Building density and its implications to COVID-19 health risk management: An example from Yogyakarta, Indonesia

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Abstract. Transmission rates of COVID-19 have been associated with the density of buildings where contact among individuals partially contributes to transmission. The research sought to analyze the spatial distribution of building density derived from satellite images and determine its implications to COVID-19 health risk management using Yogyakarta and its surrounding districts as an example. Fine-scale building distribution obtained through remote sensing data transformation was analyzed with GIS. NDBI was applied to Landsat 8 imagery; then, using multiple linear regression analysis, it was correlated to building density’s training samples generated from high-resolution imagery. The derived percent of building density (PBD) was combined with publicly available records of COVID-19 infection to assess risk. This research found that PBD could explain the uneven COVID-19 diffusion at different stages of its development. Instead of dividing regions into zones based on confirmed cases, government and public health officials should observe new cases in high-PBD districts; then, when the cases are decreasing, their attention should shift to low-PBD districts. Remote sensing data allow for moderate-scale PBD mapping and integrating it with confirmed cases produces spatial health risks, determining target areas for interventions and allowing regionally tailored responses to anticipate or prevent the next wave of infections.

1. Introduction
A transmittable disease caused by the SARS-CoV-2 virus, COVID-19, was first identified on January 7, 2020, to call what started as curious pneumonia cases in Wuhan City. A month later, the disease was soon declared a public health emergency of international concern following reports of a shade below 100 cases with no deaths in countries outside China. By March 11, 2020, the outbreak had led to 118,000 confirmed cases and 4291 deaths in more than a hundred countries worldwide, a rapid increase in human-to-human transmission indicative of a pandemic [1]. Nearly two years after the announcement of the COVID-19 pandemic by WHO, there has been an unprecedented soar in infections: 236,599,025 confirmed cases with 4,831,486 deaths globally (WHO Coronavirus (COVID-19) Dashboard on October 8, 2021).

To curb the spread of the disease, countries placed nonpharmaceutical interventions (NPIs) at the core of their national health risk management strategies because developing an effective vaccine required time. The NPIs included mask-wearing, face covering, social distancing, and mobility reduction [1], which practically led governments to enact stay-at-home policies, nonessential facilities closure, and public gathering and travel restrictions. However, national strategies constantly changed...
NPIs following the disease dynamics [2,3], i.e., constant or slow (re-)emergence and development occurring unevenly across regions.

In search of predictors, scholars and practitioners of different fields embarked on investigating into the disease and how it spreads. Aside from virus transmissibility and infectious duration, the basic reproductive ratio of viruses, such as SARS-CoV-2, is also influenced by interpersonal contact rates that are density-dependent [4,5]. Therefore, it is highly likely that dense areas like the urban facilitate high-intensive close contacts necessary for contagions [6]. As such, the density of built environments where people reside and interact is believed to contribute to transmission probability and the diffusion of the disease [6,7].

In urban areas, building density (number of buildings per unit of area) is a complex, heterogeneous representation of rapid socioeconomic and physical development that comprises densities of settlements, public facilities, and other centers of activities. It is thought to be a vulnerability factor in various disasters, where it can reflect relative population size and describe conditions where the residents are likely or unlikely to experience damages or losses. Many have associated it with population exposure to varying degrees of impacts of heatwaves [8], earthquakes [9,10], and floods [11,12]. Recently, it has also been used to explain and map the vulnerability of interpersonal COVID-19 transmission [13,14] under the assumption that a denser area is more susceptible to contagions.

However, gathering building density data is one of the most daunting tasks in risk assessment because the growth of human occupations is not contained by administrative boundaries but rather sprawls to nearest regions to meet basic anthropogenic needs or preferences, creating settlements and urban features of different types, densities, and qualities outside the city area. To monitor building density, remote sensing data have been widely used to effectively distinguish buildings from other land covers with numerous classification methods that are constantly developing to facilitate and accelerate mapping objectively. An example is the Normalized Difference Built-up Index (NDBI), commonly used to automate built-up area mapping on a moderate scale. It proves effective in generating products that meet the standard mapping accuracy of 85.72% [15]. Normalized Difference Vegetation Index (NDVI) is another algorithm with resulting values indicative of vegetation covers. Integrating NDBI with NDVI can optimize built-up area identification to achieve higher accuracy up to 92.6%. The outcomes can be processed into percent building density (PBD), representing the percentage of built-up area per entire land unit [16].

COVID-19 resurgences have been reported in cities, including what transpired in Wuhan [17] and Jakarta [18], and countries like Singapore, Taiwan [19], and India [20]. Although publicly available data on confirmed cases provide the spatiotemporal clusters and magnitude of the pandemic, they do not implicitly explain conditions underpinning the uneven diffusion of the disease. Integrating total daily cases with building density helps local governments and health officials monitor the spread and prioritize areas (intervention targets) and determine suitable measures based on contagion risk. Therefore, the research sought to derive building density data from remote sensing and analyze the influence of its spatial distribution on health risk management, using the City of Yogyakarta and its directly neighboring districts as an example.

## 2. Research Location, Data, and Method

### 2.1. Study area

Yogyakarta is the capital city of the D.I. Yogyakarta Province in Indonesia, whose education, agriculture, and tourism sectors have led to rapid socioeconomic and physical development, causing urban features to sprawl to nearby districts [21,22]. Therefore, to capture variations in building density, this research observed 14 districts belonging to the city (urban districts) and six others located on the outskirts in Bantul and Sleman Regencies (referred to as suburban districts) (Figure 1). The entire research area is 341.98 km², spanning from 41500 to 44500 mE and from 9125000 to 9150000 mN.
In 2020, it had populations in the range of 9,148‒131,005, with mean densities of 13,126 people/km² in the city and 3,781 people/km² in the surrounding districts. Even though all urban districts had a lower population than their suburban counterparts, they have a substantially high population density. From 2010 to 2020, populations annually grew at -1.96‒0.64 (urban) and -3.21‒1.51 (suburban). For reference, the provincial and national rates were 0.58 and 1.25, respectively [23][24]. Information on the twenty districts and their populations is presented in Figure 2.

In the D.I. Yogyakarta Province, there have been 155,729 COVID-19 cases, including 5,244 deaths since 2020. The most recent surge was from about 100 to 300 new positive viral cases per day in early June 2021 after a series of holidays 2‒3 weeks prior. During the holiday, mobility from and to commercial facilities, parks, and natural attractions increased threefold. The surge continued for two months and peaked twice in the first and fourth week of July before the curve descended until the latest data reported in this research, October 9, 2021 [25].

2.2. Building density data acquisition

Landsat 8 image product was the primary data to map the percent of building density (PBD). It was downloaded through EarthExplorer system distributed by USGS. At the processing stage, the image was first converted from digital numbers (DNs) to Top-of-Atmosphere (ToA) reflectance by radiometric correction. The corrected image was then transformed to a built-up index with NDBI that combined shortwave infrared band (SWIR) with near-infrared (NIR) using the formula $\text{NDBI} = \frac{(\text{SWIR} - \text{NIR})}{(\text{SWIR} + \text{NIR})}$. To convert NDBI into PBD, the building density sample was created from high-resolution satellite imagery (HRSI) and then correlated with the NDBI value using linear regression. Although the Landsat 8 image and HRSI were acquired with five years of difference, both can still be used in one building density analysis because the built-up growth rate was 0.14%, indicating a less significant change in the classification of building density [26]. The average PBD per district unit was analyzed spatially.
2.3. Transmission risk assessment
Risk is hazard times vulnerability, where a hazard is the potential source of harm to human’s health (i.e., SARS-CoV-2), and vulnerability defines the degree of likelihood of humans to be exposed to this source [27]. Based on this definition, this research used the most recent daily confirmed cases per district (per October 9, 2021) acquired from https://corona.jogjaprov.go.id/data-statistik to measure the source of threat (hazard). Daily confirmed cases comprise three health states: active infected, recovered, and dead. Meanwhile, the building density describes the physical condition under which the residents likely have physical contact as a known transmission factor of the infectious disease (vulnerability) [28]. This risk assessment was based on the positive correlation between building density, confirmed cases, and risk of disease transmission [6]. These variables were grouped into three classes each, whose range of value was calculated with the equal interval technique that divided the difference between maximum and minimum values by the number of classes (i.e., three). The derived risk classes (Table 1) were then analyzed spatially and descriptively based on their contributing factors as the likelihood of the district to facilitate COVID-19 transmission. All maps presented in this article were produced using the ArcGIS program.
Table 1. Vulnerability, hazard, and health risk classification

| Percent of Building Density (Vulnerability) | Daily Confirmed Cases (Hazard) | Transmission Risk (Vulnerability x Hazard) |
|-------------------------------------------|--------------------------------|-------------------------------------------|
| Range Class Score Range Class Score Range Class | <40% Low 1 <2,000 Low 1 1‒3 Low | 40‒60% Medium 2 2,000‒4,000 Medium 2 4‒6 Medium | >60% High 3 >4,000 High 3 7‒9 High |

2.4. Health risk management evaluation based on building density and risk level
The interventions to curb the spread of the disease at the district level were evaluated to see if they had achieved the intended change, i.e., lowered risk, and had been properly designed for this purpose. With a descriptive, non-experimental design, this evaluation observed the resulting risk regardless of whether or not it was necessarily a result of the intervention itself because comparing changes over time was not possible due to multiple, overlapping policies and lack of data availability (publicly accessible long-term daily cases per district) [29]. Furthermore, a content evaluation was performed by comparing interventions with the derived risk [30] by qualitatively analyzing these variables: compatibility of adopted measures with building density and health risk level.

3. Results and Discussion
3.1. Percent of building density
This research used NDBI to approximate the percent of building density (PBD) from built-up areas per district unit by calculating SWIR and NIR bands on Landsat 8 image captured in 2020. This approach is based on the strong correlation between PBD and NDBI confirmed by Ardiansyah et al. [16], which also mapped PBD using a semi-automatic method to integrate NDBI value and building density samples derived from HRSI. NDBI is a type of built-up area index expressed in the range of -1 to 1. The positive value (brighter hue) indicates built-up features, while the negative value (darker hue) represents other objects such as vegetation and water bodies (Figure 3a). The NDBI imagery was then classified into built-up and non-built-up areas by slicing (Figure 3b).

The adjusted R-squared value resulting from NDBI-PBD correlation analysis at the sampled areas was 0.77 (Figure 4a). It means that NDBI can explain 77% of the variability in PBD. Figure 4b shows the PBD of the urban and suburban districts, which is an average of the pixel’s PBD in each district. It has been classified into three categories: low (<40%), medium (40–60%), and high (>60%) [30,31]. The PBD in the City of Yogyakarta and its surroundings districts varied from 32.43% to 85.33%. Based on the categories, all 14 urban districts had high PBD, while the suburban ones were categorized into medium PBD (Banguntapan and Depok) and low PBD (Kasihan, Sewon, Gamping, and Mlati).

These results correspond to the city’s development and direction. Strong population growth has narrowed space and made several public facilities established in the peripheral areas. Combined with the inordinate land price at the city, they create promising livelihood or employment opportunities that attract influxes of migrants to settle in the area. Over time, the urban landscape starts to take form and increase building density, as transpired in the suburban districts observed in this study [21,32]. The derived PBDs also showed that the city has grown beyond its administrative borders [33], primarily east- and northeastward. With PBDs higher than 40%, Banguntapan and Depok have been the “destination” of this sprawl.
3.2 Health risk levels in the context of COVID-19 transmission

Figure 5 shows the number of COVID-19 cases spatially by districts in three hazard levels: low, medium, and high. As of October 9, 2021, the study area has reported 57,952 of its residents being infected, comprising 42,842 current active, 14,699 recovered, and 410 dead cases. The urban districts saw 717 (Pakualaman) to 3,986 cases (Umbulharjo), while the suburban reported higher positive viral test results in the range of 3,374 (Gamping) to 7,718 (Banguntapan). Based on these figures, the COVID-19 hazard was divided into three levels: low, medium, and high. Ten of the 14 urban districts were classified as having a low hazard, while the remaining four had a medium hazard, namely Gondokusuman, Kotagede, Mantrijeron, and Umbulharjo, which are located on the east and south
edges of the city. On the contrary, nearly all suburban districts fell into the category of high hazard, meaning that their residents are more exposed to the communicable COVID-19 than those in the city.
opportunities for engagement in face-to-face social interactions [34,35]. Therefore, as seen in Figure 6, the populations within the city were considered highly vulnerable to contagion, whereas those in the suburban, where buildings were less dense, had low to medium vulnerability.

Figure 7 shows the distribution of health risk levels in the city and its neighboring districts. Seventy percent of which was categorized into low risk, while the remaining 30% had medium risk. No districts fell into the high-risk category. The low risk was mostly found in the urban, starting from the city center then fanning out toward the outskirts, which make up the western half of the study area. Some medium-risk districts were scattered in the city (Gondokusuman, Kotagede, Mantrijeron, and Umbulharjo) and on the outskirts (Banguntapan and Depok), or in the eastern half. Furthermore, the distribution of medium risk corresponds to the direction of the city’s development. Several universities were established in Depok and Banguntapan, which triggered the emergence of physical structures that initially aimed to accommodate the needs of the students, e.g., lodging, food stalls, retail stores, and copy shop, and over time, created space for the sprawl of urban features from the physically saturated city center, increasing building density and population size [22].

Table 2. Matrix of districts and their corresponding risk levels based on hazard and vulnerability.

| Hazard Vulnerability | Low (PBD<40%) | Medium (PBD=40–60%) | High (PBD>60%) |
|----------------------|--------------|---------------------|----------------|
| Low (<2,000 cases)   | -            | Gamping\(^a\)       | Kashihan\(^b\), Sewon\(^b\), Mlati\(^a\) |
| Medium (2,000–4,000 cases) | -            | -                   | Banguntapan, Depok |
| High (>4,000 cases)  | Danurejan, Gedongtengen, Gondomanan, Jetis, Kraton, Mergangsan, Ngampilan, Pakualamana, Tegalrejo, Wirobrajan | Gondokusuman, Kotagede, Mantrijeron, Umbulharjo | - |

\(^a\) Districts in Sleman Regency
\(^b\) Districts in Bantul Regency

Table 2 shows that low PBD does not necessarily associate with low confirmed cases or create a low risk of transmission, and high PBD is not always responsible for high confirmed cases or risks. Although building density can reflect the extent of human interactions in an area, the likelihood of contagion was only high at the emergence of a COVID-19 hotspot, as evident from infection surges being chiefly reported from dense urban areas (e.g., [17], [19], [36], [37]). When the mobility restriction policy comes into effect, public facilities are closed and traveling between provinces is restricted. However, over time, people in the city gradually return to their hometowns, especially with nonessential sectors being closed to moderate the spread of the disease, allowing remote work and study [38]. Therefore, a significant proportion of the city’s population that has shifted to the outskirts reduces the potential for crowding occurrences and person-to-person contacts in the city (despite its higher building density). This is believed to partially contribute to the high daily confirmed cases in some suburban districts (Kashihan, Sewon, Gamping, and Mlati), even though their building density was lower than their urban counterparts. For these reasons, the assumption that high building density facilitates high-intensive transmission only applies to the early stage of an outbreak. Further, it can be concluded that PBD contributes to risk at the early
stage, while later, after the outbreak gradually recedes, the risk of transmission is more dependent on daily confirmed cases.

3.2. Health risk management based on regional response

Following governor instructions on containment for the spread of COVID-19, the district governments enforced several nonpharmaceutical interventions (NPIs) basically designed to reduce the probability of transmission, such as close physical contacts. Table 3 shows the timeline of policy implementation from May to October 2021 throughout the province. The province saw a surge in daily confirmed cases from late May/early June until mid-August before gradually descending through the end of the observed period. During these months, the public health protocols always mandated masking, observing physical distance of 1–2 m, and avoiding crowd regardless of changes in the policy. Furthermore, the NPIs during varying levels and states of community activity restrictions enforcement (CARE) always included dividing people working in nonessential sectors with a specific ratio for the “home or work” order, enacting limits for capacity and opening hours of retail stores, restaurants (dine-in), shopping centers, houses of worships, and public facilities, and several travel restrictions.

| Timeline Date | COVID-19 Containment Policy                                                                 | Reference |
|---------------|---------------------------------------------------------------------------------------------|-----------|
| May 4         | Micro-based CARE\(^a\), and interprovincial travel restrictions during the holiday were extended. | [39]      |
| May 18        | Lift on interprovincial travel restrictions, but only for specific purposes with travel documents. | [40]      |
| June 15       | Capacity limits by zone were put in place.                                                  | [41]      |
| July 3        | Emergency CARE, the closing of businesses in nonessential sectors and travel restrictions.   | [42]      |
| July 21       | CARE Level 4, NPIs\(^b\) were applied with the zoning system in Micro-based CARE.           | [43]      |
| September 7   | CARE Level 3, reopening of schools, shops, markets, restaurants, food stalls, and selected attractions at limited capacity. Small-scale public gatherings were allowed. No zone-based interventions. | [44]      |
| October 19    | CARE Level 2, reopening of offices and businesses, cinemas, kids playground, attractions, and public facilities with additional capacity restrictions. | [45]      |

\(^a\) Community activity restrictions enforcement
\(^b\) Nonpharmaceutical interventions

On May 4, the governor issued an instruction to extend the pre-existing micro-based CARE to prevent more cases reported during the extended holiday, where interregional mobility is commonly high. Micro refers to the smallest administrative unit, neighborhood, from which regions are divided into green, yellow, orange, and red zones based on the number of houses with infected people in the last seven days: 0, 1–2, 3–5, and >5 houses per neighborhood, respectively. Local governments and communities were tasked with monitoring and enforcing NPIs, which were the mildest in the yellow zone and the strictest in the red zone. These NPIs were re-extended on May 18 then June 1, except for restrictions on traveling between provinces, which were lifted. Then, on June 15, the orders were adjusted to the zoning system: working from home/work at 50:50 and houses of worship at 50% capacity for yellow and orange districts, while 75:25 and less than 50% capacity for red districts; also, any activities taking place in public facilities, recreational parks, and attractions were restricted in the red zone.

On July 3, an emergency CARE order commenced following a surge in newly reported cases from 200 to 800 per day in June [25]. All districts in the province were red zones [46,47]. Most public facilities where people could gather and form crowds were entirely closed, rendering all businesses...
and activities taking place online. Nevertheless, public transportation operated at 70% capacity, and domestic traveling was allowed for passengers with a vaccination certificate and proof of a negative viral test result. On July 15, CARE Level 4 was put in place following a decrease in the second week of July, but there were no significant changes or lifts on restrictions because the daily confirmed cases were still high [47]. A decreasing trend in daily confirmed cases lowered the CARE level to 3 and prompted the reopening of some facilities and functions on September 7. This trend continued, and the CARE level was further lowered to 2 on October 19. Some interventions remained in effect from September through October, but the zoning system was not referred to in the policy documents.

3.3. Management compatibility with health risk level and building density
This research assumed that a structurally dense district creates opportunities for close contact with the infected and that people living in it and among relatively high confirmed cases are at significant risk of being infected. To decompose risk, governments and health officials tried to reduce one of the predictors, daily confirmed cases. Therefore, they set several protocols for when a case of hotspot appeared and enacted some interventions to intercept its further spread and future emergence.

From May to October 2021, NPIs had been introduced, lifted, and re-applied depending on the hazard’s severity. Seventy percent of the districts observed had low risk, and their hazard levels were low in the city but medium to high on the outskirts (see Table 4). It implies that the intended change has transpired in the city, whereas not on the outskirts. Although this outcome may or may not be the result of either single or multiple policies [29], it is true that the lowered number of daily confirmed cases coincided with and was preceded by CARE Level 4, during which nonessential sectors throughout the province were entirely closed. The remaining 30% of the districts had medium health risk with medium to high hazard, confirming pre-existing or other factors at play that have not been entirely considered in the adopted measures, including suitability with regional characteristics such as interconnectedness, economic dynamism, and urbanization trends [36,48].

Some of the NPIs also introduced measures according to region zoning, which was based on the number of houses with infected people. However, some NPIs had not been adjusted accordingly until June 15, even though the zoning system had been in effect since early May. This zoning system aimed to determine target interventions to lower the severity level of contagion (curative) and prevent further spread to other regions (preventive). In other words, each of the implemented NPIs was in and of itself designed only to suppress the hazard, but the most favorable outcome in risk management is low risk with low hazard and low vulnerability.

The diffusion of COVID-19 can be monitored and controlled using a vulnerability factor, building density, by also considering the stages or cycles of COVID-19 transmission and its risk management. At the emergence or re-emergence of rapidly spreading diseases, building density helps pinpoint potential hotspots from differences in distance between buildings, allowing lockdown orders and other restrictions to commence early. Buildings located close to each other can accelerate a case of infection to an outbreak. Then, when restrictions are regularly lifted, urban workers return home for various purposes, e.g., to compensate for economic loss due to the shutdown of commercial activities [38]. At this stage, governments and public health officials can observe districts with lower building density for COVID-19 emergence (potential epicenters). Later, when the cases show a decreasing trend, this can precipitate influxes of migrants to the city, making it at significant risk of COVID-19 resurgence [49,50]. For this reason, interventions can be targeted at denser districts, e.g., controls of internal migration at the borders.

In future research, PBD mapping accuracy can be optimized by involving multiple methods in built-up area mapping and updated HRSI in PBD assessment. Although NDVI gives satisfactory results in moderate-scale mapping in this research, it has limitations in differentiating bare earth and settlement area. Combining methods, such as (1) NDBI and Normalized Difference Vegetation Index (NDVI), (2) NDBI and Modified Normalized Difference Built-up Index (MNDWI), and (3) Index-based Built-up Index (IBI), can increase the mapping accuracy to 89–90% [15,51,52].

Furthermore, in this research, building density only distinguishes less and more dense or urban and suburban districts, meaning that it cannot be used to explain other health risk predictors, such as
spatial proximity to public areas or centers of socioeconomic activities where people gather and interact—a necessary condition for transmission. Furthermore, to fully understand the contribution of density to the diffusion of COVID-19, this factor can be integrated with population density. This can explain to what extent building density is correlated to the number and concentration of people as the at-risk elements of infectious disease. The research findings can help government and public health officials to moderate the spread and anticipate the resurgence of the disease by identifying target areas for interventions. However, to create an effective district-specific measure, the policy-making should factor in regional characteristics, e.g., socioeconomic condition, infrastructural and institutional networks, and demographics.

4. Conclusion
Remote sensing data, particularly Landsat 8 imagery, allow for moderate scale mapping of percent of building density (PBD), which can be inputted to risk assessment as a physical vulnerability factor. Using the built-up index in PBD calculation gives reliable results because it is based on the actual distribution that the imagery has captured. This research has also found that building density explains the uneven distribution of COVID-19 at different stages of its development, although the assumption that high building density facilitates transmission is only true for the early stage of its emergence. By using it as a vulnerability factor, governments and public health officials can differentiate districts based on the percentage of physically occupied land (PBD) to pinpoint potential outbreaks or hotspots and mitigate the spread of an emerging case. Furthermore, integration of PBD and daily confirmed cases enables the assessment of health risk spatially, which helps determine target areas for interventions and allows responses to the next wave of infections to be regionally tailored. The current nonpharmaceutical interventions are designed to lower health risk based on confirmed cases only, which is more curative and preventive rather than promotive. A promotive measure claims more control over health and quality of life with varying social and environmental interventions. On this ground, observing building density and daily confirmed cases can anticipate, or better, prevent the next wave of COVID-19 outbreak.

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