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Research Paper

Linking window-view nature exposure with health and wellbeing outcomes: Using photorealistic 3D city models and computer vision technique

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HIGHLIGHTS

- Three window-view indices were calculated for nearly the whole Hong Kong area.
- Significant spatial gap between window- and street-view nature exposure was found.
- Window- and street-view nature exposure impacted human outcomes comparably.
- Window-view nature exposure became more significant during the COVlD-19 pandemic.

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ABSTRACT

It is well established that nature exposure can improve both physical and mental health and wellbeing outcomes. However, in the context of rapid urbanization and high-density urban development, many urban residents face limited opportunities to visit natural environment, such as urban parks, greenways, and water bodies. In such situations, window view often serves as the primary means of people's nature exposure. Traditional methods of assessing window-view nature exposure are time-consuming and labor-intensive, thus impractical for citywide evaluations. This study used a novel approach to quantify citywide assessment of window-view nature exposure, including the Window Greenery Index (WGI), Window Water Index (WWI), and Window Sky Index (WSI), using photorealistic 3D city models. We further analyzed the non-linear associations between window-view nature exposure with physical and mental health and wellbeing among 1,660 participants in Hong Kong for two periods: before and during the COVID-19 pandemic. For comparison, street-level nature exposure was also assessed. The result illustrates spatial mismatch between window-view and street-view nature exposure. Furthermore, window-view nature exposure had a greater influence than street-view nature exposure on physical and mental health and wellbeing. Furthermore, the effect of window-view nature exposure becomes more pronounced during the COVID-19 pandemic than before the pandemic. The results shed light on the link between window-view nature exposure and health and wellbeing outcomes, providing a new research front to understand the joint impacts of urban planning (i.e., provision of green space) and architectural design (i.e., location and orientation of windows) on public health.

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1. Introduction

Nature exposure has been consistently associated with benefits to both physical and mental health and wellbeing through multiple pathways. From a psychological perspective, both Ulrich's Stress Reduction Theory and Kaplan's Attention Restoration Theory suggest that natural settings reduce stress and mental fatigue by fostering positive affective responses and replenishing attentional resources (Kaplan, 1995; Ulrich et al., 1991). Empirical studies show that regular exposure to green space is linked with reduced risks of depression, anxiety, and stress-related disorders, while also promoting higher levels of subjective wellbeing (Bratman et al., 2019; White et al., 2013). On the physical health and wellbeing side, access to nature has been associated with lower incidence of cardiovascular disease, and improved immune functioning, potentially mediated by both increased physical activity and reduced stress levels (Mitchell & Popham, 2008; Twohig-Bennett & Jones, 2018).

It is anticipated that approximately 70% of the global population will reside in urban areas by 2050 (UN, 2018). Rapid urbanization has led to greater urban density and worse ecological system, limiting residents' physical access to natural environments, such as parks and water bodies, which may negatively impact physical and mental health and wellbeing (Cox et al., 2018). Despite this, urban residents may still experience nature in other means (Cox et al., 2017). For example, people may enjoy views of nature from windows without being physically present in it, or they may encounter natural element incidentally while commuting (Chang et al., 2020). The extent of these experiences varies among individuals, with many primarily experiencing nature passively through window views (Cox et al., 2017). The visual access to nature via windows is particularly prevalent among individuals with mobility challenges or during pandemic lockdowns (Soga et al., 2021). However, window-view nature exposure is unevenly distributed across different neighborhoods or population groups, and many lack opportunities to experience nature via windows at home or work, especially in high-density urban environments (Li et al., 2022). The provision of a window-view nature exposure is influenced not only by the surrounding built environment but also by the building's design, including the size, orientation, and placement of its windows (Turan et al., 2021).

A substantial body of work has examined links between window-view nature exposure and physical and mental health and wellbeing across different spatial scales (Table 1). At the building scale, Ulrich's hospital window study (1984) showed that surgical patients with a view of trees, compared with a brick wall, recovered faster and required less analgesic medication, demonstrating one of the earliest causal links between window views and health. Building on this, the Kaplans' research used both experimental and field approaches to show that even brief visual contact with natural scenes, including through windows, restores attentional capacity (Kaplan, 1995). Subsequent research in this domain has frequently utilized picture-based surveys (Masoudinejad & Hartig, 2020; Matusiak & Klöckner, 2016) and controlled laboratory experiments (Abboushi et al., 2021; N. Wang & Boubekri, 2011) to assess different factors of window view, e.g., contents (Ko et al., 2022), shape (Keighley, 1973; Masoudinejad & Hartig, 2020), size (Butler & Biner, 1989), and location (Turan et al., 2021; N. Wang & Boubekri, 2011), influencing different outcomes, e.g., living or job satisfaction (Abboushi et al., 2021), stress level (Leather et al., 1998), mood (Ko et al., 2020; N. Wang & Boubekri, 2011), and mental wellbeing (Leather et al., 1998). Methodologically, such studies have traditionally relied on field observations of actual windows (Abboushi et al., 2021) or assessment of photographs of window view (Lin et al., 2022). More recently, methodological approaches have expanded to include Virtual Reality (VR) simulations (F. Wang & Munakata, 2024). While producing high-quality results, these studies often lack large-scale, city-wide evidence necessary to capture population-level patterns and complexity of the real world.

Large-scale epidemiological studies at the urban and neighborhood scale commonly use questionnaires to evaluate self-reported health and wellbeing. For example, population surveys with 479 respondents in Andalusia, Spain, for example, showed that residents with a view of green space from home reported significantly lower levels of anxiety and depression (Braçe et al., 2020). Similar patterns were observed during COVID-19 restrictions in China, Bangladesh, and Egypt, where self-reported access to greenery through windows predicted reduced depressive and anxiety symptoms among homebound populations (Bi et al., 2022; Patwary et al., 2024). A significant limitation of these studies is their dependence on self-reported assessments of window view nature content. This methodological approach is inherently subjective and introduces considerable measurement bias. Recently, street view imagery has gained popularity for assessing the large-scale visible nature elements, such as greenery, sky, and water, from a pedestrian's

Table 1
Studies examining links between window-view nature exposure and human health and wellbeing outcomes

	Health outcome	Health outcome assessing methods	Window view assessing methods	Window-related variables	Sample size	Spatial scale
(Ulrich, 1984)	Speed of recovery	Field observation	Field audit	With or without windows	N=46	Building/ room level
(Masoudinejad & Hartig, 2020)	Psychological restoration	Survey	Digital photos	Ratio of sky, presence of greenery	N=212	Building/ room level
(Matusiak & Klöckner, 2016)	Working satisfaction	Survey	Photos	Weather, ratio of greenery, aesthetic quality	N=106	Building/ room level
(Abboushi et al., 2021)	Comfort and preference	Survey	Field audit	Subjective rating of view quality	N=33	Building/ room level
(Leather et al., 1998)	Job satisfaction, general wellbeing, and intention to quit	Survey	Field audit	Presence of rural features, sunlight penetration	N=100	Building/ room level
(Ko et al., 2020)	Emotion, cognitive performance	Test of performance	Field audit	With or without windows	N=86	Building/ room level
(Lin et al., 2022)	Preference	Survey	Digital photos	Ratio of element, aesthetic quality	N=445	Building/ room level
(Olszewska-Guizzo et al., 2018)	Emotion status	Alpha and Beta Rhythms in EEG	Photos	Ratio of greenery	N=29	Building/ room level
(F. Wang & Munakata, 2024)	Perception, preference	Survey	VR	Ratio of element, window-to-wall ratio	N=50	Building/ room level
(Braçe et al., 2020)	Health status, lifestyle, mood	Door-to-door household surveys	Door-to-door household surveys	Self-reported possibility of nature view	N=479	City-wide
(Bi et al., 2022)	Life satisfaction, loneliness, depression	Online questionnaire	Online questionnaire	Self-reported ratio of nature	N=508	City-wide
(Patwary et al., 2024)	Mental health	Online questionnaire	Online questionnaire	Self-reported scores of nature view	N=1216	City-wide

perspective, and linking them to health outcomes (Y. Lu, 2019; Nguyen et al., 2019). However, the nature elements extracted from street view imagery often differ significantly from what individuals view from their windows due to three-dimensional nature of buildings in a city (Labib et al., 2021). For example, a person living in the top of a high-rising building may enjoy a scenery mountain view, though he or she cannot view any greenery on streets in a compact and dense urban area. Furthermore, legal constraints in certain jurisdictions may preclude researchers from obtaining authorization to use proprietary street view imagery or from deriving freely reusable datasets from it (Helbich et al., 2024).

To date, few studies have explicitly combined these approaches—linking city-scale environmental data with fine-grained building-scale window-view measures—to understand how everyday visual contact to greenery, water, or sky through windows links to health and wellbeing outcomes. Furthermore, the differential impacts of nature exposure from streets and windows on human behavior and health outcomes remain less explored. Our study seeks to fill this gap by integrating both domains, thereby responding directly to the need for cross-scale evidence in the nature–health literature. To achieve this, our study undertook the following tasks. First, we utilized photorealistic 3D city models to quantify nature exposure via windows and employed Google Street View images to assess nature exposure from the street level. Then, we mapped window-view nature exposure indices and street-view nature exposure indices and highlighted their spatial mismatches. Next, we applied Gradient Boosting Decision Trees (GBDT) and Partial Dependence Plots (PDPs) to examine and compare how window-view nature and street-view nature exposure are associated with physical and mental health and wellbeing among 1,660 participants across Hong Kong. Health and wellbeing data were collected for both the pre-COVID-19 and COVID-19 periods to assess temporal changes under different public health and social conditions.

2. Methodology

2.1. Study area

The study is conducted in Hong Kong, one of the world's most densely populated cities, which has a population density of 6,690 per km^2 and only 2.5 m^2 of urban park per capita in 2021(Shan & He, 2025) (Fig. 1). Hong Kong's residents predominantly live in high-rise apartments with limited physical access to public green spaces, rendering window views a primary source of daily nature exposure. The city's vertical urban form, characterized by stark contrasts between high-rise developments and fragmented green spaces, creates spatial inequities in nature accessibility, offering a natural laboratory to explore how visual access to nature via windows influences health outcomes. Furthermore, during the COVID-19 era, Hong Kong residents spent 32.2% more time at home compared to pre-pandemic times, with a notable reduction in time spent across various other settings such as workplaces and public transport (Zhang et al., 2021). The reduced mobility may further amplify the role of window-view nature exposure in mitigating the negative health outcomes caused by the pandemic.

2.2. Assessment of window-view nature exposure

Photorealistic 3D city models allow the simulation of photorealistic views of any window without the need for manual photographing on site. This method offers three main advantages: realistic simulation, reduced labor costs, and increased efficiency. The photorealistic 3D city models have been publicly available by governmental institutions and agencies, e.g., Hong Kong Planning Department, Lands Department, and Google Earth Studio. The photorealistic 3D city models provide realistic textures of cityscapes with precise geo-coordinates, enabling detailed and accurate assessments of window views across urban environments.

We quantified window views using the Window View Index (WVI) following a recent study (Li et al., 2022) (Fig. 2(a)). The Window Greenery Index (WGI), Window Water Index (WWI), and Window Sky Index (WSI) ranging between 0 and 1 represented the proportions of greenery, water, and sky visible from a window. We generated citywide window views using photorealistic 3D city models in a geo-visualization platform, Cesium (Cesium, 2022). Specifically, the virtual camera of Cesium was placed at the center of a window to capture external views. Its orientation was aligned with the windows' surface normal to capture the horizonal views. The field of view was set to 60 degrees to simulate what a normal person typically sees from a window. We sampled windows of all building floors with intervals of 20 m along the perimeters of a building (Li et al., 2022) to estimate WVIs for the whole building efficiently (Li et al., 2023).

Finally, we computed WVIs from window views using semantic segmentation. By fine-tuning the Segment of Anything Model (SAM) on a photorealistic 3D city model-generated Window View dataset, CIM-WV (Li et al., 2024) and 500 manually annotated window views, we segmented images into categories such as greenery, water, sky, building,

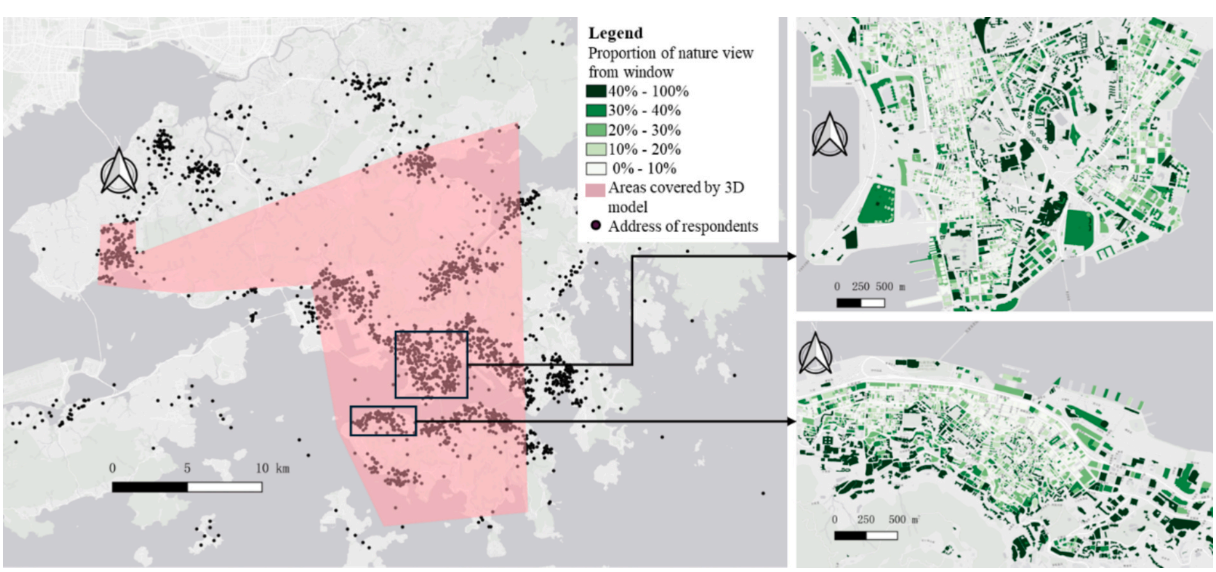

Fig. 1. Study area. The pink shading represents areas covered by photorealistic 3D city models, where window-view nature exposure can be calculated. The color of the building footprints indicates the average level of window-view nature exposure.

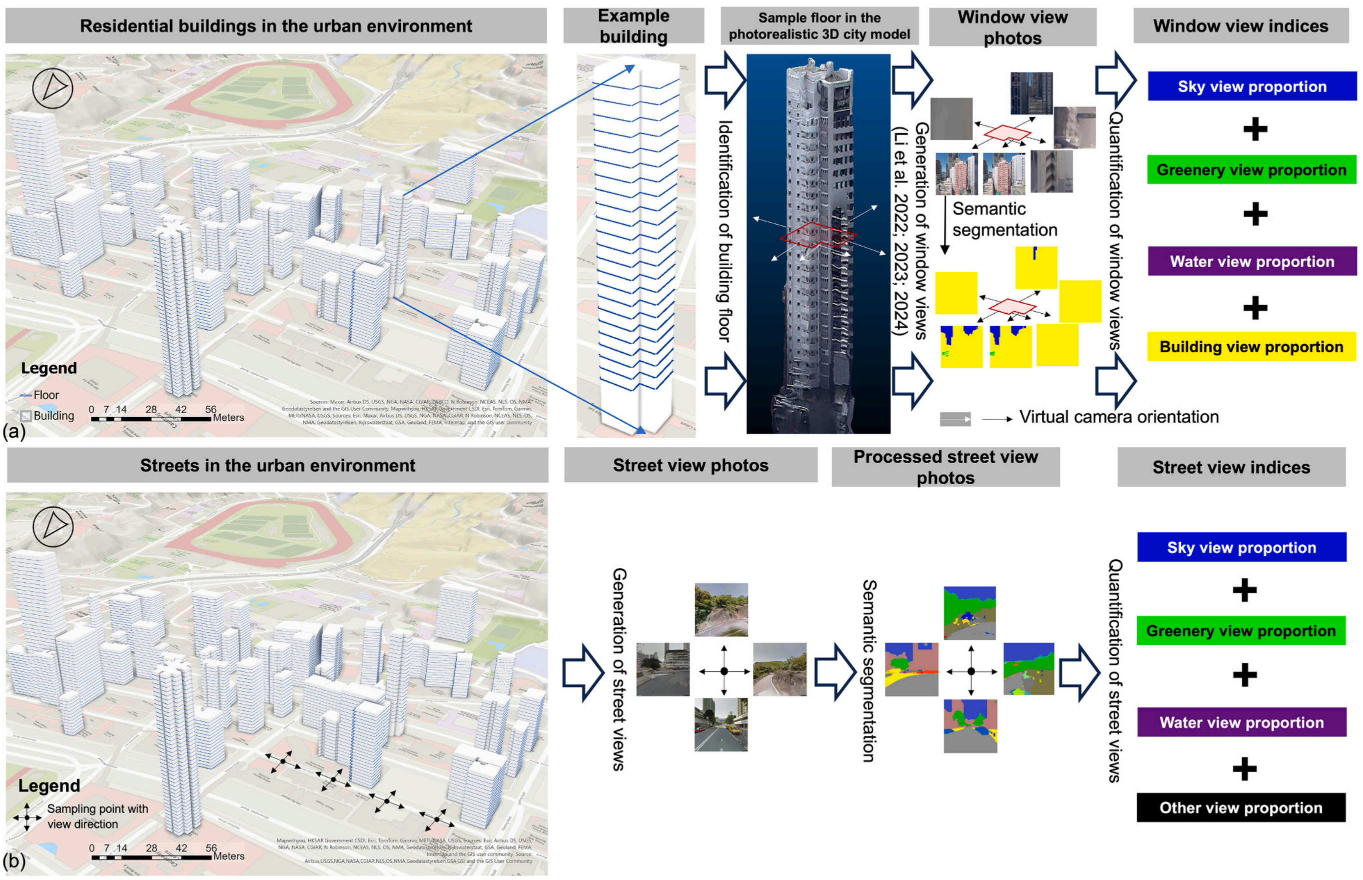

Fig. 2. Process of the assessment of (a) window-view nature and (b) street-view nature. (a) The window-view nature assessment approach comprises three steps: (i) building and window positioning (ii) the generation of window photos, and (iii) semantic segmentation of pixels and estimation of view indices. The main inputs are photorealistic 3D city models and corresponding 2D building footprints. The output is a set of WVIs. (b) The street-view nature assessment approach also comprises three steps: (i) street positioning and sampling point generation (ii) street view image generation, and (iii) semantic segmentation of pixels and estimation of view indices. The main inputs are a set of street view images and positions of sampling points. The output is a set of SVIs.

and road. The WGIs, WWIs, and WSIs were determined by the ratio of pixels corresponding to greenery, water, and sky to the total number of pixels in an image. The R^2 values of our model achieved 0.952, 0.965, and 0.978 for WGI, WWI, and WSI. A total of 38,833 buildings (Fig. 1) were assessed by a total of 1,289,431 window-view images extracted from the photorealistic 3D city models. Due to privacy concerns, survey respondents did not disclose their specific floor of residence. Consequently, the WVIs for individuals were approximated using the mean value calculated for their respective building. To evaluate the reliability of this methodological choice, we conducted a variance component analysis. The results indicate that differences between buildings account for the majority of the variance in exposure metrics (WGI: 48.1%; WWI: 57.4%; WSI: 49.2%). In contrast, variance between floors within the same building constitutes a smaller proportion (WGI: 22.2%; WWI: 11.9%; WSI: 22.6%). While this indicates that building-level means capture a primary source of variation, the remaining with-building variance represents a non-negligible source of potential exposure misclassification, which is a limitation of current analysis.

2.3. Assessment of street-view nature exposure

As a comparison, we utilized Street View Indices (SVIs), including greenery, water, and sky, derived from street view images to quantify natural element exposure in outdoor environments (Fig. 2(b)). Street view images capture the urban physical environment from a perspective closely aligned with pedestrians, effectively representing a view of streetscapes (Kang et al., 2020). Google Street View, the earliest online street-view service launched in 2007, covering cities across approximately 200 countries.

We estimated Street Greenery Index (SGI), Street Water Index (SWI), and Street Sky Index (SSI), respectively. First, GSV image capture points were systematically established at fixed 50-meter intervals along all road segments across Hong Kong. Second, 70,000 GSV images were retrieved from the Google Maps platform. At each capture point, we acquired four images with headings of 0°, 90°, 180°, and 270°, representing the front, right, back and left sides of the camera respectively. Third, the same semantic segmentation model used in window view images was employed to automatically segment and extract pixels corresponding to greenery, water, and sky from Google Street View images. Fourth, the residential locations of sampled respondents were geocoded using precise longitude and latitude coordinates. Fifth, all sampling points within a 500-meter buffer zone of each residential location were automatically identified, and the average values of the three SVIs (SGI, SWI, and SSI) were used to represent the values of each residential location.

2.4. Physical and mental health and wellbeing, physical activities, and other covariates

A survey was conducted to examine the lifestyle habits of Hong Kong residents both before and during the pandemic, as well as their levels of life satisfaction. The data was collected during Hong Kong's fifth wave of COVID-19 (October 18–24, 2022), a period marked by severe pandemic impacts and restricted social distancing measures. Participants were selected from Hong Kong Island, Kowloon, and the New Territories ensuring representation aligned with the Hong Kong's current geographical population distribution (Guo et al., 2024). To facilitate participant recruitment during the critical phase of the pandemic, the study utilized an online Public Participation Geographic Information System (PPGIS) platform. Data collection was administered via the PopPanel. The PopPanel is a joint panel consisting of: (1) a probability-based sample, recruited randomly via telephone surveys to be representative of the Hong Kong general population, and (2) a non-probability-based sample of volunteers recruited through online registration (Sit et al., 2021). All panel members were regularly invited to participate in various surveys. The PPGIS platform enabled participants to provide Volunteered Geographic Information (VGI), specifically, the data pertaining to location-based matters, through interactive maps and other digital tools. Overall, 4,702 panel members clicked on the link of invitation and started the survey. About 68.9% of respondents (n=3,237) have completed the questionnaire.

Respondents were asked to report on their physical and mental health and wellbeing status, physical activities (vigorous physical activity, moderate physical activity, and sedentary behavior), and personal information (age, gender, and income). Physical wellbeing was assessed based on a domain of the Hong Kong version of Personal Wellbeing Index–Adults (PWI-A), a widely utilized global instrument for evaluating subjective personal wellbeing (Lau et al. 2005). To assess physical health, respondents were asked to rate their satisfaction with their personal health based on a 10-point Likert scale ranging from 0 (“Very dissatisfied”) to 10 (“Very satisfied”), with a midpoint of 5 indicating a neutral opinion. Mental health and wellbeing were measured based on the single-item measure of Self-Rated Mental Health (SRMH) (Ahmad et al., 2014). Respondents were asked to select the descriptor that best characterized their overall mental health: “Excellent,” “Very good,” “Good,” “Fair,” or “Poor.” All responses were then converted a five-point numeric scale.

We adopted the traditional Chinese version of International Physical Activity Questionnaire-Short Form (IPAQ-SF) to assess physical activities of all respondents (Liou et al., 2008). Respondents were also asked to report on weekly frequency (in days per week) of their vigorous physical activity (defined as activities such as running or football that led to significant increases in breathing or heart rate), moderate physical activity (defined as activities such as brisk walking, cycling, or swimming that resulted in slight increases in breathing or heart rate), and cumulative duration of sedentary behavior (e.g. sitting).

These metrics were answered both retrospectively (pre-COVID-19 era) and concurrently (during the COVID-19 era). Each respondent was asked to indicate their residential location on a map. We then matched each point to the nearest building within a 10-meter radius. Points without any building within this radius were excluded from further analysis.

The following personal sociodemographic covariates were also included in the survey: age (in years), sex (male or female), annual household income per capita (in Hong Kong dollars), educational attainment (categorized as primary school and below, high school, or college and above), and employment status (employed or other).

2.5. Built-environmental covariate

In line with existing literature, some important built environmental factors were included in the study as covariates. At the neighborhood level, several built environment variables were adjusted for using a 500-meter circular buffer around the residential location of respondents. These variables included population density (persons per square kilometer), street connectivity (number of street sections per square kilometer), and a land use mix index (ranging from 0 to 1). The 2018 Google Map Point-of-Interest (POI) data for Hong Kong were utilized to calculate the density of surrounding amenities, including retail establishments, restaurants, schools, public services, bus stops, and train stations. Additionally, the distance to the nearest park (in meters) in 2018 was included as a proxy for green space accessibility.

2.6. Machine learning model

We employed the well-established Gradient Boosting Decision Trees (GBDT) (Ke et al., 2017) to model the nonlinear effects of window-view nature and street-view nature on physical and mental health and wellbeing. In brief, as the GBDT converges, residuals are calculated using a gradient boosting algorithm, which iteratively minimizes the model's loss function to achieve the lowest residuals for each tree. The final residuals are obtained by aggregating the residuals from all trees. GBDT offers several advantages over alternative algorithms. First, model comparison studies have demonstrated that GBDT achieves high prediction accuracy. Second, unlike traditional regression models, GBDT is not constrained by assumptions regarding normal distributions or linear relationships between covariates and outcomes, making it suitable for handling skewed data. The results of our statistical analysis confirm the skewed nature of physical activity, sedentary behavior, as well as the physical and mental health and wellbeing before and during the COVID-19 era. Third, GBDT is robust to multicollinearity among covariates, outliers, and missing values. Fourth, GBDT allows for the assessment of covariates' relative importance in predicting outcomes.

We employed a python package named “GradientBoostingRegressor” to conduct the analysis. Variance Inflation Factors (VIFs) indicated no severe multicollinearity among covariates, with all VIF values below 3 (Marcoulides & Raykov, 2019). Hyperparameters were selected based on a preliminary study to maximize accuracy. Specifically, we conducted grid-based tuning by evaluating combinations of learning rates (0.0001, 0.001, 0.01, 0.1) and model depths (8, 10, 12, 15). Cross-validation results guided the selection of the parameter set yielding the lowest Root Mean Square Error (RMSE). The final model employed a shrinkage rate (λ) of 0.001, depth of 12, and was initialized with 30,000 trees. Finally, the model convergence was achieved after approximately 2,000 iterations (trees), corresponding to the minimum RMSE.

To facilitate a more effective comparative analysis, all independent and dependent variables were standardized into z-scores. We calculated the Relative Importance (RI) of all predictors, and Partial Dependence Plots (PDPs) were used to specifically visualize the impact of the three WVIs on physical and mental health and wellbeing both before and during the COVID-19 pandemic. RI is a measure that quantifies how much each input variable contributes to the predictions made by a model, relative to the other features, which can be used to rank features from the most impactful to the least impactful. PDP represents the expected value of the model's predictions for a dependent variable when input variable is held at a specific value, averaged across the observed distribution of all other explanatory variables in the dataset.

3. Results

3.1. Descriptive data

The descriptive statistics of variables of the survey (Table A1 in Appendix) and built environmental variables (Table A2 in Appendix) are shown below. After excluding incomplete questionnaires and data that could not be matched with building footprints covered by the 3D city model, a total of 1,660 respondents were retained for analysis. Although the Hong Kong government did not impose formal restrictions on public movement during the pandemic, a marked decline was observed in vigorous and moderate physical activity levels compared to the pre-pandemic period, coupled with a significant increase in sedentary behavior and a concomitant deterioration in both physical and mental health and wellbeing.

The histograms of physical and mental health and wellbeing before and during the COVID-19 era in Fig. 3, confirm their skewed nature, justifying the use of GBDT over conventional regression models.

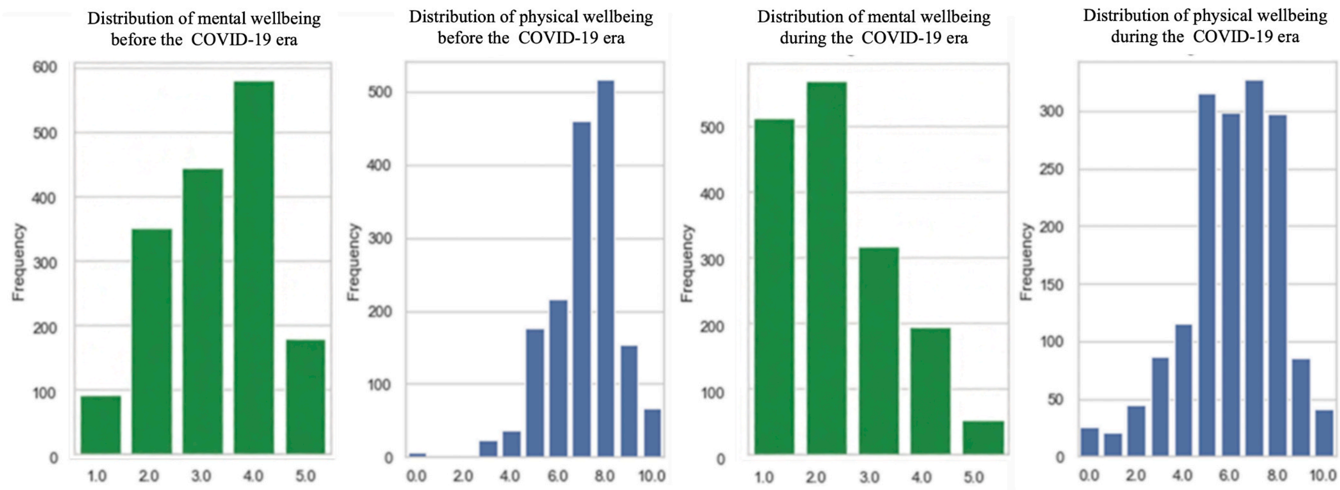

Fig. 3. The frequency plots for the distributions of mental and physical health and wellbeing before and during the COVID-19 era.

3.2. Spatial distribution of WVIs

We mapped the average values of three WVIs at 500 × 500 m rectangular grids in Hong Kong (Fig. 4). The WGI exhibits notably low values within the core urban areas of Hong Kong, including Kowloon and the northern Hong Kong Island (enclosed by the black boundary), as well as in satellite towns such as the centers of Tsuen Wan, Shatin, and Tuen Mun. The WSI shows a similar spatial distribution to the WGI, though it is less pronounced. Certain highly developed areas, such as central parts of Kowloon and Tuen Mun, also demonstrate high WSI values. Unlike the WGI and WSI, high WWI values are predominantly distributed along the coastline. One notable exception is Victoria Peak, which is located relatively far from the coast but still exhibits a high WWI.

3.3. Spatial mismatch between street view and window view

We also mapped the spatial mismatch between three WVIs and three SVIs at 500 × 500 m rectangular grids in Hong Kong (Fig. 5(a), (b), &(c)).

The spatial distributions of WGIs and SGIs exhibit strong similarity, with areas of high WGIs generally corresponding to high SGIs and areas of low WGIs aligning with low SGIs. However, spatial mismatches between WGIs and SGIs are observed in the peripheral zones of some satellite towns.

Compared to the greenery view index, there is a notable mismatch between WSIs and SSIs. In a significant portion of the Victoria Peak area, the SSIs are below the median value, while the WSIs exceed the median value. Conversely, in certain satellite towns, such as Sha Tin and Kwun Tong, the SSIs are relatively high, whereas the WSIs remain low.

The distributions of WWI and SWI also exhibit similarity, with high values of both indices predominantly located along the coastline. One notable exception is Victoria Peak, which, despite being inland, demonstrates low SWIs but high WWIs. Additionally, certain scattered coastal areas exhibit high SWIs but low WWIs.

3.4. Relative importance of independent variables

Besides WVIs and SVIs, we also incorporated vigorous physical activity, moderate physical activity, sedentary behavior, building environment factors, and demographic factors as covariates in the non-linear model (Fig. 6). For mental wellbeing, the most impactful variable was street-view sky (SSI) before the COVID-19 era with about 0.095 contribution, which meaned out of all the features used in the model, the total contribution of street-view sky was ranked first and is calculated to be 9.5% of the total "importance" allocated to all features. The RI of window-view greenery (WGI) increased from the 2nd position before the COVID-19 era to the 1st position during the COVID-19 era with about 0.125 contribution, while the rank of window-view sky (WSI) and window-view water (WWI) remained unchanged. For physical wellbeing, the RI of WGI rose from the 5th position before the COVID-19 era to the 1st position during the COVID-19 era, whereas the RI of WSI

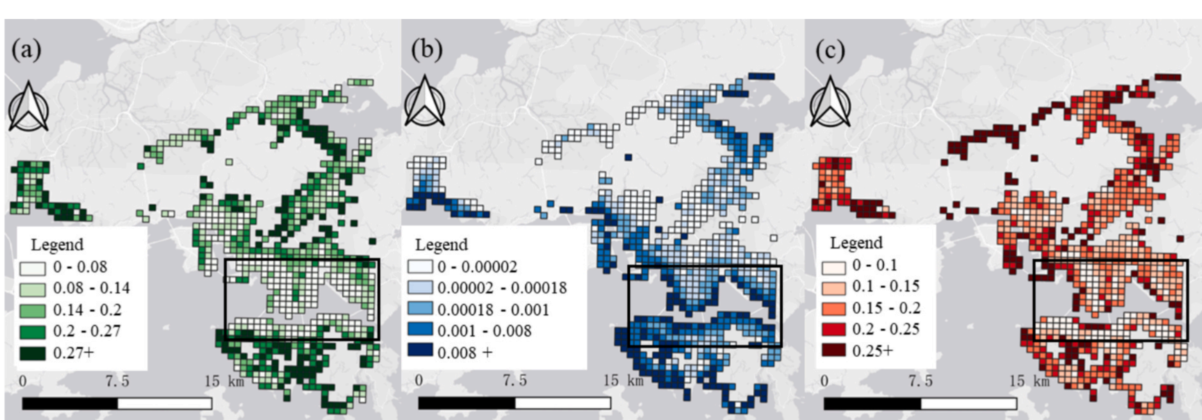

Fig. 4. Spatial distribution of (a) WGI, (b) WWI, and (c) WSI at 500 × 500 m rectangular grids in Hong Kong. The black boundary includes the core urban area of Hong Kong.

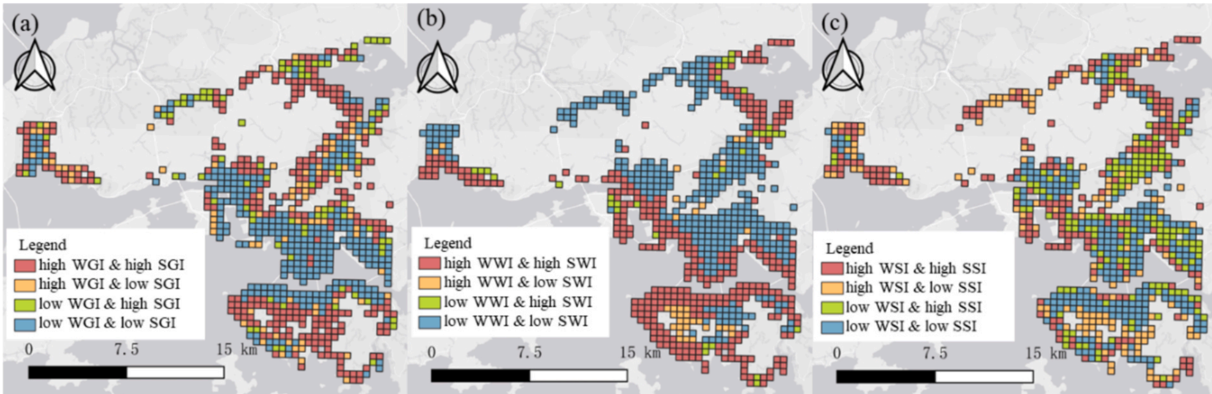

Fig. 5. Spatial mismatch between (a) WGI and SGI, (b) WWI and SWI, and (c) WSI and SSI at 500 × 500 m rectangular grids in Hong Kong.

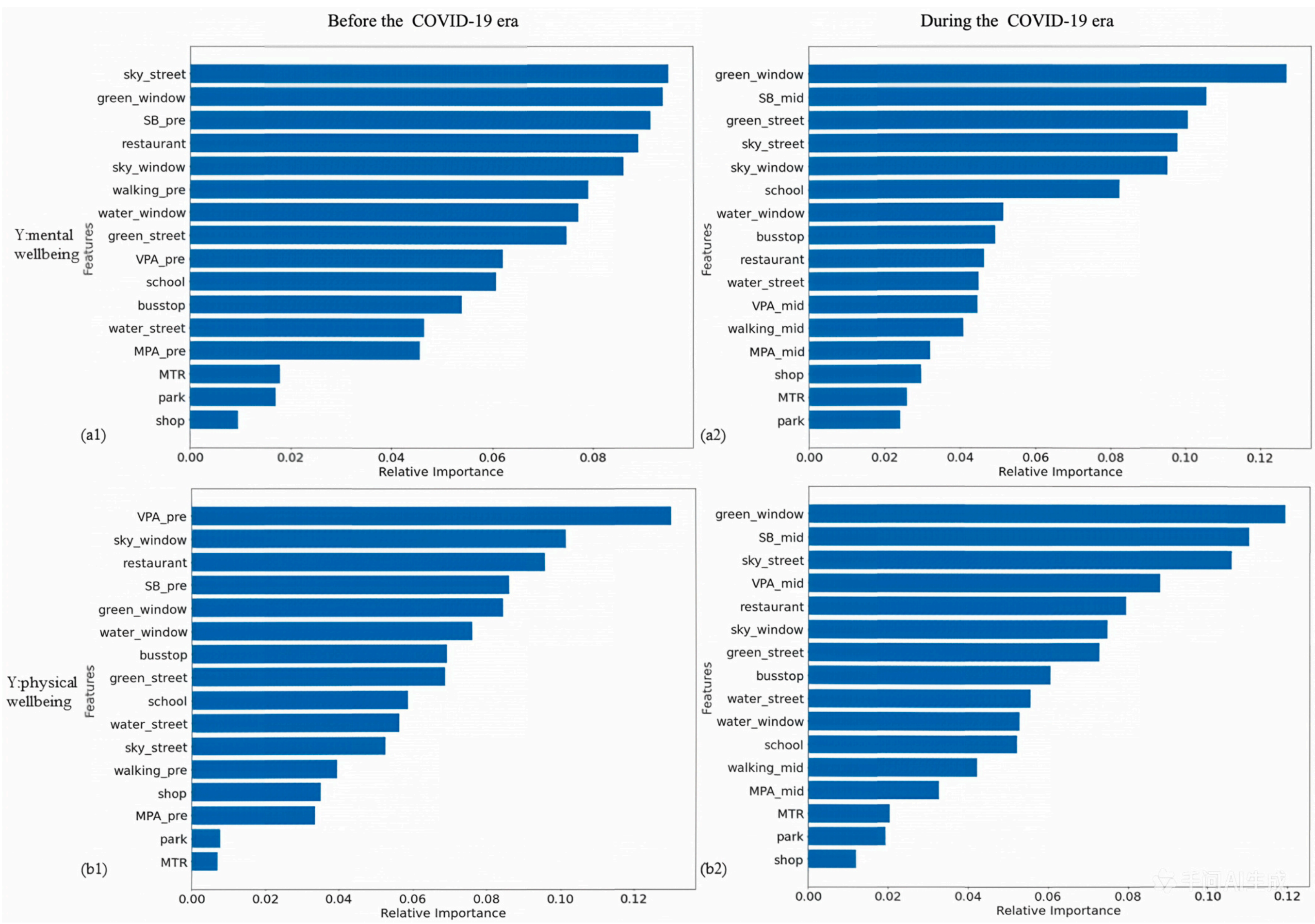

Fig. 6. The relative importance of the top 18 variables with the highest influence on (a1) mental and (b1) physical health and wellbeing before the COVID-19 era, as well as (a2) mental and (b2) physical health and wellbeing during the COVID-19 era. Note: SB_pre (Sedentary Behavior before the era), SB_mid (Sedentary Behavior during the era), VPA_pre (Vigorous Physical Activity before the era), VPA_mid (Vigorous Physical Activity during the era), MPA_pre (Moderate Physical Activity before the era), MPA_mid (Moderate Physical Activity during the era).

declined from the 2nd to the 6th position, and the RI of WWI dropped from the 6th to the 10th position. Additionally, it is noteworthy that the RI of sedentary behavior increased from the 3rd to the 2nd position for mental wellbeing and from the 4th to the 2nd position for physical wellbeing. Conversely, the RI of vigorous physical activity decreased from the 9th to the 11th position for mental wellbeing and from the 1st to the 4th position for physical wellbeing.

3.5. Nonlinear effect of WVIs on health and wellbeing outcomes

We also illustated how WVIs impact on mental health and wellbeing employing PDP (Fig. 7). PDPs illustrate the marginal effect of WVIs on the predicted outcomes of physical and mental wellbeing. Both dependent variables and independent variables had been transformed into z-scores to make them easier to compare. -1, -2, +1, +2: Represent the number of standard deviations away from the mean. WGI exhibited a

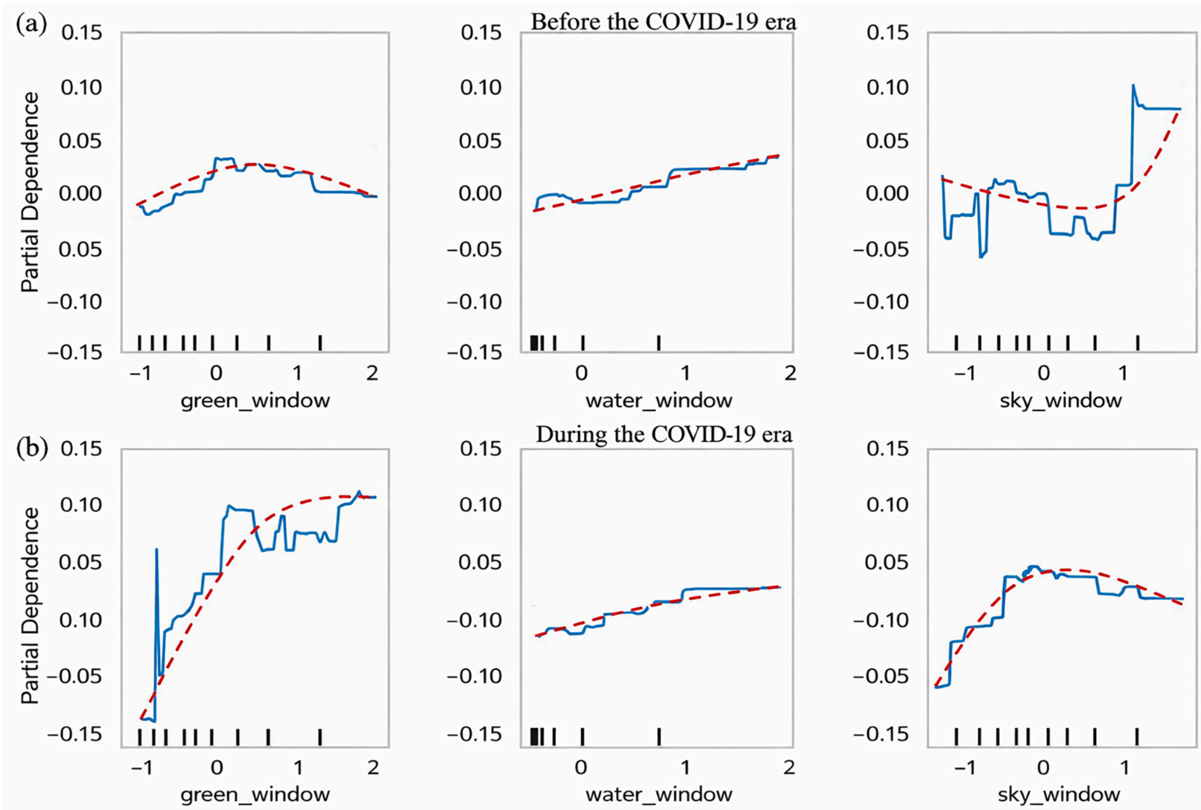

Fig. 7. PDPs of non-linear impacts of three WVIs on mental health and wellbeing (a) before and (b) during the COVID-19 era.

fluctuating effect on mental health and wellbeing before the COVID-19 era, whereas during the COVID-19 era, higher WGI values were

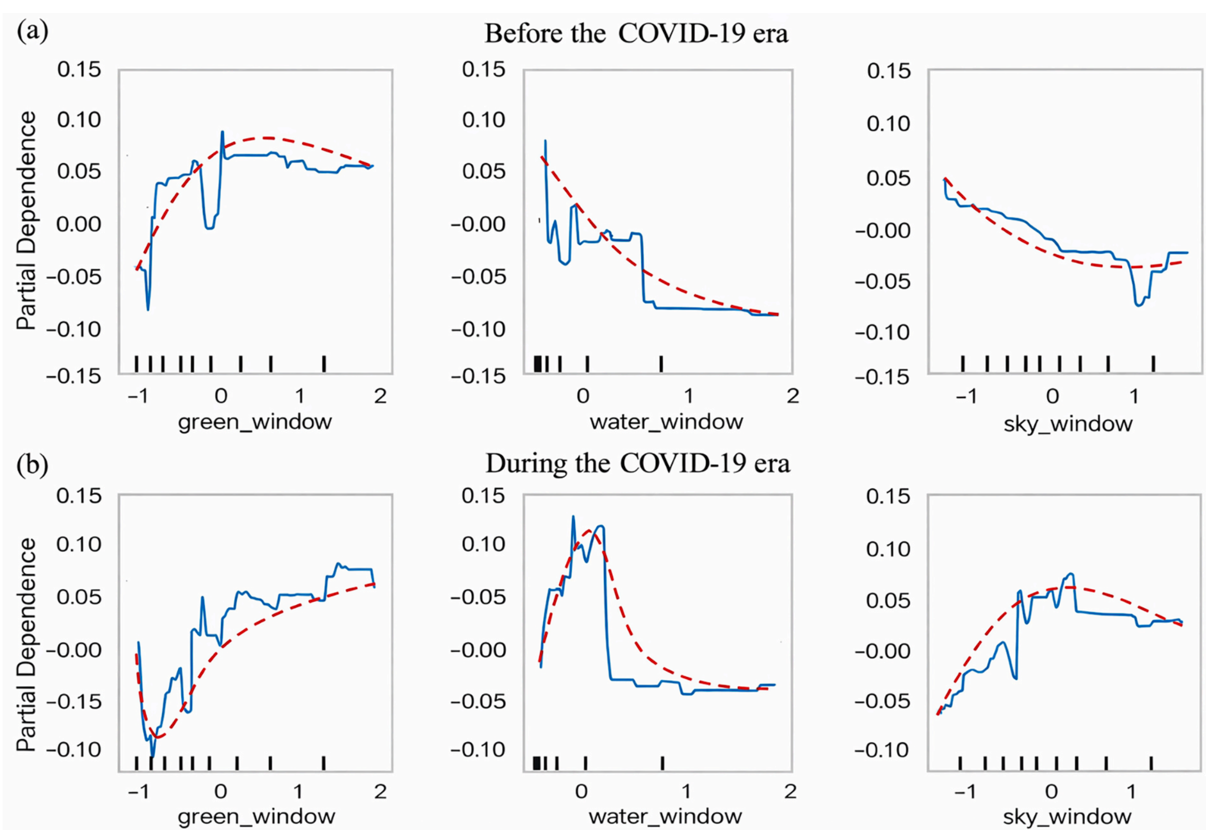

Fig. 8. PDPs of non-linear impact of three WVIs on physical health and wellbeing (a) before and (b) during the COVID-19 era.

associated with better mental health and wellbeing (higher value) with fluctuation. Both before and during the COVID-19 era, an increased WWI was linked to slightly better mental wellbeing. Before the COVID-19 era, values of WSI were consistently fluctuated with mental health and wellbeing. During the COVID-19 era, a higher WSI was associated with better mental health and wellbeing when the WSI was samller than 0. In contrast, when the WSI exceeded 0, mental health and wellbeing showed a slight increase with a rising WSI.

The effects of WVIs on physical wellbeing are demonstrated in Fig. 8. Prior to the COVID-19 pandemic, an increase in WGI led to an abrupt rise in physical health and wellbeing, followed by sustained fluctuations. During the pandemic, however, higher WVIs and WGIs were associated with a continued upward trend in physical health and wellbeing, albeit with intermittent fluctuations. The association between WWIs and physical health and wellbeing was non-robust both before and during the COVID-19 era, exhibiting marked fluctuations. Prior to the pandemic, physical health and wellbeing demonstrated a negative relationship with WWIs. In contrast, during the pandemic, the association followed an inverted U-shaped pattern. The WSI-physical health and wellbeing relationship reversed direction before and during the pandemic. Before the COVID-19 era, higher WSIs led to an initial physical health and wellbeing decline followed by slight recovery, whereas during the COVID-19 era, the pattern shifted to an initial physical health and wellbeing increase succeeded by a mild decrease.

4. Discussion

Urban lifestyles are increasingly indoor-centric, especially in densely populated urban areas (Lu et al., 2017). Natural elements visible through windows are known to enhance biophilic experiences even without direct physical contact, contributing to restorative effects and reducing mental fatigue. Consequently, it is critical to understand the role of visual access to natural elements via windows in promoting human health and wellbeing for urban residents. Only by understanding this, architects and urban designers may prioritize strategies that enhance visual connectivity to greenery, water, sky, and other natural features, contributing to the design and planning of healthier urban environment. Hence, the effort in this study deepens the academic discourse by focusing on the nuanced interplay between window-view nature exposure and human health and wellbeing, ultimately encouraging the creation of cities that actively promote both health and wellbeing resilience and environmental equity. In this study, three major findings are yielded.

4.1. Evaluations on window-view nature exposure

Our study contributes to a growing body of research that utilizes modelled environmental data to assess window-view nature exposure at scale (Li et al., 2022; Liu et al., 2025). Positioning our work within this methodological landscape clarifies its specific contributions and limitations.

The foundational work in this field relied on field audits and manually captured photographs of actual windows (Ulrich, 1984). This method captures the exact view from a specific window at a specific time, including ephemeral qualities like lighting, weather, and seasonal changes (Ko et al., 2022; Masoudinejad & Hartig, 2020). Our approach shares the goal of analyzing visual content but diverges fundamentally in scale and methodology. While manual photo studies provide deep, validated insights at the room or building level, they are inherently limited in sample size and geographic scope due to labor and access constraints. Our method, using photorealistic 3D city models, trades the granular, ground-truth accuracy of a single photo for the ability to systematically generate and analyze 1.28 million simulated views across an entire city. This allows us to detect population-level patterns and spatial inequities that are beyond the reach of manual audits. However, this scalability comes with compromises: our simulated views lack dynamic elements (e.g., people, vehicles, weather) and rely on the static textures and geometric accuracy of the photorealistic 3D city models, which may not capture all real-world details like interior window framing or movable obstructions. Besides, this computational focus means we do not capture the mediating role of window design characteristics, such as size, shape, transmittance, or framing, which are known to influence visual comfort, perception, and the restorative potential of a view (Ko et al., 2022).

Studies employing procedural 3D modeling or GIS-based sightline analysis often generate simplified 3D city models from building footprints and height data (Qi et al., 2024; Yu et al., 2016). These models excel at calculating isovists and theoretical visibility to green spaces or water bodies over large urban extents. A key strength is their computational efficiency for city-wide analyses of potential visual exposure. However, a common limitation is the lack of photorealistic texturing, requiring assumptions about the visual content within a sightline (e.g., classifying an entire visible parcel as “green”). Our approach aligns with this scalability objective but diverges by using photorealistic 3D city models. This allows us to move beyond binary visibility metrics to quantify the actual proportion of greenery, water, and sky within the simulated view, offering a more nuanced and content-specific exposure index that better approximates human visual experience (Li et al., 2022, 2024).

Research utilizing self-sampled LiDAR data combined with aerial or oblique imagery achieves high geometric accuracy and realistic texturing (Bolte et al., 2024; Xia et al., 2024). These studies can produce highly accurate window-view assessments for specific buildings or neighborhoods. Our method shares the goal of realism but relies on pre-existing, government-issued photorealistic 3D city models. These models are often more readily available and standardized for entire cities, offering a pragmatic and replicable pathway for large-scale, policy-relevant studies in jurisdictions where such open 3D data exists. A key contrast lies in view generation; some LiDAR-based studies calculate viewsheds in GIS software, whereas we use a real-time 3D engine to render perspective-correct images, simulating the human field of view more directly.

4.2. Spatial discrepancy between window-view and street-view nature exposure

Our study reveals a significant discrepancy between nature exposure measured by window views and street views. Specifically, window-view greenery exposure closely aligns with street-view greenery exposure, as does water exposure. The Victoria Peak region exhibits a notable discrepancy, with lower street-view water indices but higher window-view water indices (Fig. 9). In contrast, window-view sky exposure and street-view sky exposure exhibit significant spatial mismatches. Areas with high window-view sky indices but low street-view sky indices are predominantly concentrated in the Victoria Peak region and its vicinity, which is an affluent area. Conversely, areas with low window-view sky indices but high street-view sky indices are scattered across Kwun Tong, Sham Shui Po, and Sha Tin, which are socially deprived areas in Hong Kong. Hence, these outcomes indicate that using street view images to represent nature exposure may inaccurately capture the real nature exposure by urban residents within buildings where they spend the majority of their time.

Urban environments often embed socio-economic inequalities in their design, and access to natural views from residential spaces might reflect disparities in wealth, geographic location, or housing quality. Buildings with expansive views of greenery or waterfronts may largely be accessible to wealthier populations, while lower-income residents, living in dense urban cores, may face limited or obstructed access to natural views. By focusing on window-view nature exposure, this study provides critical insights into environmental inequalities that might otherwise be overlooked in traditional street-view-based measurements.

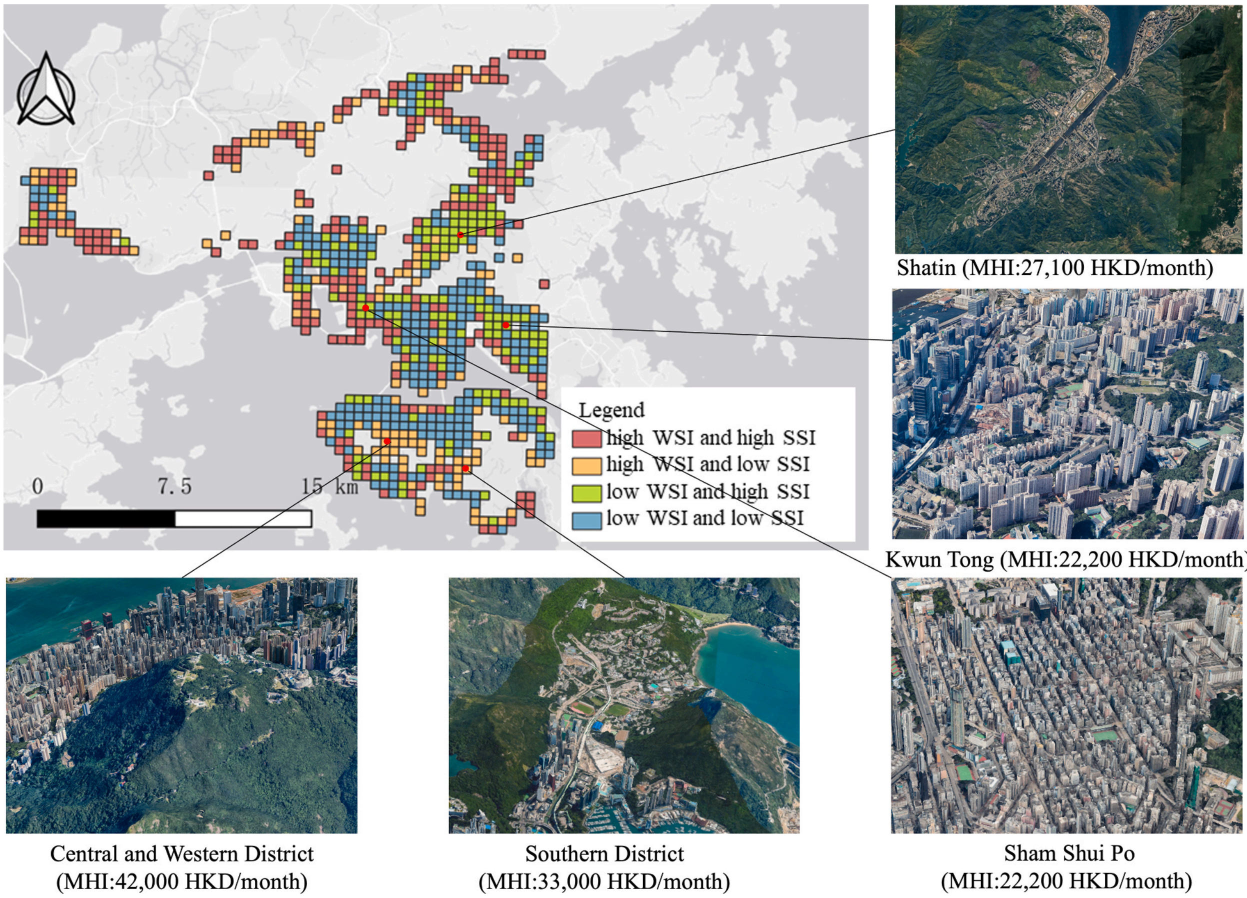

Fig. 9. Spatial mismatch between WSI and SSI at 500 × 500 m rectangular grids in Hong Kong and MHI of specific areas.

4.3. The health impact of window-view nature exposure vs street-view nature exposure

Our study reveals that window-view nature exposure has a distinct impact on human outcomes to street-view nature exposure, with window-view greenery becoming even more significant during the COVID-19 pandemic. Most existing research relies on street-view nature exposure derived from street view images as a proxy for eye-level nature exposure. However, street-view nature exposure may not fully capture the nature experiences of most individuals, as people spend the majority of their time indoors, particularly in high-density urban areas and during periods of restricted mobility, such as pandemic-related lockdowns (Cox et al., 2017).

Our findings suggest that window-view nature exposure exerts comparable, if not stronger, effects on both mental and physical health and wellbeing, compared with those of street-view nature exposure. For mental health and wellbeing, the nature exposure variable with highest relative importance shifted from street-view sky index during the pre-pandemic period to window-view greenery index during the COVID-19 era. Window-view nature exposure predominantly supports mental health and wellbeing by offering passive, sustained visual contact with nature, which buffers against indoor stressors (e.g., work-related anxiety) and fosters emotional regulation (Browning et al., 2020). This is particularly critical in high-density cities or during pandemics, where window views serve as a primary restorative resource (Dzhambov et al., 2021).

For physical health and wellbeing, WVIs (sky and greenery respectively) have the highest relative importance during both pre-pandemic and pandemic periods. As previously mentioned, during the COVID-19 pandemic in Hong Kong, individuals spent less time outdoors, resulting in reduced engagement in physical activity and increased sedentary behavior. Window-view nature exposure may increase physical health and wellbeing, via the increased motivation to adopt healthy lifestyle at home, such as maintaining a balanced diet, engaging in indoor exercise, and following a regular daily routine (Pérez-Urrestarazu et al., 2021). Furthermore, exposure to green or blue views has been associated with improved sleep quality and circadian rhythm regulation (Grigsby-Toussaint et al., 2015), which are critical to maintaining physical health resilience during the pandemic. In the dense urban setting of Hong Kong, where private access to gardens, parks, or green roofs is limited for most residents, the presence of sky and greenery through windows represents an important and accessible health-promoting resource.

4.4. The health impacts of window-view nature exposure during the pandemic vs. normal period

Although the relative importance of window-view nature exposure on health and wellbeing outcomes during the pandemic was not consistently stronger than in the pre-pandemic period, increased WVIs generally had a positive effect on both physical and mental health and wellbeing during the pandemic—an effect that was more variable before the pandemic. Specifically, the relationships between window-view greenery and both mental and physical health and wellbeing were more robust, linear, and pronounced in magnitude during the COVID-19 era than before. During the pandemic, respondents spend more time indoors (Zhang et al., 2021). As a result, the window-view nature exposure likely constitutes a larger share of total daily nature exposure during the pandemic than in normal periods, hence exerting stronger health impacts (Soga et al., 2021). Notably, the impact of window-view sky on mental health and wellbeing remained similar before and during the pandemic; however, while increased window-view sky was associated with poorer physical health and wellbeing before the pandemic, it was linked to improved physical health and wellbeing during the pandemic. Sky views were sometimes associated with reduced amenity (Lu et al., 2022). Besides, overly open spaces with too much visible sky may reduce feelings of security or enclosure, thereby diminishing restorative benefits (Lu et al., 2022; Yao et al., 2024). However, they may have provided valuable psychological relief for people confined indoors.

During pandemics, time spent at home rises sharply while opportunities for outdoor nature exposure diminish. Under these conditions, window-mediated nature becomes a primary channel of exposure rather than a complement. On the one hand, baseline stress and uncertainty are elevated, so SRT's rapid affective regulation is likely to yield larger absolute benefits (stronger reductions in negative affect and physiological arousal) (Ulrich et al., 1991). On the other hand, ART's restoration may be amplified by high cognitive load (e.g., remote work and caregiving), making brief, incidental "micro-restorative" glances through windows disproportionately valuable for maintaining attentional control and emotion regulation (Kaplan, 1995).

4.5. Planning and policy implications

Our findings suggest that urban planners and policy makers should implement building-level interventions to enhance nature exposure via windows, such as establishing mandated window nature exposure standards, to enhance residents' exposure to nature through window views. Targeted green retrofits, e.g., vertical gardens, green façades, and communal green rooftops, should be conducted in neighborhoods lacking both public greenspaces and window-view nature exposure, ensuring equitable visual and physical accesses to natural environments. Priority should be given to for vulnerable populations including low-income residents and the elderly, who often experience restricted mobility and/or limited nature exposure.

4.6. Limitation and future studies

This study provides directional evidence on the influence of window-view nature exposure on mental and physical health and wellbeing, demonstrating that WVIs have a more significant impact than SVIs. However, the findings are suggestive rather than precisely quantifiable, and therefore cannot yet yield specific metrics for planning and building design. While the Window View Index (WVI) methodology possesses the inherent potential to inform such standards, several limitations currently constrain its application. The primary limitation of this study is that the survey data did not include the floor levels of participant's residential flat, and we had to use of the average WVI values of all windows in a building as an approximation for individual's window-view nature exposure. While our variance component analysis indicates that between-building variation is larger, the residual within-building (floor-to-floor) error represents a potential source of bias that may attenuate or obscure true associations. Therefore, the reported effect sizes should be interpreted with caution. Second, the cross-sectional and observational design precludes causal inference. Besides, respondent-reported residential locations are subject to potential bias due to self-reporting on a map. Additionally, this study used the differential impacts of window views on health and wellbeing outcomes before versus during the COVID-19 pandemic as a proxy for mobility-related change. However, the pandemic itself is a significant confounding variable, independently affecting human health and wellbeing. Moreover, physical activity, sedentary behavior, and physical and mental health and wellbeing were self-reported and prone to recall bias. Consequently, the current findings are suggestive and not yet suitable for deriving specific design metrics.

To translate these directional findings into actionable design thresholds, future research must collect more granular data, including room locations of respondents and window positions. Subsequently, empirical studies can be designed to establish minimum WVI thresholds for use by urban planners and architects. The accuracy and reliability of future findings would be substantially enhanced by employing objective measures of behavior and health and wellbeing outcomes, complemented by validation experiments to address these methodological complexities.

5. Conclusion

This study highlights the spatial mismatch between street-view and window-view nature exposures, and reveals significant associations between window-view nature exposure and physical and mental health and wellbeing outcomes among residents in high-density urban areas. The findings elucidate underlying mechanisms linking urban nature and health and wellbeing benefits. From a methodological perspective, this study illustrates the value of using photorealistic 3D city models to derive window-view nature exposure indices, offering a promising approach for future research on urban environment-health associations. Since window-view nature is influenced not only by spatial distribution of urban nature elements but also by architectural design features, such as window placement and surrounding building massing, this study highlights the joint effects of macro-scale urban design characteristics and micro-scale architectural factors on residents' behaviors and health and wellbeing outcomes. These findings provide new evidence for targeted interventions aimed at fostering healthy and inclusive urban environments.

CRediT authorship contribution statement

Dongwei Liu: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Di Wei:** Data curation. **Hung Chak Ho:** Investigation, Data curation. **Maosu Li:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **Yi Lu:** Writing – review & editing, Supervision, Project administration.

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Appendix

Table A1
Descriptive statistics of variables on the survey.

Category	Variable	Abbreviation	Mean	Standard Deviation	Median	Range and unit
Subjective wellbeing	Mental Wellbeing before COVID-19	MW_pre	2.25	1.08	4	5:"excellent, 4:" "very good," 3: "good," 2: "fair," 1: "poor"?

(*continued on next page*)

Table A1 (*continued*)

Category	Variable	Abbreviation	Mean	Standard Deviation	Median	Range and unit
	Mental Wellbeing during COVID-19	MW_mid	1.21	1.11	3	
	Physical wellbeing before COVID-19	PW_pre	7.12	1.5	7	Scale from 0 to 10, where 0 means "very dissatisfied," 10 means "very satisfied," and 5 represents "neutral."
	Physical wellbeing after COVID-19	PW_mid	6.06	2	6	
Physical activities	Vigorous physical activity before COVID-19	VPA_pre	2.03	1.91	2	Conducted VPA more than 10 minutes in 1-7 days of a week
	Vigorous physical activity after COVID-19	VPA_mid	1.54	1.88	1	
	Moderate physical activity before COVID-19	MPA_pre	2.53	2.22	2	
	Moderate physical activity during COVID-19	MPA_mid	2.16	2.2	1	
	Walking more than 10 minutes before COVID-19	Walking_pre	5.43	1.98	6	Walking more than 10 minutes in 1-7 days of a week
	Walking more than 10 minutes during COVID-19	Walking_mid	4.79	2.25	5	
	Sedentary behavior before COVID-19	SB_pre	482.92	255.71	480	Minutes a day
	Sedentary behavior during COVID-19	SB_mid	536.67	278.07	480	
Individual sociodemographic variables	Under 30 years old		0.164	0.37	0	Average value of blocks within 500 meters' buffer
	Between 30 and 60 years old		0.701	0.458	1	
	Over 60 years old		0.136	0.342	0	
	Education: high school or below		0.322	0.467	0	
	Education: bachelor		0.419	0.493	0	
	Education: Master or above		0.26	0.439	0	
	Income under 40000 HKD/month		0.508	0.5	1	
	Income between 40000 and 100000 HKD/month		0.371	0.483	0	
	Income over 100000 HKD/month		0.12	0.326	0	

Table A2
Descriptive statistics of neighborhood-level built environment characteristics.

Variable	Mean	Standard Deviation	Median	Metrics
Bus stop	32.574	16.706	32	Number of POI within 500 meters' buffer
Restaurants	129.051	117.945	92	
MTR stations	1.697	1.061	1	
Parks	1.697	1.061	1	
Retails	22.617	13.866	21	
School	16.428	7.919	16	
Primary school	3.997	2.281	4	
Secondary school	3.766	2.323	3	
Public service	7.348	3.972	7	
Road intersections	96.090	45.016	90	
Population density	42414.72	27308.71	37843.76	Average value within 500 meters' buffer
Areas of parks	11.48	6.27	9.99	The sum areas of parks 500 meters' buffer
Land use mix	0.613	0.265	0.609	Entropy for the diversity of land uses within 500 meters' buffer. $Landusemix = \Sigma_i(p_i lnp_i)/lnN$, where pi is the ratio of the ith land use, and N is the total types of land uses. Five categories of land uses (residential, business, industrial, open space, and commercial) are considered (N = 5).
Under 30 years old	0.164	0.370	0	Average value of blocks within 500 meters' buffer
Between 30 and 60 years old	0.701	0.458	1	
Over 60 years old	0.136	0.342	0	
Education: high school or below	0.322	0.467	0	
Education: bachelor	0.419	0.493	0	
Education: Master or above	0.260	0.439	0	
Income under 40000 HKD/month	0.508	0.500	1	
Income between 40000 and 100000 HKD/month	0.371	0.483	0	
Income over 100000 HKD/month	0.120	0.326	0	

Data availability

Data will be made available on request.

References

Abboushi, B., Elzeyadi, I., Van Den Wymelenberg, K., Taylor, R., Sereno, M., & Jacobsen, G. (2021). Assessing the Visual Comfort, Visual Interest of Sunlight Patterns, and View Quality under Different Window Conditions in an Open-Plan Office. *LEUKOS, 17*(4), 321–337. https://doi.org/10.1080/15502724.2020.1785309

Bi, W., Jiang, X., Li, H., Cheng, Y., Jia, X., Mao, Y., & Zhao, B. (2022). The More Natural the Window, the Healthier the Isolated People—A Pathway Analysis in Xi'an, China, during the COVID-19 Pandemic. *International Journal of Environmental Research and Public Health, 19*(16), 10165. https://doi.org/10.3390/ijerph191610165

Bolte, A.-M., Niedermann, B., Kistemann, T., Haunert, J.-H., Dehbi, Y., & Kötter, T. (2024). The green window view index: Automated multi-source visibility analysis for a multi-scale assessment of green window views. *Landscape Ecology, 39*(3), 71. https://doi.org/10.1007/s10980-024-01871-7

Braçe, O., Garrido-Cumbrera, M., Foley, R., Correa-Fernández, J., Suárez-Cáceres, G., & Lafortezza, R. (2020). Is a View of Green Spaces from Home Associated with a Lower Risk of Anxiety and Depression? *International Journal of Environmental Research and Public Health, 17*(19), 7014. https://doi.org/10.3390/ijerph17197014

Bratman, G. N., Anderson, C. B., Berman, M. G., Cochran, B., De Vries, S., Flanders, J., Folke, C., Frumkin, H., Gross, J. J., Hartig, T., Kahn, P. H., Kuo, M., Lawler, J. J., Levin, P. S., Lindahl, T., Meyer-Lindenberg, A., Mitchell, R., Ouyang, Z., Roe, J., & Daily, G. C. (2019). Nature and mental health: An ecosystem service perspective. *Science Advances, 5*(7), Article eaax0903. https://doi.org/10.1126/sciadv.aax0903

Browning, M. H. E. M., Shipley, N., McAnirlin, O., Becker, D., Yu, C.-P., Hartig, T., & Dzhambov, A. M. (2020). An Actual Natural Setting Improves Mood Better Than Its Virtual Counterpart: A Meta-Analysis of Experimental Data. *Frontiers in Psychology, 11*, 2200. https://doi.org/10.3389/fpsyg.2020.02200

Butler, D. L., & Biner, P. M. (1989). Effects of Setting on Window Preferences and Factors Associated with Those Preferences. *Environment and Behavior, 21*(1), 17–31. https://doi.org/10.1177/0013916589211002

Cesium, G. S. (2022). *The Cesium Platform [Computer software]*. USA: Cesium GS, Inc.. https://cesium.com/platform/.

Chang, C., Oh, R. R. Y., Le Nghiem, T. P., Zhang, Y., Tan, C. L., Lin, B. B., Gaston, K. J., Fuller, R. A., & Carrasco, L. R. (2020). Life satisfaction linked to the diversity of nature experiences and nature views from the window. *Landscape and Urban Planning, 202*, Article 103874.

Cox, D. T. C., Hudson, H. L., Shanahan, D. F., Fuller, R. A., & Gaston, K. J. (2017). The rarity of direct experiences of nature in an urban population. *Landscape and Urban Planning, 160*, 79–84. https://doi.org/10.1016/j.landurbplan.2016.12.006

Cox, D. T., Shanahan, D. F., Hudson, H. L., Fuller, R. A., & Gaston, K. J. (2018). The impact of urbanisation on nature dose and the implications for human health. *Landscape and Urban Planning, 179*, 72–80.

Dzhambov, A. M., Lercher, P., Browning, M. H., Stoyanov, D., Petrova, N., Novakov, S., & Dimitrova, D. D. (2021). Does greenery experienced indoors and outdoors provide an escape and support mental health during the COVID-19 quarantine? *Environmental Research, 196*, Article 110420.

Grigsby-Toussaint, D. S., Turi, K. N., Krupa, M., Williams, N. J., Pandi-Perumal, S. R., & Jean-Louis, G. (2015). Sleep insufficiency and the natural environment: Results from the US Behavioral Risk Factor Surveillance System survey. *Preventive Medicine, 78*, 78–84. https://doi.org/10.1016/j.ypmed.2015.07.011

Guo, C., Wong, K. F., Xu, Y., Hung, K. K. C., & Ho, H. C. (2024). Personal Wellbeing Amid Pandemic Response: Impacts of Neighborhood Built Environment, Risk Communication and Health. *Applied Research in Quality of Life*. https://doi.org/10.1007/s11482-024-10395-w.

Helbich, M., Danish, M., Labib, S. M., & Ricker, B. (2024). To use or not to use proprietary street view images in (health and place) research? That is the question. *Health & Place, 87*, Article 103244. https://doi.org/10.1016/j.healthplace.2024.103244

Kaplan, S. (1995). The restorative benefits of nature: Toward an integrative framework. *Journal of Environmental Psychology, 15*(3), 169–182. https://doi.org/10.1016/0272-4944(95)90001-2

Ke, G., Meng, Q., Finley, T., Wang, T., Chen, W., Ma, W., Ye, Q., & Liu, T.-Y. (2017). *Lightgbm: A highly efficient gradient boosting decision tree* (p. 30). Advances in Neural Information Processing Systems.

Keighley, E. C. (1973). Visual requirements and reduced fenestration in office buildings—A study of window shape. *Building Science, 8*(4), 311–320. https://doi.org/10.1016/0007-3628(73)90016-9

Ko, W. H., Kent, M. G., Schiavon, S., Levitt, B., & Betti, G. (2022). A Window View Quality Assessment Framework. *LEUKOS, 18*(3), 268–293. https://doi.org/10.1080/15502724.2021.1965889

Ko, W. H., Schiavon, S., Zhang, H., Graham, L. T., Brager, G., Mauss, I., & Lin, Y.-W. (2020). The impact of a view from a window on thermal comfort, emotion, and cognitive performance. *Building and Environment, 175*, Article 106779. https://doi.org/10.1016/j.buildenv.2020.106779

Labib, S. M., Huck, J. J., & Lindley, S. (2021). Modelling and mapping eye-level greenness visibility exposure using multi-source data at high spatial resolutions. *Science of The Total Environment, 755*, Article 143050. https://doi.org/10.1016/j.scitotenv.2020.143050

Leather, P., Pyrgas, M., Beale, D., & Lawrence, C. (1998). Windows in the Workplace: Sunlight, View, and Occupational Stress. *Environment and Behavior, 30*(6), 739–762. https://doi.org/10.1177/001391659803000601

Li, M., Xue, F., Wu, Y., & Yeh, A. G. (2022). A room with a view: Automatic assessment of window views for high-rise high-density areas using City Information Models and deep transfer learning. *Landscape and Urban Planning, 226*, Article 104505.

Li, M., Xue, F., & Yeh, A. G. (2023). Bi-objective analytics of 3D visual-physical nature exposures in high-rise high-density cities for landscape and urban planning. *Landscape and Urban Planning, 233*, Article 104714.

Li, M., Yeh, A. G. O., & Xue, F. (2024). CIM-WV: A 2D semantic segmentation dataset of rich window view contents in high-rise, high-density Hong Kong based on photorealistic city information models. *Urban Informatics, 3*(1), 12. https://doi.org/10.1007/s44212-024-00039-7

Lin, T.-Y., Le, A.-V., & Chan, Y.-C. (2022). Evaluation of window view preference using quantitative and qualitative factors of window view content. *Building and Environment, 213*, Article 108886. https://doi.org/10.1016/j.buildenv.2022.108886

Liu, D., Lu, Y., & Biljecki, F. (2025). A methodological review of the assessment of urban greenery exposure. *Urban Forestry & Urban Greening, 129169*.

Lu, S., Oh, W., Ooka, R., & Wang, L. (2022). Effects of Environmental Features in Small Public Urban Green Spaces on Older Adults' Mental Restoration: Evidence from Tokyo. *International Journal of Environmental Research and Public Health, 19*(9), 5477. https://doi.org/10.3390/ijerph19095477

Lu, Y. (2019). Using Google Street View to investigate the association between street greenery and physical activity. *Landscape and Urban Planning, 191*, Article 103435.

Lu, Y., Xiao, Y., & Ye, Y. (2017). Urban density, diversity and design: Is more always better for walking? A study from Hong Kong. *Preventive Medicine, 103*, S99–S103. https://doi.org/10.1016/j.ypmed.2016.08.042

Marcoulides, K. M., & Raykov, T. (2019). Evaluation of Variance Inflation Factors in Regression Models Using Latent Variable Modeling Methods. *Educational and Psychological Measurement, 79*(5), 874–882. https://doi.org/10.1177/0013164418817803

Masoudinejad, S., & Hartig, T. (2020). Window View to the Sky as a Restorative Resource for Residents in Densely Populated Cities. *Environment and Behavior, 52*(4), 401–436. https://doi.org/10.1177/0013916518807274

Matusiak, B. S., & Klöckner, C. A. (2016). How we evaluate the view out through the window. *Architectural Science Review, 59*(3), 203–211. https://doi.org/10.1080/00038628.2015.1032879

Mitchell, R., & Popham, F. (2008). Effect of exposure to natural environment on health inequalities: An observational population study. *The Lancet, 372*(9650), 1655–1660. https://doi.org/10.1016/S0140-6736(08)61689-X

Nguyen, Q. C., Khanna, S., Dwivedi, P., Huang, D., Huang, Y., Tasdizen, T., Brunisholz, K. D., Li, F., Gorman, W., Nguyen, T. T., & Jiang, C. (2019). Using Google Street View to examine associations between built environment characteristics and U.S. health outcomes. *Preventive Medicine Reports, 14*, Article 100859. https://doi.org/10.1016/j.pmedr.2019.100859

Olszewska-Guizzo, A., Escoffier, N., Chan, J., & Puay Yok, T. (2018). Window View and the Brain: Effects of Floor Level and Green Cover on the Alpha and Beta Rhythms in a Passive Exposure EEG Experiment. *International Journal of Environmental Research and Public Health, 15*(11), 2358. https://doi.org/10.3390/ijerph15112358

Patwary, M. M., Bardhan, M., İnan, H. E., Browning, M. H. E. M., Disha, A. S., Haque, M. Z., Helmy, M., Ashraf, S., Dzhambov, A. M., Shuvo, F. K., Alam, M. A., Billah, S. M., Kabir, M. P., Hossain, M. R., Azam, M. G., Rahman, M. M., Swed, S., Sah, R., Montenegro-Idrogo, J. J., & Rodriguez-Morales, A. J. (2024). Exposure to urban green spaces and mental health during the COVID-19 pandemic: Evidence from two low and lower-middle-income countries. *Frontiers in Public Health, 12*, Article 1334425. https://doi.org/10.3389/fpubh.2024.1334425

Pérez-Urrestarazu, L., Kaltsidi, M. P., Nektarios, P. A., Markakis, G., Loges, V., Perini, K., & Fernández-Cañero, R. (2021). Particularities of having plants at home during the confinement due to the COVID-19 pandemic. *Urban Forestry & Urban Greening, 59*, Article 126919. https://doi.org/10.1016/j.ufug.2020.126919

Qi, L., Hu, Y., Bu, R., Xiong, Z., Li, B., Zhang, C., Liu, H., & Li, C. (2024). Spatial-temporal patterns and influencing factors of the Building Green View Index: A new approach for quantifying 3D urban greenery visibility. *Sustainable Cities and Society, 111*, Article 105518.

Shan, L., & He, S. (2025). The role of peri-urban parks in enhancing urban green spaces accessibility in high-density contexts: An environmental justice perspective. *Landscape and Urban Planning, 254*, Article 105244. https://doi.org/10.1016/j.landurbplan.2024.105244

Sit, S.-M.-M., Lam, T.-H., Lai, A.-Y.-K., Wong, B.-Y.-M., Wang, M.-P., & Ho, S.-Y. (2021). Fear of COVID-19 and its associations with perceived personal and family benefits and harms in Hong Kong. *Translational Behavioral Medicine, 11*(3), 793–801. https://doi.org/10.1093/tbm/ibab018

Soga, M., Evans, M. J., Tsuchiya, K., & Fukano, Y. (2021). A room with a green view: The importance of nearby nature for mental health during the COVID-19 pandemic. *Ecological Applications, 31*(2), e2248.

Turan, I., Chegut, A., Fink, D., & Reinhart, C. (2021). Development of view potential metrics and the financial impact of views on office rents. *Landscape and Urban Planning, 215*, Article 104193. https://doi.org/10.1016/j.landurbplan.2021.104193

Twohig-Bennett, C., & Jones, A. (2018). The health benefits of the great outdoors: A systematic review and meta-analysis of greenspace exposure and health outcomes. *Environmental Research, 166*, 628–637. https://doi.org/10.1016/j.envres.2018.06.030

Ulrich, R. S. (1984). View Through a Window May Influence Recovery from Surgery. *Science, 224*(4647), 420–421. https://doi.org/10.1126/science.6143402

Ulrich, R. S., Simons, R. F., Losito, B. D., Fiorito, E., Miles, M. A., & Zelson, M. (1991). Stress recovery during exposure to natural and urban environments. *Journal of*

Environmental Psychology, 11(3), 201–230. https://doi.org/10.1016/S0272-4944(05)80184-7
Wang, F., & Munakata, J. (2024). Exploring perceived oppressiveness of high-rise window views: A virtual reality assessment of planning measures and visual elements' influence. *Journal of Building Engineering, 96*, Article 110476. https://doi.org/10.1016/j.jobe.2024.110476
Wang, N., & Boubekri, M. (2011). Design recommendations based on cognitive, mood and preference assessments in a sunlit workspace. *Lighting Research & Technology, 43*(1), 55–72. https://doi.org/10.1177/1477153510370807
White, M. P., Alcock, I., Wheeler, B. W., & Depledge, M. H. (2013). Would You Be Happier Living in a Greener Urban Area? A Fixed-Effects Analysis of Panel Data. *Psychological Science, 24*(6), 920–928. https://doi.org/10.1177/0956797612464659
Xia, T., Zhao, B., Yu, J., Gao, Y., Wang, X., Mao, Y., & Zhang, J. (2024). Making residential green space exposure evaluation more accurate: A composite assessment framework that integrates objective and subjective indicators. *Urban Forestry & Urban Greening, 95*, Article 128290.
Yao, T., Lin, W., Bao, Z., & Zeng, C. (2024). Natural or balanced? The physiological and psychological benefits of window views with different proportions of sky, green space, and buildings. *Sustainable Cities and Society, 104*, Article 105293. https://doi.org/10.1016/j.scs.2024.105293
Yu, S., Yu, B., Song, W., Wu, B., Zhou, J., Huang, Y., Wu, J., Zhao, F., & Mao, W. (2016). View-based greenery: A three-dimensional assessment of city buildings' green visibility using Floor Green View Index. *Landscape and Urban Planning, 152*, 13–26. https://doi.org/10.1016/j.landurbplan.2016.04.004
Zhang, N., Jia, W., Lei, H., Wang, P., Zhao, P., Guo, Y., Dung, C.-H., Bu, Z., Xue, P., & Xie, J. (2021). Effects of human behavior changes during the coronavirus disease 2019 (COVID-19) pandemic on influenza spread in Hong Kong. *Clinical Infectious Diseases, 73*(5), e1142–e1150.