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Impacts of Building Environment and Urban Green Space Features on Urban Air Quality: Focusing on Interaction Effects and Nonlinearity

Binsheng Wu [1] and Chunqing Liu [1,2,*]

[1] College of Landscape Architecture and Art, Jiangxi Agricultural University, Nanchang 330045, China; wubinsheng@stu.jxau.edu.cn
[2] Jiangxi Rural Culture Development Research Center, Nanchang 330045, China
* Correspondence: liuchunqing@jxau.edu.cn

Abstract: Air pollution is a rising environmental concern that has detrimental effects on human health and the environment. Building environment and urban green space features play a crucial role in the dispersion and accumulation of air pollutants. This study examines the impacts of building environment and urban green space on air pollution levels in the highly urbanized city of Hong Kong, focusing on their interaction effects and potential nonlinearity. For the analysis, this paper investigates how building density, building height, building types, urban green space size, and number of urban green space clusters, as well as their interplays, impact $PM_{2.5}$ concentrations using high-resolution, satellite-based $PM_{2.5}$ grids coupled with spatial analysis techniques. The findings reveal that a unit increase in the size of urban green space and the standard deviation of building height contribute to a 0.0004 and a 0.0154 reduction in PM levels, respectively. In contrast, air pollution levels are found to be positively associated with building density (0.1117), scatteredness of urban green space (0.0003), and share of commercial buildings (1.0158). Moreover, it has been found that building height presents a U-shape relationship with $PM_{2.5}$ concentrations. Finally, the negative association between the size of urban green space and air pollution levels tends to be enlarged in districts with more low-rise buildings. This study conveys important building environment and urban green space planning implications.

Keywords: air pollution; building environment; urban green space; interaction effects; multivariate regression

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1. Introduction

Urban air pollution has emerged as a pressing global issue, posing significant threats to human health and the environment. The rapid urbanization and industrialization witnessed in recent decades have led to a sharp increase in air pollutants, such as particulate matter (PM), nitrogen dioxide (NO_2), and volatile organic compounds (VOCs), in urban areas [1]. These pollutants not only contribute to health problems but also have adverse effects on the climate and ecosystems [2,3]. For example, the World Health Organization (WHO) estimates that around 4.2 million premature deaths occur annually due to exposure to ambient air pollution, with most of these deaths occurring in low- and middle-income countries [4]. Moreover, urban air pollution has been linked to a wide range of health issues, including asthma, lung cancer, and heart disease [5]. In addition, air pollution also contributes to climate change by altering the Earth's energy balance, leading to global warming and other environmental consequences [6]. Against this background, mitigating urban air pollution has become a primary concern for urban planners, policymakers, and researchers.

Recently, the roles of building environments and urban green spaces in air pollution mitigation have gained considerable attention. Buildings, being central to urban landscapes, significantly impact air quality through their design, construction materials, ventilation systems, and operation. At one level, Buildings emit pollutants through various processes, such as combustion of fossil fuels for heating and cooling, construction activities, and off-gassing of building materials [7,8]. Numerous efforts have been made to explore how building operation and construction, as potential pollution sources, contribute to air pollution emissions. For example, energy consumption in buildings, particularly for heating, cooling, and lighting, is a major source of air pollution. The combustion of fossil fuels, such as coal, oil, and natural gas, releases pollutants like PM, NO_x, and SO_2 into the atmosphere [9]. Consequently, improving energy efficiency in buildings has become a key strategy for reducing air pollution in urban areas. Strategies such as passive design, green building materials, and renewable energy systems have been found to be effective in reducing energy consumption [10]. In addition, building construction activities, including material production, transportation, and on-site operations, contribute to air pollution through dust emissions and exhaust from construction machinery [11]. Research has suggested that adopting sustainable construction practices, such as minimizing construction waste, using low-emission materials, and implementing dust control measures, can help reduce pollution from construction activities [12].

At another level, building design and layout can significantly affect the dispersion and concentration of pollutants in the surrounding environment [13–15]. Thanks to the increasing availability of air quality concentration data, recent studies have started to investigate the interplays between building structure features and ambient air quality, focusing particularly on their dispersion and accumulation of air pollutants. The height of buildings has been identified as a key factor influencing urban air pollution, but conflicting results have been presented in the literature. On the one hand, some studies show that higher buildings can create canyons that trap pollutants and hinder their dispersion, resulting in increased pollutant concentrations at street level [16]. For example, a study conducted in Hong Kong found that high-rise buildings can lead to elevated concentrations of NO_2 at street level due to reduced ventilation and limited air exchange within the street canyons [17]. Similarly, a study in New York City revealed that tall buildings can create localized pollution hotspots due to the increased concentrations of PM and NO_x within the canyons formed by the buildings [18]. On the other hand, another group of studies argues that building height does not pose any significant impacts on urban air quality or have mixed effects on air pollution dispersion [19,20]. This contradictory evidence may be explained by the fact that low-rise buildings tend to reduce wind speed and make air pollution dispersion more difficult, while when the building is too high, air pollution will be generated along with increased wind speed. This posits a non-linear relationship between building height and ambient air pollution, which still needs to be examined with rigorous analyses.

The configuration of buildings, including their arrangement and spacing, also influences urban air pollution. The layout of buildings can affect the dispersion of pollutants and the formation of microclimates within urban areas. Research has shown that compact building configurations can lead to the accumulation of pollutants within urban areas. Compact urban forms, characterized by high building densities and narrow street widths, can restrict airflow and hinder the dispersion of pollutants, resulting in increased pollutant concentrations. For instance, a study in Wuhan has revealed that areas with high building densities experienced higher concentrations of $PM_{2.5}$ compared with areas with lower densities [21]. In contrast, dispersed building configurations with more open spaces and larger setbacks between buildings can facilitate better ventilation and pollutant dispersion, leading to lower pollutant concentrations. A study conducted in Singapore found that residential areas with more dispersed building layouts had lower levels of PM and NO_2 compared with areas with compact building configurations [22].

Apart from building environments, attention has also been paid to urban green spaces, which provide a vital ecosystem service by absorbing and filtering air pollutants, thereby improving air quality [23]. Urban green spaces, including parks, gardens, and green roofs, have been widely recognized for their potential to improve air quality and mitigate air pollution in urban areas. The ability of green spaces to remove air pollutants can be attributed to several mechanisms, such as deposition on plant surfaces, absorption by stomata, and the breakdown of pollutants by microorganisms in the soil [24]. Previous empirical studies have demonstrated that urban green spaces can effectively reduce the concentration of PM, NO_2, and other pollutants [25]. For instance, a study conducted in Strasbourg, France, found that urban green spaces removed approximately 88 tons of pollutants, including 56 tons of O_3, 12 tons of PM_{10}, 14 tons of NO_2, and 6 tons of other pollutants annually, providing significant benefits to air quality [26]. Similarly, a study in Canada has estimated that urban forests removed approximately 16,500 metric tons of air pollutants per year, with an associated health benefit of $227 million (CAD) [27]. However, the effectiveness of green spaces in mitigating air pollution depends largely on various factors, such as the size, type, and spatial distribution of green spaces, as well as the specific pollutant in question. Research has shown that larger green spaces with diverse vegetation types tend to be more effective in pollutant removal than smaller, less diverse spaces [28]. Additionally, certain plant species have been found to be more effective in removing specific pollutants, suggesting that targeted planting strategies could enhance the pollution removal capacity of green spaces [29].

While the aforementioned studies have assessed the impacts of building environment and urban green space on air quality levels, there are still research gaps that remain unfilled. One research gap is that few studies have empirically examined the interaction effects of building environments and urban green spaces on urban air pollution, although some simulation models detect mediating effects of urban green space on the building–pollution relationship [30,31]. Another research gap is that previous studies have often focused on the linear effects of building environments and urban green spaces on air quality, while neglecting the potential non-linear relationships. In fact, previous studies have suggested that air pollution level tends to be higher in places with either more low or tall buildings compared with those with median average building height [32–34], positing a U-shape relationship between building height and air pollution. That is, this relationship between building height and air pollution level can be plotted as a U shape in a coordinate axis, with the *y*-axis indicating the air pollution level and the *x*-axis showing building height.

In recognition of these research gaps, this study has the following three objectives: (1) to investigate the interaction effects of urban green spaces and the building environment on air pollution levels, using empirical approaches; (2) to explore the nonlinearity underlying the building–pollution nexus; and (3) to suggest practical implications regarding building environment and urban green space planning for the improvements of urban air quality. For the analysis, the impacts of building environments and urban green spaces on urban air quality are examined, using multivariate regression models on satellite-based, high-resolution $PM_{2.5}$ data. Hong Kong is chosen as a case study for two reasons. Firstly, because Hong Kong's diverse urban landscapes create a favorable environment in which to investigate how air quality is affected by building features, providing new insights into environmental sustainability for other cities around the world. Secondly, Hong Kong has abundant urban green spaces spread across the city, allowing us to better capture the relationship between urban green spaces and urban air pollution. The novelty of this study is threefold. First, compared with conventional studies that have been conducted based on air quality data that were collected from air monitoring stations, the use of satellite-based $PM_{2.5}$ data in this study substantially extends the spatial scope of analysis. Second, this study analyzes the effects of both urban green spaces and the building environment on air quality within a single framework, and further highlights their interaction effects. Finally, the non-linear relationship between building features and urban air quality is explored in this study.

2. Methods

In this study, a multivariate regression approach is adopted to examine the impacts of building environment and urban green space features on urban air pollution. The main hypothesis is that urban air quality can be seen as a function of urban green space and building environment features, with other conditions being controlled. Specifically, the baseline model is given as follows.

$$PM_i = \beta_1 \cdot \mathbf{GS_i} + \beta_2 \cdot \mathbf{BE_i} + \beta_3 \cdot \mathbf{X_i} + \varepsilon_i \tag{1}$$

where PM_i is the $PM_{2.5}$ concentration for grid cell i at year 2020; $\mathbf{GS_i}$ is a vector of urban green space indicators for grid cell i; $\mathbf{BE_i}$ is a vector of building environment indicators for grid cell i; $\mathbf{X_i}$ is a vector of control variables; β_1, β_2, and β_3 are parameters to be estimated; and ε_i is the error term.

Then, the quadratic terms of building environment features are further added to the model to capture the non-linear relationship between the building environment and urban air quality. All notations are identical as defined in Equation (1), and the model is specified as follows.

$$PM_i = \beta_1 \cdot \mathbf{GS_i} + \beta_2 \cdot \mathbf{BE_i} + \beta_3 \cdot (\mathbf{BE_i})^2 + \beta_4 \cdot \mathbf{X_i} + \varepsilon_i \tag{2}$$

Finally, to examine the interaction effects of the building environment and urban green spaces, interaction terms $\mathbf{BE_i} \cdot \mathbf{GS_i}$, are introduced to the regression model. The model specification is shown as follows, with all notations being identical to Equations (1) and (2).

$$PM_i = \beta_1 \cdot \mathbf{GS_i} + \beta_2 \cdot \mathbf{BE_i} + \beta_3 \cdot \mathbf{BE_i} \cdot \mathbf{GS_i} + \beta_4 \cdot \mathbf{X_i} + \varepsilon_i \tag{3}$$

For the analysis, two urban green space indicators are used, including the size of urban green space (S_GS) and the number of urban green space clusters (N_GS). In addition, seven building environment indicators are included, namely number of buildings (N_BULD), dispersion degree of building distribution (DD_BULD), mean building area (M_BA), mean building height (M_BH), standard deviation of building height (SD_BH), share of industrial building GFA (SHR_I), and share of commercial building GFA (SHR_C). Finally, two control variables, total road length (T_RL) and elevation (M_DEM), which are not categorized into building environment and urban green space but have strong impacts on urban air quality, are included.

The computational process of the building environment indicators of DD_BULD and SD_BH is also worth mentioning. Specifically, the DD_BULD is estimated using the following equation.

$$DD\_BULD_i = \frac{\sigma_i}{\mu_i} = \sqrt{\frac{\sum_{j=1}^{n} \left(DTC_{ijc} - \overline{DTC_i}\right)}{n}} \cdot \frac{1}{\overline{DTC_i}} \tag{4}$$

where σ_i is the standard deviation of the distance of buildings to the grid center within grid i; μ_i is the average of the distance of buildings to the block center within grid i; DTC_{ijc} is the distance of building j to the grid center c within grid i; $\overline{DTC_i}$ is the average distance of buildings to the grid center within grid i; and n is the number of grids.

The SD_BH is calculated using the following equation.

$$SD\_BH_i = \sqrt{\frac{\sum_{j=1}^{n} \left(BH_{ij} - \overline{BH_i}\right)}{n}} \tag{5}$$

where BH_j is the building height of building j within grid i and $\overline{BH_i}$ is the average building height within grid i. All other notations are identical as defined in previous equations.

3. Study Area and Data

The areas with buildings in the Hong Kong Special Administrative Region (HKSAR) are selected as study areas for this study (Figure 1). Hong Kong, located on the southeastern coast of China, is a vibrant and densely populated city known for its striking urban form and unique geographical characteristics.

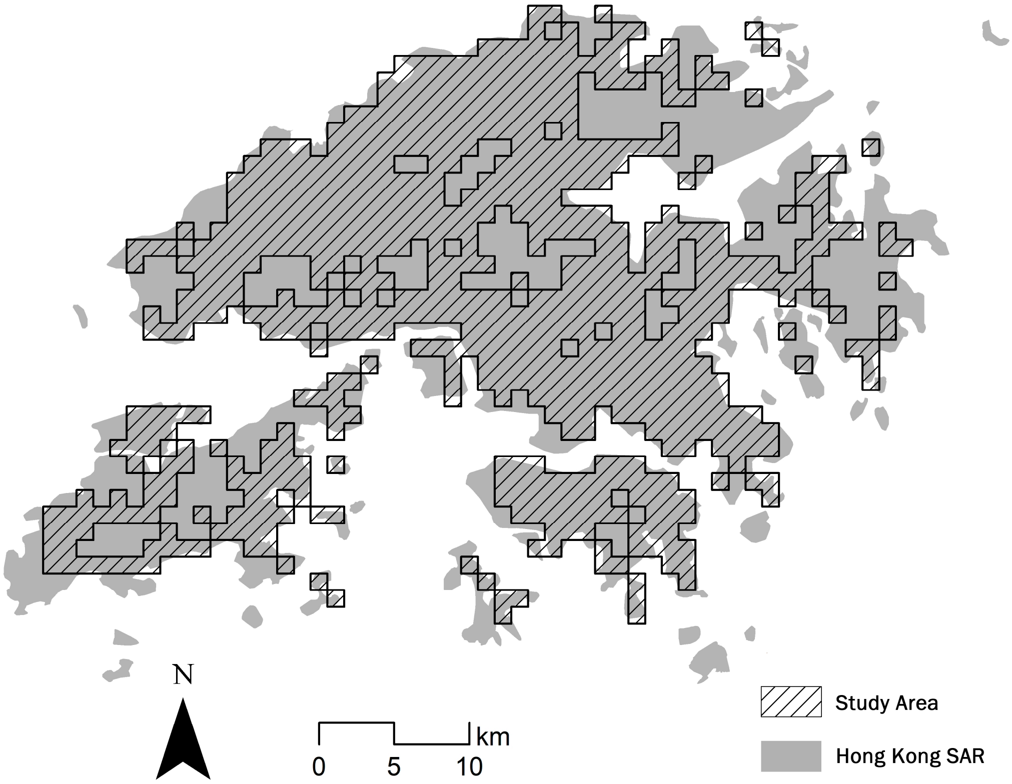

Figure 1. Study areas in Hong Kong.

Hong Kong's spatial layout is shaped by its unique geographical features, including a hilly terrain and a deep natural harbor. The city is divided into three main regions: Hong Kong Island, Kowloon Peninsula, and the New Territories. Hong Kong Island, the heart of the city, is characterized by steep slopes and a compact urban core. Kowloon Peninsula, located to the north of Hong Kong Island, is relatively flat and densely populated. The New Territories, comprising the northern part of the territory, are more rural and include a mix of residential, agricultural, and conservation areas. Land use in Hong Kong is carefully planned and regulated due to the limited availability of developable land. The government has implemented a comprehensive land use zoning system, which designates specific areas for different purposes, such as residential, commercial, industrial, and recreational. The majority of the population resides in high-rise residential buildings, often clustered in densely populated neighborhoods known as "towers in the park" developments. Commercial activities are concentrated in the Central district and other major commercial centers, while industrial zones are primarily located in the New Territories.

A cross-sectional dataset for 659 grids at the spatial resolution of 1 km $\times$ 1 km is constructed for HKSAR in 2020 from various sources. The $PM_{2.5}$ data are obtained from [35], which is originally estimated from the satellite-based aerosol optical depth (AOD) and ground-level observations. High-resolution $PM_{2.5}$ grids have been widely adopted in recent urban and transportation studies [36,37], partly confirming the validity of applying such data to building environments and urban green space studies.

The urban green space data are extracted from high-resolution land use and land cover (LULC) data, provided by Yang and Huang (2021) [38]. The LULC dataset contains nine land use types: cropland, forest, shrub, grassland, water, snow/ice, barren, impervious, and wetland. Among these, five land use types (cropland, forest, shrub, grassland, and wetland) are used to characterize urban green space features in this study. Specifically, two commonly adopted urban green space indicators are tested. One is S_GS, which is defined as the total area of urban green space within a grid. Another is N_GS, which refers to the number of urban green space clusters.

Building environment data are collected from the Hong Kong Geodata Store provided by the Land Department of the Government of Hong Kong Special Administrative Region [39]. In detail, a 3D model of all buildings in Hong Kong is provided in this dataset, and we extract the information on building height, building location, building type, as well as build area for each building using a spatial analysis tool, and then aggregate them at the district level to calculate N_BULD, DD_BULD, M_BA, M_BH, SD_BH, SHR_I, and SHR_C, respectively.

Finally, two control variables, T_RL and M_DEM, are collected from the Open Street Map (OSM) [40] dataset and the USGS Earth Explorer [41], respectively, as traffic and topological conditions are closely relevant to air pollution levels [42,43]. A detailed list of variables and descriptive statistics are presented in Table 1, and the spatial variations in air quality, building environment features, and urban green space characteristics are visualized in Figure 2.

Table 1. Variables list and descriptive statistics.

Variable	Description	Obs.	Mean	Std. Dev.
Dependent Variable				
PM	Annual mean $PM_{2.5}$ levels (μg/m^3)	659	16.86	1.04
Urban Green Space Indicators				
S_GS	Size of green space (10^4 m^2)	659	63.04	39.67
N_GS	Number of green space clusters	659	1.94	1.81
Building Environment Indicators				
N_BULD	Number of buildings	659	290.83	395.75
DD_BULD	Dispersion degree of building distribution	659	0.30	0.14
M_BA	Mean building area (m^2)	659	399.37	825.09
M_BH	Mean building height (m)	659	11.43	10.82
SD_BH	Standard deviation of building height (m)	659	11.09	11.68
SHR_I	Share of industrial building GFA	659	0.03	0.14
SHR_C	Share of commercial building GFA	659	0.02	0.10
Control Variables				
T_RL	Total road length (km)	659	10.01	7.43
M_DEM	Mean of digital elevation model	659	108.36	108.98

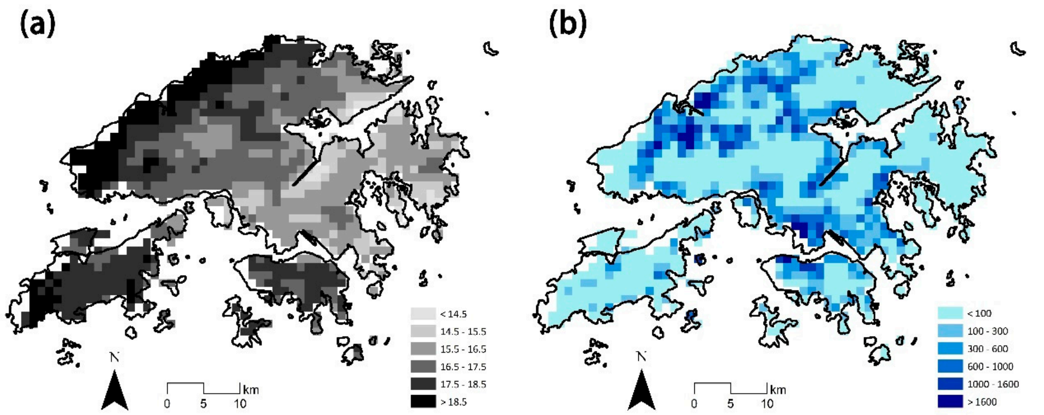

Figure 2. *Cont.*

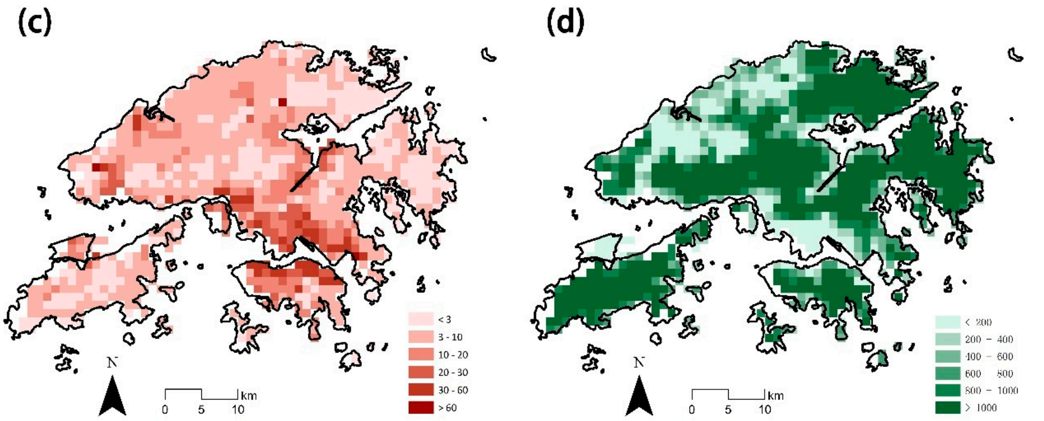

Figure 2. Spatial distribution of (**a**) $PM_{2.5}$ concentrations, (**b**) number of buildings, (**c**) mean building height, and (**d**) size of green space.

4. Results

Before conducting the regression analysis, the multicollinearity among independent variables is first tested, which could potentially bias the regression results, by estimating the variance inflation factor (VIF) values. As shown in Table 2, The VIF values estimated for all of the included independent variables are below the threshold of 10 [44], suggesting that the adopted regression model is not subject to serious multicollinearity problems.

Table 2. Baseline model results.

Independent Variables	(1)	VIF
S_GS	-3.96×10^{-4} ** (1.64×10^{-4})	3.56
N_GS	1.12×10^{-1} *** (2.36×10^{-2})	1.23
N_BULD	3.12×10^{-4} ** (1.38×10^{-4})	2.04
DD_BULD	3.15×10^{-1} (3.07×10^{-1})	1.18
M_BA	-4.93×10^{-5} (5.66×10^{-5})	1.49
M_BH	8.93×10^{-3} (8.39×10^{-3})	5.61
SD_BH	-1.54×10^{-2} * (8.01×10^{-3})	5.96
SHR_I	2.62×10^{-1} (2.87×10^{-1})	1.06
SHR_C	1.02×10^{0} ** (4.18×10^{-1})	1.21
Control variables	Yes	
Constant	1.70×10^{1} *** (2.00×10^{-1})	
R2	0.11	
N	659	

Note: standard errors are in parentheses; *, ** and *** indicate significance at the 10%, 5% and 1% levels respectively.

The baseline model results show that most of the building environment and urban green space features are significantly associated with $PM_{2.5}$ concentrations (Table 2). As shown in Model (1), the coefficients for both of the two urban green space indicators are significant at the 5% or higher levels, with the size of urban green space negatively associated with $PM_{2.5}$ levels and number of urban green clusters positively associated with $PM_{2.5}$ levels. On the one hand, the negative association between urban green space size and air pollution may be related to the total size of the urban green space in a given unit of analysis determining the capacity of ecosystems to absorb and filter air pollutants. On the other hand, the positive association between number of urban green space clusters could be interpreted such that, with a fixed total size, a large-sized urban green space cluster is found to perform better in mitigating air pollution than several small-sized clusters.

Among the seven building environment indicators, number of buildings and share of commercial building GFA are positively associated with PM concentrations, while the standard deviation of building height is negatively associated with PM levels. The positive associations may be explained by the increased energy consumption associated with a rising number of buildings and the high energy intensity for commercial buildings compared with residential buildings in Hong Kong's context [45]. The negative association between the standard deviation of building height and air pollution can be attributed to the better ventilation environment encouraged by the diverse building height features within a neighborhood [46]. In contrast, the coefficients of three other building environment characteristics, the dispersion degree of building distribution, mean building area, and share of industrial building GFA, are not statistically significant. On the one hand, the omitted variable limitation embedded in the adopted method may partially explain the insignificant results. Some detailed building design features or grid-specific characteristics (e.g., building-level ventilation conditions and geographical conditions), which potentially correlate with building distribution and building area and cause estimation biases, cannot be fully controlled. On the other hand, Hong Kong has experienced deindustrialization during the past decades, and many industrial buildings have maintained a relatively high vacancy rate and, thus, a low energy consumption when compared with commercial buildings [47].

The results from Table 3 show that mean building height presents a non-linear relationship with PM concentrations, while such nonlinearity has not been found for the standard deviation of building height. As displayed in Model (2), a negative sign is observed for the coefficient of mean building height, and a positive sign is detected for the quadratic term of mean building height, suggesting a U-shape relationship between building height and air pollution. On the one hand, low building height will not be able to create an ideal ventilation environment, leading to accumulations of air pollutants [19]. On the other hand, higher buildings can create canyons that trap pollutants and hinder their dispersion, resulting in increased pollutant concentrations at street levels [20]. In comparison, as presented in Model (3), a non-linear relationship does not exist between the standard deviation of building height and air pollution.

Table 3. Model results: non-linear effects.

Independent Variables	(2)	(3)
S_GS	-3.58×10^{-4} ** (1.63×10^{-4})	-3.88×10^{-4} ** (1.64×10^{-4})
N_GS	1.14×10^{-1} *** (2.33×10^{-2})	1.13×10^{-1} *** (2.36×10^{-2})
N_BULD	3.60×10^{-4} ** (1.38×10^{-4})	3.22×10^{-4} ** (1.39×10^{-4})
DD_BULD	3.69×10^{-1} (3.04×10^{-1})	3.30×10^{-1} (3.07×10^{-1})
M_BA	5.61×10^{-6} (5.80×10^{-5})	-3.22×10^{-5} (5.78×10^{-5})
M_BH	-4.17×10^{-2} *** (1.60×10^{-2})	1.19×10^{-3} (9.95×10^{-3})
M_BH × M_BH	3.59×10^{-4} *** (9.67×10^{-5})	
SD_BH	6.25×10^{-3} (9.84×10^{-3})	-2.41×10^{-2} ** (1.00×10^{-2})
SD_BH × SD_BH		3.01×10^{-4} (2.08×10^{-4})
SHR_I	1.81×10^{-1} (2.85×10^{-1})	2.54×10^{-1} (2.87×10^{-1})
SHR_C	1.06×10^{0} ** (4.18×10^{-1})	1.00×10^{0} ** (4.18×10^{-1})
Control variables	Yes	Yes
Constant	1.71×10^{1} *** (2.02×10^{-1})	1.71×10^{1} *** (2.02×10^{-1})
R2	0.12	0.12
N	659	659

Note: standard errors are in parentheses; **, and *** indicate significance at the 5%, and 1% levels, respectively.

The interaction effects of building environments and urban green spaces on PM pollution are further tested (Table 4). Model (4) shows that the interaction term, S_GS × M_BH_L, where M_BH_L is a dummy variable indicating that the mean building height is less than 27 m, is statistically significant at the 5% level with a negative sign, suggesting that increased supply of urban green spaces tend to result in more air pollution mitigations in places with low-rise buildings than in those with high-rise buildings. In contrast, the results of Model (5), showing that the coefficient for the interaction term, S_GS × N_BULD_L, is not statistically significant at the 10% level, reflect that there are no interaction effects of building density and urban green space supply on local air quality. This may be explained by the fact that the pollution mitigation effects of urban green space supply can be largely offset by the positive effect of building density on air pollution levels [48].

Table 4. Model results: interaction effects.

Independent Variables	(4)	(5)
S_GS	-3.51×10^{-4} (3.61×10^{-4})	-6.76×10^{-4} *** (2.52×10^{-4})
S_GS × M_BH_L	-8.25×10^{-4} ** (3.55×10^{-4})	
S_GS × N_BULD_L		-3.76×10^{-4} (2.67×10^{-4})
N_GS	1.09×10^{-1} *** (2.36×10^{-2})	1.17×10^{-1} *** (2.38×10^{-2})
N_BULD	2.67×10^{-4} * (1.39×10^{-4})	3.52×10^{-4} ** (1.71×10^{-4})
DD_BULD	2.86×10^{-1} (3.06×10^{-1})	3.96×10^{-1} (3.11×10^{-1})
M_BA	-6.63×10^{-5} (5.70×10^{-5})	-4.21×10^{-5} (5.73×10^{-5})
M_BH	5.92×10^{-3} (9.19×10^{-3})	8.19×10^{-3} (8.40×10^{-3})
SD_BH	-1.35×10^{-2} * (8.04×10^{-3})	-1.43×10^{-2} * (8.03×10^{-3})
SHR_I	2.19×10^{-1} (2.87×10^{-1})	2.80×10^{-1} (2.88×10^{-1})
SHR_C	1.16×10^{0} ** (4.23×10^{-1})	1.04×10^{0} ** (4.19×10^{-1})
M_BH_L	4.46×10^{-1} * (2.42×10^{-1})	
N_BULD_L		-1.19×10^{-1} (2.08×10^{-1})
Control variables	Yes	Yes
Constant	1.67×10^{1} *** (3.24×10^{-1})	1.71×10^{1} *** (2.53×10^{-1})
R2	0.12	0.12
N	659	659

Note: standard errors are in parentheses; *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

5. Discussion

5.1. Significance and Implications

The significance of this study lies in two aspects. From the academic perspective, it enriches the empirical literature on the effects of air pollution on the building environment and urban green spaces by further uncovering their interaction effects and the nonlinearity underlying the nexus between building environment features and urban air pollution. In addition, our use of high-resolution $PM_{2.5}$ grids tends to supplement the findings drawn from previous monitoring-station-based studies and extend the spatial scope for the analysis.

From the policy perspective, the findings extracted from our multivariate regressions convey several important policy implications. Firstly, the results suggest that increasing the size of urban green spaces can contribute to reduced local air pollution. This finding highlights the importance of allocating sufficient land for the creation and preservation of green spaces within urban areas [49]. Policymakers should prioritize the development of parks, gardens, and green roofs as part of urban planning strategies to mitigate air pollution. Secondly, the study reveals that the standard deviation of building height also plays a role in reducing air pollution. This implies that incorporating a mix of building heights can promote better dispersion of pollutants and improve air quality. Urban planning policies should encourage the integration of different building heights and avoid excessive uniformity to create a more diverse and effective urban form in terms of air pollution mitigation. Thirdly, the positive associations between building density, scatteredness of urban green spaces, and the share of commercial buildings with air pollution levels suggest the need for careful land use planning. Policymakers should consider the optimal density of buildings and the distribution of commercial activities to minimize their contribution to air pollution [50]. This may involve implementing regulations on building height, floor area ratios, and commercial zoning to control the overall intensity and distribution of development.

Furthermore, the U-shape relationship between building height and $PM_{2.5}$ concentrations suggests that there is an optimal range of building heights that can effectively reduce air pollution levels. Policymakers should carefully consider the potential impacts of tall buildings on air circulation and pollutant dispersion. This may involve setting height restrictions or incorporating design guidelines that promote better ventilation and pollutant dispersion in high-rise developments [51]. Finally, the study highlights the importance of considering the interaction between building height and the size of urban green spaces. The negative association between the size of urban green spaces and air pollution tends to be amplified in districts with more low-rise buildings. This finding suggests that low-rise developments can enhance the air-purifying effects of green spaces. Policymakers should encourage the integration of green spaces in low-rise areas and promote the preservation of existing green spaces in these districts to maximize their potential to mitigate air pollution.

5.2. Limitations

Despite the valuable insights provided by this study, there are also some limitations that need to be acknowledged. Firstly, this is a cross-sectional study focusing on only one year; thus, it may not fully capture the temporal heterogeneity of the effects of air pollution. To address these problems, future studies are encouraged to incorporate time-series data together with fixed-effects model settings. Secondly, the chosen multivariate regression model for empirical analysis exhibits some potential limitations. For example, it may not effectively control for omitted variable problems and spatial autocorrelation of air pollution levels. Coupling spatial econometric models with the inclusion of more external influencing factors of air pollution levels may be a possible solution to address these methodological constraints and should be performed in future research. Thirdly, the study focuses on a specific city, Hong Kong, which may limit the generalizability of the findings to other urban areas with different geographical and socio-economic characteristics. Replication studies in different cities can provide more comprehensive evidence and enhance the understanding of the relationship between building environment, urban green space, and air pollution. Finally, the study primarily focuses on the physical characteristics of building environments and urban green spaces and does not consider other factors, such as human behavior and socio-economic factors, that may influence air pollution levels [52]. Future research could explore the interplay between these factors to provide a more holistic understanding of the complex dynamics between urban form, human activities, and air pollution.

6. Conclusions

This study investigates the impacts of building environment and urban green space features on urban air pollution levels, taking a multivariate regression analysis of satellite-based high-resolution $PM_{2.5}$ data. The baseline results show that the size of urban green space and the standard deviation of building height are two factors that contribute to urban air pollution alleviation. This can be attributed to the pollution removal potentials of vegetation cover and the improved ventilation system deriving from building height diversity. In contrast, the scatteredness of urban green space, building density, and share of commercial buildings are positively related to urban air pollution. On the one hand, the positive association between the scatteredness of urban green spaces and air pollution may be explained by the fact that aggregated urban green spaces have greater pollution removal effects than scattered urban green spaces. On the other hand, the increased air pollution brought by rising building density and the share of commercial buildings may be interpreted in terms of the growing demand for energy consumption. Finally, the results of nonlinearity reveal that building height has a U-shape relationship with urban air pollution, with increased building height first contributing to reduced air pollution, then driving up air pollution levels after a certain point. In addition, the results of interaction effects show that increasing urban green space in districts with more low-rise or mid-rise buildings would be an effective strategy to mitigate air pollution.

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