowland topography combined with varying TB incidence among neighboring areas confirms the existence of a spatial relationship between altitude and TB transmission in these regions.

Table 4 Autocorrelation of Average Humidity with Pulmonary Tuberculosis Cases Based on 15 Subdistricts in Madiun Regency

District	Lisa_I	Lisa_P	Lisa_CL
Kebonsari	0.303444	0.409	0
Geger	-0.089146	0.004*	3
Dolopo	-0.050343	0.023*	3
Dagangan	-0.1284499	0.035*	3
Wungu	0.040718	0.404	0
Kare	-0.182647	0.282	0
Gemarang	-0.284159	0.187	0
Saradan	0.716461	0.412	0
Pilangkenceng	0.007383	0.343	0
Mejayan	0.182421	0.349	0
Wonoasri	-0.061322	0.469	0
Balerejo	-0.020302	0.221	0
Madiun	-0.092397	0.454	0
Sawahan	1.509161	0.106	0
Jiwan	-0.055898	0.001*	4

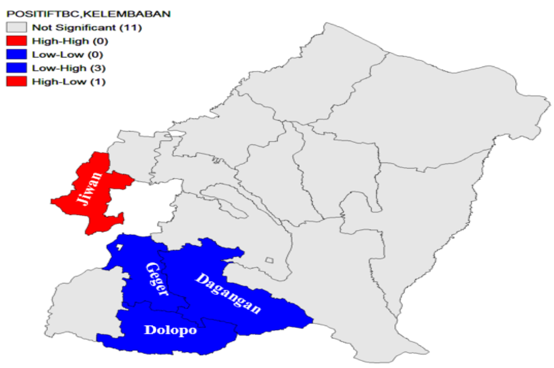

Figure 4 Cluster Map of Humidity Variables with Tuberculosis Cases in Madiun District in 2022

The results of the bivariate LISA analysis showed that there is local spatial autocorrelation between average air humidity and the incidence of pulmonary tuberculosis in several sub-districts. Four sub-districts—Dagangan, Geger, Dolopo, and Jiwan—demonstrated statistically significant results with p-values below 0.05. Each of these areas also had negative Ii values, indicating a pattern of negative spatial autocorrelation or dispersed distribution, where adjacent locations tend to have dissimilar values. This suggests that the spatial distribution of TB cases in these areas does not form clusters but instead spreads unevenly across the region.

In 2022, Dagangan Sub-district recorded 24 cases of pulmonary TB, Geger had 28 cases, Jiwan recorded 41 cases, and Dolopo noted 29 cases. All four sub-districts reported an average annual humidity level of 86%, exceeding the threshold where many bacteria and fungi—including *Mycobacterium tuberculosis*—can survive and remain active in the external environment. Air humidity levels of 70% or higher are known to support microbial persistence outside the human body. The presence of spatial autocorrelation in these areas implies that high ambient humidity may be associated with the continued presence and transmission of TB bacteria, although the relationship varies between locations, as seen in the dispersed spatial pattern. The environmental suitability for bacterial survival likely contributes to the spatial dynamics of TB incidence observed in these sub-districts.

Table 5 Autocorrelation of Average Wind Speed with Pulmonary Tuberculosis Cases Based on 15 Subdistricts in Madiun Regency

District	Lisa_I	Lisa_P	Lisa_CL
Kebonsari	-0.245899	0.063	0
Geger	0.049876	0.251	0
Dolopo	0.064954	0.266	0
Dagangan	0.119470	0.443	0
Wungu	0.027258	0.314	0
Kare	-0.432643	0.032*	3
Gemarang	-0.760895	0.001*	3
Saradan	1.918476	0.255	0
Pilangkenceng	-0.064954	0.001*	3
Mejayan	0.387407	0.053	0
Wonoasri	-0.343331	0.001*	3
Balerejo	0.178625	0.268	0
Madiun	0.103463	0.438	0
Sawahan	0.310853	0.481	0
Jiwan	-0.983596	0.001*	4

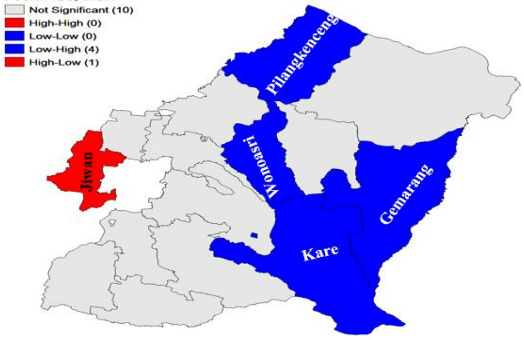

Figure 5 Cluster Map of Wind Speed Variables with Tuberculosis Cases in Madiun District in 2022

The bivariate LISA analysis indicated a significant spatial autocorrelation between average wind speed and the incidence of pulmonary tuberculosis in five sub-districts: Kare, Gemarang, Pilangkenceng, Wonoasri, and Jiwan, each showing a p-value < 0.05. These results confirm that local spatial relationships exist, although the direction and pattern vary. The average wind speed in these sub-districts ranged between 3.57 and 3.88 knots. Wind plays an important role in facilitating the airborne transmission of *Mycobacterium tuberculosis*, especially in open environments or poorly ventilated spaces. A single cough from a tuberculosis patient can release approximately 3,000 sputum droplets (droplet nuclei), which may remain suspended in the air and travel depending on wind movement. The presence of spatial autocorrelation in these areas suggests that wind speed may contribute to the potential spread of infection between neighboring regions with differing or similar TB incidence levels.

DISCUSSION

Analisis Univariat

The result of the global analysis using Moran's Index showed a p-value of 0.475 (> 0.05), which indicates the absence of spatial autocorrelation. This means that the number of tuberculosis cases in Madiun District in 2022 does not follow a spatial clustering pattern. The Moran's I value was within the range of $-1 < I < 0$, reflecting negative spatial autocorrelation. This suggests that the characteristics of a sub-district differ from those of the surrounding areas, forming a dispersed distribution. In other words, there is no statistically significant relationship between the number of tuberculosis cases across neighboring sub-districts in Madiun Regency, reinforcing the finding of a scattered or uneven spatial distribution of pulmonary TB cases.

The visual representation of the distribution shows a gradation of colors on the map: light orange indicates sub-districts in the low category, orange for the medium category, and dark brown for the high category. In 2022, Saradan Sub-district was the only area classified under the high category (dark brown), recording more than 86 TB cases. Eight sub-districts fell under the medium category (28–86 cases), marked in orange: Pilangkenceng (29 cases), Balerejo (36 cases), Mejayan (42 cases), Wungu (34 cases), Jiwan (42 cases), Kebonsari (45 cases), Geger (28 cases), and Dolopo (29 cases). Meanwhile, six sub-districts were classified under the low category with light orange color, each reporting fewer than 28 cases: Sawahan (13 cases), Madiun (16 cases), Wonoasri (21 cases), Dagangan (24 cases), Kare (6 cases), and Gemarang (9 cases).

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Autocorrelation Analysis of Population Density on Pulmonary Tuberculosis

The results of the Bivariate Local Indicators of Spatial Autocorrelation (LISA) test showed that there is local spatial autocorrelation between population density and tuberculosis incidence in four sub-districts: Kebonsari, Gemarang, Saradan, and Mejayan. Among these, Kebonsari Sub-district is identified as the most at-risk area because it lies in quadrant I (High-High), indicating a Hot Spot area—where a high number of cases are adjacent to other high-incidence areas. Kebonsari, with a population density of 1,296 people/km², recorded 45 cases of pulmonary tuberculosis.

Hot Spot areas categorized as High-High (HH) require serious attention, as they are prone to amplifying disease spread to surrounding regions. A study on geospatial Hot Spot roles in rural TB transmission indicates that approximately 75% of infections are caused by contacts within Hot Spot zones. Neighboring regions with relatively low case numbers remain vulnerable to becoming future Hot Spots due to close proximity to these high-transmission zones.

To prevent such spread, it is crucial to strengthen prevention programs through active case finding within TB clusters, particularly in areas with a high number of cases. Regular mapping of cases is also necessary to support disease surveillance and targeted intervention efforts.

Population density refers to the number of residents divided by the land area, with the following classification: 0–50 people/km² (not dense), 51–250 people/km² (less dense), 251–400 people/km² (moderately dense), and >400 people/km² (very dense). Kebonsari falls under the very dense category (>400 people/km²), which, combined with its high TB incidence, demonstrates a strong autocorrelation. This suggests that population density in Kebonsari contributes significantly to transmission risks in neighboring sub-districts.

This study align with Triana Srisantyorini's research in 2017-2019, which revealed a significant correlation between population density and new TB cases. High population density facilitates airborne disease transmission, as germs suspended in the air can be easily inhaled in crowded environments (Srisantyorini et al., 2022).

Similarly, research by Andini Ayu Lestari on spatial analysis in West Java (2019–2021) found that areas in quadrant I (High-High) showed significant spatial autocorrelation between population density and new TB cases (Lestar et al., 2021). Anisa Yulia Nafsi and Rahayu (2020) also found that TB incidence frequently occurred in high population density areas (Nafsi & Rahayu, 2020). Furthermore, Febie Trisna Suryani and Mursyidul Ibad (2022) reported that most regions with high population density also had a high incidence of tuberculosis (Suryani & Ibad, 2022).

Population density, therefore, plays a critical role in accelerating the spread of airborne diseases like TB. Preventive interventions—such as public health education, ventilation improvement, and cross-sector collaboration—are needed in low-incidence regions that border high-incidence areas, to minimize the risk of transmission.

Autocorrelation analysis of Regional Altitude on Pulmonary Tuberculosis

The results of the Bivariate Local Indicators of Spatial Autocorrelation (LISA) test show that there is local spatial autocorrelation between regional altitude and the incidence of pulmonary tuberculosis in three sub-districts: Dagangan, Balerejo, and Sawahan. Among them, Balerejo Sub-district is categorized as high risk because it lies in the High-Low (HL) cluster, meaning that areas with a high number of TB cases are adjacent to areas with a low number of cases. In 2022, Balerejo, situated at an altitude of 61 meters above sea level, recorded 36 pulmonary tuberculosis cases.

This finding aligns with the study conducted by Teguh Dwi Hartanto, which found that pulmonary TB cases predominantly occur in areas with altitudes ≤150 meters above sea level. Lowland areas have been shown to have a 3.28 times greater likelihood of high TB incidence. Altitude influences environmental factors such as temperature, humidity, oxygen concentration, and ultraviolet light exposure, all of which affect the survival of *Mycobacterium tuberculosis*. Theoretically, this bacterium is less likely to survive at certain higher altitudes due to these less favorable conditions. (Hartanto et al., 2019)

Supporting evidence also comes from the study by Mutassirah et al. (2020), who found that lowland areas in Gowa Regency had a high number of TB cases (1,021 cases). They attributed this to various physical environmental factors such as population density, inadequate ventilation, floor type, temperature, humidity, and lighting conditions—all of which can support TB transmission in lowland residential settings (Mutassirah, et al 2020).

Furthermore, the study by Yalemzewod Assefa Gelaw (2019) added that differences in altitude may lead to variations in temperature (monthly/yearly), seasonal patterns, social environments, and population health conditions, which altogether influence TB transmission. Higher altitudes are believed to reduce TB transmission risks, partly due to greater UVB exposure which promotes higher Vitamin D levels, thereby enhancing immune responses and reducing the likelihood of TB reactivation. Additionally, populations in high-altitude areas typically experience lower density and spend less time in confined indoor spaces, further minimizing transmission risks (Gelaw et al., 2019).

In the context of Madiun Regency, the high number of TB cases in Balerejo Sub-district may be related not only to low altitude but also to a combination of environmental and housing conditions, such as occupancy density, inadequate ventilation, temperature, humidity, lighting, or other contributing factors including rainfall and wind speed. These findings suggest that altitude, as an ecological determinant, plays a significant role in the spatial distribution of TB cases, particularly in low-lying and densely inhabited regions.

Autocorrelation analysis of Humidity on Pulmonary Tuberculosis

The results of the bivariate test show that there is local spatial autocorrelation between average air humidity and the incidence of pulmonary tuberculosis in Geger, Dolopo, and Dagangan

Subdistricts, which are located in quadrant III (Low-Low). This indicates that areas with low average humidity are adjacent to areas with low pulmonary tuberculosis cases. Thus, the low humidity observed in Geger, Dolopo, and Dagangan Subdistricts has a spatial relationship with the low incidence of pulmonary tuberculosis in neighboring areas. Additionally, one subdistrict—Jiwan—is located in quadrant IV (High-Low), meaning that it has high humidity but is adjacent to areas with low TB cases. The results of the Bivariate Autocorrelation test confirm that there is a significant spatial autocorrelation between the variable of average humidity and the incidence of pulmonary tuberculosis. Dagangan, Geger, Jiwan, and Dolopo Subdistricts all have a p-value < 0.05, indicating significance. The average annual humidity in 2022 in these subdistricts was 86%. Dagangan reported 24 cases, Geger 28 cases, Jiwan 41 cases, and Dolopo 29 cases. It is known that most bacteria and fungi can survive in air humidity conditions ≥ 70%. This suggests a conducive environment for the airborne survival and potential spread of *Mycobacterium tuberculosis.*

This finding is supported by the research of Achmad Rizki Azhari et al., which found similar patterns in Serang Regency between 2014 and 2020, where the highest monthly humidity was recorded at 87% in February 2014, and the lowest at 70% in September 2015. The study also highlights the direct influence of relative humidity on the airborne survival or infectivity of pathogenic bacteria. In general, most bacteria and fungi—including *Mycobacterium tuberculosis*—can survive in environments with relative humidity ≥ 70% (Azhari, et al 2022).

The findings are also consistent with the study by Nayaka Nayottama Pamadi et al. In 2021, which emphasized that humidity is one of the climatic risk factors that can influence the progression and transmission of tuberculosis. Their study identified a negative correlation between TB incidence and humidity, suggesting that lower humidity levels may facilitate TB spread. However, it also acknowledged that Indonesia's overall humidity tends to be high due to its tropical climate, which results in increased evaporation and precipitation, thereby maintaining high atmospheric moisture for extended periods (Pamadi et al., 2023)

In the case of Madiun Regency, particularly in Dagangan, Geger, Jiwan, and Dolopo Subdistricts, the combination of high humidity levels (86%) and notable TB case numbers—particularly Jiwan with 41 cases—suggests that humidity contributes to environmental conditions that allow TB bacteria to survive and possibly transmit outdoors. This further supports the existence of spatial autocorrelation between humidity and pulmonary tuberculosis in the region. Nonetheless, this study has certain limitations. The humidity data used were obtained from secondary sources, which introduces the risk of temporal ambiguity. Consequently, the study may not be able to definitively explain how the independent variable of humidity directly affects the proportion of TB cases in a given area.

Autocorrelation analysis of wind speed on pulmonary tuberculosis

The Bivariate Local Indicators of Spatial Autocorrelation test results show that there is local spatial autocorrelation between average wind speed and the incidence of pulmonary tuberculosis in Gemarang, Wonoasri, and Kare Subdistricts, all of which are located in quadrant III (Low-Low). This means that low wind speeds are associated with adjacent areas that also have low pulmonary tuberculosis cases. In addition, one subdistrict—Jiwan—is located in quadrant IV (High-Low), indicating high wind speed in an area adjacent to subdistricts with low TB incidence.

The results of the Bivariate Autocorrelation LISA test confirm that there is significant local spatial autocorrelation between average wind speed and the incidence of tuberculosis in five subdistricts: Kare, Gemarang, Pilangkenceng, Wonoasri, and Jiwan. These areas have p-values < 0.05, indicating statistical significance, with average wind speeds ranging from 3.57 to 3.88 knots.

Transmission of pulmonary tuberculosis occurs through the air, particularly via droplet nuclei released during coughing. A single cough can produce approximately 3,000 sputum splashes, which may carry *Mycobacterium tuberculosis*. In this context, wind speed becomes a key environmental factor, as it facilitates the movement and spread of TB germs both indoors and outdoors. The role of wind is also closely linked to the design and effectiveness of ventilation systems in homes, with inadequate airflow potentially enhancing the persistence of airborne pathogens. Wind speed serves as a medium for the dispersal and development of *Mycobacterium tuberculosis*. The relationship between wind speed and TB incidence reveals that normal wind speed areas—especially in upland, swamp, and coastal regions—tend to report higher case counts. High wind speeds can influence environmental variables such as air temperature, humidity, and rainfall. These changes in turn alter the physical conditions inside dwellings, potentially reducing humidity and temperature, which can affect the viability and transmission dynamics of the TB bacteria (Aja et al., 2022).

This finding aligns with the results of Xiao's study in Jinghong City, Southwest China, which demonstrated that average wind speed was unidirectionally associated with TB incidence, with no observable lag, and wind speeds ranging from 0.7 to 1.6 m/s. Wind contributes to TB transmission by transporting droplet nuclei and airborne pollutants. Furthermore, research by Dbouk and Drikakis (2020) found that in the absence of wind, salivary droplets typically do not travel beyond 2 meters. However, under wind conditions between 4 km/h (1.1 m/s) and 15 km/h (4.2 m/s), droplets were observed to travel up to 6 meters, albeit with reduced concentration and particle size depending on the direction of the wind. The author assumes that wind speed has a considerable influence on TB spread, especially following the subsiding of the COVID-19 pandemic, when people resumed outdoor activities and gatherings. Increased outdoor activity could enhance the possibility of *Mycobacterium tuberculosis* transmission through airborne particles carried by wind.

This study employed an ecological study design, which inherently has limitations such as temporal ambiguity—meaning it cannot fully explain how the independent variables (e.g., wind speed) directly affect the proportion of TB cases in a specific area (Adnyana, 2023). Additionally, the spatial analysis used defines contiguity based on neighboring areas, which excludes certain subdistricts from the autocorrelation analysis. Since this study focuses on population-level data, it cannot account for individual-level risk factors that may also contribute to TB incidence in Madiun Regency.

CONCLUSION AND SUGGESTION

There needs to be a strengthening of pulmonary tuberculosis eradication and control programs, with greater prioritization and focus on Hot Spot areas such as Kebonsari Subdistrict. In addition, preventive efforts are needed in subdistricts with low tuberculosis incidence but surrounded by areas with high incidence (low-high pattern), considering that the distribution pattern of tuberculosis cases in Madiun Regency is clustered. Saradan Subdistrict, which recorded a significantly higher number of cases compared to neighboring areas, has yet to receive adequate follow-up. The variables examined in this study may not be sufficient to determine the primary causal factors; therefore, it is necessary for the government and the Health Office to pay greater attention—particularly given the presence of a charcoal factory in the Saradan area.

The establishment of pulmonary tuberculosis service posts can be prioritized in subdistricts where TB incidence remains high. Moreover, it is important to enhance the capacity and supervision of community-based tuberculosis care organizations or Community Tuberculosis Care Groups, as well as to improve the capacity of family members as directly observed treatment supporters.

For future researchers, this study is expected to serve as input and reference for further studies on tuberculosis. Future research is encouraged to include additional relevant variables that were not covered in this study and to expand the study area. It is also advisable to use incident-based data rather than notification data to reduce the potential bias caused by under-reporting of tuberculosis cases.

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