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Multi-Domain Environmental Quality of Indoor Mixed-Use Open Spaces and Insights into Healthy Living—A Quarantine Hotel Case Study

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Abstract: In the post-pandemic context, data-driven design interventions that can endow architectural spaces with mixed-use and open characteristics that are adaptable and environmentally resilient are increasingly important. Ubiquitous semi-public architecture, such as hotel buildings, plays a crucial role in public health emergencies. Many hotels adopt mixed-use and open room spatial layouts, integrating diverse daily functions into a single tiny space, fostering flexible utilization and micro-scale space sharing; however, these also introduce potential health risks. This study offers a comprehensive evaluation of the indoor environmental quality (IEQ) of a hotel room space and discusses feasible intervention strategies for healthier renovation and rehabilitation. Taking a hotel in Shenzhen as a case, a multi-domain environmental assessment was conducted during the COVID-19 quarantine period in the summer of 2022. The study examines the health risks inherent in the hotel's guest room and the varying patterns of IEQ factors across the hotel's domains, including volatile organic compound concentrations, physical environmental parameters, and heat stress indices. The results illustrate diverse change trends in the chemical, physical, and heat stress factors present in the tested quarantined hotel room space throughout a typical summer day. Although most of the examined environmental factors meet local and global standards, some problems draw attention. In particular, the PM2.5 concentration was generally observed to be above the World Health Organization (WHO) air quality guideline (AQG) standards, and the interior lighting did not meet required standards most of the time. Moreover, correlation and multiple regression analyses uncover significant influence by physical environmental conditions on the concentrations of chemical pollutants in the hotel room. The study preliminarily identifies that higher relative humidity could lead to a lower concentration of CO_2 while a higher PM2.5 concentration. Wet bulb globe temperature (WBGT) was observed to positively affect CO_2 concentration. Further, the results suggest that even with relatively rigorous initial adjustment and re-renovation, multi-domain environmental quality in air-conditioned quarantine hotel rooms should be monitored and ameliorated from time to time. Overall, this study offers a scientific foundation for healthier upgrades of existing hotel buildings as well as provides insights into achieving environmental resilience in newly constructed hotel buildings for the post-pandemic era.

Keywords: multi-domain environmental quality; indoor mixed-use open space; environmental data analysis; quarantine hotel; adaptive design; healthy building

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1. Introduction

1.1. Mixed-Use and Open: From Urban Blocks to Architectural Spaces

Safe and efficient use of urban spaces through multifunctional integration has become a development trend under the background of rapid urban transformation and global climate change [1,2]. With the higher demands for health, safety, and flexibility on the living environment in the post-pandemic era, there has been a gradual transformation of concepts and design practices for urban and architectural spaces in the direction of "environmental resilience" and "flexible adaptation" [1,3]. This transformation has not only reshaped the urban forms but has also profoundly affected the conception and practical exploration of public health systems and public structures. As a type of architectural space well-suited to respond to social and environmental changes, mixed-use and open spaces (similar with the concept of multi-zone spaces to some extents) in buildings are increasingly emphasized in current and future development [4–8]. Such spaces break the regular fixation of functional zoning, presenting flexible boundaries of time and space, and offer a high degree of composite and flexible use. Generally, mixed-use and open buildings feature "flexible changes in architectural spaces, allowing different functional spaces to be converted into each other based on changing usage conditions" [4,9]. With their unique semi-public attributes and highly flexible and adaptable layout, indoor mixed-functional and open spaces play an indispensable role in meeting the diverse needs of users and responding to public health emergencies.

Current hotel room design greatly enhances the efficiency and flexibility of space utilization by breaking down traditional spatial boundaries and integrating a variety of daily activities such as work, entertainment, dining, sleeping, dressing, and washing (Figure 1). As ubiquitous open spaces with diverse functions and characteristics, hotel rooms significantly influence their occupants' physical and mental health. They need to be systematically evaluated in terms of chemical, physical, and psychological conditions as their highly mixed and open spatial layout can pose challenges to indoor environmental quality (IEQ) control and management [10–14]. The IEQ problems, such as poor air circulation in an air-conditioned hotel room space for a long period of time, may exacerbate air pollutant accumulations and thermal discomfort situations, posing a probability of virus transmissions and a potential threat to both the physical and mental health of occupants. These urgently need extensive attention and in-depth research and establish more systematic scientific evaluation frameworks for both objective improvement and subjective adaptation.

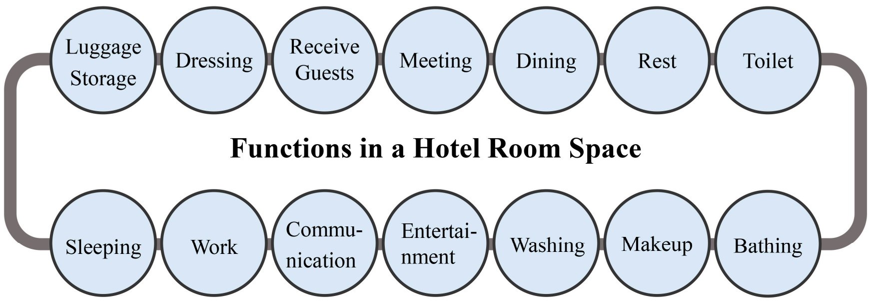

Figure 1. Relationships between multiple functions in a mixed-use and open hotel room space (source: drawn by authors).

1.2. Literature Review

Currently, there has been some progress in research on multiple environmental performances in indoor mixed-function open spaces with a major focus on the construction of air quality assessment systems [12,15–19], the monitoring of environmental qualities under different states of occupant use [20–22], the analysis of major pollutants and their patterns of change [23], as well as the exploration of technical means and management measures to improve indoor air quality [24–27]. Research methodologies also integrate environmental measuring techniques, in-depth case studies, and mathematical modeling, as well as statistical analysis, to obtain comprehensive and accurate data support [6,28,29]. These studies have also identified a few key factors affecting the indoor air quality of the mixed-use and open spaces, such as the design of the ventilation system [26], the choice of interior surface decoration materials [30,31], as well as the arrangement of furniture [32–34].

In studies addressing hotel buildings, increasingly, concerns have been raised regarding air quality, significantly motivated by travel restrictions, and increased public awareness of health risks due to the COVID-19 pandemic [35–37]. Notably, Qi et al.'s study on pollutant concentrations in guest rooms in middle- and small-size hotels located in north China found the concentration of pollutants to exceed standard limits [38]. Their analysis also identified a significant link between air temperature and the concentration of PM2.5, as well as between relative humidity and formaldehyde (HCHO) concentration. Moreover, they further suggested indoor air quality in hotel rooms could be effectively improved by adjusting linked physical conditions (e.g., air temperature and relative humidity). Similarly, through computational simulation, Li et al. explored and analyzed the efficiency of ventilation design strategies in improving air quality in a centralized quarantine community in Guangzhou at multiple spatial scales, including the neighborhood, building, and hotel room [39]. They therefore suggested adopting mixed strategies to enhance ventilation, providing some guidance for practice. Additionally, Yan et al. carried out multizonal modeling of airborne SARS-CoV-2 Quanta transmission in five prototype commercial buildings by the US Department of Energy (including a small hotel) to evaluate infection mitigation strategies [6]. Their test results suggested that both in-duct air treatment and in-room treatment facilities should be adopted to more effectively mitigate infection risks.

Besides air quality, many researchers have also focused on the physical and mental health effects on travelers living in quarantine hotels during the pandemic. A survey of 703 individuals quarantined on entry to Shanghai showed that over 70% reported having anxiety during their hotel quarantine, and 86.34% experienced depression [40]. The survey results indicate that, beyond enhancing air quality in hotel rooms, more soft interventions and healing strategies should also be adopted to establish a healthy and comfortable room space for extended stays. Other researchers have also looked at the service quality of quarantine hotels and its influence on travelers' perceptions and well-being. Drawing on 3896 online reviews of 52 quarantine hotels from TripAdvisor.com and semantic network analysis (SNA), Leutwiler-Lee et al. examined several aspects of hotel service quality, such as catering services from the hotel staff, meal quality, and room comfort [41]. Their findings suggested that travelers in quarantine hotels have similar physical and mental health care requirements as hospital patients. Architectural researchers and practitioners have also explored the possibility of more adaptable spatial layouts to counter the negative impacts of the pandemic by establishing warm and stable living environments for travelers during their quarantine periods [11,42–44].

However, on the whole, existing studies on quarantine hotel spaces mainly examine how to modify spatial layouts and architectural elements to fit urgent pandemic situations and fail to engage in multi-domain environmental evaluation of the health impacts of extended stays in hotel spaces. Understanding and accounting for urgent situations and problems that resulted from the COVID-19 pandemic should be conducted in such a way as to both enable more adaptive architectural design and effective building maintenance for normal time, as well as enable quick spatial adjustment and equipment preparation for emergency time of epidemics in the future [45]. Thus, it is of great importance to measure and investigate the multi-aspect of environmental performance of mixed-use and open hotel room spaces and identify their environmental problems and potential health risks in normal and extreme conditions, so as to adopt necessary interventions for rehabilitation.

1.3. Research Objectives

This study conducts a multi-domain environmental evaluation of air-conditioned quarantine hotel room space with mixed functions and aims to provide a more comprehensive insight into the rehabilitations of existing hotel rooms and the new construction of new hotel buildings. Based on the results of on-site measurements during the quarantine periods in 2022, the study further proposes to use correlation and multiple regression analysis to explore the critical factors affecting the environmental performances of the hotel guest room space in terms of chemical pollutant concentration, physical environmental performance, and heat stress conditions. In addition, by combining the concepts of "environmental resilience" and "mixed-use open spaces", the study proposes some practical suggestions for improving indoor air quality through more flexible and adaptable design means, so as to provide healthier and more comfortable living environments for hotel room occupants. Objectives of the study:

- To evaluate the environmental performance characteristics of mixed-use and open hotel room spaces, including chemical pollutant concentration, physical environmental performance, and heat stress conditions;
- To assess the variations in indoor environmental quality across functional zones in mixed-use and open hotel room spaces;
- To examine the relationships between physical conditions and chemical pollutant concentrations in mixed-use and open hotel room spaces;
- To provide preliminary insights into the improvement of environmental quality in mixed-use and open hotel room spaces and future further investigation.

2. Theoretical Framework

2.1. Healthy Building Concept

In the context of post-pandemic, enhancing inhabitants' physical health and social wellbeing through data-driven strategic optimization of architectural and urban design is becoming more and more crucial. The concept of "healthy building" highlights the intricate and mutually influential relationship that exists between occupants' quality of life and built environment. It is widely acknowledged that environmental factors play a pivotal role in shaping individual health outcomes and personal development. Healthy buildings encapsulate both core factors and surrounding factors, where core factors (e.g., age, gender, and genetic predisposition) form the foundational basis yet are intricately affected by surrounding factors, including personal lifestyle choices, community social networks, and residential and working spaces, etc. These surrounding factors exert a profound and far-reaching influence on the physical and psychological statuses of occupants. The theoretical underpinnings of the "healthy building" paradigm emphasize that buildings, situated within the broader socio-cultural and economic milieu, maintain a close and intricate connection with public health [11,17,46,47]. This perspective underscores the criticality of adopting integrated approaches in the design of spaces, aiming not merely to fulfill functional requirements but also to positively contribute to the holistic wellbeing of the occupants.

2.2. Healthy Building Evaluation Dimensions

There are multiple dimensions that need to be evaluated and rehabilitated when constructing a "healthy building", generally covering chemical-physical, psychological, and socio-cultural, and facility dimensions [11,17]. Each dimension represents a crucial pillar in fostering a holistic and conducive environment for occupants' wellbeing, which are elaborated as follows (Figures 2 and 3).

2.2.1. Chemical-Physical Dimension

The chemical-physical dimension refers to a building's air quality, thermal environment, lighting, acoustics, and materials adhering to stringent health standards, mitigating potential hazards, and promoting a clean and safe space.

- Air Quality: Reduce the concentrations of air pollutants, such as CO, CO_2, PM2.5, formaldehyde, and TVOC.
- Thermal environment: maintain a thermally comfortable indoor environment, as well as keep good ventilation.
- Lighting condition: Adopt reasonable use of natural light and energy saving artificial lighting equipment.
- Acoustic environment: Implement highly efficient sound insulation measures to reduce noise interference.

- Building materials and decoration: Utilize environmentally friendly and healthy materials to reduce indoor pollution.

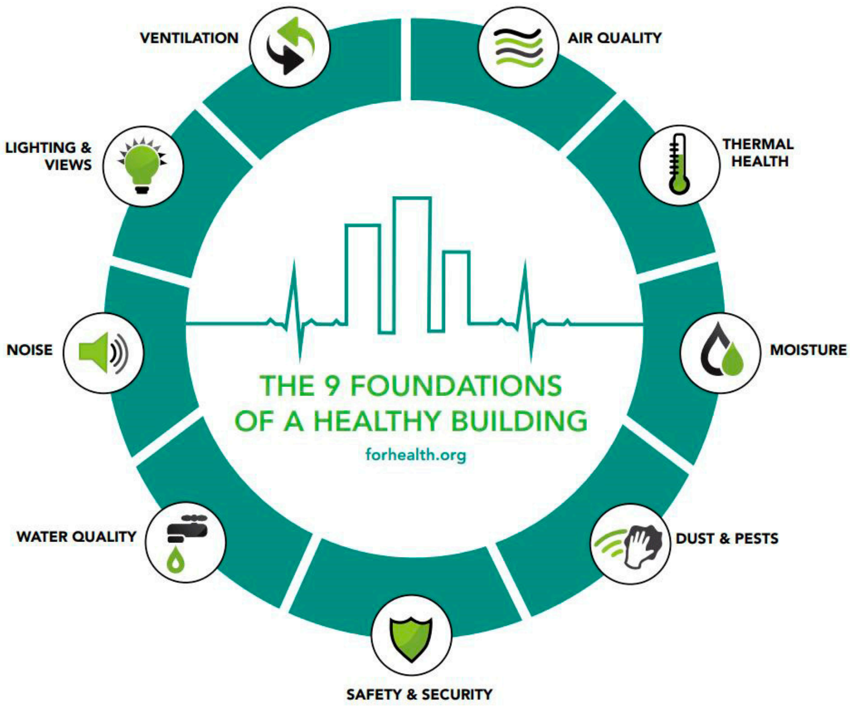

Figure 2. The nine foundations of a healthy building (source: https://9foundations.forhealth.org/).

9 Foundations	*ASHB, China*	*GM-HW, Singapore*	*SBM-2015, Germany*	*WELL, USA, V2*	*Fitwel, USA*
Ventilation	Air	**Sustainable Design and Management**	**Fields Waves Radiation**	Air	Location
Air Quality	Water	Base Building Selection	AC Electric Fields	Water	Building Access
Thermal Health	Comfort	Project Team	AC Magnetic Fields	Nourishment	Outdoor Spaces
Moisture	Fitness	Management Commitment	Radio-Frequency Radiation	Light	Entrances and
Dust and Pests	Humanity	and User Engagement	Static Electric Fields	Movement	Ground Floor
Safety and	Service	**Energy and Resource Management**	Static Magnetic Fields	Thermal Comfort	Stairs
Security		Lighting	Radioactivity	Sound	Indoor Environments
Water Quality	***HB, France***	Air-Conditioning	Geological Disturbances	Materials	Dwellings
Noise	Clean Air	Plug Loads	Sound Waves	Mind	Shared Spaces
Lighting and	Good Water	Water	Light	Community	Water Supply
Views	Quality	Materials and Products	**Indoor Toxins Pollutants**		Prepared Food Areas
	Good Comfort	Waste	**Indoor Climate**		and Grocery Stores
	Prevention of Risks	**Office Environment**	Formaldehyde		Vending Machines
		Indoor Air Quality (IAQ)	Solvents		Snack Bars
		Spatial Quality	Pesticides		Emergency
		Workplace Health and Well-being	Heavy Metals		Preparedness
		Promoting Healthier Eating	Particles and Fibers		
		Promoting Physical Activity	Indoor Climate		
		Promoting Mental Well-being	**Fungi Bacteria Allergens**		
		Promoting Smoke-Free Workplace	Molds		
		General Workplace Health	Yeasts		
		Advanced Green and Health Efforts	Bacteria		
		Advanced Green Efforts	Dust Mites		
		Advanced Health Efforts			

Figure 3. Evaluation dimensions in healthy building standards across different countries (source: reviewed and summarized by Liu et al., 2023 [11], reorganized and redrawn by authors).

2.2.2. Psychological Dimension

The psychological dimension suggests creating spaces that reduce stress and foster a sense of comfort and well-being among occupants. These are related to color palettes, natural light exposure, and visual access to nature.

- Spatial layout: Optimize the spatial layout to enhance the occupant's satisfaction of living and working.
- Environmental color: Consider color harmony to create a comfortable atmosphere.
- View: Provide good views to promote visual comfort and mental health.
- Healing space: Offer meditation, catharsis, and psychological counseling spaces to alleviate undesirable psychological conditions.

2.2.3. Socio-Cultural Dimension

The socio-cultural dimension emphasizes the diversity of occupants and their specific needs, aiming to foster social inclusivity, community engagement, and cultural sensitivity within the built environment. This necessitates designing spaces that cater to different communities attached with diverse cultures and lifestyles, support social interactions, and respect variations of cultural norms and values.

- Social connection: Promote communication and interactions among occupants and enhance community cohesion.
- Community services: Offer access to service facilities and amenities (e.g., gyms and swimming pools, and community libraries) to meet occupants' needs of daily life.
- Barrier-free designed spaces: Pay attention to the needs of special groups and ensure barrier-free access.

2.2.4. Facility Dimension

The facility dimension encompasses the accessibility, functionality, and efficiency of amenities and infrastructure within the building and its surrounding contexts. All facilities should be designed to meet the daily needs of occupants, facilitate ease of access and use, as well as promote sustainability and environmental responsibility.

- Water quality: Provide safe and clean drinking water.
- Health promotion facilities: Offer shared fitness spaces to encourage healthy lifestyles and inspire exercises.
- Health-risk monitoring systems: Employ intelligent monitoring systems to assess the interior environmental quality and occupants' physical conditions and mental health.

The theoretical model of "healthy building" emphasizes the potential to holistically improve residents' physical, mental, and social well-being through strategic optimization of the built environment and community services. From the chemical-physical to the facility dimensions, the model of "healthy building" advocates for integrated approaches and measures that transcend mere architectural considerations and instead prioritize the overall well-being of those who inhabit these spaces.

3. Materials and Methods

3.1. Case Study City and Context

3.1.1. Background Context of the City

Shenzhen (22°27′ N~22°52′ N, 113°46′ E~114°37′ E) is a coastal city in the southern area of China's Pearl River Delta Region adjacent to Hong Kong Special Administrative Region, as well as China's pioneer special economic zone. Over decades, it has transformed into an international metropolis, a transit point for multiple resources and massive amounts of information, and a place where people with diverse socio-cultural characteristics live and work. As of March 2024, there are a total of 25,094 hotels on record in Shenzhen, with 7287 of these hotels distributed in the Longgang District (details refer to https://sz.city8.com/hotel/692/, accessed on 15 October 2024. The quantity of hotels is monthly updated on this website).

During the COVID-19 pandemic, as one of the major transition points between other countries and mainland China, Shenzhen implemented quarantines as an epidemic prevention and control measure. These quarantines were often carried out in hotels. Therefore, the availability, spatial layout arrangement, and indoor environmental quality (IEQ) of the city's hotels, especially in regard to quarantine, are a critical issue to be investigated and discussed. Moreover, Shenzhen has a subtropical monsoon climate, with long summers (April to November) and short winters. The city's average temperature in January is the lowest, averaging 15.7 °C, while the average temperature in July is the highest, averaging 29.0 °C. The city has adequate sunlight exposure with 1853 h of average annual sunshine duration. As a result, Shenzhen features hot and humid summer climatic conditions, making the mitigation of heatwave threats and amelioration of both indoor and outdoor thermal environments in summer a crucial issue, especially for quarantine hotels. Further, some of the quarantined hotel spaces have been reported to contain multiple chemical pollutants and physical environmental elements that significantly affected occupants' health and well-being. Many quarantine occupants were limited to and exposed exclusively to quarantine hotel room spaces during the pandemic for periods of 10~21 days (or even more, subject to the policies of applicable regions) [36]. This study specifically focuses on the summertime situation during Shenzhen's quarantines, where both air quality and thermal comfort conditions in mixed-functional architectural spaces, specifically hotel spaces, require special consideration.

3.1.2. Characteristics of the Case Study Hotel Room

The case study utilizes data collected in early September 2022 in a quarantine hotel room in a hotel located in the urban center of Shenzhen's Longgang District (Figure 4).

Figure 4. Location of the case study hotel in Shenzhen's Longgang District (Baidu satellite map and photograph by authors).

The case study hotel building is nine floors high. It underwent renovation and opened for use in 2018. The case study hotel room is a standard king room and located on the sixth floor and south-facing end of the building. The room has a net area of approximately 23.1 m^2 (4.2 m $\times$ 5.5 m) with a window area of 4.35 m^2 on its south wall. The room consisted of five distinguishable but physically connected daily use zones, including the transit area, dining and working area, living area, breaking area, and washing area (Figure 5 and Table 1). During quarantines, the hotel room hosted all the occupants' daily activities, including living, exercising, working, dining, sleeping, washing, etc. (Figure 1). However, at a fine scale, there are differences among the various functional zones in the room in terms of spatial characteristics, architectural elements, decoration materials, and environmental performances. Moreover, looking at these micro-scale differences could provide more specific insights into rehabilitation or upgradation of the room space from a perspective of human-scale investigation.

Figure 5. (**Top**) Typical floor plan of the hotel and spatial layout of the functional zones in the case study hotel room (source: drawings by authors); (**Bottom**) Photos of the different functional zones in the case study hotel room (source: photographs by research volunteer).

Table 1. Physical and spatial characteristics of the tested functional zones in the case study hotel room (measurements by research volunteer).

Monitoring	Zone Name	Function and Location in the Room	Floor Material	Wall Material	Area (m^2)	Volume (m^3)
Zone A	Transit area	Entryway and corridor	Marble tile	Wood	3.42	10.26
Zone B	Working and dining area	Next to the window, open space for working and dining	Hardwood	Fabric wallpaper, tempered glass	7.56	22.68
Zone C	Living area	Next to the window, Leisure and exercise	Hardwood	Fabric wallpaper, tempered glass	4.41	13.32
Zone D	Breaking area	Next to washing space, Bed space	Hardwood	Fabric wallpaper, tempered glass	3.15	9.45
Zone E	Washing area	Washing space, bath space, and toilet	Marble tile	Glazed tile, tempered glass	4.56	13.68

3.2. Measurement Protocol

3.2.1. Examined Environmental Indices

This study assesses the multi-domain environmental quality of a hotel room space, examining chemical, physical, and heat stress environmental indices [13,24,48]. These environmental indices have been widely found to critically influence indoor environmental quality and humans' health (Table 2) [12,18,27,49,50]. The study therefore measured the following indices: (*i*) Chemical indices: carbon dioxide concentration (CO_2) (ppm), fine particulate matter (PM2.5) concentration (μg/m^3), formaldehyde (HCHO) concentration (μg/m^3), and total volatile organic compounds (TVOC) concentration (μg/m3); (*ii*) Physical indices: air temperature (Ta) (°C), relative humidity (RH) (%), air velocity (v) (m/s), horizontal illumination level (IL) (lx), illumination uniformity (U_o) (0–1). In addition, the study uses (*iii*) Heat stress indices: heat index (HI) (°C) and wet bulb globe temperature (WBGT) (°C) to examine the thermal air comfort condition and heat stress level of the hotel room [16,51–55].

Table 2. Standards for IEQ factors in China and globally (based on a literature review).

Examined Index	China Standards	WHO, CIE, Europe Standards	USA Standards	Japan Standards	South Korea Standards
CO_2	≤700 ppm	≤920 ppm (24 h)	≤1000 ppm	≤1000 ppm	≤1000 ppm
PM2.5	≤75 μg/m^3 (24 h avg.) ≤35 μg/m^3 (annual avg.)	≤15 μg/m^3 (24 h avg.)	≤75 μg/m^3 (annual avg.)	≤35 μg/m^3 (24 h avg.) ≤15 μg/m^3 (annual avg.)	
HCHO	≤80 μg/m^3 (1 h avg.)	≤100 μg/m^3 (30 min)	≤0.1 ppm	≤100 μg/m^3	≤100 μg/m^3
TVOC	≤600 μg/m^3 (8 h avg.)	200–600 μg/m^3		≤500 μg/m^3	400–1000 μg/m^3
Ta	22–28 °C (summer)				
RH	40–80% (summer)				
v	≤0.30 m/s (summer)				
IL	75–300 lx (vary from different functional zones)				
U_o	0.40–0.60 (vary from different functional zones)	≥0.70 (core working area) ≥0.50 (surrounding areas)			
HI			≤32.78 °C		
WBGT	≤28.0 °C		≤26.6 °C		

- **Heat index (HI)**

Heat index (HI), also known as apparent temperature, is an environmental index widely used to measure occupants' perceived temperature in hot and humid environmental contexts [56]. In humid environments, the rate of evaporation of sweat slows down, reducing the efficiency of the human body's heat dissipation. For this reason, even at the same temperature, higher humidity conditions feel hotter and more uncomfortable to people [57]. Therefore, in indoor and outdoor environments, measurement of HI is important to reflect the combined effect of air temperature and relative humidity, as well as to warn occupants of potential heat-related health risks [58,59]. Although Lans P. Rothfusz obtained a heat index equation via multiple regression analysis in 1990, a simpler equation is suggested, especially for conditions of temperature and humidity warranting a heat index value below about 80 °F (26.67 °C) [60] (Equation (1)). That is,

$$\text{HI} = 0.5 \times \{\text{Ta} + 61.0 + [(\text{Ta} - 0.68) \times 1.2] + (\text{RH} \times 0.094)\} \quad (1)$$

where Ta is air temperature in degree F, and RH is relative humidity (%).

- **Web bulb globe temperature (WBGT)**

Web bulb globe temperature (WBGT) is another widely adopted heat stress index for evaluating perceived thermal comfort and heat stress conditions. Proposed by Yaglou and Minaed in 1957, WBGT reflects the combined effects of temperature, humidity, radiation, and air flow velocity and is often utilized to assess the suitability and potential risks of working and residential environments for humans [61,62]. For indoor conditions or outdoor environments without solar radiation, Moran et al. suggested the following WBGT equation (Equation (2)) [63].

$$WBGT = 0.7T_{nw} + 0.3Ta \quad (2)$$

where T_{nw} is natural wet temperature (°C) and Ta is air temperature (°C).

- **Illuminance uniformity (U_o)**

To evaluate indoor lighting environmental quality, the study examines the indices of horizontal illuminance level (IL) and illuminance uniformity (U_o). The U_o is defined as the ratio of minimum illuminance level (IL_{min}) to average illuminance level (IL_{avg}) on a given surface, and a higher value (0–1) of U_o denotes a more uniform illuminance (Equation (3)) [64,65]. This study uses the ratio of the lowest IL among the five functional zones to their average IL to generally analyze the illuminance uniformity of the tested hotel room.

$$U_o = IL_{min}/IL_{avg} \quad (3)$$

3.2.2. Instrumentations and Data Collection

Due to the special situation of the quarantine policy, it was hard to conduct a large-scale multi-case investigation of the indoor air quality of quarantine environments. However, there was the opportunity to recruit a research volunteer to assist in the collection of indoor environmental data ahead of the quarantine period in a hotel room by employing low-cost and portable environmental meters. This approach provided the opportunity to observe the actual IEQ of the quarantine hotel rooms during occupancy, which should offer real-time (first-hand data) insights into the rehabilitation of existing hotels and new construction of new hotels to meet the standards of flexibility, health, and comfort. After the measurement protocol was pre-designed, the volunteer was trained in instrument calibration and data collection. The data collection was conducted in early September 2022 when the research volunteer traveled from Hong Kong SAR to mainland China and was randomly assigned and settled in a quarantine hotel located in the urban center of Shenzhen's Longgang District (Figure 4). Due to the constraints of the quarantine policy as well as the limitations of manpower and instrumentation, this study adopted a flexible protocol for the collection of indoor environmental data for the various functional zones of the room. Portable intelligent environmental testing instruments were employed for the in-situ measurement and moved as necessary to measure the various zones within the room. The equipment, however, satisfied the ISO 7726 standard minimum requirements for accuracy and resolution [66]. The observation height for measuring IL and U_o was set at 0.75 m above the floor surface [67]. Monitoring of other environmental indices was set at 1.1 m high, the assumed center of mass of a standing human [66,68,69].

Chemical environmental parameters, including concentrations of CO_2, PM2.5, HCHO, and TVOC, were monitored and collected using a portable digital RoHS air quality detector (H8 type). Physical environmental parameters, including air temperature (Ta), relative humidity (RH), air velocity (v), and horizontal illumination level (IL), were monitored and collected using a fast response pocket climatic meter Kestrel 5400 (Kestrel Instruments, Boothwyn, PA, USA) and a DELIXI DLY-1802 digital illuminometer (DELIXI, Yueqing, China). Heat stress parameters, including heat index (HI) and wet bulb globe temperature (WBGT), were also monitored and collected using the Kestrel 5400 environmental meter

(Table 3). All instruments were placed at the previously stated heights at the center of each measured zone and away from interior walls or architectural components (Figure 6).

Table 3. Direction range and accuracy of the measuring equipment.

Instrument Model	Parameter Type	Parameter	Unit	Range	Accuracy	Photo of Instrument
RoHS Air Quality Detector—H8	Chemical	CO_2	ppm	400–5000 ppm	±5%	
	Chemical	PM2.5	μg/m^3	0–999 μg/m^3	±10%	
	Chemical (volatile)	HCHO	μg/m^3	0–9999 μg/m^3	±10%	
	Chemical (volatile)	TVOC	μg/m^3	0–9999 μg/m^3	±10%	
Kestrel 5400 Pocket Climatic Meter	Physical	Ta	°C	−29–70 °C	±0.5 °C	
	Physical	RH	%	10–90%	±2%	
	Physical	v	m/s	0.6–40m/s	±3%	
	Heat stress/ thermal comfort	HI	°C	Complies with ranges of Ta and RH	±4 °C	
	Heat stress/ thermal comfort	WBGT	°C	Complies with Ta, RH, and atmospheric pressure	±0.7 °C	
DELIXI DLY-1802 Digital Illuminometer	Physical	IL	lx	0–200,000 lx	±3% rdg ± 0.5% f.s. (<10,000 lx) and ±4% rdg ± 10 dgts. (>10,000 lx)	
	Physical	U_o	0–1	--	--	

Figure 6. Monitoring process in the quarantine hotel room (photographs by research volunteer).

To ensure accuracy and minimize deviation, all employed instruments were pre-calibrated on 1 September 2022, one day before formal monitoring and data collection began. The formal monitoring and data collection was conducted from 09:00 am to 22:00 pm, between 2 September 2022 and 4 September 2022 (over a three-day period), during Shenzhen's typical summertime, with sunny or clear sky conditions outside. The examined hotel room was air-conditioned, and the indoor air temperature setting was kept at 26 °C via the hotel room air-conditioner thermostat. It is worthy of note that though the occupant could open and close the windows freely, he mostly kept the window closed most of the time during the three-day measurement period due to the hot summer conditions outside. Therefore, airflow exchanges between the indoor and outdoor environments are disregarded in this study. Hourly recordings of environmental variables were carried out in sequence, proceeding from Zone A to Zone B, then Zone C, Zone D, and finally Zone E. The order was determined by the occupant's daily routine and the general use sequence of the areas in the room. Each round of environmental monitoring in the five tested zones of the hotel room was completed within one hour to minimize the impact of the time difference. During each round of monitoring and data collection in the room, the employed digital instruments were left untouched for five minutes to stabilize before data recording during measurements. In addition, the research volunteer recorded his daily routines and activities. At the end of the experiment, all the data collected in a three-day measurement period was then hourly averaged for further processing and analysis.

3.3. Data Assembly and Analysis

All the measurement data was assembled, processed, analyzed, and visualized in Microsoft Office Excel 2021. Based on preliminary analysis of the change trends, correlation, and multiple regression analyses were conducted using the IBM SPSS Statistics 20.0 software (IBM, Armonk, NY, USA) to explore the relationships between various physical indices of the hotel room space and chemical pollutant concentrations. This provided insights into the trade-offs in thermal comfort conditions and indoor air quality in hotel room design and integrated environmental amelioration. Statistically, the coefficient of determination (R^2) as well as the *p*-values were utilized to examine how significant the relationships between the chemical, physical, and heat stress indices were. $p < 0.05$ was utilized as the threshold for significant correlations and regressions [70,71].

4. Results and Discussion

4.1. Occupant's Daily Activities

The measurement results illustrate the diverse environmental performances of the five tested zones in the air-conditioned hotel room space in terms of the environmental index type and the functional zone of the space. Beyond setting up the instruments for data collection, the occupant had a planned daily routine of other activities during his quarantine in the hotel room. The variations in different aspects of the environmental performances could be explained by the occupant's daily routines and activities in the room during measurement periods. Moreover, calibration of instruments and conducting data collection, the occupant (the research volunteer) also conducted a variety of regular daily activities during the studied quarantine periods, including doing morning exercise, working on a laptop, watching TV, having lunch and dinner, walking around in the room, as well as doing yoga (Table 4). While the impacts of the occupant's activities on indoor environmental quality was not the focus of the study, further investigations of this part are crucial and necessary [48,72,73].

4.2. Change Trends of Different Environmental Indices

4.2.1. Concentration of Chemical Pollutants

The CO_2 and PM2.5 concentrations showed different trends across the day. From 09:00 am to 22:00 pm, CO_2 concentrations in the air-conditioned hotel room generally exhibited a decreasing but fluctuating trend with the highest value occurring in the morning period (10:00 am–11:00 am, 416.60 ppm), which might have resulted from poorer ventilation while sleeping during the night. There was also a dramatic increase in the late afternoon (17:00 pm–18:00 pm) and a dramatic decline to the lowest value in the evening (20:00 pm–21:00 pm, 406.40 ppm), because the occupant kept actively working on his laptop during the late afternoon period. By contrast, the concentration of PM2.5 generally presented an increasing and fluctuating trend over the same period, achieving its peak of value (27.93 $\mu g/m^3$) around 17:00 pm–18:00 pm, and then slightly decreasing to 26.73 $\mu g/m^3$ afterward (in the evening) (Figure 7). However, though PM2.5 levels (<30 $\mu g/m^3$) in the tested hotel room were higher than the stricter WHO standard ($\leq$15 $\mu g/m^3$, 24 h avg.), they were lower than China's local standards as well as lower than standards in USA, Japan, and

Republic of Korea (Table 2). Major variations in PM2.5 concentration in the air-conditioned hotel room were not observed during the day since external sources were kept out by the closed windows and smoking and cooking were not allowed in the quarantine room. There were however slight variations throughout the day possibly from the operations of various devices and appliances. PM2.5 level could also be influenced by disturbance of the physical environment of the interior space, which has also been detected by previous studies but needs further investigation and verification [38,74].

Table 4. Occupant's daily activities during quarantine period (recorded by research volunteer).

Period of the Day	Hour	Intensity of Activities	Occupant's Regular Daily Activities	Staying Zone
	Before 09:00	High	Morning exercise, breakfast, temperature measurement	A, B, C, D, E
Morning	09:00–10:00	Low	Office work (laptop)	B
	10:00–11:00	Low	Office work (laptop)	B
	11:00–12:00	Low	Office Work (laptop), and nucleic acid test	B, C
Early Afternoon	12:00–13:00	Moderate	Lunch, watching TV	B, C
	13:00–14:00	Quiet	Afternoon nap	C, D
	14:00–15:00	Low	Afternoon tea, walking around, temperature measurement	A, B, C, D
Late Afternoon	15:00–16:00	Low	Work (via laptop)	B
	16:00–17:00	Low	Work (via laptop)	B
	17:00–18:00	Low	Work (via laptop)	B
Evening	18:00–19:00	Moderate	Dinner, watching TV	B, C
	19:00–20:00	Low	Work (remote meeting)	B
	20:00–21:00	Low	Work (via laptop)	B
	21:00–22:00	High	Yoga and evening exercise	A, B
Sleeping Time	After 22:00	Quiet	Bath, sleep	C, D, E

Even more dissimilar, the concentrations of both HCHO and TVOC were relatively stable with only small fluctuations occurring over the course of the day. In addition, the TVOC change trend concentration was more stable than the HCHO concentration in this study. More specifically, the HCHO concentration varied between 1.67 $\mu g/m^3$ to 2.20 $\mu g/m^3$, with its peak values occurring at noon and in late afternoon (12:00 pm–13:00 pm and 17:00 pm–18;00 pm, respectively). The average hourly TVOC concentration varied between 4.53 $\mu g/m^3$ to 5.87 $\mu g\ /m^3$, with its lowest value appearing in the late afternoon (16:00 pm–17:00 pm) (Figure 7). Both HCHO and TVOC levels in the tested hotel room were monitored and found far below the thresholds required by existing standards (Table 2). Beyond the sanitation measures taken to prepare the space for quarantine (e.g., employing air purifier before arranging travelers to check-in), other reasons might be that the hotel was completed in 2018 and emitting sources (e.g., the materials of interior decorations and furniture) have slowed down their rate of emissions of HCHO and TVOC. Though some of the published studies have revealed that the concentrations of HCHO and TVOC are significantly influenced by the physical environments of the room as well as the occupants' indoor activities [38,75], the hidden mechanisms will need further exploration and verification.

4.2.2. Physical Environmental Performance

In terms of physical indices, the average air temperature (Ta) was 25.84 °C, which was very close to the set indoor temperature (26 °C) on the air conditioner. The slight difference might be explained by the impact of the occupant's activities. However, the real-time air temperature exhibited significant fluctuations from morning to evening, in particular, it experienced dramatic decreases from 26.05 °C between 16:00 pm–17:00 pm to a low of 25.25 °C between 19:00 pm–20:00 pm, and then experienced steep increases to peak (26.43 °C) in 21:00 pm–22:00 pm (Figure 8). Whether the variation in Ta might have resulted from the impact of occupant's activities or was merely a random phenomenon needs to be further explored and analyzed through more systematic long-term monitoring and analysis.

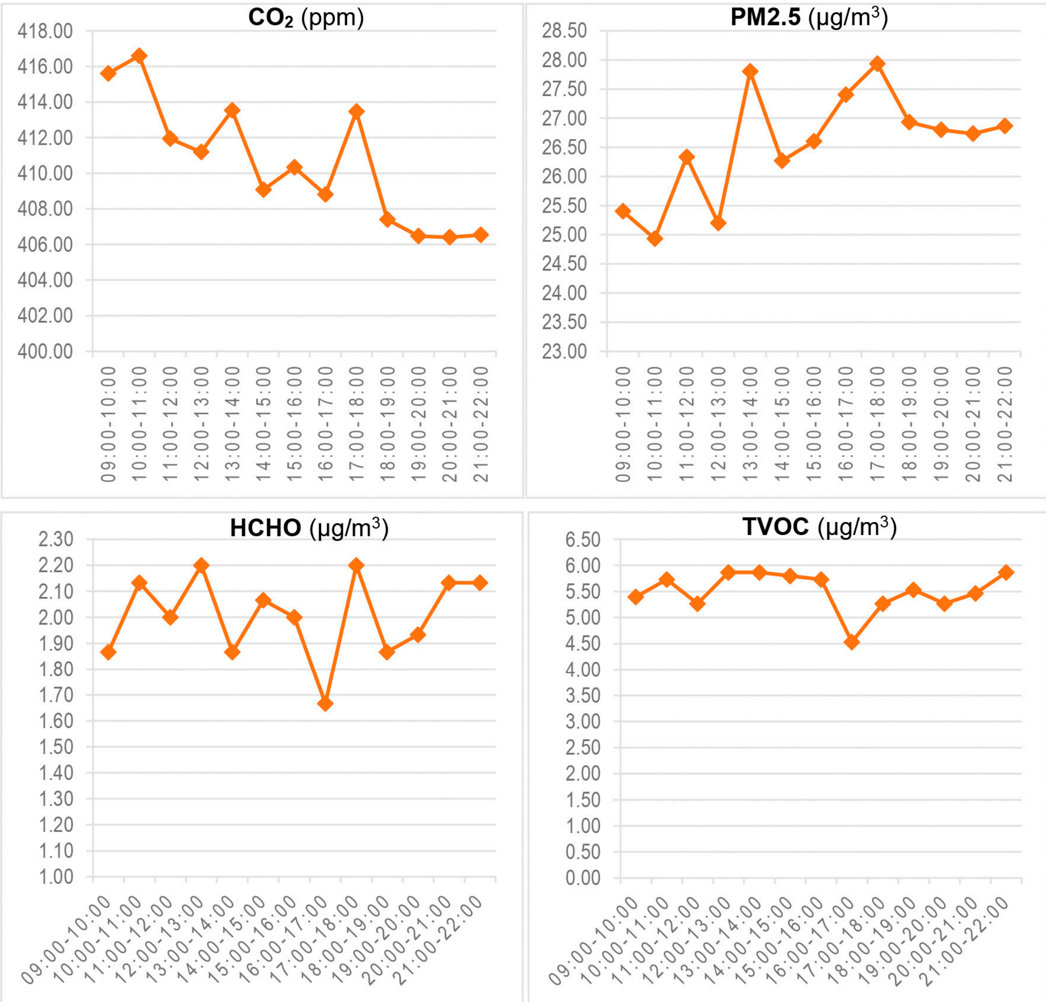

Figure 7. Daily change trends in examined chemical environmental indices in the tested hotel room.

For relative humidity (RH), it generally tended to increase from its lowest value of 43.49% in the morning (09:00 am–10:00 am) and peak at a value of 58.03% in the evening (21:00 pm–22:00 pm), with a daily average value of 51.36% (Figure 8). As the studied hotel room was equipped with an air conditioning system which was set a constant temperature by the occupant and wind conditions were stable and quiet during the quarantine period. The significant variation in RH likely resulted from the occupant's different behaviors and fluctuating metabolism during the measurement [73,76]. This RH range also partly meets the *Standards for Indoor Air Quality GB/T 18883-2022* [77] in China which requires indoor RH to be not higher than 80% and not lower than 40% during summertime.

Regarding lighting environmental performance, a clear decreasing trend of hourly average horizontal illuminance level (IL) was observed, with IL declining from 578.33 lx between 09:00 am–10:00 am to 34.07 lx in 21:00 pm–22:00 pm. In contrast, the illumination uniformity (U_o) of the room space exhibited significant variations in different periods of the day, due to the availability of the natural daylight in the daytime and the use of artificial lighting in the evening, and the varied habits and activity routines of the occupant. The highest illumination uniformity (U_o = 0.27) was observed between 18:00 pm–19:00 pm, during the transition from late evening to night. In this period, the room was irradiated by both the sunset glow from outside and artificial lighting from inside, making it showcase the most uniform brightness compared to the performances in other time periods of the day (Figure 8). The lighting environment was not sufficiently investigated and analyzed or even neglected in the previous studies, which is crucial by the fact that most of the IEQ standards in China for hotel rooms were merely designed with very basic demands of daily leisure activities [38,75]. However, quarantine hotel rooms were occupied exclusively by cross-border travelers for several days or weeks, forcing them to conduct normal daily life activities as they do in their homes. Therefore, hotel design standards for the lighting environment should be the same or even higher than those for normal residential spaces.

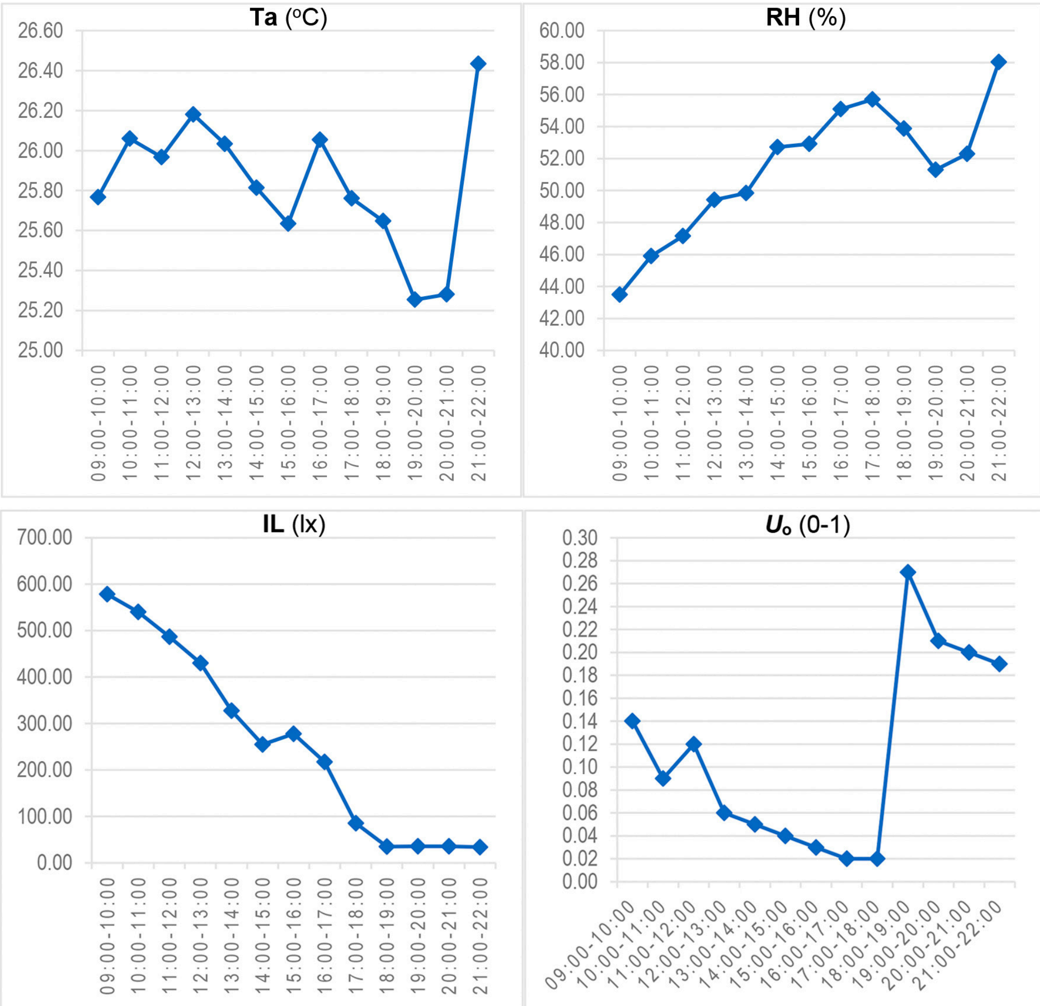

Figure 8. Daily change trends in examined physical environmental indices in the tested hotel room.

4.2.3. Heat Stress and Thermal Comfort Conditions

In terms of heat stress indices, the air-conditioned hotel room presented an average HI of 25.51 °C and average WBGT of 18.71 °C, both well under alarm levels according to two widely used evaluation standards (Table 2). Being an air-conditioned room space, HI and WBGT exhibited similar trends with slight increases from 09:00 am to 17:00 pm, before declining to reach their respective lows at 19:00 pm–20:00 pm, then dramatic increases to their respective average peaks of 26.98 °C and 20.33 °C, respectively at 21:00 pm–22:00 pm (Figure 9). The slight variations in HI and WBGT levels might have resulted from changes in the physical environmental conditions of the tested room, e.g., air temperature and relative humidity, due to the occupant's activities, as HI and WBGT significantly correlate to these two basic environmental parameters (Equations (1) and (2)). These changes may also be due to the occupant's daily activities and use of house appliances, such as use of the TV and laptop or having dinner.

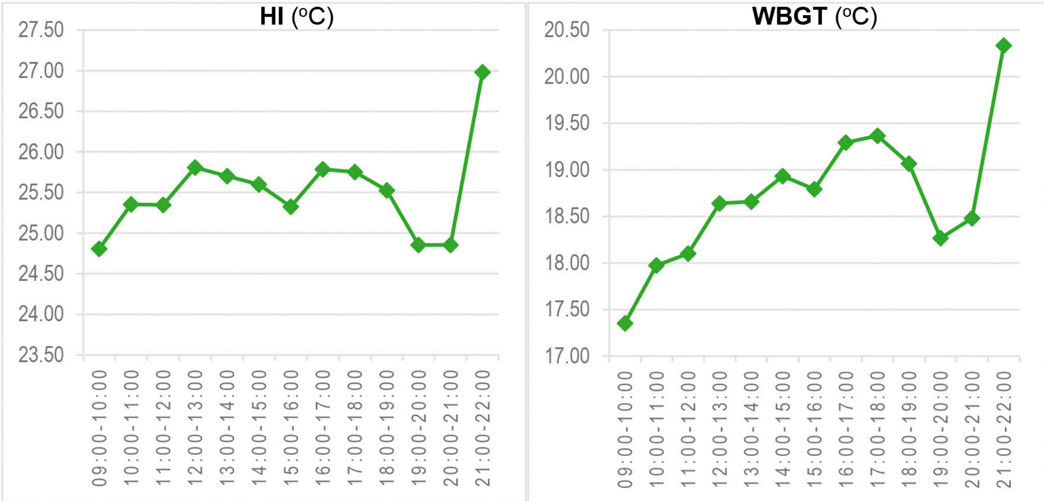

Figure 9. Daily change trends in examined heat stress indices in the tested hotel room.

4.3. Performance Variations Among Functional Zones

When making comparisons among the five functional areas in the room (Zones A, B, C, D, and E), the measured environmental indices presented another layer of performance variations (Figures 10 and 11). Generally, most environmental index values for the five tested zones were observed to be within threshold standards, except for PM2.5 concentration and illuminance level in late afternoon and evening [58,59,66,77,78]. Specifically, although China's *Ambient Air Quality Standards (GB 3095-2012)* [79] and *Standard of Indoor Air Quality (GB/T 18883-2022)* [77] suggest that the 24-h average PM2.5 concentration should be lower than 75 $\mu g/m^3$ and 50 $\mu g/m^3$, respectively, the updated WHO Air Quality Guidelines [80] advise a more rigorous threshold ($\leq$15 $\mu g/m^3$). The ASHRAE standard [81] similarly requires an 8-h average PM2.5 concentration of not exceeding 15 $\mu g/m^3$.

(a) Zone A—transit area (entryway and corridor, measuring point A) exhibited the second highest average CO_2 concentration (412.38 ppm) but also the lowest PM2.5 concentration (25.85 $\mu g/m^3$) among the five measured zones in the room. Its HCHO and TVOC concentrations were relatively low, averaging 1.95 $\mu g/m^3$ and 1.44 $\mu g/m^3$, respectively. However, this zone presented the highest daily average Ta (26.05 °C) and HI (25.69 °C), as well as the lowest average RH (49.71%) during the experiment. The average IL in this zone was also low at only 58.05 lx (Figure 11a).

(b) Zone B—dining and working area (next to the window, measuring point B) presented the highest average CO_2 and TVOC concentrations among the five tested zones at 414.38 ppm and 5.82 $\mu g/m^3$, respectively. By contrast, even though this zone exhibited relatively high Ta (25.89 °C) and lower RH (50.55%), it generally presented the lowest WBGT value (18.60 °C) among the five tested zones (Figure 11b).

(c) Zone C—living area (leisure and exercise, measuring point C) presented the lowest concentrations of HCHO (1.87 $\mu g/m^3$) and TVOC (5.28 $\mu g/m^3$). It also had relatively low concentrations of CO_2 (408.90 ppm) and PM2.5 (26.54 $\mu g/m^3$). The zone also exhibited the lowest Ta (25.55 °C), the best average illumination (avg. IL = 500.92 lx), and better thermal comfort conditions than other areas (avg. HI = 25.24 °C, avg. WBGT = 18.63 °C) (Figure 11c).

(d) Zone D—breaking area (bed space, measuring point D) presented the lowest concentration of CO_2 (407.67 ppm) and the highest PM2.5 concentration (27.23 $\mu g/m^3$)

and HCHO (2.21 μg/m^3) among the five tested zones. It also exhibited the second highest average RH and WBGT and the second-best lighting conditions (avg. IL = 409.69 lx) throughout the day (Figure 11d).

(e) Zone E—washing area (washing room, bathroom, and toilet, measuring point E) presented the second highest PM2.5 concentration (26.64 μg/m^3) but relatively low CO_2, HCHO, and TVOC concentrations (409.49 ppm, 1.97 μg/m^3, 5.36 μg/m^3, respectively). It also had higher average Ta (25.98 °C) and RH (52.33%) values, as well as relatively high average HI (25.68 °C), and WBGT (18.93 °C) values. In addition, it exhibited the lowest average illumination level (avg. IL = 40.64 lx), possibly because this zone is designed to be more enclosed and located in the more interior side of the room (Figure 11e).

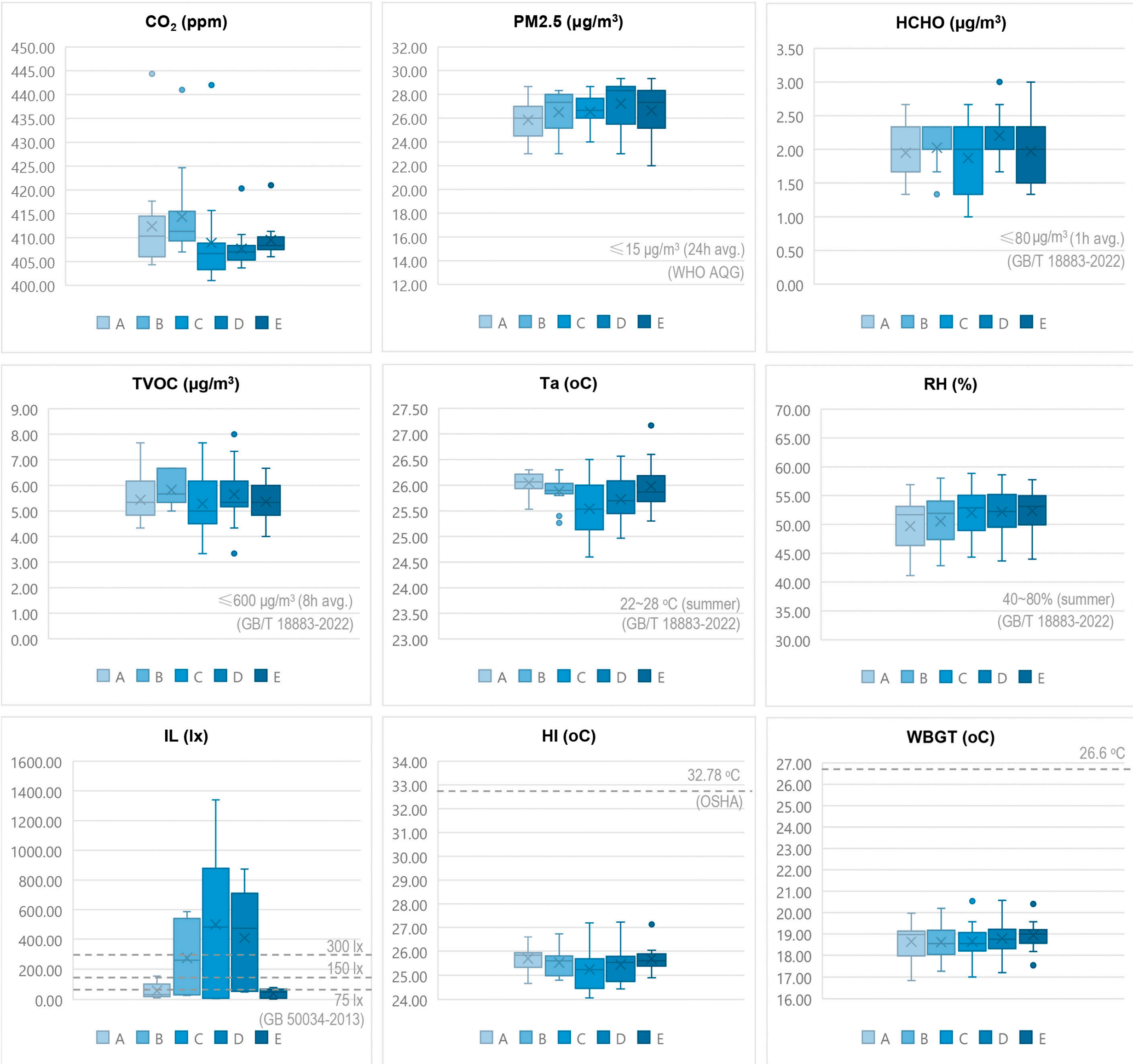

Figure 10. Five tested zones' boxplots in multiple aspects of environmental performance throughout the day (09:00 am–22:00 pm).

4.4. Impacts of Physical Conditions on Pollutant Concentrations

4.4.1. Correlations Among Chemical, Physical, and Heat Stress Indices

Existing studies have illustrated the significant effects of physical conditions of architectural spaces on the air pollutant emissions and/or concentrations [23,30,69,82,83]. To start, the study preliminarily analyzed effects of physical and heat stress indices on chemical environmental indices via the Pearson's correlation test (Table 5 and Figure 12).

The preliminary results demonstrated that most examined physical and heat stress indices did not exhibit significant correlation with chemical indices, except for RH and WBGT. In particular, RH was observed to negatively correlate with CO_2 concentration (|r| = 0.317, $p < 0.05$ level, 2-tailed), but positively correlate with PM2.5 concentration (|r| = 0.353, $p < 0.01$ level, 2-tailed). This suggests that higher humidity levels could lead to both lower CO_2 and higher PM2.5 concentrations. In addition, WBGT showed significant positive correlation with PM2.5 concentration (|r| = 0.255, $p < 0.05$ level, 2-tailed), indicating a possible potential opportunity to both reduce PM2.5 concentration and improve indoor thermal comfort conditions.

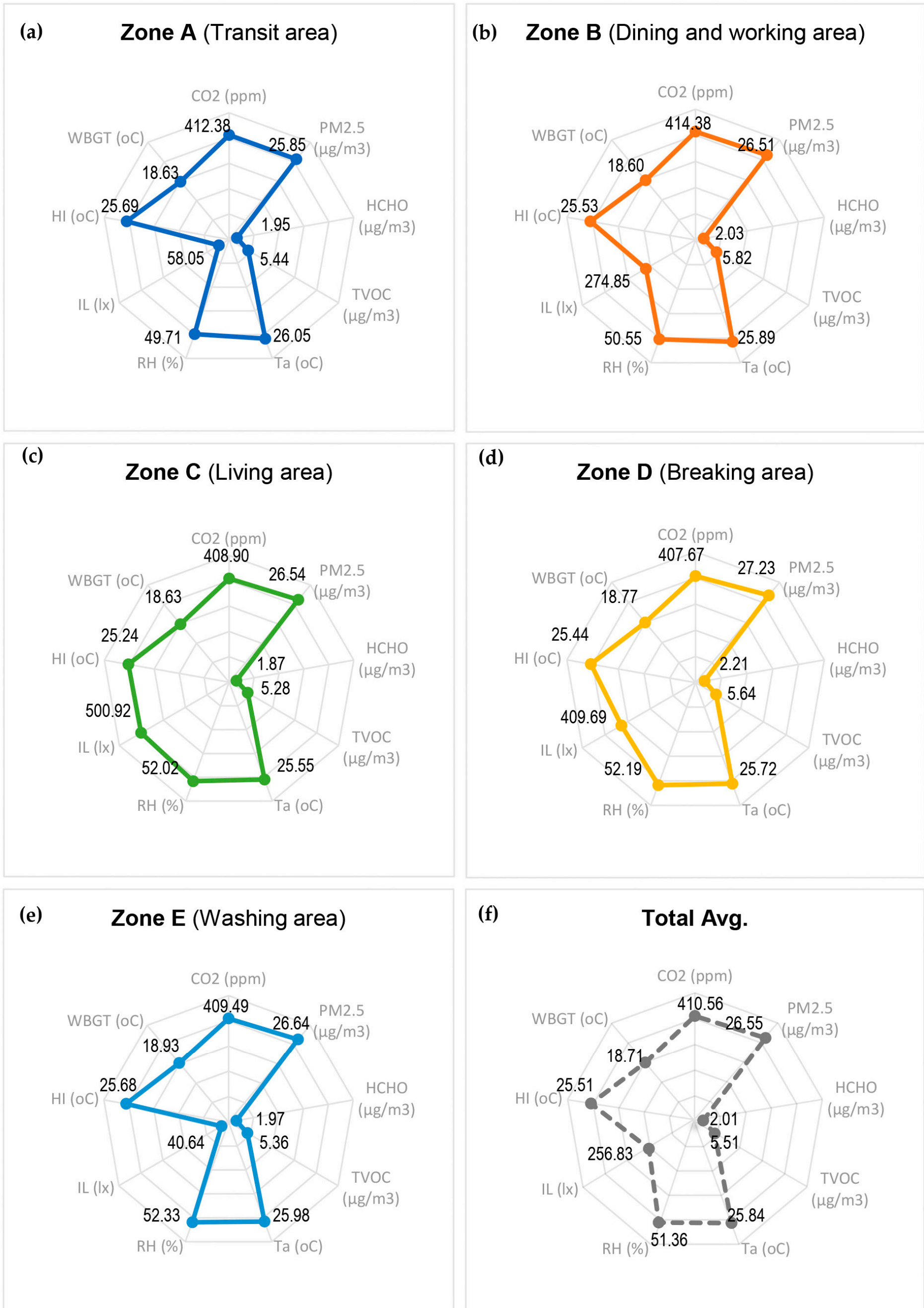

Figure 11. Comparison of the five tested zones' daily average values (09:00 am–22:00 pm) of multiple aspects of environmental performance (data with different units has been scaled to be presented): (**a**) Zone A—transit area; (**b**) Zone B—dining and working area; (**c**) Zone C—living area; (**d**) Zone D—breaking area; (**e**) Zone E—washing area; (**f**) average values of five tested zones in multiple environmental performances.

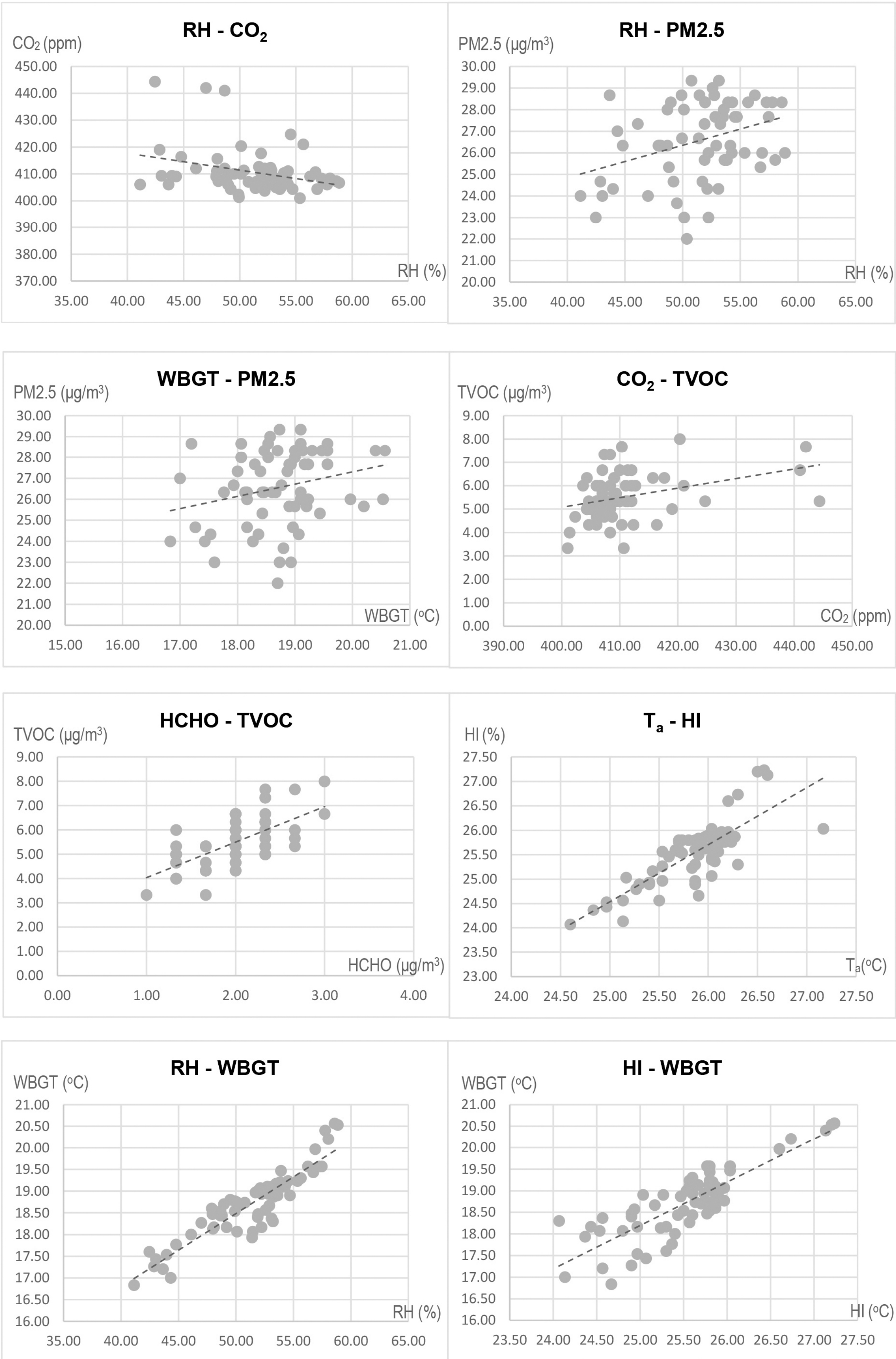

Figure 12. Scatter plots for the general trends of correlation among two examined environmental indices with relatively significant levels to be preliminarily identified in this study.

Table 5. Pearson's correlations among the examined chemical, physical, and heat stress indices.

	Chemical				**Physical**		**Heat Stress**		**Physical**
	CO_2	**PM2.5**	**HCHO**	**TVOC**	**Ta**	**RH**	**HI**	**WBGT**	**IL**
CO_2	--	−0.310 *	0.215	0.350 **	0.235	−0.317 *	0.034	−0.182	0.147
PM2.5		--	−0.138	−0.131	−0.128	0.353 **	0.057	0.255 *	−0.046
HCHO			--	0.632 ***	0.163	0.067	0.156	0.128	0.039
TVOC				--	0.214	−0.009	0.164	0.095	0.098
Ta					--	0.036	0.801 ***	0.411 ***	−0.032
RH						--	0.537 ***	0.910 ***	−0.437 ***
HI							--	0.832 ***	−0.240
WBGT								--	−0.401 ***
IL									--

* Correlation is significant at the 0.05 level (2-tailed). ** Correlation is significant at the 0.01 level (2-tailed). *** Correlation is significant at the 0.001 level (2-tailed).

Further, the mutual correlation among chemical environmental indices was also identified in this study. Most notably, the CO_2 concentration exhibited a significant negative correlation with PM2.5 concentration ($|r| = 0.310$, $p < 0.05$ level, 2-tailed), but a positive correlation with TVOC concentration ($|r| = 0.350$, $p < 0.01$ level, 2-tailed). The concentration of HCHO was also observed to positively correlate with TVOC concentration at a high level ($|r| = 0.632$, $p < 0.001$ level, 2-tailed). Moreover, correlation analysis verified that HI positively correlates with WBGT ($|r| = 0.832$, $p < 0.001$ level, 2-tailed), which is expected given the similar formulas for these two indices (Equations (1) and (2)). It is also worth noting that, in this study, Ta ($|r| = 0.801$, $p < 0.001$ level, 2-tailed) was found to have a stronger correlation with HI than RH did ($|r| = 0.537$, $p < 0.001$ level, 2-tailed). In contrast, RH ($|r| = 0.910$, $p < 0.001$ level, 2-tailed) exhibited a more significant impact on WBGT than Ta ($|r| = 0.411$, $p < 0.001$ level, 2-tailed).

4.4.2. Multiple Regression Analysis

Existing studies indicate that physical environmental parameters, particularly indoor relative humidity, can influence other aspects of indoor air quality [54,82–84]. Supporting this finding, Pearson's correlation analysis in this study illustrated significant correlations of indices such as RH and WBGT with chemical indices such as CO_2 and PM2.5 concentration (Table 5). In addition, it showed mutual correlation and influences among chemical indices. To further identify and validate these effects, the study conducted a multivariable linear stepwise regression analysis. The tested physical and heat stress indices were set as independent variables, while the tested chemical indices were set as dependent variables. Steps were further taken to ensure independent variables with high collinearity did not coexist in the regression model, except in special cases.

The regression analysis demonstrated that the air temperature (Ta) might affect the concentration of TVOC, but there was a high likelihood it was a random effect, and thus this study treated it as not significant ($p = 0.088 < 0.10$) (Table 6 and Equation (4)). However, further investigation and testing is recommended, as some published studies suggest that air temperature affects the concentration of TVOC to some extent [23,69,85]. Overall, the regression analysis illustrates that Ta and heat stress index HI did not significantly impact the concentration of chemical pollutants in the quarantine room. However, regression identified RH to have the most considerable impact on the concentration of indoor pollutants, especially the concentration of CO_2 and PM2.5 (Tables 7 and 8). The model indicated that every 10% increase in RH could be expected to decrease CO_2 concentration by 17.44 ppm and increase PM2.5 concentration by 1.50 $\mu g/m^3$ (Equations (5) and (6)). Relevantly, despite the high correlation of the RH index with the WBGT index, the WBGT index was also retained as an independent variable in the regression model to measure the effect of indoor thermal comfort conditions on CO_2 concentration. Specifically, the model indicated that every 1 °C increase of WBGT could be expected to increase the concentration of CO_2 by 6.611 ppm under some circumstances (Equation (5)). While further in-depth investigation is still necessary, the above evidence of the mechanism of influence of physical environmental parameters on chemical pollutant concentrations provides preliminary insights into directions for upgrading hotel room spaces to be healthier and more comfortable, especially by ameliorating indoor physical environmental conditions.

$$\text{Concentration of TVOC} = 0.467\ \text{Ta} - 6.552 \quad (4)$$

$$\text{Concentration of } CO_2 = -1.744\ \text{RH} + 6.611\ \text{WBGT} + 376.406 \quad (5)$$

$$\text{Concentration of PM2.5} = 0.150\ \text{RH} + 18.840 \quad (6)$$

Table 6. Regression analysis for TVOC of the measured zones in the hotel room.

Models		**Model a1**	
Variables	**B**	**SE**	**Beta**
Ta	0.467 *	0.269	0.214
Constant			−6.552
R^2			0.046
Adjust R^2			0.030 *
F static			3.009
n			65

* $p < 0.10$ (2-tailed tests).

Table 7. Regression analysis for CO_2 of the measured zones in the hotel room.

Models		**Model b1**			**Model b2**	
Variables	**B**	**SE**	**Beta**	**B**	**SE**	**Beta**
RH	−0.628 *	0.237	−0.317	−1.744 **	0.553	−0.881
WBGT	–	–	–	6.611 *	2.984	0.619
Constant			442.816 ***			376.406 ***
R^2			0.101			0.167
Adjust R^2			0.086 *			0.140 **
F static			7.044			6.195
n			65			65

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$ (2-tailed tests).

Table 8. Regression analysis for PM2.5 of the measured zones in the hotel room.

Models		**Model c1**	
Variables	**B**	**SE**	**Beta**
RH	0.150 **	0.050	0.353
Constant			18.840 ***
R^2			0.125
Adjust R^2			0.111 **
F static			8.973
n			65

** $p < 0.01$; *** $p < 0.001$ (2-tailed tests).

5. Architectural Design and Rehabilitation Implications

This study measured and illustrated the diverse trends in the changes of the chemical, physical, and heat stress environmental factors in a quarantine hotel room on a typical summer day in Shenzhen, southern China. Although most of the examined environmental indices met local and global standards, the study identified some environmental problems with the PM2.5 concentration and interior lighting environment during both daytime and nighttime. PM2.5 concentration in particular was generally observed to exceed WHO AQG standards (24-h, 15 μg/m^3). Regarding mutual influence effects among measured environmental factors, CO_2 concentration was found to be significantly affected by relative humidity (RH) and possibly the occupant's daily activities (e.g., breath and house appliances use). On a spatial level, chemical environmental factors were impacted by the spatial layouts, the outdoor surrounding environments, window open-closed statuses, occupant's activities, operation of equipment (air conditioners, hair dryers, TVs, etc.), as well as the interior physical environmental conditions (e.g., relative humidity). These findings offer some implications and point to a few adoptable suggestions for improving the IEQ of hotel rooms that may potentially be used as quarantine or long-term residences, which are elaborated in the following sub-sections.

5.1. Enhancing Standards for Interior Lighting

Despite relatively recent rigorous adjustment and re-renovation, as a mixed-use and open short-term residential space, the interior lighting environment in the tested hotel room generally did not meet the required standards (Table 2 and Figure 9). It is imperative to meticulously balance multifaceted factors to concurrently enhance energy efficiency, work performance, and the psychological well-being of mixed-use and open-space occupants. The illuminance level and occupants' perception of lighting designs play a pivotal role in shaping psychological states, particularly in air-conditioned room spaces, and inadequate lighting can exacerbate stress as well as physical and mental fatigue [86]. Where occupants reside for extended periods, such as in the context of quarantine hotel rooms, lighting design particularly should adhere to or even exceed standards set for normal residential spaces. Central to this is illumination uniformity (U_o), which ensures balanced light distribution in the hotel room space [64,87].

5.2. Establishing Flexible Interior Spatial Layout System

To foster adaptability and enhance user experience, designers could consider adopting the concept of "Open Building" to open flexible layouts that integrate multiple daily living functional zones. This approach encourages seamless transitions between living, working, and recreational areas, creating a versatile and spacious ambiance. The methodology of "Open Building" emphasizes the importance of designing and organizing the elements "support level" and "infill level" to achieve the goal of establishing adaptive and long-lasting housing [88,89]. It has been widely applied in the design and rehabilitation of normal residential spaces and talent apartments [89–92]. Moreover, as most existing residential and hotel buildings in China adopt the frame structural system, there is the possibility of redefining interior spatial layouts through dealing with the issue of "zones and margins" (e.g., utilization of soft and flexible partition system), so as to better fit this style of design for living needs (Figure 13) [91]. It is recommended in assembling micro-architectural elements and systems to further refine the spatial configurations of the hotel room, manipulating light, airflow, and heat to tailor intimate or expansive spaces to occupants' preferences. In addition, spatial layout arrangement strategies as well as artificial lighting equipment should better incorporate daylighting to enrich spatial aesthetics and minimize energy consumption, alongside providing nighttime artificial lighting tailored for functionality and occupant comfort.

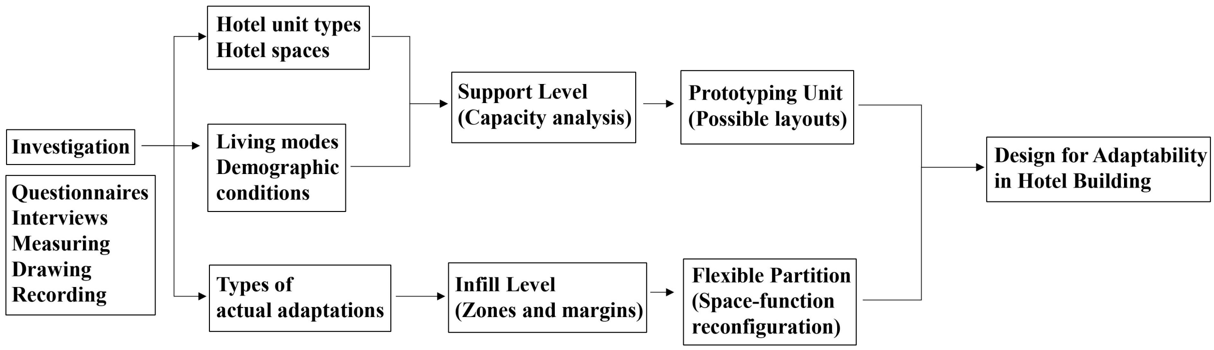

Figure 13. Workflow of design for flexible hotel room spaces based on Open Building theory and method (source: redrawn by authors by taking reference from a study on residential spaces [91]).

5.3. Adopting Soft Interventions and Smart Environmental Re-Architecting Strategies

The adoption of soft interventions can enable occupants and hotel managers to create functional, adaptable, and health-supportive hotel room spaces. To facilitate swift spatial adjustments, portable equipment and fast measurement tools, such as air purifiers, mini-electric fans, and mobile desk lamps, are useful [26,27,93]. The intelligent management of indoor air quality can leverage digital platforms and internet of things (IoT) technology to ensure a healthier and more comfortable room environment [25,29,94]. Moreover, building envelopes such as windows and doors are always providing opportunities for virus and pollutant circulations [95], and thus intelligent indoor environmental monitoring systems can provide real-time insights for more timely and effective management, aiding in informed layout adjustments [28]. Incorporating biophilic interventions and integrating natural elements, such as adding indoor plants, could promote occupants' wellness by reducing stress and anxiety [96,97].

5.4. Promoting Advocay of Healthy Living and Self-Help Adjustment

To improve hospitality and wellness in spatial design, it is recommended that the hotel room spaces be semi-self-designed or customizable by occupants, empowering them to personalize their surroundings and elevating their living experience [32,98]. Notably, during quarantine periods, occupants' daily activities may need to modify the environment to promote physical and psychological health and ensure well-being amidst extended indoor stays [99]. It is also suggested that design be modified to enable and promote healthy living, such as providing exercise zones in the hotel rooms and tips on healthy lifestyles and behaviors for occupants.

6. Conclusions and Outlooks

This study provides a sample case on mixed-use and open spaces to the area of multi-domain indoor environmental quality (IEQ) studies. It explored the multi-domain environmental quality of an air-conditioned quarantine hotel room in Shenzhen City, investigating factors of chemical pollutant concentrations, physical environmental parameters, and heat stress indices. The results illustrated diverse trends in the chemical, physical, and heat stress parameters of the quarantine hotel room space over the course of a typical summer day in Shenzhen. The main findings can be summarized as follows:

- During the studied extended quarantine stay, most examined indoor environmental indices meet both local and global IEQ and IAQ standards, indicating the suitability and general effectiveness of the tested hotel room as a quarantine residential space.
- However, the PM2.5 level was observed to exceed the WHO AQG standard (24-h avg., 15 $\mu g/m^3$), suggesting that there is still space to enhance hotel rooms to be healthier for travelers during both normal times and epidemic situations.
- In many situations, the interior lighting environment did not meet task-specific needs, particularly at night, when artificial lighting was mainly relied on to conduct activities,

suggesting that hotel illumination standards do not sufficiently consider the specific needs of quarantine occupants.

- Relative humidity (RH) was preliminarily identified as a critical physical environmental index, impacting both CO_2 and PM2.5 concentrations. Higher RH seemed to lead to lower concentrations of CO_2 but higher concentrations of PM2.5.
- The wet bulb globe temperature (WBGT) heat stress index was observed in this study to positively correlate with CO_2 concentration to some extent.

These findings have revealed and verified that the physical conditions of the room space could significantly influence the chemical pollutant concentrations. This case study offers a scientific foundation for restoring and upgrading existing hotel buildings in the post-pandemic era, as well as optimizing "environmental resilience" in the adaptive design of newly constructed buildings with similar spatial characteristics. Recommendations for hotel room rehabilitation and improvements:

- Incorporating biophilic interventions and integrating natural elements, such as indoor plants, to promote occupants' wellness by reducing stress and anxiety as well as improving indoor air quality.
- Offering low-cost portable IEQ monitoring devices (e.g., portable air purifier and environmental meter) to residing guests or employing fixed smart environmental meters to be linked to IoT systems for dynamic monitoring.
- Increasing window areas in non-load-bearing walls to introduce sufficient natural light into the hotel room spaces that function for dining and working.
- Installing adjustable illuminance lighting fixtures in hotel rooms, which can be adjusted by occupants based on their needs and activities.
- Adopting the "Open Building" design methodology and establishing a spatial system that enables occupants to achieve flexible and self-help layout adjustments.
- Promoting healthy living functionalities and providing tips on healthy lifestyles and behaviors during extended stays or quarantine in hotel rooms.

Moreover, this study indicates that even with relatively recent rigorous adjustment and re-renovation, hotels and other mixed-use and open spaces should evaluate the hybrid combined effects of the multiple environmental performances in both normal and pandemic contexts to inform more effective retrofitting and rehabilitation. In particular, despite occupying adjoining spatial conditions, different functional zones exhibit quite different environmental performances and even conflicting effects on occupants in terms of physical and mental health. It is also of great importance to systematically understand the synergy and mutual impacts among multi-environmental parameters so as to more accurately identify potential problems and health-related risks.

Limitations and Directions for Future Studies

This study attempted to provide analysis, case documentation, and preliminary insights into upgrading of mixed-use and open hotel room spaces. However, a few limitations apply to the study. Firstly, due to quarantine policy restrictions and limitations of instrumentation and manpower, the short-term measurement period may not have fully encapsulated the full dynamic range of indoor environmental quality (IEQ) factors. The exclusive focus on summertime neglected the unique IEQ challenges posed by winter and transitional season conditions. Secondly, the lack of acoustic analysis and evaluation of subjective perception restricts the study's practical holistic. Also, the use of a single case study also limits the generalizability of findings to some extent, though it can still offer some useful insights into amelioration of IEQ issues in hotel rooms. To improve the robustness and comprehensiveness of insights for construction and rehabilitation of hotels, the following research directions are suggested:

- Conducting comprehensive analysis of the impacts of daily occupant activities within hotel room spaces on indoor environmental quality.

- Extending measurement periods and study durations to capture seasonal variations and long-term trends through cooperating with local governmental agencies and adopting computational simulations in order to provide more systematic direction for upgrading hotel guest rooms.
- Integrating more aspects of the "healthy building" (e.g., noise, moisture, water quality, dust, and bioaerosols) into building design consideration and regulation and evaluating occupants' subjective perceptions.
- Collecting more granular data by employing more smart instruments with higher measuring accuracy and adopting machine-learning analysis to enable exploration of deeper mechanisms and hidden factors that affect the indoor environmental quality of the hotel rooms in both objective and subjective dimensions.

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Abbreviations

IEQ	Indoor environmental quality
IAQ	Indoor air quality
AQG	Air quality guideline
AQI	Air quality index
CO_2	Carbon dioxide (ppm)
PM2.5	Particulate matter (μg/m^3)
HCHO	Formaldehyde (μg/m^3)
TVOC	Total volatile organic compounds (μg/m^3)
VOC	Volatile organic compounds (μg/m^3)
Ta	Air temperature (°C)
T_{nw}	Nature wet temperature (°C)
Tg	Globe temperature (°C)
RH	Relative humidity (%)
v	Air velocity (m/s)
IL	Horizontal illumination level (lx)
U_o	Illumination uniformity (0–1)
HI	Heat index (°C)
WBGT	Wet bulb globe temperature (°C)
ppm	Parts per million
IoT	Internet of Things
ISO	International Organization for Standardization
WHO	World Health Organization
OSHA	Occupational Safety and Health Administration
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
MOE	Ministry of the Environment (Republic of Korea)
FISIAQ	Finnish Society of Indoor Air Quality and Climate
JBSA	Japan Building Standard Act

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