frontiers in Built Environment

ORIGINAL RESEARCH
published: 17 January 2022
doi: 10.3389/fbuil.2021.813399

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Specialty section:
This article was submitted to
Construction Management,
a section of the journal
Frontiers in Built Environment

Received: 11 November 2021
Accepted: 24 December 2021
Published: 17 January 2022

Citation:
Li M, Peng Y, Wu Y, Xu J, Tan T,
Guo H, Lu W, Yeh AGO and Xue F
(2022) Role of the Built Environment in
the Recovery From COVID-19:
Evidence From a GIS-Based Natural
Experiment on the City Blocks in
Wuhan, China.
Front. Built Environ. 7:813399.
doi: 10.3389/fbuil.2021.813399

Role of the Built Environment in the Recovery From COVID-19: Evidence From a GIS-Based Natural Experiment on the City Blocks in Wuhan, China

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The built environment closely relates to the development of COVID-19 and post-disaster recovery. Nevertheless, few studies examine its impacts on the recovery stage and corresponding urban development strategies. This study examines the built environment's role in Wuhan's recovery at the city block level through a natural experiment. We first aggregated eight built environmental characteristics (BECs) of 192 city blocks from the perspectives of density, infrastructure supply, and socioeconomic environment; then, the BECs were associated with the recovery rates at the same city blocks, based on the public "COVID-19-free" reports of about 7,100 communities over the recovery stages. The results showed that three BECs, i.e., "number of nearby designated hospitals," "green ratio," and "housing price" had significant associations with Wuhan's recovery when the strict control measures were implemented. At the first time of reporting, more significant associations were also found with "average building age," "neighborhood facility development level," and "facility management level." In contrast, no associations were found for "controlled residential land-use intensity" and "plot ratio" throughout the stages. The findings from Wuhan's recovery pinpointing evidence with implications in future smart and resilient urban development are as follows: the accessibility of hospitals should be comprehensive in general; and the average housing price of a city block can reflect its post-disaster recoverability compared to that of the other blocks.

Keywords: built environment, post-disaster recovery, COVID-19-free community, natural experiment, GIS

HIGHLIGHTS

- Natural experiment for testing correlations between the built environment and Wuhan's recovery from COVID-19.
- Designated hospitals, neighborhood facility level, green ratio, housing price, building age, and facility management level were associated with the early recovery ($p < 0.01$).
- Only designated hospitals, green ratio, and housing price were still associated with the recovery in later stages ($p < 0.05$).

- No association found for controlled residential land-use intensity and plot ratio throughout the whole stage.
- New evidence and implications for smarter and resilient urban development.

1 INTRODUCTION

Coronavirus disease 2019 (COVID-19) is one of the deadliest pandemics in human history (Sohrabi et al., 2020). Understanding its mechanism from biological, ecological, and social perspectives is thus important, especially to avoid its wide spread and infection and further facilitates urban recovery. Since the transmission is a spatial-related process, substantial geographical research has been made to monitor, analyze, contain, and recover from the unprecedented pandemic (Desjardins et al., 2020; Franch-Pardo et al., 2020).

The built environment is the collection of human-made surroundings for human activity, ranging in scale from buildings to neighborhoods and cities. Its direct physical settings and indirect human behavior intervention have led to its significant influence on infectious disease dynamics, especially in certain infections transmitted by contact, aerosols, or droplets (Pinter-Wollman et al., 2018). Typical built environmental characteristics (BECs) include population and land-use density (Yu and Wen 2016; Ahmadian et al., 2019), infrastructure supply (Loo and Lam 2012; Chen et al., 2019), and social-economic environment (Aldrich 2012; Qu et al., 2018), the role of which has been proved critical for the known infectious diseases such as cholera (Pinter-Wollman et al., 2018), H1N1 (Lowcock et al., 2012; Ponnambalam et al., 2012), and SARS (Fang et al., 2009). Similarly, the relationship between these BECs and the COVID-19 pandemic needs to be re-identified to inspire urban recovery and future resilient urban development.

Numerous studies nowadays have been conducted on different spatial scales to unfold the impacts of BECs on the COVID-19 development (Frank et al., 2019). For instance, there existed a positive correlation between the county-level population density and the confirmed COVID-19 cases in Hubei Province, China, (Xiong et al., 2020) and US (Klompmaker et al., 2021; Sy et al., 2021). District-level land-use and population density as well as infrastructure settings including green space ratio and hospital density were significantly correlated with the morbidity rate in Wuhan of Hubei (You et al., 2020). At the block and community level, commercial vitality and infrastructure supply were found to have a significant correlation with the number of confirmed cases in Wuhan (Li et al., 2020) and Huangzhou of Hubei (Li et al., 2021) as well as Hong Kong (Kan et al., 2021).

Nevertheless, the role of the BECs in the COVID-19 recovery may be different from that in urban development. For instance, it is found that although the high land-use density may increase the concentration of people and facilitate disease transmission, their superior health and educational systems are also more prepared to handle pandemics, leading to higher rates of recovery and lower rates of mortality (Dye 2008; Hamidi et al., 2020). In contrast, inadequate healthcare management would decrease the rate of recovery among COVID-19 patients (Hopman et al., 2020). Although some cities have experienced recoveries from the pandemic, most cities are still struggling with handling COVID-19. Thus, the impacts of BECs on COVID-19 recovery from different spatial scales are scarce for exploration. Compared to the large-scale analysis, block-level BECs and the COVID-19 recovery can present more fine-scale insights into a precious non-pharmaceutical intervention and inspire the future resilient urban development (Li et al., 2021). However, its comprehensive understanding is desired but overlooked.

Wuhan is a megacity with over 11 million inhabitants living in about 7,100 residential communities. As the first lockdown and recovered city, the city was locked down on 23 January 2020 and resumed in early April 2020. Strong interventions such as closed community management were implemented to restrict the inner-city transmission. The non-commutable urban environment enables a natural experiment test bed to explore the role of BECs in the COVID-19 recovery (Thomson 2020). This study attempts to investigate the associations between the BECs and their recovery from COVID-19 in the block level through geospatial statistical analysis. Two questions are examined: 1) What is the initial recovery distribution of Wuhan city blocks with different built environments? 2) Under strong interventions such as the intracity mobility restriction and community-based lockdown, what is the role of the built environment in the later urban recovery?

2 RESEARCH METHODS

2.1 Research Area

This study mainly focuses on the 192 city blocks in the central urban area of Wuhan. They were from the eight districts, including Caidian, Hanyang, Hongshan, Jiang'an, Jianghan, Qiaokou, Qingshan, and Wuchang as shown in **Figure 1**. The city block delineated by the Wuhan Natural Resources and Planning Bureau is the study unit in this research (WNRPB 2015). A city block is a group of communities with the same controlled residential land-use intensity.

2.2 Research Design

Figure 2 shows the flowchart of the GIS-based data aggregation and statistical analysis methods. First, eight typical BECs and COVID-19-free rate (CFR) are defined in **Section 2.3**. Four kinds of datasets from different sources were collected and cleansed using GIS spatial measurement, as described in **Section 2.4**. Spearman's rank correlation analysis between BECs and CFR is explained in **Section 2.5**.

2.3 Definitions of BECs and CFR

Table 1 lists the definitions of eight BECs as independent variables. The BECs represent three types of quality of the built environment at the city block level, namely the density, infrastructure supply, and socioeconomic environment. Besides the eight BECs, the dependent variable CFR is also measured at the city block level.

In this research, two BECs are defined to represent the density of the built environment. One is the controlled residential land-

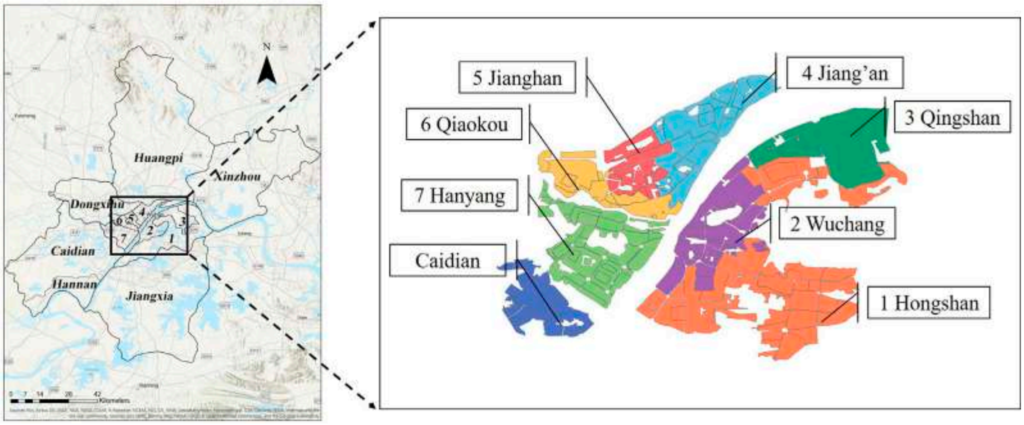

FIGURE 1 | Location of 192 city blocks of eight districts in Wuhan, China.

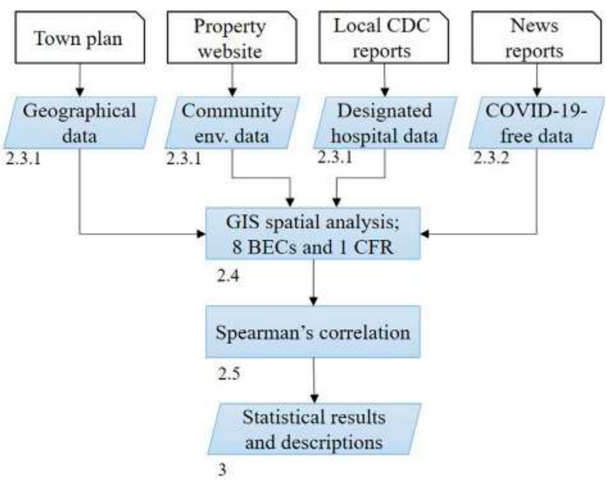

FIGURE 2 | Natural experiment research design of this study.

TABLE 2 | Controlled residential land-use intensity (*CR*) defined for Wuhan (WNRPB 2015).

CR	Base plot ratio	Density of buildings
1	3.2	≤20%
2	2.9	
3	2.5	≤25%
4	1.5	

use intensity defined by the Wuhan government for each city block, as listed in **Table 1**. According to local regulations, the controlled residential land-use intensity strictly limits the intensity of residential land development. For example, a block with the controlled residential land-use intensity = 1 has the guideline permission of developing not more than 20% density of buildings and a base plot ratio at 3.2, as shown in **Table 2**. Another BEC is the average of actual plot ratios of communities within the city blocks reflecting the real land-use intensity, the

TABLE 1 | Eight BECs and CFR defined for a city block in this study.

	Type	Abbreviation.	Full name	Description	Range	Unit
BECs	Density	*CR*	Controlled residential land-use intensity	Lower value indicates the higher planned base residential plot ratio and building density	[1, 4]	—
		PR	Plot ratio	The actual average ratio of the gross floor area to the total land area of communities	$\mathbb{R}^+$	—
	Infrastructure supply	*DH*	Nearby designated hospitals	The number of designated hospitals and clinics in the block or in an *x*-km buffer zone	0, 1, 2, …	—
		NF	Neighborhood facility development level	The average level of matureness of the neighborhood facilities. Higher is better	[1, 4]	—
		GR	Green ratio	The average ratio of the green land area to total land area of communities	[0, 1]	—
	Socioeconomic environment	*HP*	Housing price	The average unit price at which the estates were offered for sale	$\mathbb{R}^+$	10,000 RMB/m^2
		BA	Building age	The average building age	$\mathbb{R}^+$	Year
		FM	Facility management level	The average level of the facility management. Higher is better	[1, 4]	—
CFR			COVID-19-free rate	Ratio of communities won the COVID-19-free title	[0, 1]	—

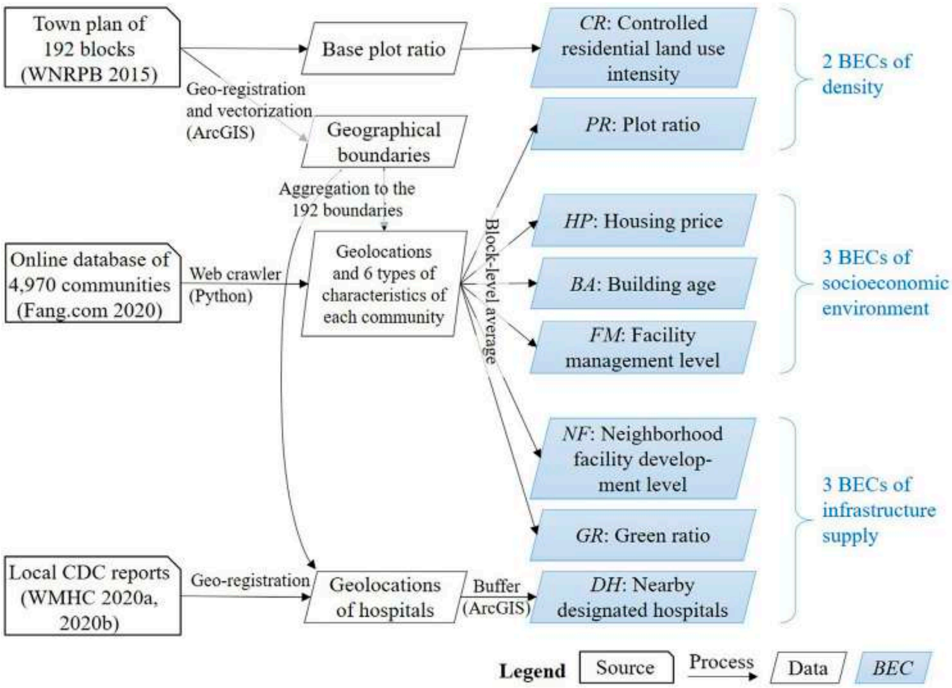

FIGURE 3 | Data collection and preprocessing for the eight BECs.

range of which belongs to $\mathbb{R}^+$ representing the positive real numbers. In addition, it also indirectly reflects the population density of the city blocks because of the blocked transportation system.

Three BECs in **Table 1** represent the infrastructure supply for each city block. One is the number of designated hospitals and clinics, which is measured within the block with a buffer of 3 km. The other two BECs are the average development level of the neighborhood facility and the green ratio of the city blocks. The neighborhood facility development level using a four-point scale is assessed as the matureness of the neighborhood in terms of public facilities and commercial and transportation services, whereas the green ratio was the average ratio of the green land area to the total land area of the communities. For both, the higher indices stand for the better infrastructure settings.

Last, three BECs including housing price, building age, and neighborhood facility management level are defined to depict the socioeconomic environment. Housing price refers to the average unit price of residential communities in the city blocks, where the unit is 10,000 RMB/m^2. The building age refers to the average age of residential buildings. For the facility management level of blocks, we assessed them in a four-point scale where 1 indicated "poor" and 4 stood for "excellent."

CFR is defined as the "COVID-19-free ratio" of communities in the city blocks. On 5th March 18:00, 42 days after the lockdown, the Centers for Disease Control and Prevention of Wuhan consistently started to report a series of "COVID-19-free community" honor lists. A community was called "COVID-19-free" if both of the following conditions were met (Xiao 2020):

(1) no new confirmed, suspected, fever, or close contact cases in the past 14 days;
(2) strictly social distancing, closed estate management, fully screened inhabitants, and regular sterilization.

2.4 Data Sources

2.4.1 Built Environmental Data

Three datasets of the built environment were collected, as shown in **Figure 3**. The printed plan of 192 city blocks was from the Wuhan Natural Resources and Planning Bureau (2015). We geo-registered and reconstructed the topographical boundaries of the city blocks with ArcGIS 10.1 and saved the geographical boundaries in the vector format of GeoJSON, as shown in **Figure 3**. Meanwhile, we collected the controlled residential land-use intensity data for the case area. The residential land-use intensities and their spatial distribution pattern are shown in **Figure 4A**.

An online property dataset was collected using Python web crawler for the profile of the communities, as shown in **Figure 3**. The data source was Fang.com (2020), a city-wide property database listing residential estates in over 7,000 communities of whole Wuhan City. After using a geospatial analysis, the boundaries of the 192 city blocks selected 4,138 communities for this study. For each community, there are six characteristics related to the population density including 1) plot ratio, infrastructure supply including 2) neighborhood facility development level and 3) green ratio as well as socioeconomic

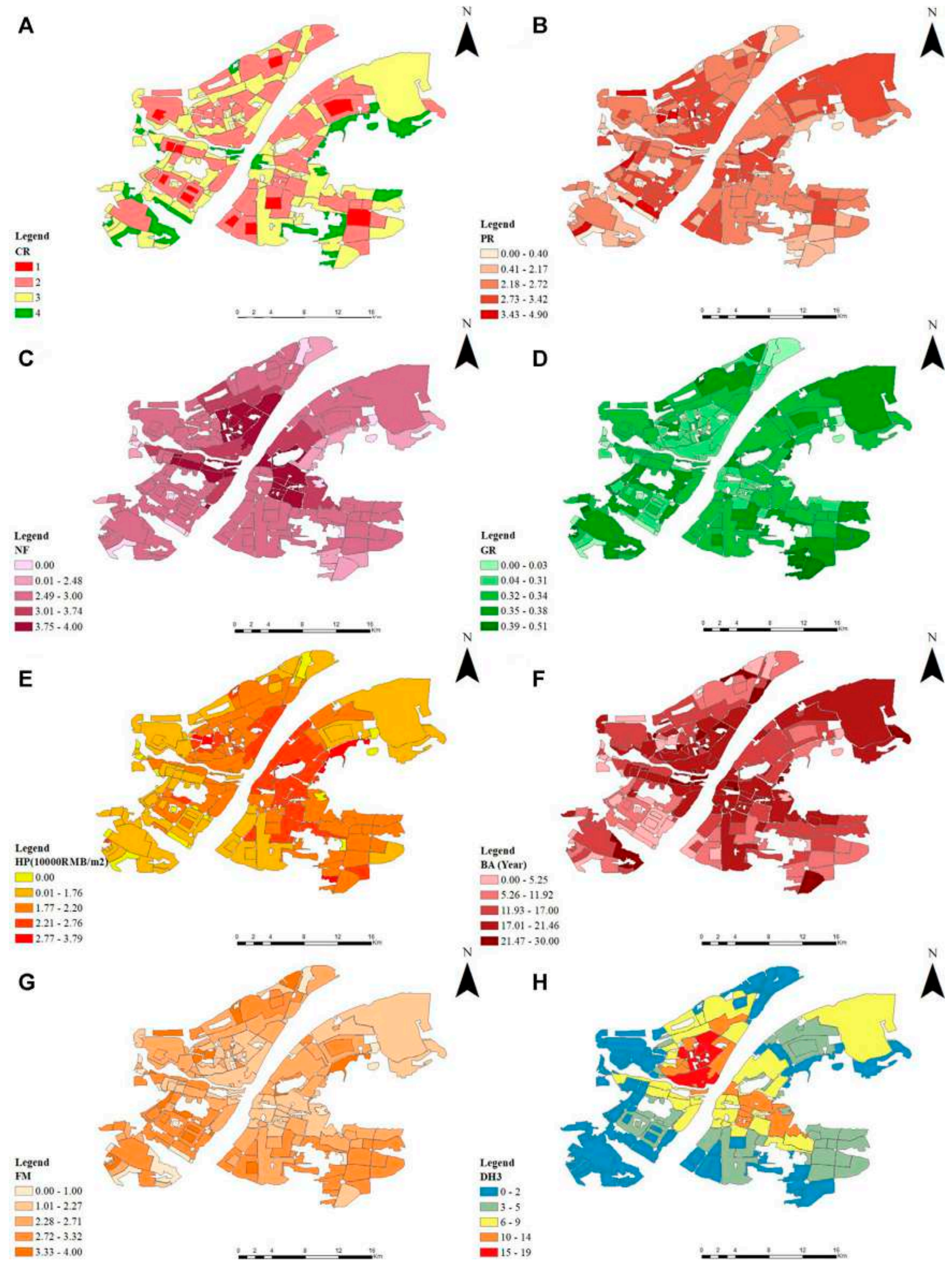

FIGURE 4 | Visualized patterns of the eight BECs of the city blocks in Wuhan. **(A)** Controlled residential land-use intensity (*CR*), **(B)** plot ratio (*PR*), **(C)** neighborhood facility development level (*NF*), **(D)** green ratio (*GR*), **(E)** housing price (*HP*), **(F)** building age (*BA*), **(G)** facility management level (*FM*), and **(H)** nearby designated hospitals (DH_3).

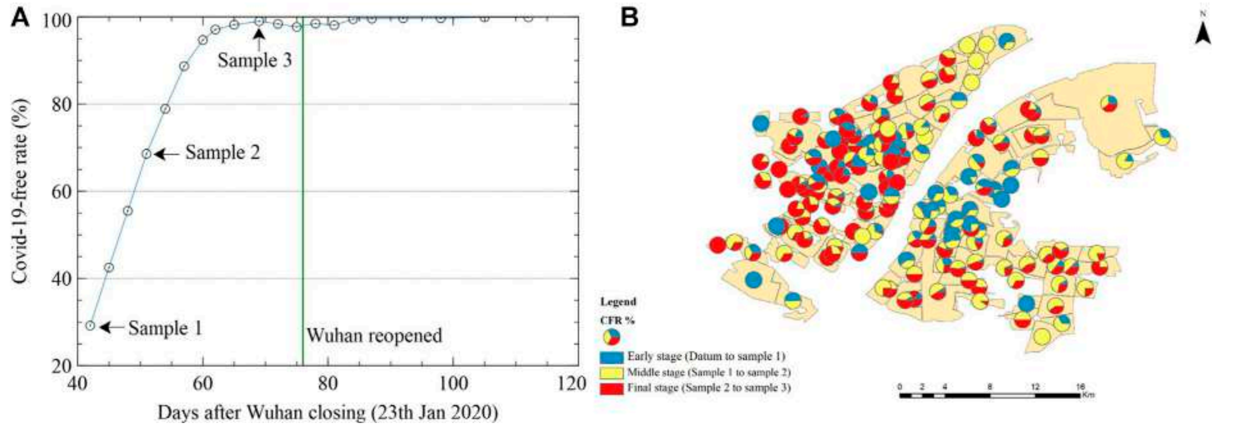

FIGURE 5 | Accumulated COVID-19-free rates of communities in Wuhan. **(A)** Three sampling time points and **(B)** recovery rates in three stages.

environment including 4) housing price, 5) building age, and 6) facility management level. We extracted all the residential communities for the case area and associated each community with the actual geolocation on WGS-84 globe (transformed from the China's local BD-09 coordinate system). Six related BECs were extracted as an average by aggregating the communities into city blocks. The spatial distribution patterns of the BECs are shown in **Figures 4B–G**.

Furthermore, a list of 48 designated hospitals and 60 designated fever clinics were collected, as shown in **Figure 3**. The name list of hospitals designated for COVID-19 treatment in urban Wuhan was collected from the Wuhan Municipal Health Commission (2020a), while the list of designated fever clinics was collected from the Wuhan Municipal Health Commission (2020b). By matching the two lists and removing the duplicates, 72 hospitals and fever clinics were confirmed, with their full names, addresses, and geocoded locations on the WGS-84 globe. We aggregated them into city blocks to examine the spatial distribution pattern of DH_3 as shown in **Figure 4H**.

2.4.2 Urban Recovery Data

As shown in **Figure 5A**, 20 lists of COVID-19-free communities were authorized from 5th March to 14th May by the Wuhan Municipal Headquarters. Before the reopening of the city in early April 2020, as shown by the green line in **Figure 5A**, the *CFR* was about 99% in urban Wuhan. On 30 June 2020, all 7,102 communities were branded COVID-19-free. From late January to early March 2020, Wuhan increasingly implemented a series of measures, such as bans on transportation, suspension of public gatherings, closed management of villages, communities, and units. Thus, we assume that the access to the built environment was totally controlled when the first report was released.

We selected three data samples from the series of COVID-19-free community reports, as shown in **Figure 5A**, based on the overall *CFR*. The first sample on 5 March 2020 represented CFR_1 = 29.2%, while the second was CFR_2 = 68.6% released on 14th March and the third was CFR_3 = 99.0% on 1st April. The second sample was selected for an approximate average of CFR_1 and CFR_3. We downloaded the reports of about 7,100 communities from Changjiang Daily (CJD, 2020a; CJD, 2020b; CJD, 2020c), parsed the name list from the report images. Then, we registered and fine-tuned the geo-locations of all the communities to the WGS-84 globe using Amap.com (https://lbs.amap.com/api/webservice/, ver. 3), which is one of the most popular digital maps and offers accurate geocoding services in China. Finally, about 4,970 residential communities were associated with the 192 city blocks in the case area.

Figure 5 visualizes the recovery rates of each block from the three phases, including datum-to-CFR_1 (early stage), CFR_1-to-CFR_2 (middle stage), and CFR_2-to-CFR_3 (final stage). A general pattern is found that the western Wuhan relatively lagged in terms of city block recovery. In this research, the basic recovery rate, i.e., $CFR_{P1} = CFR_1$ was selected to present the initial recovery situation of all blocks at the early age. Then, the percentages of recovery for the rest two stages, i.e., $CFR_{P2} = (CFR_2 - CFR_1)/(1 - CFR_1)$ and $CFR_{P3} = (CFR_3 - CFR_2)/(1 - CFR_1)$ were selected as the 'pure' recovery rates of the city blocks.

2.5 Statistical Analysis

We first apply Spearman's rank correlation to examine the relations between the eight BECs and the three CFR variables. Pearson's linear correlation is inappropriate in this study due to some non-normal variables. The Spearman's correlation coefficient ρ is defined as:

$$\rho = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} = \frac{cov(x, y)}{\sigma_x \sigma_y}, \tag{1}$$

where n is the total number of the city blocks, x_i and y_i stand for the ranks of the variables, $\bar{x}$ and $\bar{y}$ are the mean ranks, $cov(x, y)$ represents the covariance, and σ_x and σ_y are the standard deviations. The top 60 dense residential city blocks (number of communities ≥20) were selected out of 192 to suppress errors from insufficient community samples. The greater the coefficient ρ is, the stronger the relationship is between two variables.

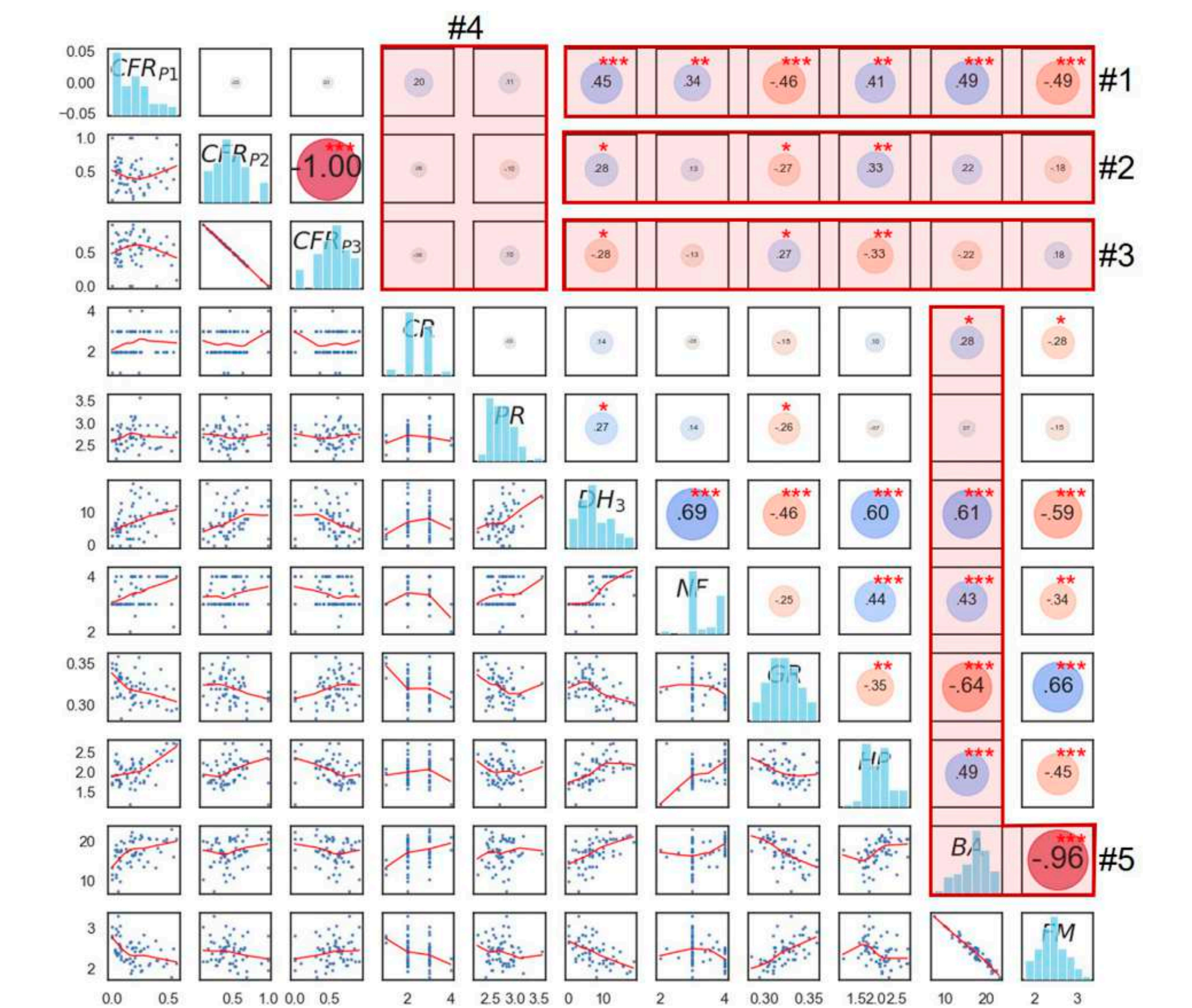

FIGURE 6 | Results of Spearman's rank correlation analysis (n = 60), with the histograms at diagonal subfigures (abbreviations referring to **Figure 4**), scatter plots in the lower triangle, and the area of the circle in the upper triangle indicates the absolute value (cold color = positive; warm = negative) of the Spearman coefficient ρ (two-tailed significance p: *** ≤0.001 < ** ≤0.01 < * ≤0.05).

3 RESULTS

Figure 6 shows the results of analysis, where the data spreadsheet is available in the **Supplementary Material**. The diagonal subfigures show that some variables, such as CFR_{P1} and neighborhood facility development level, were not in normal distributions. The upper triangle in **Figure 6** shows Spearman's rank correlation tests, while the lower triangle displays the scatter plots. The scales of two axes target the two variables of the scatter plots.

As shown in the red rectangle #1 in **Figure 6**, CFR_{P1} was significantly associated with all six BECs from the infrastructure supply and socioeconomic environment, i.e., nearby designated hospitals (3 km), neighborhood facility development level, green ratio, housing price, building age, and facility management. In particular, the neighborhood facility development level had a weak positive association ($\rho = 0.34$, $p \leq 0.05$, $n = 60$), while others had moderate associations ($0.41 \leq \rho \leq 0.49$). In other words, on 5 March 2020, or the first sample point, the city blocks with more aged communities and nearby hospitals, a lower green ratio, more mature public facilities, and a higher housing price and property management level had higher recovery rates. The possible reasons include 1) probably lower infection rates at the initial stage and 2) earlier recoveries in such city blocks.

Next, the associations of the six BECs against CFR_{P1} had a sharp decline against CFR_{P2}, as shown in the red rectangle #2 in **Figure 6**. It indicates that the strictly closed management, i.e., complete isolation from the outdoor urban environment for most dwellers, comprehensively weakened the associations. For example, the ρ

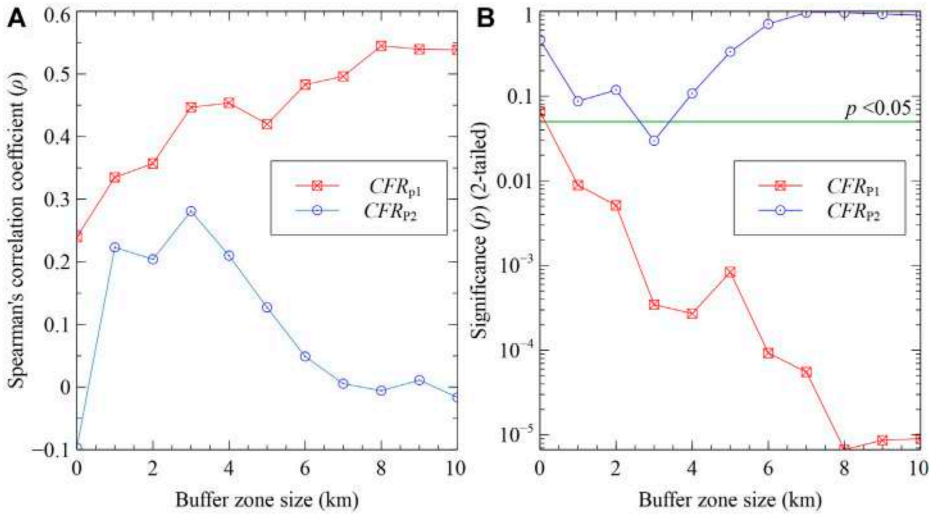

FIGURE 7 | Results of sensitivity analysis against the buffer zone size for nearby designated hospitals. **(A)** Spearman's coefficient and **(B)** significance level (n = 60).

values were approximately halved except for housing price. Yet, three BECs, nearby designated hospitals (3 km), green ratio, and housing price, were still found significant ($p < 0.05$, $n = 60$). Besides, the signs of the two ρ values for housing price were seen as consistent.

The correlations of the six BECs against CFR_{P3} in the red rectangle #3 in **Figure 6** were mirror reflections of those regarding CFR_{P2}. In contrast, the controlled residential land-use intensity and plot ratio representing the density of the built environment, as shown in the red rectangle #4 of **Figure 6**, had no considerable roles in resumptions in Wuhan.

Other significant correlations between BECs mainly from the infrastructure supply and socioeconomic environment were also observed. For instance, aged communities in Wuhan were strongly associated with lower green ratios ($\rho = -0.64$, $p \leq 0.001$, $n = 60$), as shown in the red rectangle #5 in **Figure 6**. Such an association also prevails in most of China's megacities due to the fast urbanization. Besides, the associations between the building age and other BECs such as nearby designated hospitals (3 km), neighborhood facility development level, housing price, facility management level, and controlled residential land-use intensity were also in line with the spatial distribution patterns shown in **Figure 4**. Large proportion of aged city blocks was mainly located in the central part of Wuhan, which owned a higher housing price, higher-level nearby facility development, and more hospitals but less facility management.

In addition, a sensitivity analysis using eleven sample sizes of buffer zones from 0 to 10 km was implemented to test the trends of associations considering the modifiable areal unit problem (MAUP) (Openshaw 1981). **Figure 7** shows that the trends in the first two stages. The nearby designated hospitals within an increasing buffer zone size had a consistent strengthening correlation with CFR_{P1} and a declining p-value to 10^{-5} at 8 km. The correlation with CFR_{P2} had a different trend. When the buffer zone size increased, the figure for the coefficient in **Figure 7A** rose at first and reached the maximum at 3 km; then, it declined gradually. Under the line of $p = 0.05$ in **Figure 7B**, 3 km was the only significant point for CFR_{P2} ($\rho = 0.2810$, $p \leq 0.05$, $n = 60$). It indicates that 3 km was a "sweet point" for Wuhan to aggregate the number of designated hospitals and clinics in both the early and later stages.

4 DISCUSSION

4.1 The Role of Built Environment in Wuhan's Recovery

The findings of this article suggest that both infrastructure supply and socioeconomic environment factors had significant associations with city block–level COVID-19 recovery in Wuhan. Six examined BECs, i.e., nearby designated hospitals (3 km), neighborhood facility development level, green ratio, housing price, building age, and facility management level were significantly associated with Wuhan's initial recovery from the COVID-19 pandemic. The associations on the first sampling point may refer to the combination of BECs' impacts on COVID-19 transmission and the different initial confirmed possibility of blocks in different areas, which should be further explored.

Two BECs concerning the density of the built environment, i.e., controlled residential land-use intensity and plot ratio, were not significant for the city block–level recovery throughout the study period. In contrast, studies on COVID-19 transmission have found a significant positive association between the population density and the possibilities of transmission (Chhikara et al., 2020; You et al., 2020). The comparison of the findings shows the macro-BECs have varied associations in different stages such as disaster control (i.e., COVID-19 transmission) and post-disaster recovery.

Furthermore, these BECs were associated with each other. Besides the findings of aged city blocks mentioned in **Section 3**, the housing price was found to be the strongest correlation with the number of nearby designated hospitals and clinics (medical facilities). Surprisingly, the green ratio was negatively associated with COVID-19 recovery in Wuhan's case, which echoes some studies in China, for example, high public green space density increased the COVID-19 morbidity rate in Wuhan (You et al., 2020).

In the middle and final recovery stages, the six BECs' associations with the recovery rates were weakened in general. It implies that strict measures against human mobility at the neighborhood and city block level showed a statistical impact on the BECs' roles. However, three BECs, i.e., nearby designated hospitals (3 km), green ratio, and housing price, still had significant associations in the later stages of recovery; in addition, the three BECs may indicate the city blocks' innate urban resilience levels due to the full isolation of residents from the environment. The effectiveness of human activity and mobility control measures, as weakened associations with BECs, also echoes the findings in the literature (Chhikara et al., 2020; Hartley and Perencevich 2020; Hirschhorn et al., 2020; Islam et al., 2020; Xiong et al., 2020).

4.2 Significance

This study aims to fill in the research gap of the BECs and COVID-19 recovery associations at the city block level. The findings provide new evidence at a fine-spatial scale for researchers and practitioners in the fields of urban development, urban health, post-disaster recovery, and public policy. For example, Wuhan's tight control measures for COVID-19 have effectively weakened BECs' associations with COVID-19 transmission. The findings also echo classical urban development and post-disaster recovery theories. For example, the infrastructure settings such as medical resources and neighborhood greenery management show significant but inverse impacts on Wuhan's recovery; some BECs of the socioeconomic environment, such as housing price, can effectively reflect the disaster and secondary disaster development (Aldrich 2012; Peng et al., 2020; Rouhanizadeh et al., 2020).

The findings may inspire smarter and more resilient urban development, in Wuhan and elsewhere. For Wuhan, a city that just completed its 2010–2020 Town Plan (GovWH 2010), the accessibility of medical infrastructures, nature, and public services—besides the existing density and transport—should be emphasized in the next plan. In addition, the BECs' associations may inspire the cities that are struggling with the pandemic (Allam and Jones 2020; Parnell 2020). Under the strong mobility intervention, preparedness should concern more on the infrastructure supply and socioeconomic environment for epidemic response and recovery.

The positive associations of nearby designated hospitals suggest systematic review and reshaping of the density and accessibility of public health and medical resources in urban development. The trends of the buffer ranges to the medical facilities seem to suggest a walkable distance, such as 3 km for Wuhan, may be a "sweet point" for optimal infrastructure designs for planning residential blocks. This finding may be more helpful to the fast urbanization in China and other emerging economies, where public health facilities in the marginal areas or new towns cannot match the speed of real estate development.

The negative associations of green ratios revealed an unusual case. It did not disprove the role of greenery on urban health in megacities. Instead, it implies that public health facilities outweighed a town's greenery landscape in terms of epidemic recovery. In addition, the negative association between greenery and housing price in Wuhan may infer a disparity in accessibilities in Wuhan. That is, the high-income population sacrifices their access to nature for public services and resources—such as hospitals, subways, and education, which echoes studies in property valuation (Huang & Yin 2015; Xu et al., 2016). Thus, the housing price of a city block can reflect its post-disaster recoverability to an extent. In the future, one way to resolve the disparity of infrastructure supply is to encourage integration and sharing of resources across city blocks from the sharing economy perspective (Liu et al., 2016). Another possible way is comprehensive and inclusive planning that equally meets the needs of low-income and vulnerable groups in Wuhan and other cities.

4.3 Limitations and Future Work

This study also has limitations. Our main data source was government reports distributed by newspapers, which were based on medical tests and self-reporting fever data. Due to the incubation period and asymptomatic patients, the aggregated CFR values may contain small errors. Furthermore, the correlation analysis between aggregated COVID-19 recovery and built environment in the city block level was reasonable, but lost data details such as causes and causality data. Another limitation lies in the source of the online property database, which does not assess the streets and parks surrounding the communities. The significant associations in Wuhan may also be limited by the urban plans, climate, ethnicity, and culture though the methodology can be replicated in other cities.

In the future, we look forward to seeing studies on BECs associations and impacts on different cities and countries with different intervention conditions so that the findings can be further verified thoroughly. More quantified urban data sources, such as city information modeling (Xue, Wu et al., 2021) and computable street view features (Xue, Li et al., 2021), might reveal new evidence as well. Encouragements and subsidies based on solid evidence, for example, to increase the quantities of nearby hospitals, promote residential landscape sanitary management levels, and take prioritized measures for targeted economic city blocks should be further recommended for sustainable and smart urban development.

5 CONCLUSION

This study employed a randomized GIS-based natural experiment study across the city blocks in Wuhan to investigate whether different built environmental characteristics (BECs) were associated with COVID-19 recovery rates. All the six BECs from the infrastructure supply and socioeconomic environment were found significantly associated with the initial COVID-19 recovery in the megacity of Wuhan. They were nearby designated hospitals (3 km), neighborhood facility development level, green ratio, housing price, building age, and facility management level. The strict measures in the later recovery stages seemed to weaken all the six associations in general. As a result, three BECs, i.e., nearby designated hospitals (3 km), green ratio, and housing price, still had significant associations. In contrast, both BECs presenting the density of the built environment had no association with the recovery throughout the whole stage. The statistical results in the article may be useful for the cities that are still fighting COVID-19. More importantly, the evidence can pinpoint several implications for smart and resilient urban development, for example, comprehensive and balanced accessibility of medical facilities and public facility services.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

ML and FX contributed to the conception and design of the study. ML and FX organized the database. ML, YW, and FX performed the statistical analysis and charting. ML and FX wrote the first draft of the manuscript. YP, JX, TT, and HG wrote subsections of the manuscript. All authors contributed to manuscript revision and read and approved the submitted version.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fbuil.2021.813399/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.