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Research article

Mapping the Information of Social Vulnerability of Covid-19 Pandemic in Bandung City, Indonesia

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Abstract

The COVID-19 pandemic has widened socioeconomic disparities in urban Indonesia, where studies on the interaction between demographic factors and population density are often overlooked. This leaves a gap in the holistic understanding of spatial vulnerability. This gap is pressing for Bandung, one of Indonesia's key economic hubs, where the lack of integrated, evidence-based data hampers mitigation efforts against the pandemic's impact. This research is motivated by the need to fill this gap by mapping the social vulnerability of Bandung residents to COVID-19. This study uses a multi-criteria approach (Analytical Hierarchy Process/AHP) using four main parameters: building density, population density, potential crowd locations, and demographic structure, to assess the level of social vulnerability. The analysis reveals that six districts Babakan Ciparay, Batununggal, Bojongloa Kaler, Cibeunying Kidul, Coblong, and Kiaracondong show very high social vulnerability. The study also identifies the distribution of COVID-19 cases and these social factors, particularly in densely populated and crowd-prone areas. Consequently, this study highlights the need for policy alignment to reduce social vulnerability and mitigate the impact of the pandemic in Bandung City. It also recommends increasing public awareness and strengthening health protocols to minimize the risk of COVID-19 transmission. These findings offer strategic direction for the government and stakeholders to develop more effective policies in dealing with future health crises.

Keywords: urban spatial vulnerability; pandemic mitigation; multicriteria analysis; demographic resilience; inclusive health policy.

1. Introduction

Since the onset of COVID-19, its disruption has continued to impact nearly every aspect of daily life worldwide. In Indonesia, the pandemic has exposed deep-rooted public health weaknesses and exacerbated long-standing socioeconomic inequalities (Arifin, 2022; Ningrum & Lotta, 2024). As of March 2023, official tallies showed 6.7 million confirmed cases and 160,958 deaths, illustrating how rapidly the virus has spread across large swaths of the country (Alsairafi *et al.,* 2024; Harapan *et al.,* 2023; Surendra *et al.,* 2023). Economic scale and social inclusiveness were already lagging before the outbreak, and response policies have exacerbated rather than alleviated these disparities, with limited access to healthcare and stable employment still concentrated among the same marginalized groups (Choongik & Kwang-Hoon, 2023; Siimsen *et al.,* 2023). These same governments, overburdened and often reactive, have relied on gradual quarantines and mobility restrictions whose uneven implementation has sometimes exacerbated disparities rather than reduced them (Biswas & Nautiyal, 2023; Kim *et al.,* 2025; Roy *et al.,* 2024). These policies have weakened economic participation, exacerbated vulnerabilities in densely populated metropolitan peripheries, and underscored the ongoing need for economic recovery to coexist with public health interventions.

The vulnerability of urban communities to pandemics, particularly COVID-19, is a multidimensional issue influenced by the complex interaction between demographic characteristics, health system capacity, and urban policy frameworks (Grum & Grum, 2023; Jiang *et al.,* 2024; Qazi *et al.,* 2022). Bandung City, one of Indonesia's economic centers, with a population of around 2.5 million people and a population density of 15,176 people/km^2 (Miftah *et al.,* 2022). The high mobility of Bandung's population within this urban agglomeration inherently increases the complexity of mitigating the spread of infectious diseases (Taqi & Rasheed, 2025; Widya *et al.,* 2023). The preparedness of Bandung City's health system in facing the pandemic crisis has been the subject of critical evaluation, where the level of community compliance with health protocols shows significant variability (Miftah *et al.,* 2024; Mustikawati *et al.,* 2024; Roosmini *et al.,* 2022;

Widarna *et al.,* 2024). From an urban policy perspective, cities with less diversified economic structures tend to be vulnerable to pandemics.

Understanding social vulnerability is crucial to understanding the complexities of the COVID-19 response (Ford *et al.,* 2023; Rezaei & Dezfoulian, 2023). Social vulnerability refers to the susceptibility of different demographic groups to negative impacts during a crisis, influenced by factors such as socioeconomic status, access to health services, and community resilience (Li *et al.,* 2023; Mah *et al.,* 2023). Studies categorize social vulnerability into four interrelated domains: physical, social, economic, and environmental (Gunaratne *et al.,* 2023; Johnson *et al.,* 2023; Majumder *et al.,* 2023). In the context of disasters and health crises such as COVID-19, recognizing these vulnerabilities allows policymakers to prioritize interventions effectively, directing resources to the most impacted populations and communities (Elkady *et al.,* 2024; Kaim & Kubbe, 2025; Onyejesi *et al.,* 2025). This understanding has become increasingly relevant as the pandemic has revealed the multifaceted nature of vulnerability, encompassing health impacts as well as economic and psychosocial dimensions.

Existing research has consistently highlighted the crucial relationship between population density, urban environmental characteristics, and the dynamics of infectious disease spread. Specifically, areas with high population density are recognized as epicenters of outbreak vulnerability (Anugwom & Anugwom, 2023; Gutu *et al.,* 2021). From an urban geography perspective, this phenomenon can be explained by the increased social interaction and population mobility inherent in dense environments, which directly correlate with higher transmission rates (Kim *et al.,* 2024; Soleimani & Jalilvand, 2025). Geographical challenges in implementing public health interventions, such as effective lockdowns in densely populated areas, often facilitate the persistence of transmission (Cheshmehzangi *et al.,* 2023; Choo *et al.,* 2024; Islam *et al.,* 2024). Furthermore, the socioeconomic stratification often found in urban centers exacerbates this vulnerability, creating a complex interplay between spatial demographics and adverse health outcomes (Hossain *et al.,* 2024; Liu & Liu, 2024; Roldán-Valcarce *et al.,* 2023). Therefore, a thorough understanding of the interactions between these demographic and environmental factors in an urban geographic context, particularly in areas such as Bandung City, is imperative for designing adaptive and effective public health strategies.

Despite this, the scientific literature still demonstrates significant debate regarding the concept of social vulnerability and its implications for public health outcomes. From a geographic perspective, there are critical gaps in our understanding of how spatial configuration and specific urban demographic factors influence community adherence to health interventions during the pandemic (Häfliger *et al.,* 2023; Sahoo *et al.,* 2023). While numerous studies have confirmed the correlation between population density and disease incidence, the multifaceted interactions of these factors in a diverse urban landscape, such as Bandung, require deeper geographic exploration (Dyer *et al.,* 2024; Nandi *et al.,* 2024; Priyatna, 2024). Bandung's unique demographic characteristics, including high population density and significant socioeconomic heterogeneity, warrant focused spatial analysis to unravel how these factors influence community engagement and adherence to public health directives (Triwardhani & Kennedy, 2025). Furthermore, the role of public perceptions and levels of trust in public institutions in shaping compliance with health measures is a crucial socio-geographic dimension, yet it remains underexplored in the context of the COVID-19 pandemic (Chen *et al.,* 2024; Gröschke, 2025). This gap indicates an urgent need for more detailed research that integrates spatial analysis with socio-economic dynamics to develop a more comprehensive understanding of urban vulnerability to health crises.

The purpose of this study is to address this gap by using spatial and multi-criteria analysis methodologies to map social vulnerability in Bandung City. This study aims to explore the interactions between building density, population density, and demographic structure on public health outcomes during the pandemic. Using this methodology, this study aims to identify priority intervention zones and create a framework that improves understanding of how urban factors converge to influence health outcomes (Al-Rawashed *et al.,* 2024; Saric *et al.,* 2024). This integrated approach is crucial for developing targeted interventions that effectively address the unique challenges posed by COVID-19 in this context. This research employs the Analytical Hierarchy Process to examine social vulnerability dynamics in Bandung City, building on recent analytical frameworks (Batur *et al.,* 2025; Moslehi *et al.,* 2023; Putra *et al.,* 2023). AHP effectively organizes disparate vulnerability dimensions, allowing the systematic weighting of demographic, spatial, and health variables while integrating qualitative and quantitative inputs from diverse stakeholders. The structured comparative matrices, used iteratively, fortify the robustness and reproducibility of analytical outputs (Huang *et al.,* 2024; Zain *et al.,* 2025; Teng *et al.,* 2025). By merging high-resolution spatial and demographic data with empirical health outcomes, the study extends the public health and urban resilience discourse in policy relevant ways, offering empirical entry points for the effective assessment of health equity and resilience strategies (Liu & Mostafavi, 2025). Through a hierarchically ordered representation of urban vulnerability, the work intends to generate actionable evidence that informs evidence-based, equitable health responses and strengthens readiness for recalcitrant health crises (Okoli *et al.,* 2024; Fredericks *et al.,* 2023). The anticipated outputs are positioned to guide the calibration of public health interventions and to reinforce the adaptive capacities of Bandung communities.

2. Research Methods

2.1. Study location

The COVID-19 pandemic has further exposed and deepened pre-existing social inequalities in Bandung, placing the city on the list of regions with a steadily rising infection rate in Indonesia. The sharp surge in new cases over a short period of time has posed a severe challenge for people who, even before the pandemic, already faced health barriers, including limited access to official services (Luo *et al.,* 2023). Examining the city's demographics in the context of Bandung, Jakarta, and Surabaya, Jakarta, as the center of government and the economy, has the advantage of a more comprehensive health infrastructure. However, the challenges there are also significant, as its dense population facilitates a more rapid spread of the virus (Sarker *et al.,* 2024). Surabaya, on the other hand, has adopted a series of more sophisticated mitigation strategies, such as a more rigorous digital tracking system and stricter mobility regulations, to suppress virus transmission among its more diverse population (Rachmawati *et al.,* 2021; Rismawati & Abdullah, 2023). Nevertheless, similar challenges continue to emerge across cities. For example, in the slums affected by the apparent lack of self-sufficiency seen in Bandung, persistently high density makes physical distancing nearly impossible, resulting in a spike in the risk of COVID-19 transmission (Chen *et al.,* 2023; Giyarsih *et al.,* 2023; Huang *et al.,* 2021; Sakti *et al.,* 2022). This evidence underscores that despite differing policy and infrastructure approaches to urban space, vulnerability to COVID-19 remains a real issue that demands more inclusive and dynamic policy arrangements tailored to the demographic context of each location.

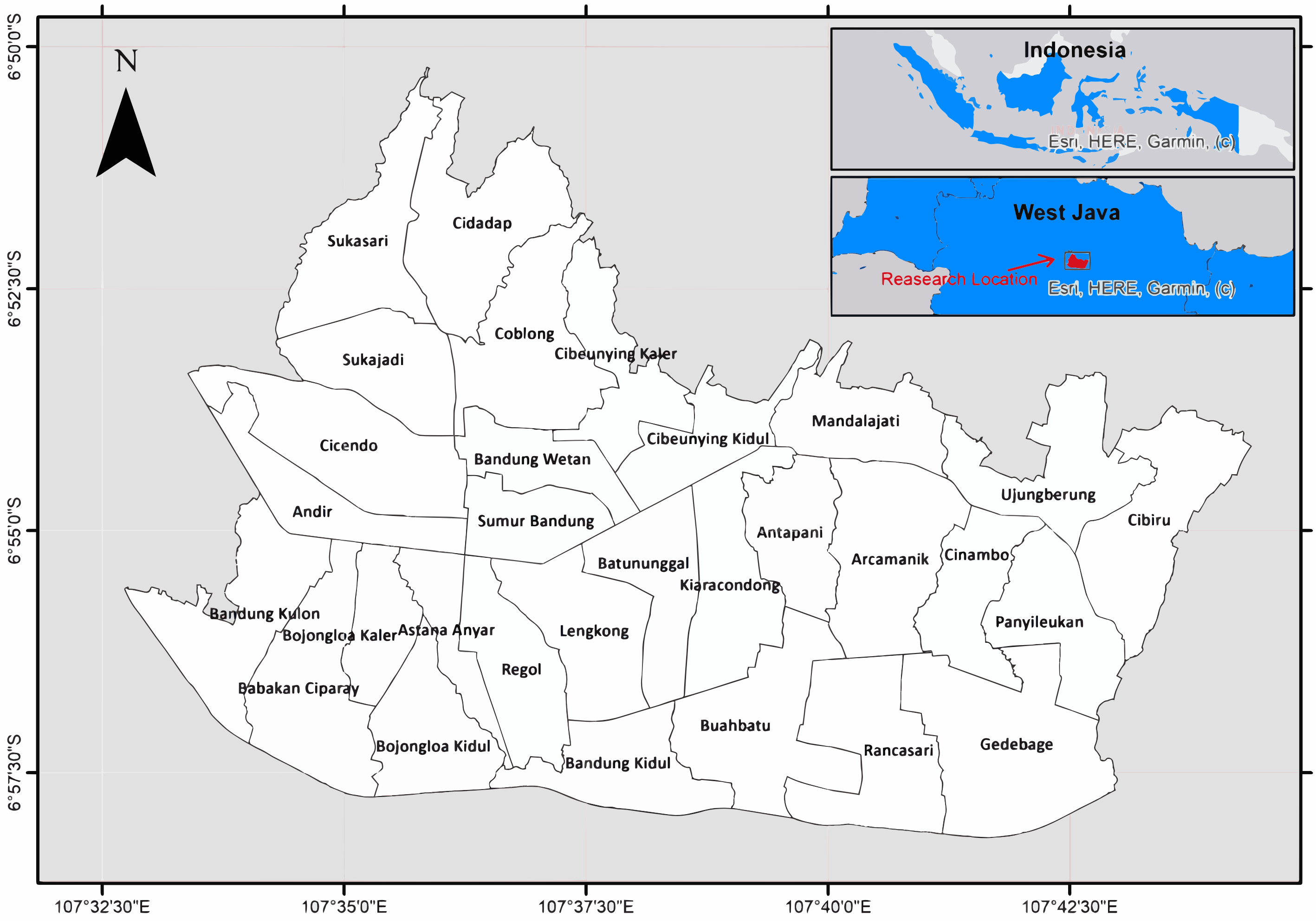

Figure 1. Research Location.

Bandung's population is characterized by diverse demographic and socioeconomic elements, making its social vulnerability analysis highly relevant. Studies indicate that densely populated areas are at higher risk of virus transmission, particularly when pre-existing vulnerabilities such as advanced age and underlying health conditions are high (Prada *et al.,* 2024; Soiza *et al.,* 2023). Bandung's demographic structure, with its high proportion of elderly residents and significant comorbidities, increases overall vulnerability to COVID-19 and poses a substantial public health risk (Huang *et al.,* 2025; Ibarz *et al.,* 2024). Furthermore, the asymptomatic nature of a large number of COVID-19 infections complicates efforts to control its spread, particularly in socioeconomically diverse settings (Adeyemi *et al.,* 2025; Mustafa *et al.,* 2025).

As life transitions to a new normal, the importance of continuous monitoring and mapping of social vulnerability cannot be overstated. Effective mapping utilizing advanced analytical techniques is crucial for informing policymakers to help them design targeted strategies to manage current health risks and protect future livelihoods (Li *et al.,* 2023; Nagavi *et al.,* 2024). Therefore, understanding the complex dynamics of social vulnerability in Bandung City is crucial, not only for a rapid pandemic response but also for strengthening the city's preparedness for potential future public health crises. This comprehensive and multifaceted approach serves as a valuable resource for decision-making related to health policy and disaster risk management specific to the Bandung context.

2.1. Parameters of the social vulnerability

The four parameters of building density, population density, potential crowded locations, and population structure were chosen because they are directly related to social vulnerability to COVID-19 in dense urban areas. Building and population density limit the implementation of social distancing and accelerate transmission (Hamidi *et al.,* 2020), while crowded locations become mobility centres that drive the increase in cases (Chang *et al.,* 2020). Meanwhile, population structure, particularly the proportion of elderly people, requires attention because they have a higher risk of morbidity and mortality (Mueller *et al.,* 2020). These four parameters complement each other in explaining the spatial, demographic, and social dimensions of pandemic vulnerability in Bandung City.

Table 1. The Social vulnerability of Covid-19 Parameters.

Parameter	Year	Source	Information
COVID-19 confirmed case	2020	Health Agency of Bandung City	Cumulative cases in each sub-district
Building density	2020	Landsat-8 OLI (USGS)	Average NDBI value in each sub-district
Population density	2020	Central Statistics Agency (BPS) and Geospasial Information Agency (BIG)	Arithmetic population density
Potential crowd location	2020	Bandung City Government	Distribution of large shopping places and worships
Population structure	2020	Bandung City Government *(Dinas Kependudukan dan Pencatatan Sipil)*	Identification of vulnerable groups aged ≥ 60 years in each sub-district

In compiling social vulnerability, there are parameters used for this purpose, including building density, population density, potential crowded locations, and population composition by age. For building density, we specifically use remote sensing analysis to obtain actual data. Building density is obtained through analysis of Landsat-8 OLI imagery because it has adequate spatial-temporal resolution (Faqe Ibrahim *et al.,* 2023; Wang *et al.,* 2024). Classification of residential areas can be done through the Normalized Difference Built-up Index (NDBI), which combines the near-infrared (NIR and SWIR) bands (Ismaeel & Kumar, 2024; Zhu *et al.,* 2024). The formula for NDBI is NDBI = (SWIR – NIR) / (SWIR + NIR) (Nikkala *et al.,* 2022; Yasin *et al.,* 2022). NDBI has a major advantage because the resulting information can be combined with other spatial data, for example, land cover, which indicates population residence as a major component of disaster vulnerability (Ray, 2024). Population density can be generated by dividing the number of residents/area, resulting in population density data in units of people/km^2. Potential crowd location data is obtained by extracting points of central crowd locations, such as shopping centers and places of worship in Bandung. Then, the number is calculated in each sub-district administrative area polygon using the count point in polygon function. The results are expressed in units of number of places/km^2. Meanwhile, population structure data is obtained for people aged 60 years and above in units of people per sub-district.

For the pandemic study, the social vulnerability model will be compared with the strongest COVID-19 case data in Bandung City until the end of November 2020 (Table 1). The social vulnerability model was developed using a multi-criteria decision-making approach in the form of an analytical hierarchy process (AHP) in the context of spatial dimensions according to their importance levels from 1 to 9 (Nkonu *et al.,* 2023). The selection of reference sources was carried out purposively, considering expertise in spatial epidemiology, urban planning, and disaster management, so that the resulting weights reflect a multidisciplinary perspective. The fundamental scale of 1–9 in the AHP is used to assess the relative importance between parameters, where a value of 1 indicates two parameters are equally important, 3 is slightly more important, 5 is more important, 7 is very important, and 9 is absolutely more important. (D'Orso *et al.,* 2023). To obtain social vulnerability data for COVID-19, please refer to the Regulation of the Head of the National Disaster Management Agency (BNPB) Number 02 of 2012 concerning General Guidelines for Disaster Risk Assessment in Indonesia.

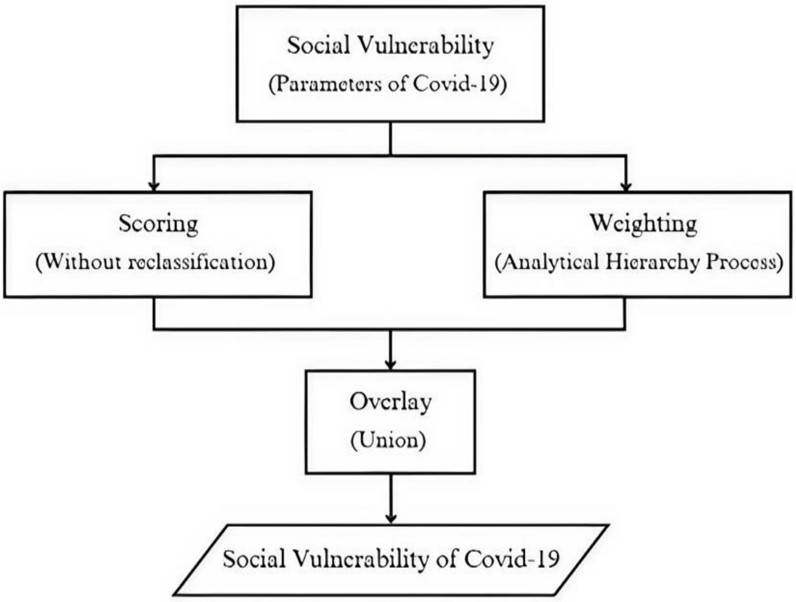

Figure 2. Scheme of Mapping Social Vulnerability of Covid-19.

Population structure data is obtained from a direct census survey, with no specific formula, and the unit is population. Regulations require weights and scores to determine the level of disaster vulnerability. AHP generates weights for each parameter through a pairwise comparison scheme based on its relative importance (Aichi *et al.,* 2024; Rout *et al.,* 2024). The weights, which calculate the eigenvectors of the matrix, are then normalized to a total value of 1 (Pant *et al.,* 2024; Trillos *et al.,* 2023). Consistency assessment in AHP can use the consistency ratio (CR), so that the eigenvector calculation is not disruptive (Frish *et al.,* 2025). CR is the ratio of the consistency index (CI) to the random index (RI), which is the average consistency of the random number matrix (Sato & Tan, 2023). The final process for obtaining this social vulnerability value incorporates the AHP results into an overlay analysis (Figure 2).

For ranking, this study used a range of positive ratio values. The social vulnerability value for the COVID-19 pandemic in Bandung City was reclassified into five classes (very high, high, moderate, low, and very low) using the geometric interval method (Sakti *et al.,* 2023; Shirato *et al.,* 2023). This reclassification method divides class intervals based on their geometric characteristics, which is useful for visualizing extremely distributed data (Shirato *et al.,* 2023). This reclassification method was used for confirmed COVID-19 case data as a comparison for the vulnerability model.

3. Results and Discussion

3.1. Result

The spatial distribution of COVID-19 cases in Bandung City, as of November 25, 2020, highlights significant disparities in social vulnerability across its regions. A total of 3,185 confirmed cases has been recorded, with the highest numbers concentrated in areas such as Andir, Antapani, and Arcamanik, each with over 200 cases. These areas have emerged as hotspots for virus transmission, indicating a higher risk of exposure and potential challenges in adhering to health protocols. In contrast, areas such as Ujung Berung and Bojongloa Kidul have shown relatively lower numbers of confirmed cases, suggesting differences in mobility patterns, population density, or socioeconomic factors influencing transmission dynamics. Data on recoveries and active cases further demonstrates the uneven impact of the pandemic across the city. A total of 2,451 recoveries has been documented, with areas such as Gedebage, Kiaracondong, and Lengkong showing higher recovery rates, potentially reflecting better access to healthcare facilities and more effective treatment strategies in these areas. In contrast, areas such as Rancasari and Regol have recorded lower recovery rates, raising concerns about disparities in healthcare access or the prevalence of comorbidities that could complicate recovery. The distribution of active cases, with higher numbers in Sukajadi and Sukasari, underscores the risk of continued transmission and the need for targeted interventions to curb further spread.

Mortality data highlights critical vulnerability in certain areas, with a total of 111 deaths recorded, resulting in a local mortality rate of 3.48%. Areas such as Bojongloa Kaler and Cicendo exhibit higher mortality rates, reflecting the influence of socioeconomic factors, population density, and access to healthcare resources. These findings underscore the importance of local policy interventions to address disparities in healthcare access and mitigate future vulnerabilities. Spatial analysis of COVID-19 dynamics in Bandung City underscores the need for a tailored approach to pandemic management, ensuring equitable resource distribution and targeted support for socially vulnerable populations. (Figure 3).

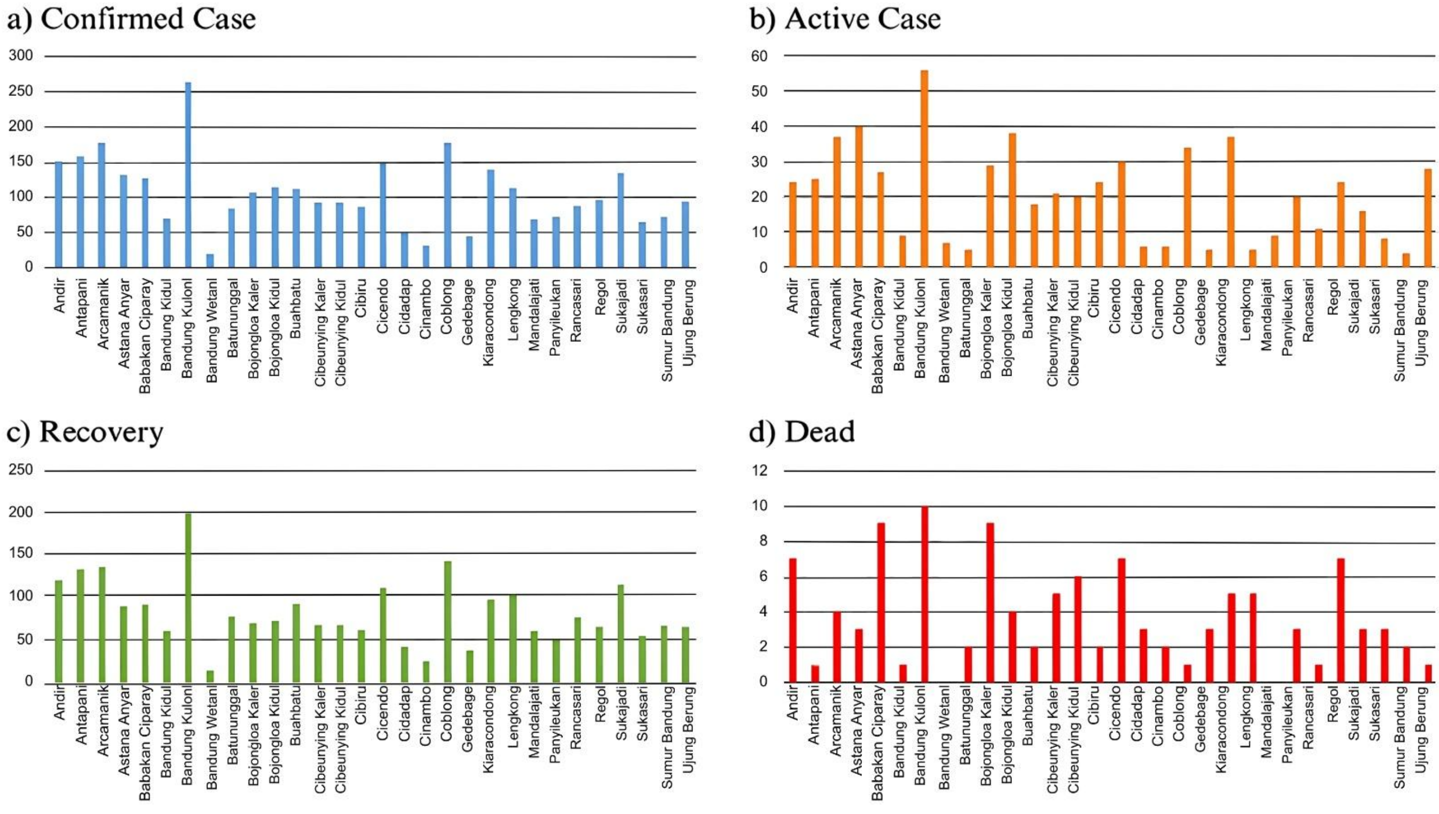

Figure 3. The COVID-19 pandemic situation in Bandung City, 2020.

In early December 2020, the Bandung City Government implemented Large-Scale Social Restrictions (PSBB) until December 23, 2020, to control the exponential growth of COVID-19 cases and await the effectiveness of the COVID-19 vaccine being tested in the community. The COVID-19 pandemic in Bandung City exhibits distinct characteristics when analyzed through the lens of confirmed cases, active cases, recoveries, and deaths. While a high number of confirmed cases often aligns with a higher death rate, this pattern does not apply in the Bandung Kulon District. Disparities in case distribution indicate that the risk posed by the virus is influenced by differences in social vulnerability (Table 2). This study analyzes four social vulnerability parameters, which are assumed to mitigate or exacerbate the potential risk of COVID-19 transmission in each district, assuming similar pandemic management capacity across the city.

The social vulnerability parameters presented in Table 2 initially lack spatial detail for comprehensive analysis. However, when visualized as a regional map (Figure 4), spatial variations become apparent, influencing the distribution of confirmed COVID-19 cases after reclassification using the interval geometry method. Each parameter exhibits a unique spatial distribution, although greater geographic proximity is observed between districts, particularly in terms of building density and potential crowding locations. For example, the second parameter indicates a concentration in the western region of Bandung City, which serves as a growth center. In contrast, the population and age parameters exhibit a diffuse distribution pattern, reflecting the complexity of social vulnerability across the city.

Table 2. Attributes of social vulnerability in Bandung City.

No	Sub-district	Building density (Ratio)	Population density (people/km²)	Potential crowd location (places/km²)	Population structure (people/district)
1	Andir	0.1	23761	4	12418
2	Antapani	0.07	18853	0.086111111	9597
3	Arcamanik	0.01	10179	1.13	8054
4	Astana Anyar	0.12	28090	0.140972222	10324
5	Babakan Ciparay	0.09	19866	0.33	13183
6	Bandung Kidul	-0.01	11176	0.096527778	6006
7	Bandung Kulon	0.08	19359	0.23	11609
8	Bandung Wetan	0.02	8517	0.259027778	4398
9	Batununggal	0.09	25460	3.31	13831
10	Bojongloa Kaler	0.13	40125	0.051388889	13017
11	Bojongloa Kidul	0.06	16654	0.12	8533
12	Buahbatu	0.04	13724	1.19	10957
13	Cibeunying Kaler	0.02	15265	3.29	8398
14	Cibeunying Kidul	0.1	27584	0.094444444	13666
15	Cibiru	-0.06	10773	0.36	6352
16	Cicendo	0.03	12487	0.173611111	12132
17	Cidadap	-0.13	6457	1.36	6397
18	Cinambo	-0.01	5974	1.02	2306
19	Coblong	0.01	15800	8.09	14122
20	Gedebage	-0.06	4084	0.34	3633
21	Kiaracondong	0.06	22718	2.17	14101
22	Lengkong	0.08	12223	3.53	10175
23	Mandalajati	-0.01	14970	1.49	6852
24	Panyileukan	-0.01	7502	0.063888889	3911
25	Rancasari	0.01	12047	0.049305556	9377
26	Regol	0.08	17096	0.1375	10906
27	Sukajadi	0.05	19493	7.25	11905
28	Sukasari	-0.01	12256	3.02	10002
29	Sumur Bandung	0.07	10766	0.253472222	4660
30	Ujung Berung	-0.03	14003	0.050694444	8211

After identifying the social and COVID-19 vulnerability parameters in Bandung City, the next step is to determine their weights using AHP. To begin, these parameters must be assigned quantitative values based on their relative importance. The parameter with the highest relative importance, in this case, is population (scale 5), followed by population density (scale 4), potential crowd locations (scale 3), and population composition (scale 1). These parameters are categorized as more important, slightly more important, and equally important, with intermediate values being close.

The consistency index for the Analytical Hierarchy Process (AHP) was determined to be 0.06, with an average vector consistency of 4.19 distributed among its parameters. The calculated consistency ratio for the four weights of each parameter was 0.07, indicating a high level of consistency. The weights obtained from the AHP method successfully compiled the social vulnerability of COVID-19 in Bandung City, with a low error rate of seven percent, compared to the random number generator (Table 3). These results meet the standard requiring a multicriteria analysis error rate of less than 10 percent, confirming the applicability and reliability of this method for decision-making in assessing social vulnerability during the pandemic.

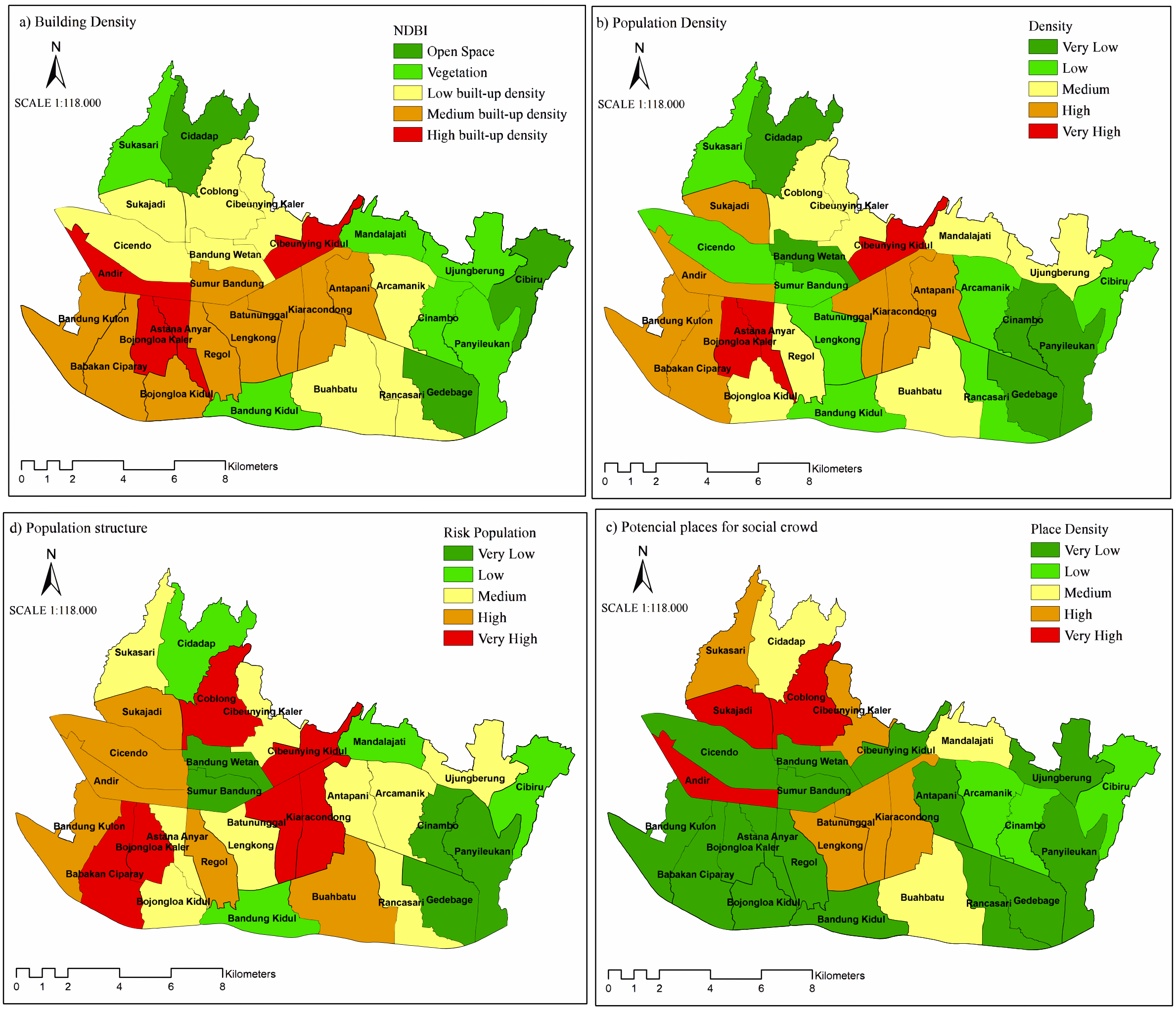

Figure 4. Comparison between The Social Vulnerability Parameters of Covid-19.

Table 3. Weight result from AHP method**.**

No	Parameter	Consistency vector	Weight
1	Population structure	4.18	7.04
2	Potential crowd location	4.2	24.92
3	Population density	4.18	28.16
4	Building density	4.18	35.2

The weights obtained from the AHP method were used to assess the social vulnerability to COVID-19 in Bandung City by multiplying the value of each parameter according to the BNPB disaster vulnerability formulation. This approach produced a pandemic social vulnerability map, as illustrated in Figure 5b. The map identified six districts with the highest social vulnerability: Babakan Ciparay, Batununggal, Bojongloa Kaler, Cibeunying Kidul, Coblong, and Kiaracondong. These districts showed high scores across all key parameters, including population density and building density, which are important indicators of social vulnerability. The calculated weights, such as population structure (7.04), potential crowd locations (24.92), population density (28.16), and building density (35.20), were crucial in determining these high-risk areas (Table 3).

Other sub-districts, including Bandung Wetan, Cinambo, Gedebage, Panyileukan, and Sumur Bandung, exhibit varying levels of social vulnerability, reflecting diverse conditions influenced by their unique demographic and infrastructure characteristics. This spatial variation underscores the importance of local strategies to address the varying impacts of the pandemic. By integrating weights derived from the AHP with geographic data, this study provides a nuanced understanding of social vulnerability, enabling policymakers to implement targeted interventions and allocate resources effectively to mitigate COVID-19-related risks in Bandung City.

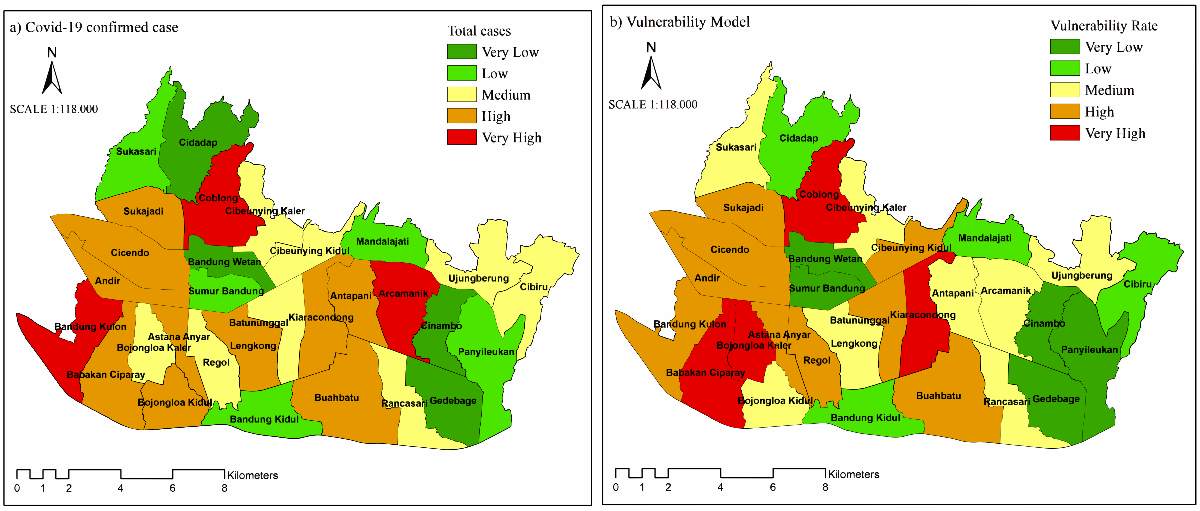

Figure 5. Comparison between Covid-19 confirmed case and social vulnerability model.

A comparison of the distribution of confirmed COVID-19 cases (Figure 5a) and the social vulnerability model (Figure 5b) reveals a generally consistent trend, as areas with high social vulnerability often show a greater distribution of cases. This finding emphasizes that social vulnerability to the pandemic in Bandung City is a crucial component that requires greater attention from the government, community, and relevant stakeholders. However, some discrepancies are evident in certain districts. For example, Arcamanik recorded relatively high confirmed cases despite only moderate vulnerability, which may be explained by localized outbreaks, higher community mobility, or temporary clusters that were not fully captured by the structural model.

In contrast, Bojongloa Kaler is classified as highly vulnerable due to its dense population and building patterns, yet the number of confirmed cases was not proportionally higher. This mismatch could be related to underreporting, limited testing coverage, or stronger compliance with mobility restrictions compared to other districts. These variations highlight that while the vulnerability model reflects long-term structural susceptibility, the actual distribution of confirmed cases is also shaped by temporal, behavioral, and policy-related factors. Therefore, strategies to reduce pandemic risk must combine structural vulnerability assessments with real-time epidemiological and behavioral data to provide a more comprehensive basis for targeted interventions.

3.2. Discussion

A spatial analysis of COVID-19 transmission in Bandung City indicates a significant interaction between social vulnerability factors and the dynamics of virus spread. Social vulnerability mapping guided by the Analytical Hierarchy Process (AHP) identified six sub-districts Babakan Ciparay, Batununggal, Bojongloa Kaler, Cibeunying Kidul, Coblong, and Kiaracondong as zones of very high social vulnerability. These areas are characterized by high population density, building density, and the presence of potential crowded locations, which are important indicators of increased vulnerability to COVID-19 transmission. Previous research has highlighted the relationship between social vulnerability factors and the spread of infectious diseases, showing that urban areas with higher social vulnerability are more susceptible to substantial COVID-19 outbreaks (Chin *et al.,* 2023; Hu *et al.,* 2024a). By integrating spatial analysis with social vulnerability assessments, public health interventions can be more effectively tailored to address high-risk areas.

The correlation between confirmed COVID-19 cases and social vulnerability parameters highlights the nuanced role of urban demographics in shaping the pandemic's impact. Districts characterized by higher population and building densities exhibit trends of higher transmission rates, underscoring the interconnectedness of urban planning, socioeconomic conditions, and public health impacts. Research consistently shows that urban demographics significantly influence the severity of the pandemic's impact, with densely populated areas often becoming hotspots for disease transmission (Carozzi et al., 2024a; Maxwell *et al.,* 2024). This pattern aligns with global studies showing that socioeconomic and environmental factors amplify the pandemic's impact on specific populations, suggesting that urban planning strategies should prioritize population density mitigation and improving public health infrastructure (Olawade *et al.,* 2024; Rahaman *et al.,* 2023).

The application of the AHP method to determine social vulnerability weights demonstrates its robustness as a decision-making tool in risk assessment. The weights calculated for various vulnerability factors, such as population structure, potential crowd locations, population density, and building density, provide a structured approach to vulnerability assessment. The reliability of this methodology is confirmed by a consistency ratio of 0.07, validating the weights derived from the AHP (Arumugam *et al.,* 2023; Guo *et al.,* 2024; Thamaga *et al.,* 2024). This methodological rigor not only enhances the credibility of the findings but also offers a reproducible framework for future studies on urban vulnerability and planning strategies (Mercader-Moyano *et al.,* 2021). Studies have shown that the application of AHP in similar contexts has positively influenced urban resilience planning and facilitated more effective responses to public health emergencies (Ray *et al.,* 2024).

The spatial variability of social vulnerability in Bandung City underscores the need for localized policy responses. While six highly vulnerable districts require immediate attention, the varying conditions in other sub-districts illustrate the complexity of managing pandemic risk in a heterogeneous urban landscape. This complexity underscores the need for local approaches that consider unique socioeconomic and geographic conditions (Raisa *et al.,* 2024; Vertovec *et al.,* 2024). Integrating weights derived from the AHP with geographic data provides policymakers with a nuanced understanding of these variations, enabling better resource allocation and the implementation of targeted interventions (Chy *et al.,* 2025; GR *et al.,* 2024; Tavakoli *et al.,* 2025). For example, these findings can be used to design targeted vaccination interventions, prioritizing areas exhibiting high vulnerability. Furthermore, micro-lockdowns can be implemented in areas at high risk of spreading infection, while still considering the social and economic impacts on communities. These tailored strategies are crucial not only for addressing the immediate challenges posed by the COVID-19 pandemic but also for enhancing the city's preparedness for future public health crises. By integrating this approach into the BNPB's risk reduction strategy, synergy can be created between emergency response efforts and long-term planning, resulting in greater resilience to potential future outbreaks.

The implications of this study extend beyond the COVID-19 pandemic, as its methodology and findings provide valuable insights for urban disaster risk management. Identification of high-vulnerability zones through spatial analysis offers a proactive approach to mitigating the impact of future pandemics and other crises. Furthermore, the emphasis on integrating social and geographic factors aligns with global calls for equitable urban planning and the integration of health considerations into urban development strategies (Kapucu *et al.,* 2024; Rojas-Rueda & Morales-Zamora, 2023). By addressing the root causes of social vulnerability, Bandung City can strengthen its resilience to multiple hazards, fostering sustainability and adaptability in the face of evolving challenges (Abdillah *et al.,* 2025; Fuady *et al.,* 2025).

Overall, this study highlights that integrating spatial analysis with social vulnerability assessment provides a robust framework to identify the most at-risk areas during a pandemic, consistent with global evidence on the links between urban density and disease transmission (Carozzi *et al.,* 2024; Hu *et al.,* 2024). The main contribution of this research lies in the application of the Analytical Hierarchy Process (AHP) to systematically combine demographic and spatial factors, offering both academic novelty and a practical tool for policymakers. Nevertheless, the study is limited by its reliance on early pandemic data and the absence of broader socio-economic variables, which restricts the comprehensiveness of the vulnerability model. Future research should integrate updated datasets and multidimensional indicators to strengthen accuracy and applicability, ensuring that vulnerability mapping can better inform urban health policies and preparedness strategies.l.

4. Conclusion

The findings of this study highlight the crucial role of social vulnerability factors in shaping the dynamics of COVID-19 transmission in Bandung City. Utilizing the Analytical Hierarchy Process (AHP) and spatial analysis, this study identified six sub-districts Babatan Ciparay, Batununggal, Bojongloa Kaler, Cibeunying Kidul, Coblong, and Kiaracondong as highly socially vulnerable. These areas are characterized by high population density, building density, and the presence of potential crowded locations, which are crucial indicators of increased vulnerability to virus transmission. This study emphasizes the importance of integrating spatial analysis with social vulnerability assessments to develop targeted public health interventions. Furthermore, the application of the AHP method demonstrates its strength as a decision-making tool, providing a structured framework for vulnerability assessment with high reliability and reproducibility. These findings underscore the need for localized policy responses to address the unique socio-economic and geographic conditions of each sub-district, ensuring equitable resource distribution and targeted interventions to mitigate pandemic risks.

This study has profound implications for public health policy and urban planning, particularly in the context of the global health crisis. It underscores the strong link between urban demographics, socioeconomic conditions, and public health outcomes, suggesting that urban planning should prioritize reducing density and improving health infrastructure. Identification of high-vulnerabi lity zones through spatial analysis offers a proactive approach to mitigating the impact of future pandemics and other crises. Furthermore, this study supports the need for greater community en gagement in health efforts, emphasizing the importance of education and awareness in improving

public health responses. Policymakers should consider the specific needs of different segments of the population to enhance the effectiveness of health interventions. Future research should aim to combine broader geographic coverage and sophisticated spatial analysis to deepen understanding of urban vulnerability and its impact on public health outcomes. By addressing the root causes of social vulnerability, Bandung City can strengthen its resilience to various threats, fostering sustainability and adaptability in the face of evolving challenges. Future research should be broader in scope and more detailed in its assessment, allowing it to consider the vulnerability of a region to pandemics or other disasters.

To address these limitations, future research can provide analysis by proposing the integration of more recent data (e.g., 2021-2023 data) and the addition of broader socio-economic variables. suggested variables for integration include: income and type of employment to assess direct economic vulnerability due to mobility restrictions; access to health services to measure the population's preparedness to face health risks; and educational status and household conditions as proxies 1for social vulnerability. with these improvements, research can provide a deeper understanding of the community's multidimensional vulnerability to the pandemic, not only from a health perspective but also from a social and economic perspective.

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Conflict of interest

All authors declare that they have no conflicts of interest.

Data availability

Data is available upon Request.

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