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SPATIOTEMPORAL ANALYSIS OF INTERACTION OF POLLUTANTS ON PNEUMONIA CASES DISTRIBUTION IN METROPOLITAN JAKARTA

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Abstract

Introduction: *Pneumonia is one of the leading causes of death in children under five globally, including in Indonesia. Large metropolitan cities such as Jakarta face a heavier burden due to poor air quality and high population density, further increasing the spread of this disease. This study aims to identify areas with high pneumonia risk and contributing pollutant factors to support more effective interventions and guide policy-making in reducing the impact of pneumonia in urban areas.* ***Methods:*** *This study used the Besag-York-Mollié 2 spatiotemporal model with INLA to analyze the geographic distribution of disease and the influence of pollutant factors. The data comes from Social Security Agency, which has not been used in previous similar studies, and the Jakarta Environmental Agency, thus providing a more accurate description of the actual conditions.* ***Results and Discussion:*** *The effects of pollutants were analyzed based on their credibility intervals, with CO (0.0004, 0.0014); SO_2 (-0.0220, 0.0092); and PM_{10} (-0.0123, 0.0362). Meanwhile, the effect of the time factor (year) has a credibility interval of (0.1669, 0.3464). Spatiotemporal analysis shows an increase in relative risk spread across Jakarta.* ***Conclusion:*** *It was shown through the study that pollutants, particularly CO, positively affected the rising cases of pneumonia, whereas other pollutants discussed under the study had no significant impact. Additionally, time also made a significant impact on the study. The risk ratio for every region of Jakarta rose, and this highlights the importance of air quality management, sustainable urban development, and access to health in an equitable equally.*

INTRODUCTION

Pneumonia is a lower respiratory tract infection that ranks among the leading health concerns due to its high morbidity and mortality (1–3). The disease is caused by viruses, bacteria, fungi, or parasites, often leads to severe respiratory complications (4–5). Treatment challenges are increasing due to drug-resistant pathogens, arising from inappropriate antibiotic use and microbial adaptation (6–7). Pneumonia is a serious problem in Indonesia, especially in the under-five population. The burden of the disease remains high despite national health programs. Globally, an estimated 2,200 children died every day in 2019 from pneumonia complications, often in combination with malnutrition and inadequate access to health care (8). In Indonesia, pneumonia causes about 15% of under-five deaths, indicating an urgent need for prevention and treatment measures (9).

Pneumonia causes about 14% of child mortality under the age of five years across the globe, according to the World Health Organization (WHO). These statistics show the continuing threat of pneumonia and the need for continuous improvement of health services. Pneumonia is a major health risk to Indonesian children under the age of five, and the leading cause of death among this age group. Socioeconomic disparities exacerbate the disease burden, with poor communities disproportionately suffering from an inability to receive health care and medication. The impact is considerable, with an estimated 19,000 under-five deaths from pneumonia in 2018.

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Global data shows that every hour, around 71 children in Indonesia are infected with pneumonia (10). This burden highlights the importance of immunization, early detection, proper treatment, and education on sanitation, nutrition, and symptom awareness (11–12). Unless measures of intervention are instituted, pneumonia will remain a killer disease that kills thousands of children annually and causes heavy economic costs to families and health facilities.

Pneumonia case detection coverage among under-fives in Indonesia showed a fluctuating pattern from 2013 to 2023. In 2013, the coverage was lowest at 24.5%, while that of 2016 was highest at 65.3%. The prevalence remains high, and its dissemination must be suppressed by stricter health policies and targeted intervention. Despite fluctualions, the prevalence remains high, and efforts are still needed to suppress its spread through stronger health policies and targeted intervention. In 2023, the Ministry of Health in the National Action Plan for Pneumonia and Diarrhea Control 2023-2030 targeted 70% coverage of standardized pneumonia treatment. Nationally, this target was exceeded with coverage reaching 94.8% (13). However, regional differences show unequal access to healthcare. DKI Jakarta Province is ranked second with the highest percentage of children under five with pneumonia in Indonesia, at 72.4%. This disparity indicates that, despite national progress, local barriers to healthcare remain and need tailored solutions.

Air pollution has emerged as a point of concern in most cities, especially big cities like Jakarta (14–15). High concentrations of poisonous particulates such as PM_{10}, SO_2, and CO are a major health risk (16–18). This pollution increase is driven by motor vehicle emissions, unsustainable industrial activities, and fossil fuel burning (19–22). The dry season exacerbates this condition by increasing the levels of pollutants in the air (23–24). These factors create unhealthy environments, especially in highly polluted areas. Chronic exposure to dirty air is a leading cause of respiratory infections, including pneumonia, cardiovascular disease, and premature death, especially in children, the elderly, and chronically ill individuals (25–26). Fine particles that reach the alveoli can directly damage lung tissue, impair immune defenses, and act as primary causative agents of pneumonia, particularly in vulnerable populations (27).

Jakarta, as an economic hub, is the main attraction for urbanization from various regions (28–29). This city attracts people seeking jobs and a better life, driving rapid population growth. Urbanization has implications for social, economic, and environmental elements, leading to slum formation, more transport, and water, soil, and air pollution, along with climate change (30–31). While urbanization brings development, it also raises challenges requiring sustainable city management. With a dense population and increasing resident mobility in Jakarta, intense community interactions also raise the chances of disease spread, including pneumonia. Therefore, understanding the spatial and temporal relationship between pollution and pneumonia cases is essential, especially in large, densely populated cities like Jakarta.

The distribution of pneumonia cases in Jakarta is influenced by individual factors and spatial variations, such as environmental differences, air quality, and population density. Changes in temporal effects due to seasonal changes and community activities also affect disease patterns. Therefore, a spatial-temporal approach must be used to identify complex distribution patterns. In this study, the Besag-York-Mollié 2 (BYM 2) method, which combines structured and unstructured spatial effects, was used to map accurate pneumonia risk and identify high-risk areas (32). The use of this method in the study of pneumonia in Jakarta is particularly relevant because it can combine spatial and temporal aspects simultaneously. Spatial analysis helps identify the influence of location, while temporal analysis shows changes over time. This approach provides a clear visualization, identifies high-risk areas, and supports the formulation of more effective and data-driven health policies. Previous research studies has not combined health insurance data with environmental pollutant data to analyze pneumonia cases using spatio-temporal methods, especially in metropolitan areas like Jakarta. Additionally, the use of BPJS data (social health insurance in Indonesia) and data from the Environmental Agency, which have not been used together in similar research before, is expected to more accurately represent field conditions and is an innovation in this study. These results will be useful for the government or relevant parties in designing more effective intervention programs and optimizing resource allocation for the treatment and prevention of pneumonia in Jakarta.

METHODS

Study Area and Data

The location of this study is Jakarta Province, with an area of 661.52 km^2 as it is ranked second with the highest percentage of children under five with pneumonia in Indonesia (Figure 1 and 2). The scope of the area used as the focus of the study is the administrative area of Jakarta Province, which is divided into 5 municipalities, namely Central Jakarta, North Jakarta, South Jakarta, East Jakarta, and South

Jakarta (33). The observation period runs from 2020 to 2022 to analyze the environmental and health dynamics caused by the Covid19 pandemic. The target audience of the analysis includes the entire population of Jakarta, especially those living in urban areas.

The variables used in this study consist of independent and dependent variables. The dependent variable in this study is the number of malaria cases in Jakarta. The variable data was obtained from BPJS. Pneumonia distribution data in Jakarta can be seen in Figure 3.

The independent variables are air pollution levels, namely PM_{10}, SO_2, and CO. Data on these independent variables were obtained from the Jakarta Provincial Environment Office. Data on pollution levels in each region of Jakarta can be seen in Figure 4.

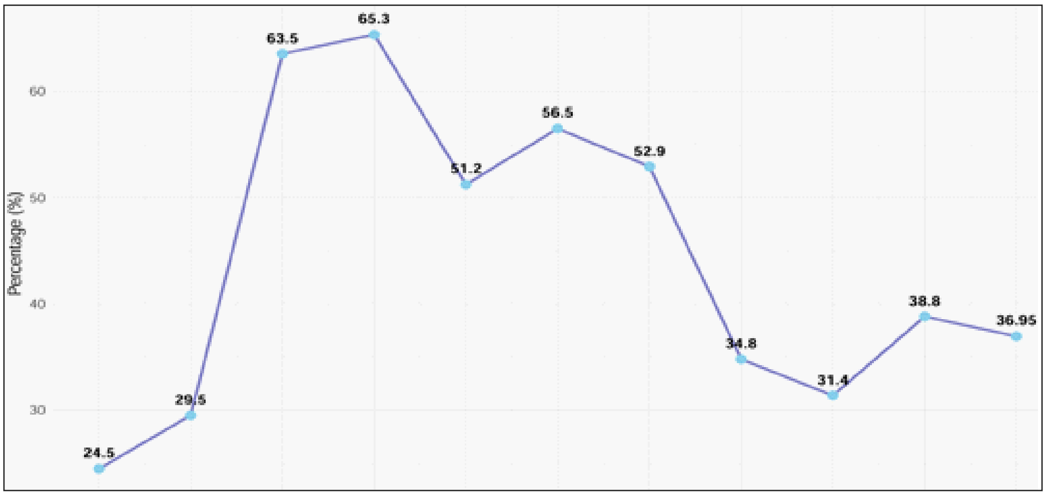

Figure 1. Percentage of Pneumonia Case Findings in Children under Five (%) in Indonesia 2013-2023 (13)

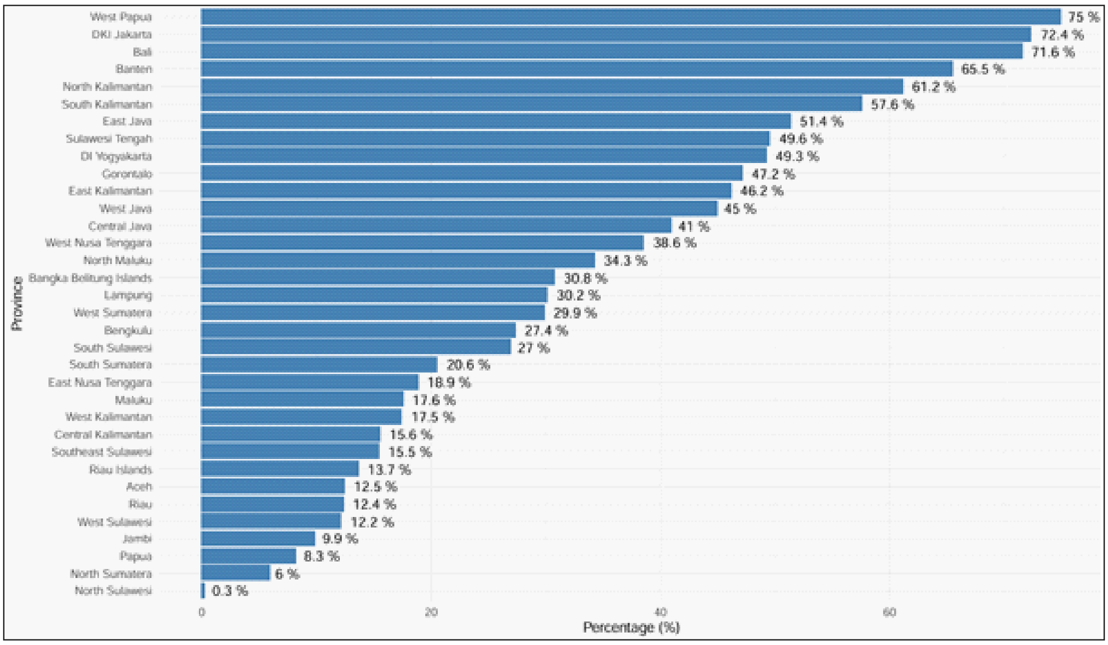

Figure 2. Pneumonia in Toddlers (%) by Province in 2023 (13)

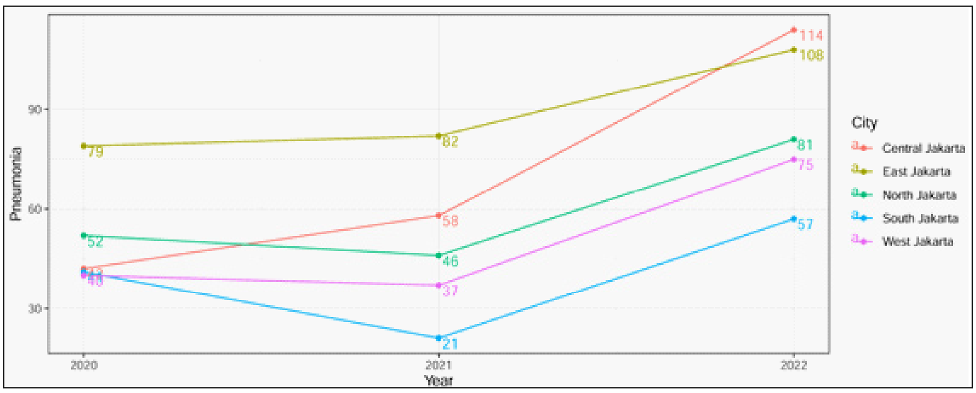

Figure 3. Pneumonia Case Data in Jakarta by Municipalities 2020-2022

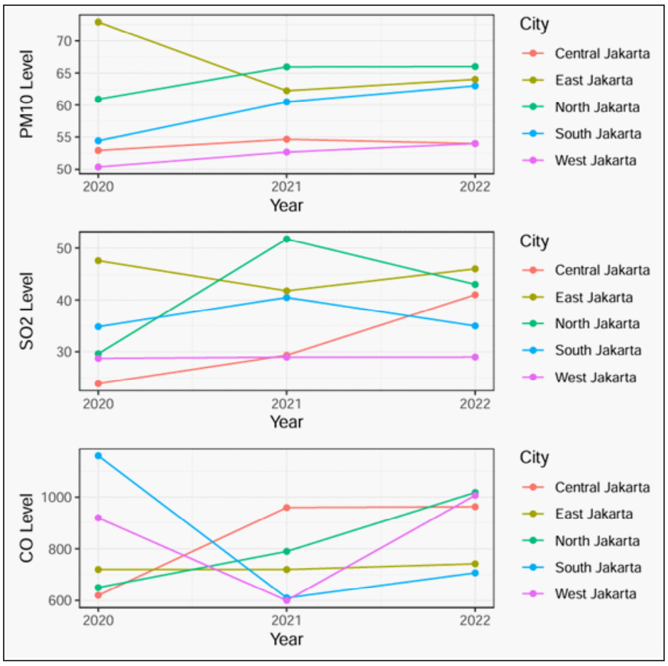

Figure 4. Air Pollution Levels Data in Jakarta by Municipalities 2020-2022

Spatiotemporal BYM 2 Model

In a spatial-temporal context, where the number of disease cases is monitored over a certain period, spatial-temporal models can be used to consider the spatial structure, temporal correlation, as well as the interaction between these two factors (34). Specifically, the number of cases Y_{ij} observed in area-*i* and time-*j* is assumed to be Poisson distributed as follows:

$$Y_{ij} \sim Poisson\left(E_{ij}\theta_{ij}\right),$$
$$i = 1, \dots, I; j = 1, \dots, J,$$

where E_{ij} is the expected number of cases, and θ_{ij} is the relative risk of region-*i* and year-*j*. $log\left(\theta_{ij}\right)$ is expressed as the sum of several components, including spatial and temporal structures that account for spatial and spatial-temporal correlations:

$$log\left(\theta_{ij}\right) = \alpha + u_i + v_i + \left(\beta + \delta_i\right) \times t_j$$

Here, α denotes interception, $u_i + v_i$ are area random effects, β is a global linear trend effect, δ_i is an interaction between space and time that represents the difference between the β global trend and area-specific trend, and t_j denotes the j^{th} temporal. This approach models u_i and δ_i using the CAR distribution, while $v_i v_i$ is assumed to be a normal variable that is independent and distributionally identical. This model allows each area to have a different intercept, $\alpha + u_i + v_i$, as well as its linear trend represented by $\beta + \delta_i$ (35–36). This study uses the Integrated Nested Laplace Approximations (INLA) approach to estimate the spatial-temporal model.

INLA

Integrated Nested Laplace Approximation (INLA) is an computational method that is used for conducting Bayesian inference in complex hierarchical models, mainly latent Gaussian models (37–40). INLA enables treatment of more complex and flexible models compared to routine Bayesian methods but with less computer time and precision (41). INLA is used in the social sciences, ecology, and epidemiology to estimate hierarchical models' parameters as well as for analyzing complex data (42). R-INLA package in R studio is implemented in the modeling. In brief, the approach in the INLA approximation estimates the marginal distribution of the single latent effects and hyperparameters, i.e., $\pi(x_j|\mathbf{y})$ dan $\pi(x_k|\mathbf{y})$. The indices j and k will move in different ranges, depending on the number of latent variables and hyperparameters being modeled. The first step of INLA will calculate the estimated posterior distribution of the hyperparameters $\pi(\theta|\mathbf{y}), \tilde{\pi}(\theta|\mathbf{y})$ which is then used to estimate the marginal distribution of the latent effects $\pi(x_j|\mathbf{y})$. In this case, θ epresents the hyperparameters of the $\mathbf{y}$ distribution. The INLA approach is expressed as follows

$$\tilde{\pi}(x_j|\mathbf{y}) = \sum_g \tilde{\pi}\left(x_j|\boldsymbol{\theta}_g, \mathbf{y}\right)\tilde{\pi}\left(\boldsymbol{\theta}_g|\mathbf{y}\right) \times \Delta_g$$

Here, $\boldsymbol{\theta}_g$ is the hyperparameter value at a particular point on the grid, with an associated weight Δ_g Δ_g. $\tilde{\pi}\left(x_j|\boldsymbol{\theta}_g, \mathbf{y}\right)$ is an estimate of the posterior distribution $\pi\left(x_j|\boldsymbol{\theta}_g, \mathbf{y}\right)\tilde{\pi}$ (43).

RESULTS

Characteristics Pneumonia

All municipalities showed an increase in cases from 2020 to 2022 (Figure 3). Presumably, at the end of the observation period, the Covid19 pandemic began to subside and various restrictions were relaxed. In 2022, Central Jakarta recorded the highest number of pneumonia cases. However, cumulatively, East Jakarta had the highest total number of cases during the study period, with 269 cases.

Multicolinearity Test

The multicollinearity test in this study is used to show that all independent variables used are independent of each other or are not strongly related. The results of the multicollinearity test of the independent variables are shown by the VIF value Table 1.

Table 1. Pollutant Multicollinearity Test Results

Pollutant	VIF
PM_{10}	3.1885
SO_2	2.9856
CO	1.2070

Significance of Fixed Effects

Table 2 presents the fixed effects model result of pneumonia distribution in Jakarta. It has a mean table that presents the intercept and coefficients of the variables, the standard deviation of all the fixed effects, and a confidence interval which can also be used to see the significance of each fixed effect influence. If the confidence interval does not cross 0, it indicates that the fixed effect has a significant influence on the distribution of pneumonia in Jakarta. As can be seen in Table 2, intercept, CO, and year have a significant effect on the distribution of pneumonia. CO levels and years have a positive significant effect, meaning that as CO levels and years increase, the spread of pneumonia also increases (44–45). When viewed from the coefficient, an increase of one level ($1\ \mu g/m^3$) of CO leads to an increase of 0.0121 pneumonia cases. Every one-year increase increased the number of pneumonia cases by 0.2562. Meanwhile, the insignificant fixed effects were PM_{10} and SO_2 levels, with variable coefficients of 0.0121 and -0.0063, respectively. The results of this study are unique in that although SO_2 did not have a significant effect, the coefficient of SO_2 is negative, which means that SO_2 is inversely correlated with the distribution of pneumonia. Previous studies have suggested that SO_2, or sulfur dioxide, has a positive effect on the distribution of pneumonia (46–47). This may be because the data used were not patterned similarly between SO_2 levels from the environmental agency and pneumonia cases from the BPJS.

Table 2. Fixed Effect Modeling Results

Fixed Effects	Mean	Standard Deviation	Credible Interval
(Intercept)	**-519.1132**	**92.3814**	**(-701.067, -338.7119)**
PM_{10}	0.0121	0.0124	(-0.0123, 0.0362)
CO	**0.0009**	**0.0002**	**(0.0004, 0.0014)**
SO_2	-0.0063	0.0080	(-0.0220, 0.0092)
Year	**0.2562**	**0.0458**	**(0.1669, 0.3464)**

Relative Risk Distribution of Pneumonia

Figure 5 shows the distribution pattern of the relative risk of pneumonia from 2020 to 2022. There was an increase across all administrative regions of Jakarta Province, which is indicated by the change in the color of the regions to increasingly reddish-black. Significant color changes were seen in almost all regions, except South Jakarta, which also experienced an increase in risk, although to a lesser extent. This is consistent with the modeling results of the fixed effects in Table 2, where the year effect has a significant positive effect on the distribution of pneumonia in Jakarta. Central Jakarta experienced the most significant changes during the observation period, with the risk increasing from 1,444 in 2020 to 2,977 in 2022. This region also recorded the highest risk during the study observation. This may be due to Central Jakarta's position as the center of activity for various sectors in Indonesia. The high level of mobility in this region has the potential to influence the spread of pneumonia, both indirectly through pollution and directly through interactions between individuals (48–50).

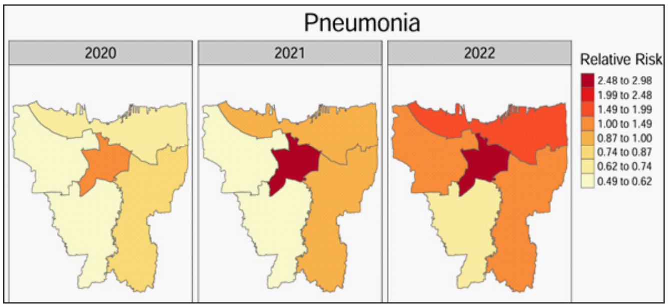

Figure 5. Mapping Relative Risk of Pneumonia in Jakarta 2020-2022

Spatial Effects of Municipal Areas

The influence of spatial random effects can be seen from the posterior mean displayed in Figure 6. Each region in Jakarta shows variations in random effects, although the differences are very small. Positive random effects were found in three regions, namely Central Jakarta, North Jakarta, and East Jakarta, indicating that these regions contributed to the increased spread of pneumonia. Central Jakarta has the largest spatial random effect with a posterior mean value of 0.0004. Meanwhile, negative random effects were found in West Jakarta and South Jakarta.

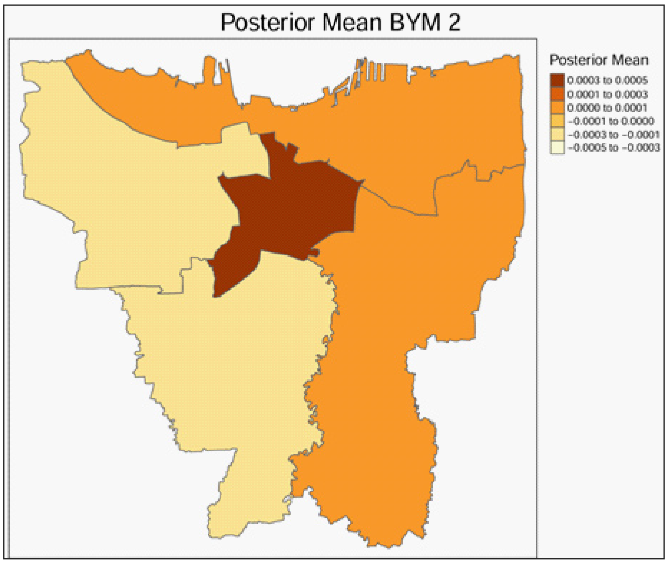

Figure 6. Spatial Random Effects Mapping of Jakarta Municipality

DISCUSSION

Characteristics Pneumonia

The increase in pneumonia cases is thought to be caused by the easing of Covid19 restrictions. Community activities, including working and interacting, began to return to normal, especially in Central Jakarta, which acts as the center of the economy. In 2022, Central Jakarta recorded the highest number of pneumonia cases, which was most likely influenced by these factors. Meanwhile, cumulatively, East Jakarta has the highest number of cases. This can be attributed to the high population density in the region, where East Jakarta has the largest population in DKI Jakarta Province, reaching 3,083,883 people in 2022 (51).

Multicolinearity Test

The results of the multicollinearity test show that for all independent variables, namely PM_{10}, SO_2, and CO, none are highly correlated between variables. This can be seen from the VIF value of the three variables which are less than 10 (52–53). Therefore, three pollutant variables can be used as independent variables in the study.

Significance of Fixed Effects

The results of this study indicate that air quality, particularly exposure to carbon monoxide (CO), has a significant relationship with the spread of pneumonia cases in Jakarta during the period 2020–2022. This is in line with the hypothesis that prolonged exposure to air pollution, especially CO, can compromise the respiratory system, placing individuals at high risk for bacterial or viral infections. This study emphasizes that respiratory infections, especially pneumonia, are not only spread by direct human-to-human interaction but also by environmental factors such as air pollution. Pneumonia is the most common lung disease due to CO poisoning (54–55). he role of pollutants causes impaired lung function and susceptibility to infection, especially in urban areas with high levels of exposure. Household pollution and industrial smoke have become universal sources of respiratory infections, including pneumonia. In addition, the risk is even higher in densely populated and poorly ventilated urban areas, such as slums. Therefore, efforts should be made to improve indoor ventilation and reduce environmental pollution to reduce the prevalence of pneumonia in urban cities.

CO was shown to have a strong positive correlation with the increase in pneumonia cases. Each increase by one unit of CO is estimated to affect the increase in 0.0121 pneumonia cases. This evidence conforms to previous research findings that illustrate how CO exposure tends to disrupt oxygen transport in the blood and therefore lead to oxygen deficiency (hypoxia) and the lowering of the body's immunity. In urban environments, high levels of CO are normally produced by motor vehicle emissions, industrial activities, and combustion of fossil fuels, so that pollution control is an integral part of pneumonia prevention strategies. This provides evidence for the hypothesis that exposure to air pollution, especially CO, suppresses the respiratory defense mechanism and increases susceptibility to bacterial or viral infection. Additionally, chronic respiratory distress due to chronic exposure to CO has also been attributed to chronic respiratory distress, and this could be an early source of severe pneumonia, especially in vulnerable groups such as children and the elderly. Conversely, however, the findings of the analysis showed that the levels of PM_{10} and SO_2 did not have a great impact on pneumonia transmission. This finding is in contrast with several previous findings that reported that both pollutants are responsible for the aggravation of respiratory diseases (56). This variation can be attributed to variations in measuring techniques and varying concentrations of pollutants by location. Furthermore, it is also important to point out the possibility of interactions among pollutants in a way that certain combinations of mixtures can harm respiratory health more than the separate impacts of each individual pollutant. One likely reason for this disparity is in data sources, whereby SO_2 concentration trends in the Environmental Agency dataset may not correlate with pneumonia case records in BPJS. This means that there is a need for additional studies to identify other confounding variables and the need for more intense integration of environmental and health data.

Relative Risk Distribution of Pneumonia

Based on the results of spatial analysis, Central Jakarta was recorded as the area with the highest risk of pneumonia during the study period. This may be due to the high economic activity and population mobility in the area, which has an impact on increasing air pollution and the intensity of interaction between individuals. As a center of industry and transportation, the area is also one of the largest sources of pollutant emissions. The combination of these two elements makes pneumonia a long-term public health problem in Central Jakarta and requires more specific handling. These findings imply that policies on air control should reduce the incidence of pneumonia in Jakarta. Government policies must be geared toward emission controls measures, such as stricter car policies, cleaner production practices in industries, and additional green urban open spaces within communities to promote cleaner air. Public awareness also needs to be strengthened, especially regarding the dangers of air pollution and the importance of preventive measures such as wearing masks and avoiding outdoor activities when pollution is at its peak. In addition, issues such as vaccine availability, early detection, antimicrobial resistance, and environmental factors must be addressed collectively. With this approach, morbidity and mortality from pneumonia can be significantly reduced. Future efforts need to be directed at more innovative prevention methods and equitably developed health services, so that pneumonia prevention activities can be accessed by all levels of society regardless of socioeconomic status.

Spatial Effects of Municipal Areas

By results of the spatial analysis, the most affected place in relation to pneumonia as it was in the study period is Central Jakarta. This is attributable to the area being a source of great economic activity and population mobility, factors that influence how concentrated air pollutants are apart from the rate with which people relate to one another. Being an industrial and transportation hub, the region is also a high source of emission of pollutants. The coming together of these factors makes pneumonia a chronic public health concern in Central Jakarta and calls for a more specific intervention. This finding is the importance of air control policies to reduce cases of pneumonia in Jakarta. The policies of the government must be geared towards controlling emissions, such as more stringent automobile standards, cleaner industrial processes, and expanding green open spaces in urban areas to allow for cleaner air. From a public health perspective, citizen education also needs to be strengthened, especially regarding the dangers of air pollution and the importance of precautionary measures such as mask use and avoidance of outdoor activities during periods of high pollution. Additionally, aspects such as vaccine availability, early detection, antimicrobial resistance, and environmental determinants need to be addressed in their entirety. With this approach, pneumonia morbidity and mortality can be significantly reduced. Efforts in the future need to be directed towards even more innovative preventive measures and equitable health services, so that prevention of pneumonia is equally within the reach of all sections of society regardless of socioeconomic status.

Future Research Suggestions

For future research, it would be better to include additional variables such as climatic factors, socioeconomic variables, and population mobility patterns. This could provide a more complete picture of the dynamics of pneumonia cases in Jakarta. Additionally, the use of more sophisticated spatiotemporal modeling techniques or the comparison of multiple analysis techniques could also increase the validity of risk projections and strengthen the basis for policy-making decisions. By combining epidemiological and environmental research, policy makers can come up with more specific solutions to declines in pneumonia incidence and improve the quality of public health, especially in urban areas.

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AUTHORS' CONTRIBUTION

All authors actively participated in the research and writing of this manuscript and share responsibility for its contents. All authors have read and approved the final manuscript. The specific roles of each author are as follows: SA: Conceptualization, Methodology, Data Collection, Statistical Analysis, Data Interpretation, Writing, Reviewing, and Editing. VS: Data Collection, Writing, Reviewing, and Editing.

CONCLUSION

This study shows that air quality, especially carbon monoxide (CO) exposure, has a significant influence on the distribution of pneumonia cases in Jakarta during the period 2020-2022. Analysis using the Bayesian-based Besag-York-Mollié 2 (BYM 2) spatial-temporal model identified that an increase in CO levels was positively correlated with an increase in pneumonia cases. Moreover, the temporal aspect suggested increasing trend in the risk of pneumonia, while other pollutant variables such as PM_{10} and SO_2 showed no statistically significant effect. These findings point towards the function of air pollution monitoring and abatement as an intervention of environment-related disease control.

Spatial distribution pattern shows that the relative risk of pneumonia increased significantly in almost all administrative regions of DKI Jakarta Province. By utilizing data from Social Security Agency and Environmental Agency, through this study the priority is made clear on applying an integrated system with a combination of air pollution control and availability of health service. For future research, it is suggested that future work includes other dimensions' variables, such as climate variables, socioeconomic variables, and population mobility to further improve the analysis.

In addition, the use of a more complex spatial-temporal modeling approach or comparison of methods may provide a more comprehensive insight. The findings should be capable of supporting the local government in formulating more effective strategic policies to address pneumonia in Jakarta.

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