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Characteristics of $PM_{2.5}$ and CO_2 Concentrations in Typical Functional Areas of a University Campus in Beijing Based on Low-Cost Sensor Monitoring

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Abstract: The air quality in educational campuses affects the health and work efficiency of teachers and students. Studies into this matter are of great significance for optimizing the management of campus living environments. Low-cost online sensors to monitor $PM_{2.5}$ and CO_2 levels were used in typical functional areas of a university campus in Beijing, China, including offices, dormitories, leisure spaces, canteens, and laboratories. By comparing the findings with data from nearby national monitoring stations, the seasonal and spatial variations in $PM_{2.5}$ and CO_2 concentrations were analyzed. Findings indicate $PM_{2.5}$ levels within the campus were notably lower compared to the surrounding urban environment. There was variation in $PM_{2.5}$ and CO_2 concentrations across different functional areas. Typically, indoor $PM_{2.5}$ levels were lower than outdoor ones, while CO_2 concentrations in enclosed indoor spaces with human activities progressively escalated. The main internal emission sources affecting the $PM_{2.5}$ level on campus included traffic emissions, dust generated by human activities, and emissions from catering. In contrast, in areas with better green coverage or where a lake system participates in the atmospheric circulation, the $PM_{2.5}$ level and $CO_2/PM_{2.5}$ were lower. This indicates that the cleansing impact of plants and aquatic systems is instrumental in lowering $PM_{2.5}$ concentrations, offering healthier leisure spaces. Seasonal variations also impact $PM_{2.5}$ levels. During the non-heating period, less pollution source emissions led to decreased outdoor $PM_{2.5}$ concentrations. The campus monitoring sites experienced an approximate 5 $\mu g/m^3$ and 29 $\mu g/m^3$ reduction in the average $PM_{2.5}$ levels as compared to the $PM_{2.5}$ of the surrounding urban environment, respectively, during the non-heating and heating period. During indoor activities or sleep, CO_2 levels can build up to as high as 2303 ppm due to breathing. It is advisable to stay indoors on days when pollution levels are high, whereas on days with clean air, it is healthier to be outdoors or to air out indoor areas by opening windows. Our research provides clearer scientific evidence for incorporating behavioral strategies for improving air quality into both daily work and life. Moreover, the findings are quite meaningful for the widespread adoption of low-cost sensor monitoring in various environments, with applications beyond just the campus settings.

Keywords: $PM_{2.5}$; CO_2; low-cost sensors; university campus; functional areas

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1. Introduction

Amid the rapid expansion of the global economy, the consumption of fossil fuels such as coal and oil has heightened concerns over environmental issues like aerosol pollution and CO_2 emissions, which have become major international concerns [1]. $PM_{2.5}$ refers to particles with a diameter of 2.5 μm or less, which can penetrate the human respiratory system and enter the bloodstream, potentially causing respiratory conditions like bronchitis and asthma [2,3]. Prolonged exposure to $PM_{2.5}$ may also increase the risk of cardiovascular diseases, including heart disease and stroke. Furthermore, $PM_{2.5}$ affects the climate through both direct and indirect climatic impacts [4].

Due to the challenges posed by global climate change and heightened environmental contamination, China is tasked with the dual challenge of cutting CO_2 emissions and managing $PM_{2.5}$ pollution levels [5]. Researches indicates that CO_2 and most aerosol species share a common origin, such as fossil fuel combustion [6]. CO_2 emission reduction activities contribute significantly to reducing $PM_{2.5}$ concentrations [7,8]. CO_2 not only affects climate change [9], but also raises health-related issues [10]. Although it is not directly harmful at low concentrations, long-term exposure to high levels of CO_2 can adversely affect health, leading to sick building syndromes such as dizziness, headaches, fatigue, and an inability to concentrate [11,12]. For example, indoor CO_2 levels greater than 800 ppm were likely to result in reports of more eye irritation or upper respiratory symptoms [12]. This can impair work and academic performance, especially in environments with inadequate ventilation. Pursuing a green, low-carbon approach that concurrently reduces PM and CO_2 emissions yields significant environmental and health advantages [13].

The precise tracking and efficacious control of pollution require monitoring with high spatiotemporal resolution [14]. The development of monitoring technology in the field of air pollution research has allowed for deeper, more detailed, and more comprehensive studies of air quality. The widespread adoption of high-precision instruments is hampered by their substantial costs for consumables and maintenance. However, the use of low-cost sensor (LCS) devices presents a viable alternative [15]. Hence, the utilization of affordable air quality monitoring equipment is gaining popularity and becoming essential in managing pollution. For example, the use of advanced online sensor monitoring methods facilitates the acquisition of real-time, detailed data, vital for air pollution research [16,17].

Using affordable sensors to measure atmospheric constituent levels in public areas, and using these as indicators to evaluate air quality, are essential for further understanding the health effects on humans [18,19]. Academic campuses emerge as distinct urban environments that are integral for the health, education, and well-being of both faculty and students, leading to heightened concerns about campus air quality. However, there is still a lack of research examining the characteristics of $PM_{2.5}$ and CO_2 in different campus areas and the factors that affect their levels. Currently, most LCSs commonly utilize non-dispersive infrared (NDIR) absorption to measure CO_2 levels [20,21], and employ laser scattering modules to estimate PM concentrations [21,22]. This study seeks to fill this gap by setting up multiple sampling sites in representative campus regions to conduct ongoing monitoring of $PM_{2.5}$ and CO_2 levels, utilizing the above two kinds of sensor measurement methods. Through analyzing the pollution patterns of $PM_{2.5}$ and CO_2 and correlating the findings with the characteristics of $PM_{2.5}$ and its source tracers—NO_2, CO, and O_3—monitored by nearby national stations, the study will reveal the specific characteristics of $PM_{2.5}$ and CO_2 within these typical functional areas. This will enhance our understanding of air quality across diverse campus sections and provide a scientific basis for developing effective environmental management plans to protect the health of educators and students, as well as improve the environmental quality of educational campuses.

2. Data and Methods

2.1. Campus and Its Typical Functional Zone Overview

Situated between Beijing's Second and Third Ring Roads, Beijing Jiaotong University (BJTU) is centrally located in the city, offering easy access to numerous major thoroughfares and public transit routes. The vicinity is dotted with universities, research establishments, and tech companies. The university campus boasts modern parklands and verdant green spaces, creating an inviting atmosphere for both academic pursuits and daily life. The campus is segmented into distinct functional zones based on their purpose and amenities, such as academic and administrative areas, laboratory facilities, residential sections, and recreational spots (Figure 1). The academic and administrative zone comprises lecture halls, offices, teaching buildings, and libraries. The laboratory zone houses various specialized labs. Residential areas consist of student dormitories, canteens, gymnasiums, and a student activity center. The green leisure zone encompasses the university's forests, lawns, lakes, and ponds.

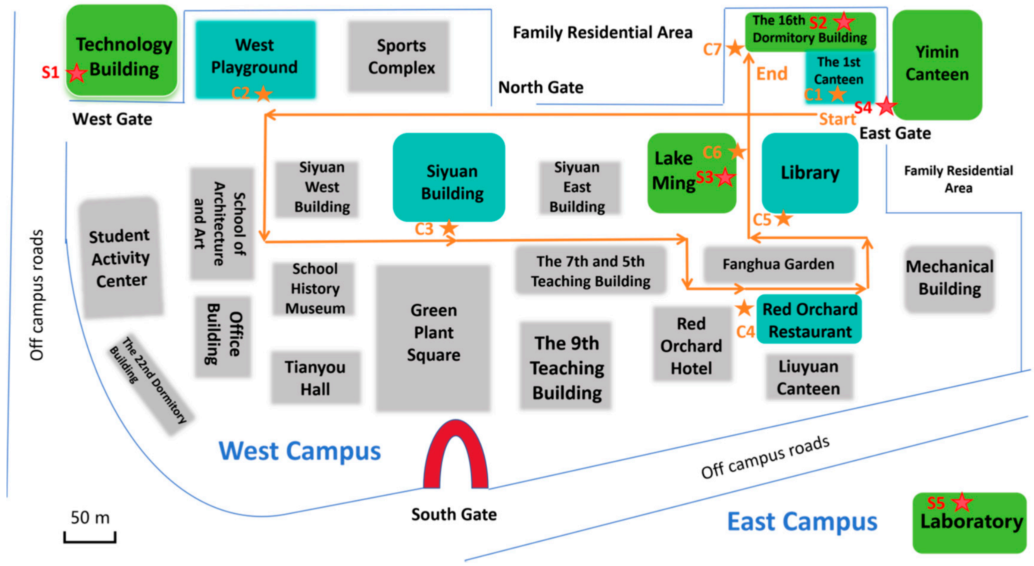

Figure 1. Campus functional area diagram and sampling point locations (red stars), along with the running track measurement paths (orange for the route, orange stars for sampling points).

The study selected five representative functional zones within the campus for sampling: the Technology Building, a study and office area; the 16th Dormitory Building, a student residential zone; Lake Ming, a green recreational space; Yimin Canteen, serving as a dining area; and the East Campus Laboratory, a laboratory area. These areas are referred to by the shorthand office, dormitory, Lake Ming, canteen, and laboratory, respectively, and their specific locations are marked as S1, S2, S3, S4, and S5 in Figure 1.

The office site for faculty and graduate students' workspace is situated on the 14th floor of the Technology Building. The office area spans over 150 square meters, featuring a variety of spaces including multiple conference and discussion zones, as well as numerous workstations. Dormitories are the primary environment where students spend their time outside of class. As such, a dormitory in the 16th Dormitory Building, positioned near the East Gate of the main campus, was selected as a representative site for evaluating the air quality within the living quarters. Lake Ming is enveloped by lush greenery, with the library to the east and the Science Hall to the west. In the absence of pollution sources, it stands as a quintessential spot for the green leisure area. Yimin Canteen, positioned next to the 16th Dormitory Building, is a bustling hub during meal times, making it a characteristic site for the living area. To examine the influence of cooking emissions on air pollution, the sampling point was set up near the kitchen's exhaust outlet at Yimin Canteen. The East District Laboratory is the experimental area for undergraduate courses, with observations scheduled during periods when students are not engaged in experiments to mitigate the impact of noise from sampling equipment.

2.2. Sampling

2.2.1. Sampling in Typical Residential Dormitory Environment

To systematically analyze the differences in $PM_{2.5}$ and CO_2 concentrations between indoor and outdoor environments in a residential dormitory environment, the online $PM_{2.5}$ and CO_2 were measured by a Qingping Air Monitor Lite (Model CGDN1, Beijing Qingping Technology Co., Ltd., Beijing, China) in a staff dormitory within a residential area, from 30 July to 3 September 2023. The dormitory, measuring 15 m^2, is occupied by a single individual who does not engage in activities that generate significant indoor pollution, such as cooking. The occupant maintains a steady schedule, keeping doors and windows closed during sleep and opening them for ventilation at other times. For comparative analysis, the dormitory was vacant from 15 August at 11:00 until 19 August at 23:00, with the doors and windows kept sealed throughout this period (Figure 2).

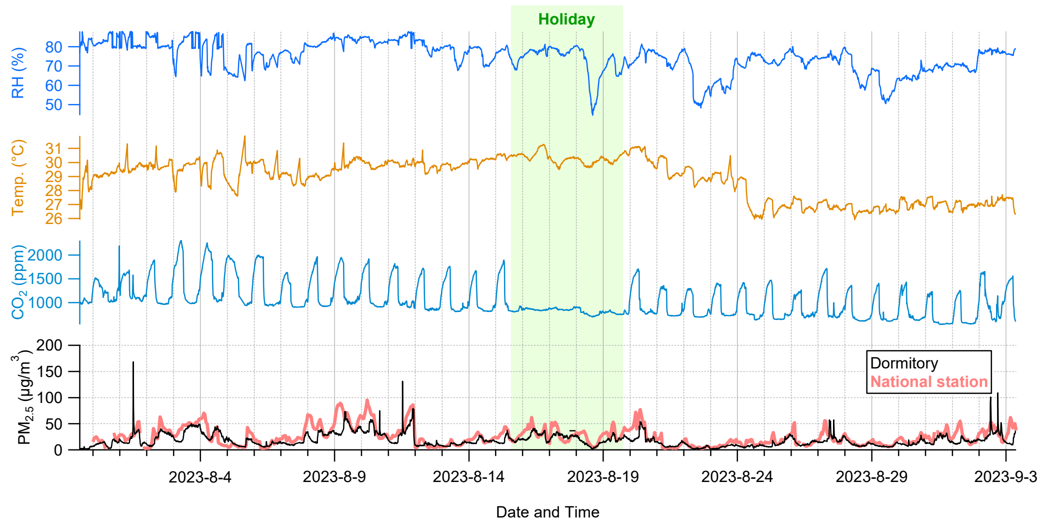

Figure 2. Time series of RH, temperature, CO_2, and $PM_{2.5}$ in the residential dormitory environment. The annotation with a green background indicates scenes of vacations that are devoid of human presence.

2.2.2. Sampling in Campus Typical Functional Area

The same sampling method was applied at the five locations, utilizing one ARA N-FRM Sampler (Model N-FRM, ARA Instruments, Eugene, OR, USA), one Qingping Air Monitor Lite, and one conventional temperature and humidity meter (Model ASAIRGSP885, Guangzhou Aoya Electronic Co., Ltd., Guangzhou, China) for synchronous online observations. The ARA N-FRM Sampler was responsible for recording $PM_{2.5}$, wind speed (WS), and wind direction (WD), while the Qingping Air Monitor Lite was used to monitor $PM_{2.5}$, CO_2, temperature, and relative humidity (RH). The temperature and humidity meter focused on gathering data for temperature and RH. The ARA N-FRM Sampler is equipped with a Plantower light scattering sensor to log temporal particulate variations [22]. The Qingping Air Quality Monitor Lite is also equipped with a high-sensitivity Plantower laser scattering particulate sensor that is designed to detect $PM_{2.5}$ particles, with a measurement range of 0–500 $\mu g/m^3$ [22]. Additionally, it includes a SenseAir CO_2 sensor (Model SenseAir S8, SenseAir AB, Västerås, Sweden) to measure the concentration of carbon dioxide in parts per million (ppm), with a measurement range of 400–9999 ppm [20]. The $PM_{2.5}$ levels at the national monitoring stations are measured using commercial instruments, e.g., the tapered element oscillating microbalance with a filter dynamics measurement system (Model TEOM® 1405-FDMS, Thermo Fisher Scientific, Waltham, MA, USA). The national air quality monitoring network is continuously operated and accurately maintained according to the most recent revisions of the China Environmental Protection Standards [23].

For locations with high human traffic, such as Lake Ming, the canteen, and the dormitory, the sampling work was completed within approximately 4 h. In contrast, for the office and laboratory, where sampling is more manageable, the sampling time was extended to about 48 h. To assess air quality variations across different seasons, two rounds of sampling were conducted at each representative location, before and during the centralized heating period in Beijing.

During the concurrent observation period of 24–96 h, whether in an office or laboratory setting, the $PM_{2.5}$ measurement values of the Qingping Air Quality Monitor Lite showed a strong correlation ($R^2 > 0.96$) with the data from the ARA N-FRM Sampler (Figure 3).

Furthermore, the RH and temperature readings also showed high correlations of over 0.9 and 0.94 with the hygrometer, respectively. In a 35-day comparative analysis, the $PM_{2.5}$ readings from the Qingping Air Monitor Lite aligned closely with those from a nearby national monitoring station (Figure 3). This indicates that the Qingping Air Monitor Lite is effective in accurately monitoring $PM_{2.5}$ levels, as well as temperature and RH.

In addition, we utilized the ARA N-FRM Sampler to conduct $PM_{2.5}$ observation at various locations across the campus within a two-hour period on a heavily polluted day. The monitoring was carried out along the route of "inside the 1st Restaurant, the West Playground Runway, the entrance to Siyuan Building, the library entrance, Lake Ming, the entrance to the 16th Dormitory" (Figure 1).

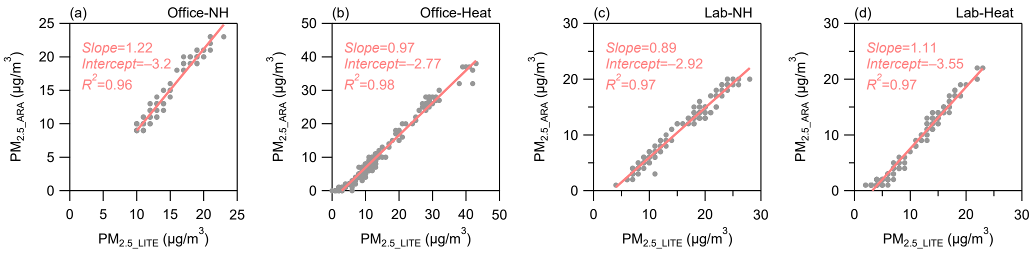

Figure 3. Parallel comparison of $PM_{2.5}$ mass concentration between the ARA N-FRM Sampler and the Qingping Air Monitor Lite before and during the heating period at the sampling points of office (**a**,**b**), and laboratory (**c**,**d**).

2.2.3. Other Air Pollutant Data

The annual average CO_2 concentration in Beijing's urban area was calculated by averaging the outdoor CO_2 concentrations from the four seasons between 2022 and 2023, which was measured by a CO_2/H_2O gas analyzer (Model Li-7500, LI-COR, Inc., Lincoln, NE, USA) at 8 m on the Beijing 325 m meteorological tower that is located between the north 3rd and 4th ring roads in the city center [24]. We also gathered data of $PM_{2.5}$, CO, NO_2, and O_3 from the nearby national air quality stations, i.e., Olympic Sports Center station (ATZX) and Guanyuan station (GY), throughout the sampling period (https://www.aqistudy.cn/, accessed on 30 December 2023), to assist in the analysis of the characteristics of campus air pollution and its influencing factors.

3. Results and Discussions

3.1. Indoor and Outdoor Characteristics of $PM_{2.5}$ and CO_2 Concentrations

Figure 2 reveals that the indoor CO_2 levels exhibited a distinct cumulative pattern, primarily due to human breathing. In contrast, during the holiday period when the room was unoccupied and sealed, the concentration of CO_2 remained stable. The indoor $PM_{2.5}$ levels were markedly lower at night compared to the national monitoring station. During the day, when windows were opened for ventilation, indoor $PM_{2.5}$ levels corresponded closely with outdoor levels. This pattern can be attributed to the lack of indoor $PM_{2.5}$ emission sources and the overnight decline in $PM_{2.5}$ indoors, likely due to deposition and other sink processes. Moreover, the increase in vehicle emissions in urban Beijing and a thinner boundary layer at night lead to elevated outdoor $PM_{2.5}$ concentrations [24,25]. Consequently, the indoor CO_2 concentration is predominantly influenced by human activity, while indoor $PM_{2.5}$ levels are subject to the exchange between indoor and outdoor air conditions.

The $PM_{2.5}$ concentration time series revealed distinct peaks, occasionally aligning with CO_2 peaks. These peaks predominantly emerged during the intervals of 10:00–13:00 and 16:00–19:30, each lasting for approximately 15 min (Figure 2). The primary source of these peaks is attributed to the cooking activities in the neighboring room, particularly corresponding to the duration required for stir-frying a meal. Notably, even when the exhaust fan is operational, the impact of cooking on PM concentration remains considerable.

It should be mentioned that cooking is not a typical activity in dormitories designated for teachers and students. However, if the occupants are family units, they often prepare more substantial meals with multiple dishes, and hence the kitchen area may necessitate a greater focus on air purification measures.

The diurnal variation characteristics of $PM_{2.5}$ and CO_2 levels both indoors and outdoors were further analyzed and are presented in Figure 4. The sporadic contributions from cooking activities did not significantly affect the diurnal variation characteristics of $PM_{2.5}$ and CO_2. Windows were typically opened by the staff between 7:00 and 9:00, and then closed around 22:00, when the staff retired for the night. After windows were opened at approximately 7:00, the indoor $PM_{2.5}$ concentration slowly rose to align with the outdoor levels. Conversely, once the windows were closed after 22:00, indoor $PM_{2.5}$ levels gradually diminished, likely due to particle deposition and other removal processes. Under usual conditions, the average indoor $PM_{2.5}$ concentration was found to be lower than outdoor levels, regardless of whether the windows were open or shut. This suggests that more substantial pollution sources significantly contribute to elevated outdoor $PM_{2.5}$ pollution levels. During holidays, outdoor $PM_{2.5}$ experienced significant peaks and valleys, with considerable daily variations. These fluctuations were primarily due to the immediate effects of emission sources and/or weather conditions [26]. The $PM_{2.5}$ at the national monitoring station was likely contributed to by much stronger emissions from traffic and catering for extended periods. Conversely, indoor $PM_{2.5}$ concentrations tended to follow a more stable trend in the absence of human activity, exhibiting a clear bimodal pattern with peaks at approximately 10:00 and 20:00. This suggests that the emitting periods from nearby catering and traffic sources were relatively brief. For example, due to distance, the obstructive influence of the urban underlying surface, and the closure of doors and windows, newly accumulated outdoor $PM_{2.5}$ did not disperse indoors effectively. When windows were kept shut during holidays, indoor $PM_{2.5}$ concentrations between 20:00 and 10:00 were substantially lower than those outdoors. From 11:00 to 19:00, both indoor and outdoor $PM_{2.5}$ levels stabilized at a background concentration of 20 $\mu g/m^3$. This indicates that during times of elevated outdoor pollution, employing a fresh air system for ventilation can help maintain low levels of $PM_{2.5}$ and CO_2 indoors. However, to significantly reduce indoor $PM_{2.5}$ levels, it is essential to focus on decreasing outdoor $PM_{2.5}$, as it is the primary source of contamination.

When the dormitory room was vacant, the diurnal CO_2 concentration spanned from 790 to 863 ppm, nearly matching Beijing's urban annual average daily CO_2 range of 805 to 881 ppm. This indicates a negligible difference between the outdoor CO_2 concentration and the daily fluctuations within the city. Additionally, the $CO_2/PM_{2.5}$ ratio was between 30 and 45 $ppm \cdot m^3/\mu g$. In the occupied dormitory, the CO_2 levels varied from 812 to 1594 ppm. The increase in the minimum value may be due to staff presence during the daytime on weekends. Consequently, the $CO_2/PM_{2.5}$ ratio varied from 38 to 124 $ppm \cdot m^3/\mu g$, significantly exceeding the levels observed indoors during the holiday period. The overall average $CO_2/PM_{2.5}$ ratio was slightly lower by approximately 14 $ppm \cdot m^3/\mu g$ than the result reported in a sleep health study conducted during the summer in Louisville, KY, because of the 5 $\mu g/m^3$ higher level of $PM_{2.5}$ in Beijing [27].

The diurnal variations in temperature and RH were also influenced by human activities. Without human interference, temperature exhibited a smooth diurnal variation pattern. However, with people present, particularly during the late-night hours between 22:00 and 6:00, there was a noticeable rise in indoor temperature. Moreover, after opening the windows, the indoor temperature initially experienced a gradual decline due to the exchange of air. Subsequently, it achieved equilibrium with the outdoor temperature, aligning with the outdoor warming trend by 15:00. During holidays, which was the hottest period in Beijing, human influence was excluded, and the diurnal variation in indoor temperature was consistent with the trends observed in previous studies on Beijing's summer outdoor temperature variations [25]. On the other hand, the outdoor RH during the summer from 22:00 to 8:00 should show an increasing trend [25], but this was not the case when the staff were inside. The main reason is that the higher indoor temperature resulted in a lower RH. Therefore, it was primarily the heat dissipation from the human body that affected the indoor temperature and RH trends.

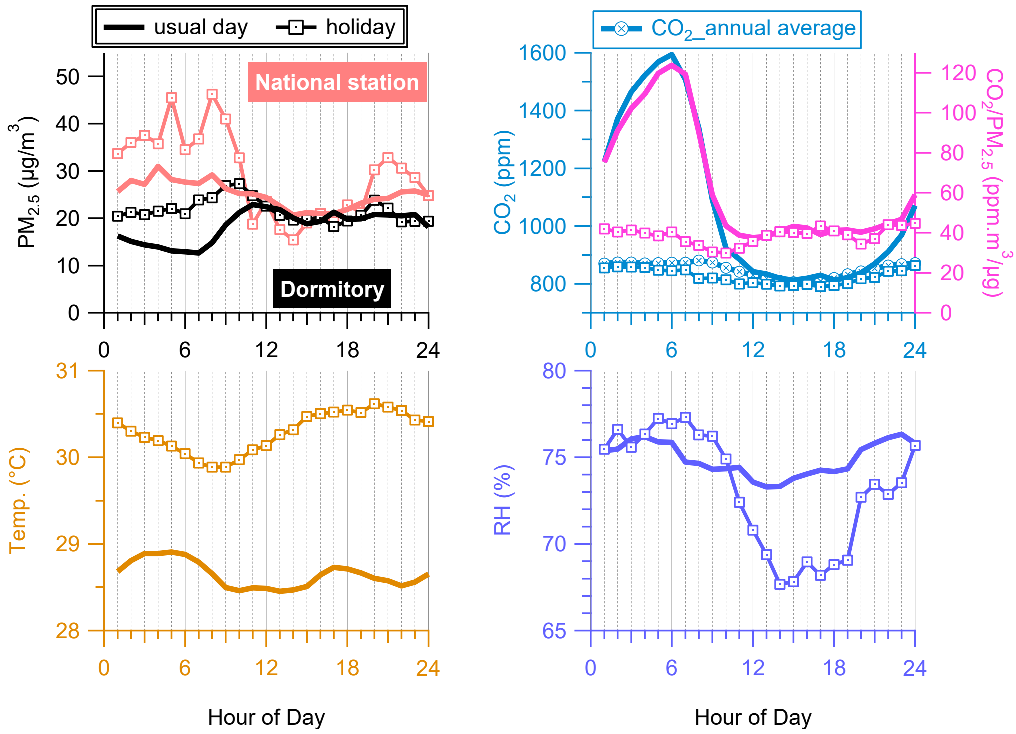

Figure 4. Diurnal profiles of RH, temperature, CO_2, $PM_{2.5}$, and $CO_2/PM_{2.5}$ in the residential dormitory environment during the usual period and holiday period, the synchronous $PM_{2.5}$ trends at a nearby national monitoring station, and the annual average diurnal trend of CO_2 in Beijing.

3.2. $PM_{2.5}$ and CO_2 Concentration Characteristics in Typical Campus Functional Areas

3.2.1. Office

We conducted air quality measurements in a corner of the office with the nearby window opened. In Figure 5a, the $PM_{2.5}$ concentration in the office was lower than that at the nearest national monitoring station, the GY site (~3 km away). Moreover, the $PM_{2.5}$ within the office was closer to that of the ATZX site (~6 km) with a lower pollution level. One reason for this is that the office is located on the 14th floor of the building, which is somewhat distant from ground-level emission sources, thus presenting cleaner characteristics. Starting at 14:00, the onset of the afternoon work session saw a surge in office activity, which correspondingly elevated the $PM_{2.5}$ concentration levels. From 14:00 to 15:00, there was a slight increase of approximately 10 ppm in CO_2 concentration, contrasting the usual pattern of a slight decline in outdoor CO_2 levels at this time (Figure 4). Office workers were accustomed to making phone calls near the sampler's placement location, and it is speculated that during this period, someone was making or receiving phone calls or discussing work near the sampler, thereby causing an increase in CO_2.

During the heating period (Figure 5b), due to the chilly outdoor temperatures, the nearby window was only partially opened, leaving a narrow 1–2 cm gap. The weekdays were 17 November and 20 November, while 18 November and 19 November were weekends. Human activity within the office was higher on weekdays, while weekend visits were sparse. From 17 November to 20 November, the overall trend of CO_2 and CO levels were similar. However, there was a distinct accumulation feature of CO_2 (~100 ppm) between 16:00 and 19:00 on the 17th and 11:00 to 14:00 on the 20th. This surge was due to the increase in gatherings and activities. The $PM_{2.5}$ levels within the office corresponded closely to those recorded at the GY station, albeit with a more stable trend. The office's average $PM_{2.5}$

concentration was approximately 11 μg/m^3, which is only one-third of the concentration at the GY station. On November 20th, between 14:00 and 18:00, there was a swift fluctuation in indoor CO_2 (~100 ppm), with corresponding peaks in indoor $PM_{2.5}$. A reasonable speculation was that someone opened the window for ventilation from a location far from the sampling point in the large office. This action reduced the CO_2 concentration and increased the $PM_{2.5}$ concentration. However, due to the limited extent of the ventilation, the indoor $PM_{2.5}$ levels remained significantly below those outdoors. The variations in NO_2 and CO, as depicted in Figure 5a,b, indicate that increases in outdoor emissions, particularly from traffic sources [28], significantly impacted outdoor $PM_{2.5}$ levels. The $PM_{2.5}$ and CO_2 levels in the office were primarily influenced by the exchange of air with the outdoors and indoor human activities.

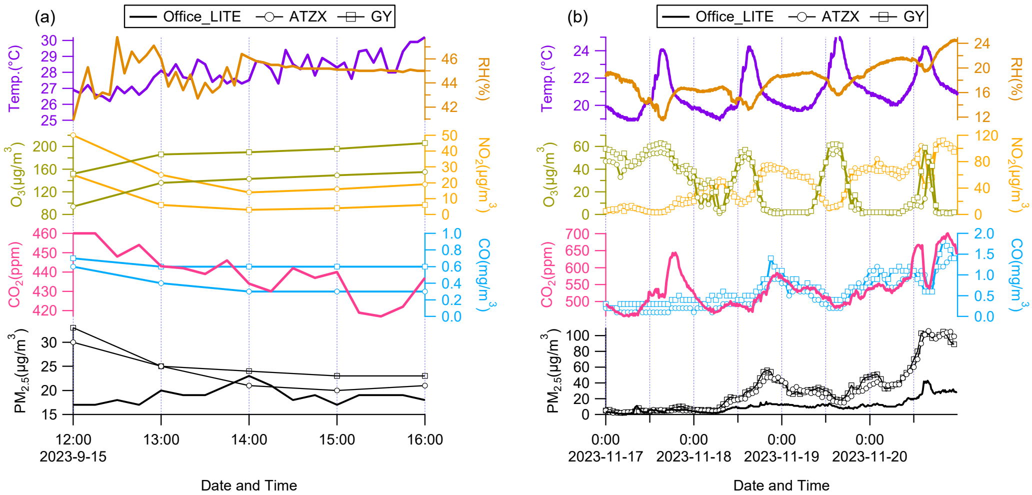

Figure 5. Time series of $PM_{2.5}$, CO_2, RH, and temperature at the office sampling point (**a**) before the heating period; (**b**) during the heating period, as well as the time series of air pollutants ($PM_{2.5}$, NO_2, CO, O_3) at the national monitoring stations (ATZX and GY).

3.2.2. Dormitory

As shown in Figure 6a, around 14:30, students were taking a nap in the dormitory, and the CO_2 level in the dormitory reached approximately 1200 ppm. After opening the windows for ventilation at 14:45, the $PM_{2.5}$ concentration gradually increased and approached the data at the GY station. Simultaneously, the CO_2 concentration significantly decreased by 644 ppm within 45 min. When students cleaned the dormitory, the $PM_{2.5}$ concentration increased by 10 μg/m^3 from 15:30 to 15:45, and then the indoor $PM_{2.5}$ concentration decreased again to a level close to that at the GY station.

Figure 6b shows that when the dormitory windows were kept closed, the indoor $PM_{2.5}$ concentration remained at a relatively low level, with an average of 17 μg/m^3, which was one-fifth of the $PM_{2.5}$ concentration at the GY station. This indicates that staying indoors can effectively reduce the inhalation of atmospheric particulates when outdoor air pollution levels were high in heating season [26,29]. However, in the evening, when students socialized and opened their doors to the corridor, the CO_2 concentration in the dormitory decreased from 1424 ppm to 609 ppm. Therefore, simply opening dormitory doors can also effectively prevent the accumulation of high CO_2 concentrations in the dormitory. Notably, this action of opening doors to the corridor did not impact the $PM_{2.5}$ concentrations.

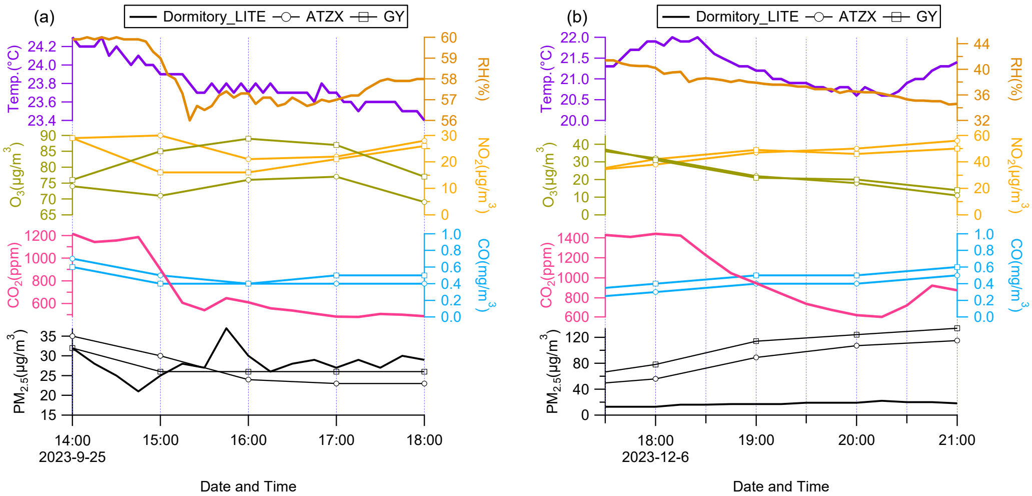

Figure 6. Time series of $PM_{2.5}$, CO_2, RH, and temperature at the dormitory sampling point (**a**) before the heating period; (**b**) during the heating period, as well as the time series of air pollutants ($PM_{2.5}$, NO_2, CO, O_3) at the national monitoring stations (ATZX and GY).

3.2.3. Lake Ming

As an outdoor station, Lake Ming exhibited a $PM_{2.5}$ concentration level of approximately 70% of the concentration at the GY station from 14:00 to 16:30 in Figure 7a, and from 14:00 to 18:00 in Figure 7b. The lower $PM_{2.5}$ concentration could be attributed to the vegetation around Lake Ming and the influence of the lake's water system [30,31].

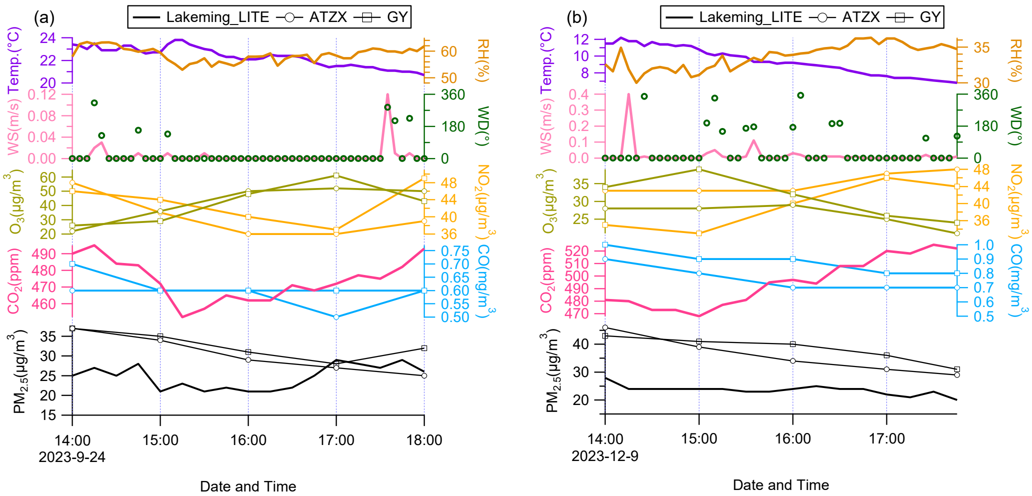

Figure 7. Time series of $PM_{2.5}$, CO_2, RH, and temperature at the Lake Ming sampling point (**a**) before the heating period; (**b**) during the heating period, as well as the time series of air pollutants ($PM_{2.5}$, NO_2, CO, O_3) at the national monitoring stations (ATZX and GY).

As shown in Figure 7a, there was a marked surge in $PM_{2.5}$ concentrations between 16:30 and 18:00, which surpassed the levels recorded at the GY station. This increase was largely attributable to the emissions from nearby restaurants around Lake Ming during their peak dinner preparation hours. Additionally, the bustling student activities near the main road at class transition times likely contributed to an increase in dust levels.

As shown in Figure 7b, from 14:00 to 18:00, the decline in $PM_{2.5}$ at Lake Ming was less pronounced than that at the GY station. This suggests that the air quality at Lake Ming is more self-contained, primarily influenced by local sources such as campus emissions and its unique micro-ecological conditions. Moreover, the reduction in $PM_{2.5}$ in the urban area might have counteracted the effects of restaurant and dust emissions on the $PM_{2.5}$ levels at Lake Ming.

In environments strongly associated with outdoor air, such as partially enclosed offices (Figure 5), ventilated student dormitories (Figure 6a), areas outside of the restaurant (Figure 8), and laboratories without human activities (Figure 9), CO_2 levels tended to correspond closely with those of CO and $PM_{2.5}$ at the GY site. However, this characteristic is not observed in Figure 7a,b. The special impact of the lake water ecosystem on $PM_{2.5}$ and CO_2 requires further research. Overall, the CO_2 concentrations at Lake Ming remained low, not exceeding 520 ppm, and $PM_{2.5}$ levels were substantially lower than those at the neighboring national monitoring station, signifying that the air quality in the Lake Ming recreational area is of a high standard, conducive to rest and leisure.

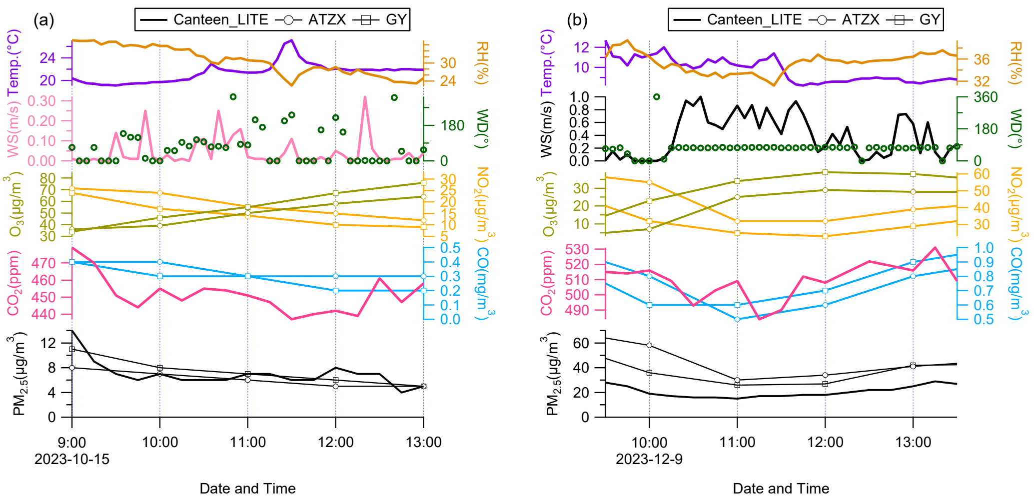

Figure 8. Time series of $PM_{2.5}$, CO_2, RH, and temperature at the canteen sampling point (**a**) before the heating period; (**b**) during the heating period, as well as the time series of air pollutants ($PM_{2.5}$, NO_2, CO, O_3) at the national monitoring stations (ATZX and GY).

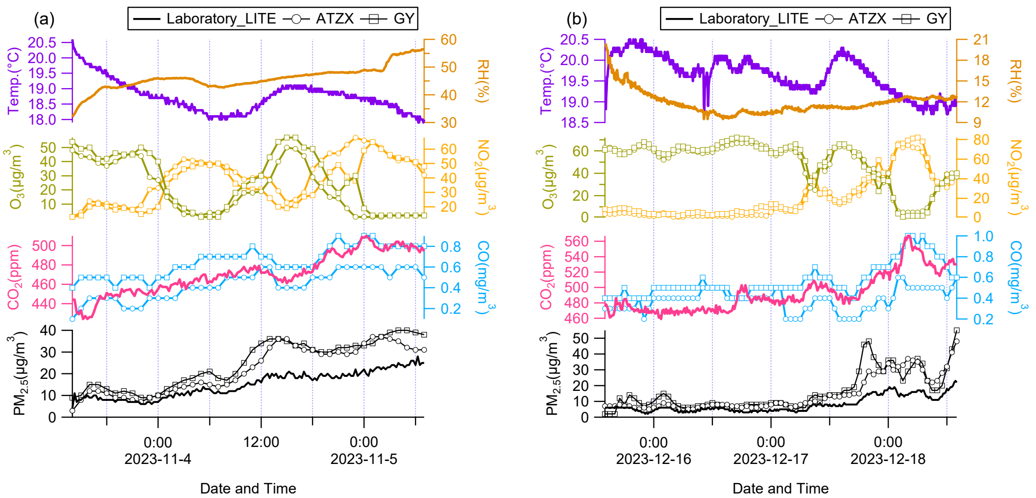

Figure 9. Time series of $PM_{2.5}$, CO_2, RH, and temperature at the laboratory sampling point (**a**) before the heating period; (**b**) during the heating period, as well as the time series of air pollutants ($PM_{2.5}$, NO_2, CO, O_3) at the national monitoring stations (ATZX and GY).

3.2.4. Canteen

As shown in Figure 8a, the $PM_{2.5}$ concentrations at the canteen site surpassed those recorded at the GY station around 12:00. Between 11:00 and 13:00, the sampling was occasionally influenced by southerly winds. The sampling point was located on the south side of the Yimin Canteen. This could account for the changes in $PM_{2.5}$ concentrations as the emissions from the lunchtime catering sources were a significant source of $PM_{2.5}$. In Figure 8b, the wind consistently originated from the east, resulting in a relatively stable $PM_{2.5}$ level at the canteen site during the lunch period. The $PM_{2.5}$ concentrations mirrored the trends recorded at the GY station. For example, between 12:00 and 14:00, as RH rose, the $PM_{2.5}$ levels at both the canteen sampling location and the GY station exhibited synchronized accumulation trends.

Figures 7b and 8b reveal that, when campus sources had minimal influence, the outdoor $PM_{2.5}$ concentrations within campus mirrored those at the GY station, with the pollution level being 29% and 56% lower in non-heating season (Figure 7b) and heating season (Figure 8b), respectively. The sampling sites of Lake Ming and the canteen exhibited a strong correlation between CO_2 and $PM_{2.5}$ concentrations, indicating that $PM_{2.5}$ and CO_2 had the same origin. However, during the heating season, the two outdoor campus sites exhibited a CO_2 trend that did not entirely align with the $PM_{2.5}$ trend observed at the GY site or within the campus itself. This suggests that the factors affecting CO_2 concentration on campus during heating season are multifaceted and necessitate additional investigation and analysis.

3.2.5. Laboratory

The laboratory observations were conducted in a sealed indoor setting, where windows and doors were kept shut throughout the duration of the observations to prevent any human interference. The room was air-conditioned, maintaining relatively constant temperature and RH. For example, the temperature remained within a range of 18–20.5 °C.

The CO_2 concentration in the laboratory correlated well with the CO concentration at the GY site, with R^2 values of 0.81 and 0.77 before and during heating season, respectively, indicating a good homogeneity between the laboratory CO_2 and the CO in the surrounding urban area. Meanwhile, the $PM_{2.5}$ in the laboratory also closely mirrored those at the GY site, with R^2 values of 0.94 and 0.85, respectively. However, the average $PM_{2.5}$ concentration in the laboratory was only 60% and 50% of the concentration at the GY site during the respective periods. This once again proves that while a closed indoor space is often perceived as an isolated air system, it actually exchanges air with the outdoors, making indoor $PM_{2.5}$ pollution synchronized with outdoor pollution. There is a certain delay and filtering effect in the diffusion of local emissions into the indoor environment, as evidenced by the indoor observations not reflecting the high $PM_{2.5}$ levels at the GY site between 19:00 and 20:00 on December 17th. Our research suggests that effectively managing indoor CO_2 and $PM_{2.5}$ levels necessitates a reduction in the overall urban concentrations of PM and CO_2.

3.3. The Impact of Surrounding Air Pollution on the Pollution within the Campus

In Table 1, linear correlation analyses between air pollutants were conducted to investigate the impact of surrounding air pollution on the pollution within the campus. The NO_2 and $PM_{2.5}$ at the GY station consistently exhibited a high positive correlation, except during the heating sampling period at the Lake Ming site. This suggests a significant contribution of nitrogen oxide emissions from Beijing's traffic sources to outdoor $PM_{2.5}$. The emissions from traffic sources, as indicated by NO_2 and CO levels around the BJTU campus, exhibited dynamic changes across different episodes and seasons. Similarly, the relationship between O_3 and $PM_{2.5}$ concentrations demonstrated dynamic fluctuations, influenced by traffic emissions, photochemical processes, and ozone oxidation [32–34]. This may explain why the $PM_{2.5}$ concentration trends observed in the functional areas on campus appear smoother compared to those recorded at the GY station. It is worth noting that we assume that analysis results with a data sampling duration exceeding 24 h are more statistically significant; therefore, these analysis results are in bold in Table 1. In sampling cases exceeding 24 h, there was almost no correlation between O_3 and $PM_{2.5}$. This is because ozone accumulation is highly dependent on solar radiation. Periods of increased solar radiation usually correspond to reduced emissions and the lifting of the boundary layer, resulting in a decrease in near-surface $PM_{2.5}$ concentrations.

Table 1. Linear correlations between atmospheric pollutants during the sampling period. The black bold font represents the analysis results of the data set with an observation duration exceeding 24 h.

		Non-Heating Season		Heating Season	
		R^2	*Slope*	R^2	*Slope*
NO_{2_GY} vs. $PM_{2.5\_GY}$	Office	0.95	2.12	**0.66**	**0.82**
	Dormitory	0.5	1.54	0.85	0.24
	Lake Ming	0.44	0.90	0.64	−0.94
	Canteen	0.99	2.61	0.90	0.75
	Laboratory	**0.29**	**0.75**	**0.62**	**1.47**
O_{3_GY} vs. $PM_{2.5\_GY}$	Office	0.95	−4.72	**0.21**	**−0.37**
	Dormitory	0.41	−1.42	0.97	−0.34
	Lake Ming	0.98	−4.05	0.74	1.10
	Canteen	0.94	−6.99	0.57	−0.78
	Laboratory	**0.10**	**−0.59**	**0.46**	**−1.12**
$PM_{2.5\_BJTU}$ vs. $PM_{2.5\_GY}$	Office	0.11	−0.20	**0.91**	**0.28**
	Dormitory	0.49	0.71	0.89	0.08
	Lake Ming	0.21	−0.45	0.86	0.58
	Canteen	0.82	1.35	0.78	0.40
	Laboratory	**0.94**	**0.56**	**0.85**	**0.37**
CO_{2_BJTU} vs. $CO_{\_GY}$	Office	0.89	215	**0.51**	**112.67**
	Dormitory	0.18	1585.71	0.63	−2490.38
	Lake Ming	0.27	152.50	0.64	−226.43
	Canteen	0.62	128.57	0.26	10.90
	Laboratory	**0.81**	**130.31**	**0.77**	**138.49**
CO_{2_BJTU} vs. $PM_{2.5\_BJTU}$	Office	0.19	−3.32	**0.48**	**4.79**
	Dormitory	0.07	−22.82	0.81	−102.95
	Lake Ming	0.39	2.62	0.34	−6.53
	Canteen	0.44	3.45	0.41	1.64
	Laboratory	**0.73**	**3.00**	**0.69**	**4.29**

Moreover, there were also strong positive correlations between campus CO_2 and campus $PM_{2.5}$, and urban CO (R^2 range of 0.48–0.73), as well as between campus $PM_{2.5}$ and the $PM_{2.5}$ at the GY station (R^2 range of 0.85–0.94), suggesting that these pollutants share common sources, primarily motor vehicles [35]. All in all, the air quality on campus is generally affected by the air pollution level in the surrounding urban area, which leads to consistent average trend changes in CO, CO_2, and $PM_{2.5}$ concentrations. The correlations between campus $PM_{2.5}$ and CO_2, and between the urban station's CO and $PM_{2.5}$, can become more dynamic when factors such as human respiration, the lake ecosystem, or catering source emissions on campus significantly influence the levels of these pollutants.

3.4. Average Pollution Characteristics across Different Functional Areas on Campus

During the heating period, the average temperature and RH at the campus sites were both relatively lower. Furthermore, the NO_2/O_3 and $PM_{2.5}/O_3$ ratios at the GY station exhibited an increasing trend (Figure 10), with a particularly notable increase in $PM_{2.5}$ concentration (Figure 11). The increase in NO_2/O_3 and $PM_{2.5}/O_3$ ratios indicates that traffic emissions during the heating season were an important source of pollution. The $PM_{2.5}$/CO ratio remained largely unchanged throughout the heating period, except for the results at the dormitory site. This suggests that the concentration of CO during the heating season was consistent with the increasing trend of $PM_{2.5}$ and remained at a higher level. Consequently, focusing on traffic sources could be a highly effective strategy for reducing air pollution in the urban area around the campus.

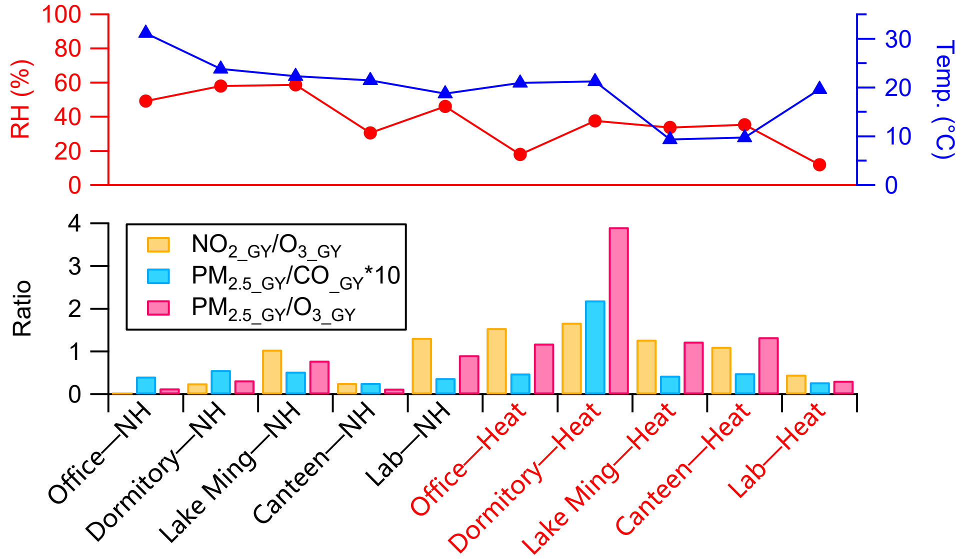

Figure 10. Average characteristics of temperature and RH in representative functional areas on campus, as well as the ratios between air pollutants at the GY station.

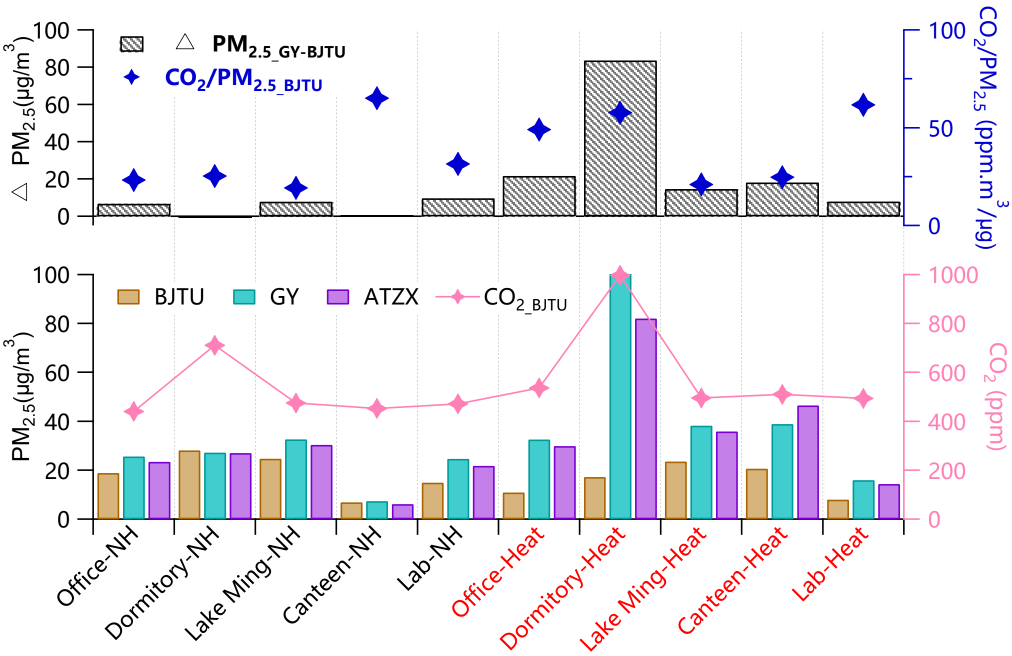

Figure 11. Variations in $PM_{2.5}$ and CO_2 concentration, and the $CO_2/PM_{2.5}$ ratio before and during the heating period in typical campus functional areas, as well as the difference in $PM_{2.5}$ concentrations between the GY station and the campus.

In Figure 11, except for the canteen site, the $PM_{2.5}$ levels on campus decreased by an average of 7 $\mu g/m^3$ during the heating period compared to the non-heating period. The heating sampling period at the canteen site occurred during more polluted periods, with $PM_{2.5}$ levels reaching 39 $\mu g/m^3$ at the GY station. Conversely, the non-heating sampling period at the canteen site took place during less polluted periods, with $PM_{2.5}$ levels at both the canteen and GY sites at only 7 $\mu g/m^3$. This minimal level during the non-heating period left little room for further reduction in $PM_{2.5}$ levels on campus during the heating period.

The average $PM_{2.5}$ concentrations at the campus sampling sites during the heating period were 29 $\mu g/m^3$ lower than the concentrations measured at the GY station. This difference is significantly greater than the 5 $\mu g/m^3$ difference observed during the non-heating period. These findings suggest that the indoor and outdoor environments on campus have lower pollution levels during both periods, with a more pronounced improvement during the non-heating period.

The emission factors of CO_2 and $PM_{2.5}$ in the atmosphere tend to change with variations in pollution control measures [36]. The average concentration of CO_2 remained relatively stable, with elevated values primarily observed in the dormitories. This trend suggests the impact of human breathing activities. The higher $CO_2/PM_{2.5}$ ratios were at the canteen site during the non-heating period and at the office, dormitory, and laboratory sites during the heating period. Notably, the elevated $CO_2/PM_{2.5}$ ratios at the canteen (65 ppm·m^3/µg) and the laboratory (62 ppm·m^3/µg) during the heating period were a result of extremely low $PM_{2.5}$ concentrations (<8 µg/m^3). When the two lowest $PM_{2.5}$ values are removed, the $CO_2/PM_{2.5}$ ratio and the $PM_{2.5}$ concentration tend to exhibit a stronger correlation coefficient. The linear correlation coefficients (r) for $PM_{2.5\_BJTU}$, $PM_{2.5\_GY}$, and $PM_{2.5\_GY\text{-}BJTU}$ are −0.7, 0.7, and 0.8, respectively. This indicates that the CO_2 concentration on campus is also primarily determined by the air pollution in the urban area surrounding the campus [37]. The high $CO_2/PM_{2.5}$ ratios at the office (49 ppm·m^3/µg) and dormitory (58 ppm.m^3/µg) during the heating period were attributable to increased human breathing activities and reduced $PM_{2.5}$ levels. Lake Ming exhibited the lowest $CO_2/PM_{2.5}$ levels (Figure 11), indicating that it maintains a low relative CO_2 concentration. Beyond its appealing surroundings, the lower CO_2 levels at Lake Ming contribute to an enhanced experience of leisure and tranquility.

3.5. Variations in $PM_{2.5}$ Concentration across Different Campus Functional Areas

Figure 12 reveals that between 18:00 and 20:00 on 8 December 2023, the $PM_{2.5}$ levels at the GY site increased from 92 µg/m^3 to 98 µg/m^3, suggesting that the air quality in urban Beijing reached a significant pollution level. On campus, $PM_{2.5}$ concentrations varied between 44 and 60 µg/m^3, with the lowest readings recorded in the 1st Canteen (C1) and the highest at the entrance of the 16th Dormitory (C7). The black dashed line, which connects these two $PM_{2.5}$ levels, represents the average trend of $PM_{2.5}$ increase across the campus over time. Notably, the slope of this average trend is less steep than that observed at the GY site. This discrepancy suggests that the external pollution intensity exceeded that within the campus boundaries. Consequently, the $PM_{2.5}$ concentration first escalated in the urban area surrounding the campus before infiltrating the campus, resulting in a rise in $PM_{2.5}$ levels within the campus.

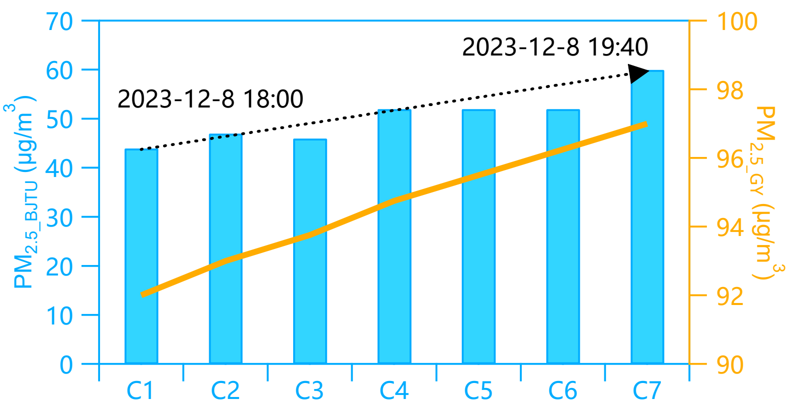

Figure 12. The $PM_{2.5}$ concentration across various functional areas of the campus and at the GY station. The black dashed line connects the minimum value at site C1 and the maximum value at site C7, representing the fitted average $PM_{2.5}$ concentration profile across the campus.

C2 was situated on the playground adjacent to the school's West Gate, with a busy road just outside. This location is significantly influenced by external emissions, resulting in $PM_{2.5}$ levels that surpass the average trend. C3 was positioned at the entrance of the Siyuan Building, centrally located on campus, surrounded primarily by academic buildings and green spaces. The $PM_{2.5}$ concentration at this site was below the average trend, suggesting a reduction in $PM_{2.5}$-contributing sources around the teaching blocks. C4 was at the entrance of the Red Orchard Restaurant, near other dining locations like the Liuyuan Canteen. During dinner time (18:55), due to the outdoor activities of teachers and students and the emissions from cooking, the $PM_{2.5}$ level was higher than the average. C5 was situated at the library entrance, close to Lake Ming (C6) and the verdant Fanghua Garden leisure zone. $PM_{2.5}$ readings at both sites were below average, suggesting cleaner air in these recreational spaces. C7 was positioned at the entrance to the student dormitories, with several canteens nearby and close to the campus's East Gate. The influx and outflow of faculty and students, coupled with bustling traffic involving pedestrians, cyclists, and electric vehicles, led to an increase in emissions from catering and dust, making the $PM_{2.5}$ concentration at this site the highest recorded.

The above analysis reaffirms the presence of variations in $PM_{2.5}$ levels across different functional areas of the campus. It is observed that indoor $PM_{2.5}$ levels are consistently lower compared to outdoor levels. Furthermore, the concentration of $PM_{2.5}$ within the campus boundaries is notably lower than that in the adjacent areas. The primary contributors to $PM_{2.5}$ within campus include dust from human activities, vehicle emissions, and those from catering services.

4. Conclusions

This study analyzed the pollution characteristics of $PM_{2.5}$ and CO_2 in typical functional areas of BJTU campus, namely, office, dormitory, leisure area, canteen, and laboratory, using low-cost sensor devices. The findings indicate that the air quality in the urban environment enveloping the campus impacts the campus's atmospheric pollution levels. However, the $PM_{2.5}$ concentration within the campus is significantly lower.

The $PM_{2.5}$ and CO_2 concentrations vary across different functional areas of the campus. Indoor $PM_{2.5}$ concentrations are generally lower than outdoor levels, while CO_2 concentrations in enclosed indoor spaces with human activities will continue to increase. The main campus internal $PM_{2.5}$ sources include traffic and dust generated by human activities, and emissions from catering. Furthermore, in areas with better green coverage or where a lake system participates in the atmospheric circulation, the $PM_{2.5}$ level is lower. This indicates that the cleansing impact of plants and aquatic systems is instrumental in lowering $PM_{2.5}$ concentrations.

During the non-heating period, the reduction in pollution source emissions leads to decreased outdoor $PM_{2.5}$ concentrations. Additionally, the higher temperatures encourage window ventilation, resulting in negligible variance from the readings at the nearby GY station (Figure 11). Conversely, during the heating season, emissions from heating in the vicinity of Beijing, coupled with increased vehicle emissions due to colder conditions, result in heightened outdoor $PM_{2.5}$ concentrations. Simultaneously, $PM_{2.5}$ concentrations on the campus are substantially lower than those observed at the GY station.

Approximately ninety percent of an individual's life is spent indoors, highlighting the importance of optimizing indoor air quality for health reasons [38]. Opening and closing windows greatly influences the levels of $PM_{2.5}$ and CO_2 within indoor spaces. In situations where there is an absence of a distinct indoor source of $PM_{2.5}$, a sealed room tends to decrease $PM_{2.5}$ concentrations. However, the respiration of individuals results in the accumulation of high CO_2 levels. For example, this study found that in a 15 m^2 dormitory occupied by one individual, with windows and doors sealed, the CO_2 concentration can surge to 2303 ppm during the night while the individual is asleep. This highlights the need for balanced ventilation strategies to maintain both low $PM_{2.5}$ and acceptable CO_2 levels. For example, in environments with elevated outdoor pollution levels, it is imperative to employ a fresh air system to prevent the infiltration of $PM_{2.5}$ particles and mitigate indoor CO_2 accumulation. However, on days with minimal outdoor pollution, such as when $PM_{2.5}$ levels are at 10 $\mu g/m^3$ or lower, opening windows to ventilate can significantly enhance health outcomes. In high-density living spaces, such as dormitories, even without ventilating to the outdoors, simply opening the dormitory doors can suffice to decrease CO_2 levels. Therefore, for students who are socially active and frequently interact with peers, such behavior might not only foster social skills but also support a healthier living environment.

This research provides improved scientific insights that can inform the advancement of campus environmental management. The recommendations may involve optimizing traffic patterns, effectively managing dust at construction sites, and expanding green spaces. Further detailed and regional-specific monitoring and analysis of air quality both inside and outside campus areas should be valuable and pursued to offer more scientific guidance.

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