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ORIGINAL PAPER

An investigation of the $PM_{2.5}$ concentrations and cumulative inhaled dose during subway commutes in Changchun, China

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Abstract

Air quality in subway systems is crucial as it affects the health of passengers and staff. Although most tests of $PM_{2.5}$ concentrations in subway stations have taken place in public areas, $PM_{2.5}$ is less understood in workplaces. Few studies have estimated the cumulative inhaled dose of passengers based on real-time changes in $PM_{2.5}$ concentrations as they commute. To clarify the above issues, this study first measured $PM_{2.5}$ concentrations in four subway stations in Changchun, China, where measuring points included five workrooms. Then, passengers' exposure to $PM_{2.5}$ during the whole subway commute (20–30 min) was measured and segmented inhalation was calculated. The results showed that $PM_{2.5}$ concentration in public places ranged from 50 to 180 μg/m^3, and was strongly correlated with outdoors. While the $PM_{2.5}$ average concentration in workplaces was 60 μg/m^3, and it was less affected by outdoor $PM_{2.5}$ concentration. Passenger's cumulative inhalations in single commuting were about 42 μg and 100 μg when the outdoor $PM_{2.5}$ concentrations were 20–30 μg/m^3 and 120–180 μg/m^3, respectively. The $PM_{2.5}$ inhalation in carriages accounted for the largest proportion of the entire commuting, about 25–40%, because of the longer exposure time and higher $PM_{2.5}$ concentrations. It is recommended to improve the tightness of the carriage and filter the fresh air to improve the air quality inside. The average daily $PM_{2.5}$ inhaled by staff was 513.53 μg, which was 5–12 times higher than that of passengers. Installing air purification devices in workplaces and reminding staff to take personal protection can positively protect their health.

Keywords $PM_{2.5}$ · Investigation · Subway station · Workplaces · Cumulative inhaled · Air quality

Introduction

The subway has become an important component of urban transportation. More and more people are choosing to travel by subway because of its punctuality and stability. As in a public building, air quality in subway stations is directly related to the health and safety of passengers and workers. $PM_{2.5}$ (particulate matter with an aerodynamic equivalent diameter ≤ 2.5 μm) is currently one of the more concerning air pollutants. $PM_{2.5}$in subway stations partly come from outdoor environments, such as industrial combustion and traffic emissions, as well as tunnels, through the wear of steel rails and brake systems (Chang et al. 2021). Subway structures are relatively complex and diverse, most of which are located underground. These semi-closed internal spaces are connected to the atmospheric environment mainly through entrance/exit channels, tunnel air shafts, and ventilation systems, which are not conducive to $PM_{2.5}$ diffusion in stations. Test studies in many cities, including Philadelphia (Shakya et al. 2020), Lisbon (Correia et al. 2020), Seoul

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(Son et al. 2021), Naples (Carteni et al. 2020), Boston, and Washington DC (Luglio et al. 2021), have shown that $PM_{2.5}$ concentrations in subway stations were significantly higher than outdoors. In many subway stations, $PM_{2.5}$ concentrations exceed the indoor air quality standard. For example, $PM_{2.5}$ concentrations on some subway platforms in Stockholm were higher than the air quality standard of 65 μg/m^3 set by the US Environmental Protection Agency (US-EPA) (Johansson. and Johansson, 2003). $PM_{2.5}$ concentrations in some subway stations in Seoul ranged from 77.7 to 158.2 μg/m^3, which also exceeded the EPA standard (Park and Ha 2008). $PM_{2.5}$ concentrations in some platforms and carriages of the Beijing subway system (25.4–145.5 μg/m^3) were higher than China's national indoor air standard ($PM_{2.5}$: 50 μg/m^3), and the same was true for Shanghai subways (He et al. 2018) (Xu et al. 2016). The 24-h concentrations in Mexican subway stations exceeded the Mexican standard of 45 μg/m^3 (Figueroa-Lara et al. 2019). There have also been concerns that $PM_{2.5}$ in subways contains more metals than in outdoor environments, such as Fe, Cu, Ba, and Al (Kam et al. 2011a, b; Ryswyk. et al. 2017; Zhang et al. 2011). Ji et al. reported that the indoor/outdoor (I/O) ratios for Fe, Cu, Mn, Sr, and V were 55.1, 16.5, 10.2, 9.6, and 7.1 in summer and 45.1, 14.1, 8.7, 6.2, and 5.2 in winter. Average daily Fe exposures for subway workers and commuters were 15.5 and 2.0 μg/m^3, respectively (Ji et al. 2021). Some studies have argued that short-term exposure to subways $PM_{2.5}$ containing higher concentrations of Fe, Cu, and other transition metals from underground stations can have acute effects on respiratory epithelial cells (Jia et al. 2018; Loxham et al. 2015; Zhang et al. 2019). Most importantly, $PM_{2.5}$ can easily become a carrier of toxic and harmful substances like bacteria or viruses, which pose a health risk to exposed people, such as the current COVID-19 (Coronavirus Disease 2019) global pandemic. The New Coronavirus Pneumonia Diagnosis and Treatment Plan (Trial Version 8) issued by the National Health Commission of China pointed out that the virus may spread through aerosols when exposed to high viral concentrations over a long time in a relatively closed environment. The World Health Organization (WHO) has also reported the same scenario. People infected with the coronavirus release virus particles when coughing, speaking, and during exhalation. These viruses generally exist in droplets (< 5 μm) (Liu et al. 2017). In addition, particulate pollution can damage the human respiratory tract and may promote viral infections (Mehmood et al. 2020). Subway spaces are relatively closed off and lack sunlight; in addition they are crowded with people, which can easily cause the spread of diseases.

$PM_{2.5}$ concentrations in subway stations in different cities vary greatly according to background concentrations. In the Northeastern United States, mean $PM_{2.5}$ concentrations measured in most underground subway stations in Boston, Philadelphia, and Washington, DC were 327 ± 136 μg/m^3, 112 ± 46.7 μg/m^3, and 341 ± 147 μg/m^3, respectively (Luglio et al. 2021). In contrast, concentrations in Lisbon subway stations were significantly lower, averaging 37.8 ± 20.8 μg/m^3 (Correia et al. 2020). At present, there have been many measurements of $PM_{2.5}$ in subways around the world, most of which were conducted in public areas, such as platforms and carriages. There is no doubt that this has been related to the health and safety of countless passengers. However, there is still very little known about $PM_{2.5}$ characteristics in subway station workplaces, which is related to staff health. Although they make up fewer people than passengers, their daily exposure time is much longer.

To assess the health risks of passengers exposed to subway environments, some studies have calculated passenger inhalation based on $PM_{2.5}$ concentrations, as shown in Table 1. For example, during a 67-min subway commute in Lisbon, passengers inhaled about 25 μg of $PM_{2.5}$ (Correia et al. 2020). $PM_{2.5}$ inhalation during a 5.7-min subway ride in Xi'an was 5 μg (Zheng et al. 2021). The intake of $PM_{2.5}$ per 15 min in the Delhi subway was 35 μg, and per kilometer was 11 μg (Goel et al. 2015). In Singapore, the $PM_{2.5}$ intake during a 14.3-min subway trip was 8.9 μg (Tan et al. 2017). These studies estimated subway commuting exposure risk levels in different cities, but inhalation at different locations within a subway system is not well understood. Aside from Singapore, other cities only had one value for the total commute despite changing $PM_{2.5}$ concentrations, which makes it difficult to provide a reference for targeted mitigation measures. Many studies have emphasized the importance of air quality in platforms and carriages, in which passengers are

Table 1 The inhalation of subway $PM_{2.5}$ in different cities

City	Subway type	Section	Duration (minute)	Outdoor $PM_{2.5}$ concentration (μg/m^3)	Inhalation (μg)
Lisbon (Correia et al. 2020)			67	30.5 ± 9.0	25
Xi'an (Zheng et al. 2021)		P–P*	5.7	72.4	5
Delhi (Goel et al. 2015)	Underground		15	133–157	35 or 11 μg/km
Singapore (Tan et al. 2017)	Underground	O–O**	14.3	27 ± 7	8.9

* P–P: The measurement started at one platform and ended at another

** O–O: The measurements began outside one station and ended outside another station exposed for a long time. However, from the perspective of inhalation, the effects of respiration rate, exposure duration, and concentration on health risk should be considered.

The underground rail transit in Changchun started operation in 2017. Internal particulate pollution must be measured in the new subway line to provide more accurate information for improving air quality. To our knowledge, this is the first test of $PM_{2.5}$ concentrations in stations after this subway line was opened. To understand the particulate pollution status of this new subway system, including public and working areas, and provide more accurate information to reduce exposure, first the $PM_{2.5}$ concentrations in subway stations were tested. Then, $PM_{2.5}$ concentrations in public areas and working spaces were summarized and the relationships between concentrations inside and outside the station were compared. Finally, $PM_{2.5}$ inhalation by staff and passengers were estimated to assess the health risks in the subway environment and identify high-risk microenvironments. Passengers' segmented and cumulative inhalation were calculated according to the real-time $PM_{2.5}$ concentration changes during the entire commuting process.

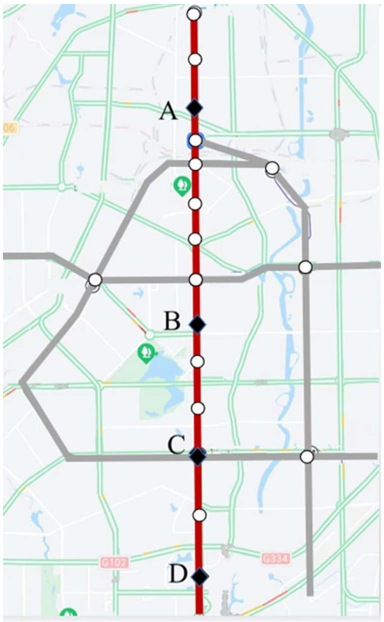


Fig. 1 Location of sampling line and stations

Materials and methods

Subway stations

Changchun is located in northeast China and is an important industrial base with a permanent population of more than nine million. There are five subway lines in Changchun with an average daily ridership of 433,000 in 2020 (METROS, 2021), and the first ground rail transit opened in 2002. The first underground line (Line 1) opened in 2017 and was selected for this study. The 40.10 km line runs along a north–south axis through the city with 15 underground stations, including four interchange stations. The city experiences long and cold winters with average outdoor temperatures less than 0℃ for five months of the year. Therefore, outside ventilation is minimized to maintain the temperature inside the stations during winter. The $PM_{2.5}$ concentrations of Line 1 were measured at four stations (A, B, C, and D) as shown in Fig. 1, of which station C is a transfer station and the other three are common stations. The selected subway stations are two floors underground, the platform is located on the second floor, and there is a platform screen door (PSD) installed between the platform and the tunnel. The hall and working area are located on the first underground level. In the working area of the tested subway stations, the communication room and security room are respectively equipped with system communications and security equipment, and there are staff to inspect them regularly. The meeting room can accommodate 15–20 people and is also used for daily staff rests with about four people in the room except during meetings. The car control room is equipped with various control panels for centralized dispatching and three to four staff on duty. The administration room has no large equipment and one to two staff. Data collection was conducted in December and January, the air conditioning in the subway station was closed, and the fresh air units and exhaust fans in the public and working areas were turned off, but a vent was opened at each end of the platform for partial piston wind flow. Station areas were mainly exhausted through natural ventilation at the entrance channels and the platform doors.

Equipment

The portable DUSTTRAK II monitor (TSI Model 8532) has been widely used to measure particulate concentrations in existing studies (Shen and Gao 2019; Xu et al. 2016), was used in this test. The instrument was equipped with a 90° light scattering sensor that can display particle concentration in real time and store data. It can measure different particle concentrations by replacing the calibration impactors. A zero calibration process was conducted using a zero filter before each test. The measuring range of the instrument is 0.001–150 mg/m^3, the accuracy is $\pm 0.1\%$, and the sampling interval ranges from 1 to 60 s.

Data collection

During testing, the subway stations ran under normal conditions, and it was sunny outside, with no sudden weather changes such as wind or rain. All data collection was completed during the non-peak period from 9:30 to 16:00 and included fixed-point and dynamic tests. In the fixed-point tests, $PM_{2.5}$ concentrations in outdoor and different spaces of subway stations were measured simultaneously, including public areas (halls, platforms, and carriages) and workplaces (communication, security, meeting, car control, and administration rooms). Sampling height was 1.5 m, the interval was set to one minute, and the single test time at each measuring point was 30 min, with sampling intervals of one minute. Data collection lasted for two weeks in public areas, and two days in workplaces with official permission.

A subway commuting route was selected for real-time testing of particulate matter concentrations between A and B station, which took 20–30 min. Station B was located in the center of the city, while Station A was on the edge of the city, passing through seven other subway stations during the commute. The instrument was carried by a person to record $PM_{2.5}$ concentrations during the commute in real time, and keep the sampling inlet at the height of the breathing zone (about 1.5 m), with sampling intervals of one second. Outdoor $PM_{2.5}$ concentrations at the start and end of the commute were also measured by the same instrument, where located about 150 m from the entrance of the subway station.

Cumulative inhaled dose

Passengers usually pass through four spaces when commuting by subways, including the outdoors, the halls, platforms, and carriages. Particulate matter concentrations in different spaces are not the same, and there may even be large differences between them (Park and Ha 2008; Zhao et al. 2017), such as between platforms and outdoors (Martins et al. 2016; Raut et al. 2009). In addition, particulate matter concentrations in subway stations fluctuate due to piston wind (Wang et al. 2016), and concentrations in carriages also change with the running of trains (Xu et al. 2016; Zheng et al. 2016). In this paper, the cumulative dose of particulate matter inhaled by passengers were calculated based on dynamic concentration changes (one second interval) during commuting. The formula for estimating inhalation dose is (Ramos et al. 2015, 2016):

$$\text{Dose}(\mu g) = \sum_{i=1}^{T} C_i \times V_E / \left(6 \times 10^4\right) \tag{1}$$

where C_i is the particulate matter concentration at time i, $\mu g/m^3$; T is the total time of a round trip commute, seconds; V_E is the inhalation rate, L/min, 1 L/min$=10^{-3}\text{m}^3/\text{min} = 1/\left(6 \times 10^4\right)\text{m}^3/\text{s}$.

Particulate matter concentrations in workplaces were measured at one minute intervals. Therefore, the formula for calculating the cumulative dose of particulate matter inhaled by employees in one day is as follows:

$$\text{Dose}(\mu g) = \sum_{i=1}^{t} C_i' \times V_E \times 10^{-3} \tag{2}$$

where C_i' is the average particulate matter concentration measured at a one-minute interval, $\mu g/m^3$; t is the work times in one day, minutes.

The per-minute ventilation V_E, also known as the inhalation rate, is defined as the volume of air that enters the lungs per minute (Tan et al. 2017). V_E depends on heart rate, the body size of the subject, activity level and health status (Martins et al. 2015; Ramos et al. 2016). There are two methods for estimating V_E. One is based on the metabolic equivalents of task or breathing rate (USEPA 2011). Recommended values are given according to activity intensity, age, gender, and physique. The other method is based on heart rate. Researchers have proposed the relationship between inhalation rate and heart rate to be (Zuurbier et al. 2009):

$$V_{\text{E}} = e^{0.022\text{HR}+0.89} \tag{3}$$

where HR is heart rate, in beats per minute (bpm).

Based on Formula 3, Tan et al. (2017) calculated V_E values that were more representative of Asian people in Singapore using heart rate data from volunteers (including male and female) during different commuting modes, and V_E values for different segments of subway commuting are shown in the table below. Due to similar commuting scenes and passenger physiques, the data in Table 2 were used in Formula 1 to calculate the cumulative dose of particulate matter inhaled during commuting, and corresponding V_E values were adopted in different spaces. Staff in the working area sit down most of the time, and their activity intensity is similar to that of passengers in the carriage.

Table 2 V_E values for different segments of subway commuting

	Section	V_E(L/min)
In-vehicle	Train	18.5
Indoor	Hall floor	25.1
	Platform	19.7
Outdoor	Sidewalk	23.9

Results and discussion

$PM_{2.5}$ concentrations in public areas of subway stations

$PM_{2.5}$ concentrations were measured in the public areas of Stations A, B, C, and D. Although tests in the four subway stations were conducted on four different days, the outdoor $PM_{2.5}$ concentrations were similar. Furthermore, the data from all four subway stations were collected during off-peak hours with a test duration for each position of 30 min. As seen in Table 3, $PM_{2.5}$ average concentrations on most subway station platforms were slightly higher than in the hall, but the differences were not significant. Except for Station A, concentrations in the other three subway stations were greater than those outdoors. $PM_{2.5}$ average concentrations in those three stations ranged from 130 to 173 μg/m^3, which were about twice the Chinese indoor air quality standard ($PM_{2.5}$: 50 μg/m^3) (State Administration for Market Regulation and Administration, 2022). The average concentration in the platform of station A was 77.7 μg/m^3, which was slightly above the standard.

Table 3 The $PM_{2.5}$ average concentrations in public areas of subway stations. (Unit: μg/m^3)

Stations	Outdoor ($n=30$)	Hall ($n=30$)	Platform ($n=30$)	I (platform) /O ratio
A	111	67.3	77.7	0.70
B	114	126	130	1.14
C	96	150	150	1.56
D	93	174	173	1.86

$PM_{2.5}$ concentration levels in Stations B, C, and D were obviously greater than Station A, about twice as high. The results were similar to the Philadelphia subway. There are significant differences in internal particulate concentrations between subway stations in the same city (Shakya et al. 2020). Under similar outdoor concentrations, the reasons for this difference may be the subway design or the surrounding station environments. For example, Station D with the highest $PM_{2.5}$ concentrations had a separate hall and only two entrances, while other stations had integrated halls and three to six entrances. More unobstructed spaces and channels to the outdoors are more conducive to air flow and particle dispersion in subway stations (Shakya et al. 2020).

According to Chinese regulations (HJ633-2012) (Ministry of Environmental Protection, 2012), the outdoor air quality in Table 3 was slightly polluted ($PM_{2.5}$ concentration ranging from 75 to 115 μg/m^3), whereas all subway stations were moderately or heavily polluted. Existing studies have shown that $PM_{2.5}$ concentrations in subway stations are strongly influenced by outdoor concentration (Chang et al. 2021). To compare the differences in $PM_{2.5}$ concentrations in subway stations in different cities under similar outdoor $PM_{2.5}$ concentrations, this paper summarized other $PM_{2.5}$ concentration measurements from underground station platforms under similar outdoor conditions, as shown in Table 4. The cities tested were all located in Asia, most of which were in China. The $PM_{2.5}$ concentrations of subway stations measured in this paper were slightly lower than the Suzhou subway stations. The Delhi subway $PM_{2.5}$ concentration was relatively low, even though the outdoor concentration was slightly higher than other tests. This may have been related to the line characteristics, of which only 48 km of the 190 km line is underground, and ground rail transit is conducive to the diffusion of particulate matter. Generally speaking, $PM_{2.5}$ concentrations in underground stations in

Table 4 $PM_{2.5}$ concentrations measured on platforms at different underground stations worldwide. (Unit: μg/m^3)

City	Open time	(Mean) concentration indoor	(Mean) concentration outdoor	Line	Platform door	Time period	Test time	I/O ratio
Suzhou (Cao et al. 2017)	2012, 2013	198	111	L1	PSD	Non-peak	Spring and summer, 2015	1.78
Xi'an (Qiu et al. 2017)	2011	43.2–77.6	48.5–122.3	L2	PSD	Non-peak	5/2016	0.63
Beijing(He et al. 2018)	2008	133.9 ± 13.9	117	L10	Full-height safety door	Non-peak	12/2014	1.24
	2008	145.5 ± 11.7	117	L8	PSD			1.47
Beijing (Pan et al. 2019)	2013	174 ± 32	117 ± 37	L14	Full-height safety door	Non-peak	10/2016	1.78
Seoul (Kim, et al., 2008)	1974–1985	150	102.1	L1-4			11/2004–2/2005	1.14
Delhi (Goel et al. 2015)	2002–2011	76	133	L2			1–5/2014	1.49

different cities under the same outdoor concentrations were not obviously different, though some differences may have been caused by operating years, platform door form, test period, and other reasons. In future studies, it is hoped that scholars will record more information about the subway stations, such as air conditioning and ventilation operation strategies, and building structures, which will provide a more detailed reference for comparison.

Subway to outdoor $PM_{2.5}$ concentration ratios (I/O) in different cities were calculated based on the data in Tables 3 and 4. I/O ratios in most subway stations were between one to two, which was the same as Mexico (1.1–1.9) (Mugica-Álvarez et al. 2012), Los Angeles (1.7) (Kam et al. 2011a, b), and Tehran (1.48) (Kamani et al. 2014). The I/O ratios at Station A were less than one, similar to Turin Metro Station (0.7–0.8) (Cartenì and Cascetta 2017). In some cities, the I/O ratio was greater than five, such as Stockholm (5–10) (Johansson. and Johansson, 2003), Helsinki (5–6) (Aarnio et al. 2005), Athens (6.9) (Martins et al. 2016), and Paris subway stations (5–30) (Raut et al. 2009). Therefore, many scholars believe that some of the $PM_{2.5}$ in subway stations is generated in the station, such as the friction between metal track and wheels when the vehicle is running, and the friction loss of the brake pads when braking.

The tests in this paper were conducted during non-peak hours to avoid safety risks at peak passenger flow. Existing studies were used to understand the $PM_{2.5}$ concentration differences between peak and non-peak hours in subway stations. A study from Shanghai showed that $PM_{2.5}$ concentrations during peak hours were 1.05–1.14 times higher than during non-peak hours in the platforms (Zhao et al. 2017). Another study in London showed that $PM_{2.5}$ concentrations in platforms during peak hours were 1.32 times higher than during non-peak hours (Chong et al. 2015). Those studies showed that the $PM_{2.5}$ concentrations during peak hours were slightly higher than those during non-peak hours. When $PM_{2.5}$ concentrations in public areas of subway stations during peak hours cannot be obtained, the data obtained during non-peak hours can also largely reflect $PM_{2.5}$ exposure levels in subway stations.

$PM_{2.5}$ concentrations in workplaces

Subway work areas are restricted to people other than employees, and with the permission of the management, $PM_{2.5}$ concentrations in the five working rooms of Station A were tested twice on two separate days (Day 1 and Day 2) under different outdoor conditions, and the results are shown in Fig. 2. Each column in Fig. 2 is the average of 30 values, representing the average $PM_{2.5}$ concentration measured at each point over a 30-min period. Concentrations differed little between the working rooms. When the outdoor

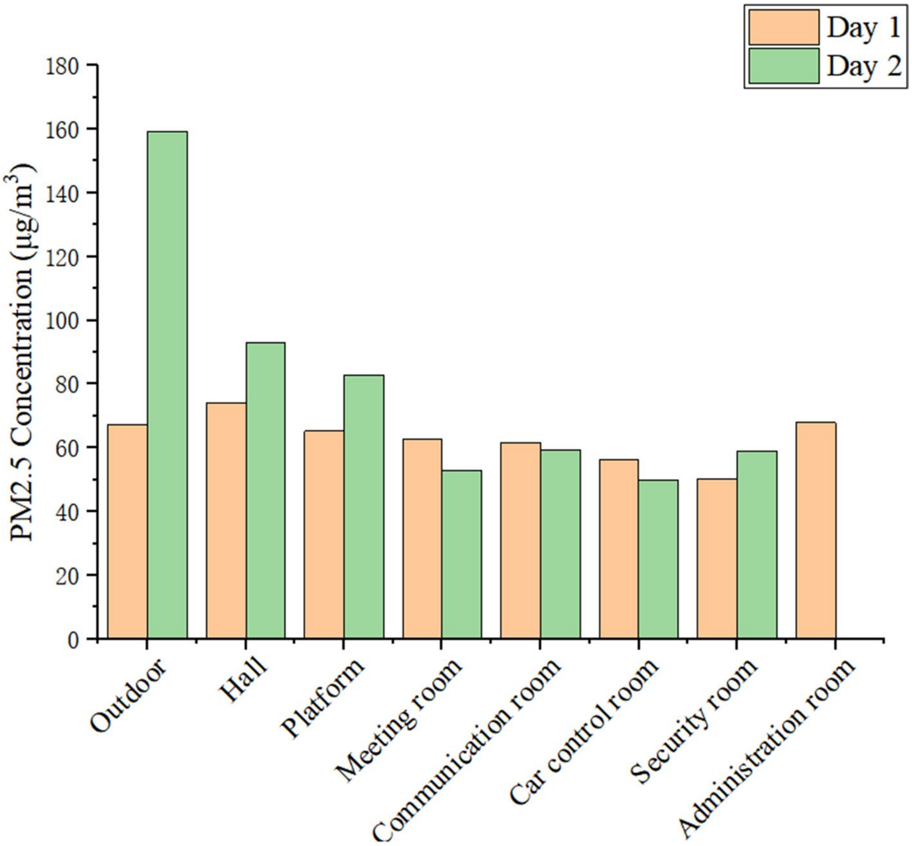


Fig. 2 $PM_{2.5}$ average concentrations at different locations in Station A

concentration was 67.26 μg/m^3, the average hall and platform concentration was 69.60 μg/m^3. Across the five working rooms, concentrations ranged from 50.41 to 67.93 μg/m^3 (mean = 59.82 μg/m^3) with little difference in the different areas. When the outdoor concentration reached 159.32 μg/m^3, the average hall and platform concentration increased to 87.92 μg/m^3. However, the $PM_{2.5}$ concentration range in the workrooms was 49.91–59.06 μg/m^3 (mean = 55.33 μg/m^3), which was obviously less than the outdoor, hall, and platform concentrations, and about half the outdoor concentration.

Compared to Day 1 (outdoor: 67 μg/m^3), the outdoor concentration was double on Day 2 (outdoor: 159 μg/m^3) and concentrations in the public areas also increased slightly, but the workplace concentrations did not change obviously. The working rooms and public areas of subway stations are equipped with separate air-conditioning and ventilation systems, and the doors of the working rooms are normally closed. They are occasionally opened when staff members enter and exit, so the working rooms are less affected by the public areas. The public areas and the outdoor environment are connected through inlet/outlet channels that are normally open, and airflow exchange is exacerbated by piston wind and when a large number of passengers are moving. The fresh air valve in the work area is closed during the test, the outdoor environment, therefore, has a limited impact on the air quality in the work rooms.

There is no evaluation standard for China's subway system air quality. The indoor air quality standard (GB/T 18,883–2022) applicable to residential and office buildings can be used as a reference. Regardless of the outdoor conditions, $PM_{2.5}$ concentrations in the working rooms of the subway stations exceeded the WHO standard ($PM_{2.5}$: 25 μg/m^3 for 24 h) (WHO 2006) and Chinese standard ($PM_{2.5}$: 50 μg/m^3 for 24 h) (State Administration for Market Regulation and Administration, 2022). The exposure time of workers in the workrooms is longer, and a large amount of $PM_{2.5}$ would be inhaled every day. Unfortunately, no further data in the workrooms were obtained. In future studies, the $PM_{2.5}$ characteristics in subway station work areas and their impacts on worker health should be considered.

Particle concentrations in restricted areas of subway stations have rarely been tested. Two similar studies conducted in Korea subways and Beijing subway, respectively. The average $PM_{2.5}$ concentration in Seoul subway stations was similar to that of Station A. However, the $PM_{2.5}$ concentration range in Seoul was greater, for example, $PM_{2.5}$ concentrations in Seoul station offices, restrooms, and ticket offices were 29.2–120.9 μg/m^3 (mean = 56.7 μg/m^3), 26.7–160.4 μg/m^3 (mean = 65.6 μg/m^3), and 38.7–138.9 μg/m^3 (mean = 65.0 μg/m^3) μg/m^3, respectively (Kim et al. 2008). The differents in the two studies may be related to the monitoring conditions. Data on the Seoul subway was collected from 22 stations, including eight above-ground stations where $PM_{2.5}$ concentrations were obviously lower than those of underground stations. In the work areas of a Beijing subway station (Pan et al. 2019), the lowest $PM_{2.5}$ concentration was found in a closed meeting room (about 170 μg/m^3) when the outdoor $PM_{2.5}$ concentration was 131 μg/m^3, but it was still two to three times higher than in Station A in this paper. This difference may have been due to the ventilation system. The fresh air system in Station A was closed. There was fresh air supplied to the working room of Beijing subway and the ventilation system could not filter $PM_{2.5}$, so $PM_{2.5}$ from outdoors entered the room with the fresh air (Pan et al. 2019). When the outdoor $PM_{2.5}$ concentration was high, the unfiltered fresh air polluted the indoor air.

The relationship between indoor and outdoor $PM_{2.5}$ concentrations

Because airflow can be exchanged inside and outside the subway station through entrances, air shafts, and ventilation systems, $PM_{2.5}$ concentrations in subway stations are strongly influenced by outdoor $PM_{2.5}$. To analyze the relationship between $PM_{2.5}$ concentrations inside and outside the station, 10-days of testing was performed in Station A, the test duration of each area was 30 min per day, and the daily average concentration is shown in Fig. 3. During the test period, the lower outdoor $PM_{2.5}$ concentration was around 50 μg/m^3, whereas the concentration inside the station was slightly higher. Most of the time, the outdoor $PM_{2.5}$ concentrations exceeded 100 μg/m^3, up to more than 250 μg/m^3, and concentrations in the station were significantly lower than outdoor. Concentrations inside the station were not always higher than outside, and the outdoor critical concentration was about 100 μg/m^3 when the concentration inside the station was higher than outside. Prior studies found that station concentrations were significantly higher than in the outdoor environment. These tests were mostly carried out when the outdoor $PM_{2.5}$ concentration is low, which agreed with some conclusions in this paper. For example, I/O ratios in subway stations in Helsinki (Aarnio et al. 2005), Seoul L4 (Lee et al. 2018), Greece (Martins et al. 2016), New York City (Vilcassim et al. 2014), and Naples (Carteni et al. 2020) were 5–6, 2.5, 6.9, 9, and 17, respectively, when the outdoor concentrations were 10 ± 7 μg/m^3, 22.2 ± 9.5 μg/m^3, 9.9 ± 3.0 μg/m^3, 10 μg/m^3, 3 ± 3 μg/m^3, respectively. These tests took place under excellent outdoor air conditions that did not worsen $PM_{2.5}$ pollution in the subway stations, but station concentrations were still at high levels that cannot be ignored, most of which exceeded the WHO standard. Therefore, many scholars reported that there are $PM_{2.5}$ sources in subway stations, such as friction between steel rails and wheels, metal brake pads, and ventilation systems (Son et al. 2021; Zhang et al. 2011). The dilution effect of clean

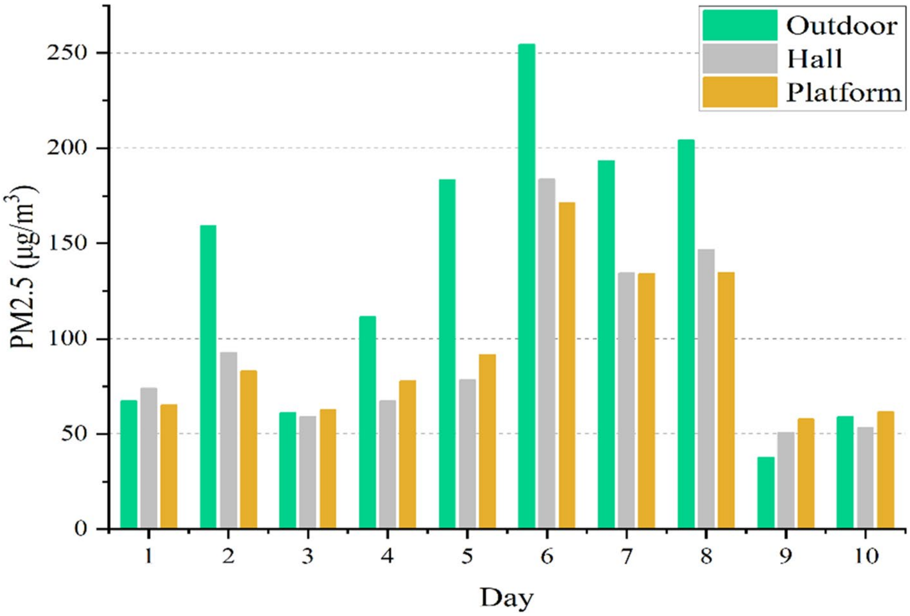


Fig. 3 $PM_{2.5}$ concentrations in the subway station and outdoors

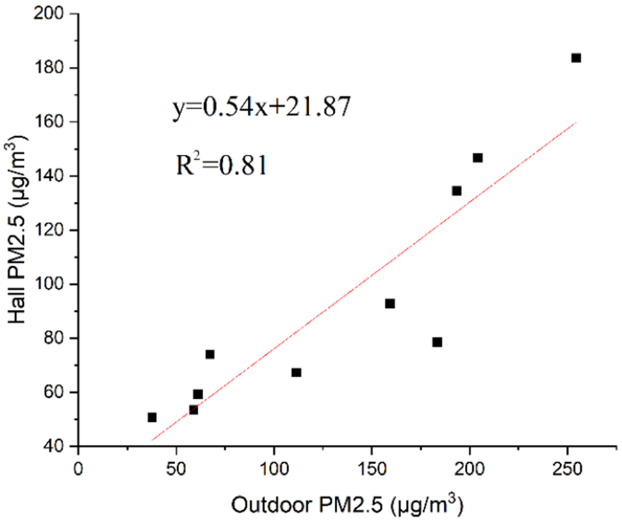
outdoor air on polluted air in subway stations is limited. In addition, some studies have shown that when outdoor concentrations are high, subway stations have lower concentrations. For example, in a subway station in Beijing, when the outdoor $PM_{2.5}$ concentration was greater than 200 μg/m^3, concentrations in the hall and platform were less than outdoors (Pan et al. 2019). This finding was the same as this paper, although the critical concentration was different, which may have been related to the structural characteristics of the subway and environmental control measures.

It can also be seen from Fig. 3 that $PM_{2.5}$ concentrations inside the station increased as outdoor concentrations increased. Pearson correlation analysis was used to obtain the mathematical relationship between indoor and outdoor concentrations, and the result is shown in Fig. 4. Concentrations in the hall and platform were strongly correlated with the outdoors, with R^2 values of 0.81 and 0.86, respectively. This result was similar to the relationship obtained in the Beijing subway station platform by Pan et al. ($R^2=0.897$) (Pan et al. 2019). The positive correlation between $PM_{2.5}$ levels inside and outside the station was also obtained in the Taipei Metro ($R^2=0.41$–0.86) (Cheng et al. 2008), Nanjing Metro ($R^2=0.76$) (Shen and Gao 2019) and Shanghai Metro ($R^2=0.993$) (Zhao et al. 2017). These conclusions all show that outdoor $PM_{2.5}$ concentrations have a greater impact in the public station areas. $PM_{2.5}$ from the outdoor environment can enter the station through a variety of ways, such as open channels and ventilation system, and sometimes passenger walking and frequent piston wind will aggravate this phenomenon. However, some studies have shown that underground $PM_{2.5}$ concentrations are weakly correlated with the outdoor conditions, in the Sydney subway system ($R^2=0.210$) (Mohsen et al. 2018) and Los Angeles subway stations ($R^2=0.38$) (Kam et al. 2011a, b). This difference may be related to the independent variable range in the analyzed data, being the outdoor $PM_{2.5}$ concentrations. Outdoor concentrations tested in Sydney and Los Angeles were less than 15 and 50 μg/m^3, respectively, whereas concentrations in the Chinese cities mentioned previously were as high as 100 – 300 μg/m^3.

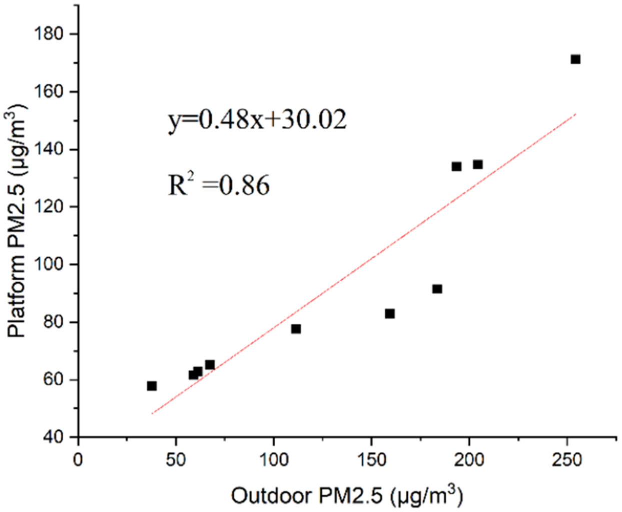
$PM_{2.5}$ exposure risk assessment in subway environments

$PM_{2.5}$ concentration changes during commuting

To calculate the cumulative $PM_{2.5}$ inhalation of passengers in the subway system, real-time $PM_{2.5}$ concentrations were first tested during commuting between stations A and B under two outdoor air quality conditions, as shown in Fig. 5. The two trips (T1 and T2) were completed on two separate days, and outdoor $PM_{2.5}$ concentrations on these two days were 20–30 μg/m^3 and 120–180 μg/m^3, respectively, corresponding to good and moderate air pollution (Ministry of Environmental Protection, 2012). There were two commutes (R1 and R2) per trip, to and from the same line. The outdoor environment was tested before entering the station, passing through the entrance/exit channel, hall, and platform of starting Station A, then while taking the train. Testing continued after five stops, when passing through the platform, hall, and channel of Station B, and finally the outdoors. The results showed that when outdoor $PM_{2.5}$ concentrations were low, concentrations gradually increased from the exterior to the interior of the subway station, especially in the platform and carriage areas. Correspondingly, the $PM_{2.5}$ exposure concentration gradually decreased during the process of leaving the



(a) Hall



(b) Platform

Fig. 4 The relationship between $PM_{2.5}$ concentrations at different Station A locations and outdoors

station. When the outdoor $PM_{2.5}$ concentration was high, concentrations declined significantly when entering the subway station from the outside. However, there were no significant differences between the channel, hall, and platform areas. Concentrations dropped dramatically after entering the carriage and remained around 100 μg/m^3 before reaching the next platform. Lastly, $PM_{2.5}$ concentrations increased when leaving the subway station to the outdoors.

The $PM_{2.5}$ concentration during T1 was the highest in the carriage, between 90 and 100 μg/m^3, and the exposure concentrations were higher than the forthcoming Chinese indoor air quality standard (GB/T 18,883–2022) (State Administration for Market Regulation and Administration, 2022), whereas all $PM_{2.5}$ concentrations in T2 exceeded the standard. In general, concentrations in the carriage are still worrying, and mitigation measures should be taken. Compared with other public spaces in subway stations, concentrations in the carriage were less affected by the outdoor concentrations and were more susceptible to the influence of the platform when the carriage door is opened or closed. Particles from the tunnel entered the carriage through cracks when the train was running at high speed. The ventilation system in the carriage also affected the $PM_{2.5}$ concentration, including the air supply method, air volumetric flow rate and filter device.

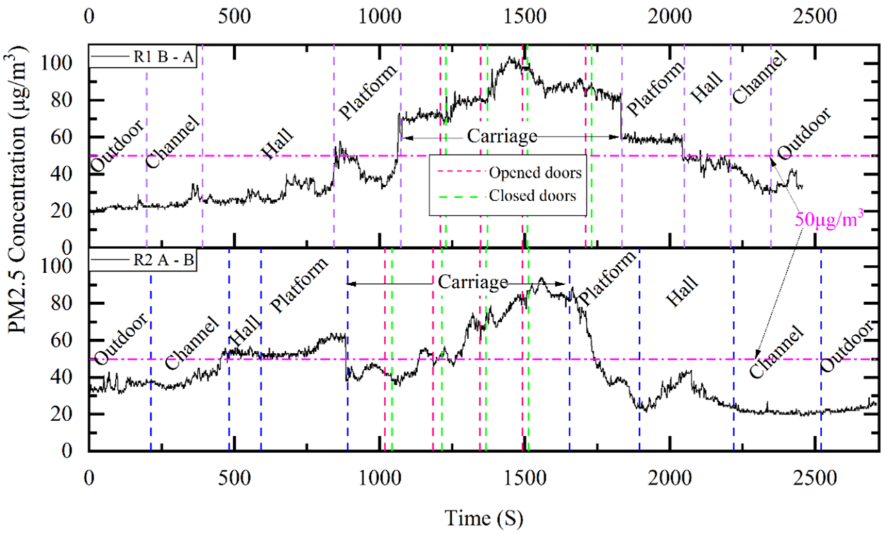
$PM_{2.5}$ cumulative inhaled dose in subway environments

To more accurately access the health risks of passengers when commuting by subway, cumulative inhalation was calculated according to the real-time $PM_{2.5}$ concentrations and Formula 2 over the whole commute. The outdoor exposure time was defined as 100 s before entering and after leaving the station. The $PM_{2.5}$ inhalation calculations over the four commutes are shown in Fig. 6, where different colors represent different microenvironments, and from left to right is the whole process of entering the station, taking the carriage, and leaving the station.

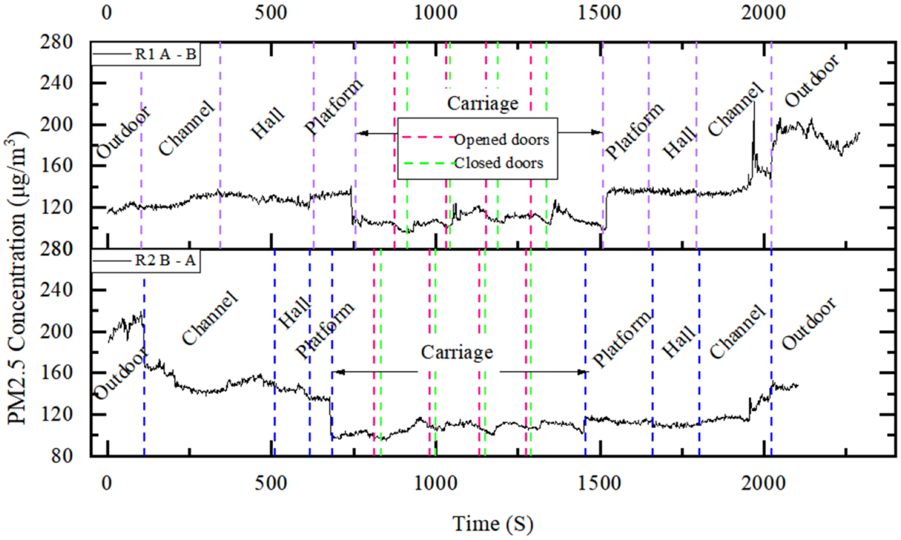
When the outdoor $PM_{2.5}$ concentration was 20–30 μg/m^3, the cumulative inhalation in a single commute was about 42 μg. When the outdoor concentration increased to 120–180 μg/m^3, the cumulative inhalation in a single commute was about 100 μg. Inhalation in the carriage accounted for the largest portion of the entire commuting process, about 40% in T1 and 25% in T2. This may be related to the high $PM_{2.5}$ concentrations and long exposure time in the carriage. Concentrations in the carriage were higher than other microenvironments in T1, which lead to significant inhalation. As shown in Fig. 5b, although concentrations in the carriage were the lowest in T2, the exposure time of passengers in the carriage was longer, about 13 min, almost half of the entire commute. Therefore, even if concentrations in the carriage were not high, the cumulative inhalation was still higher than other microenvironments, as shown in Fig. 6. $PM_{2.5}$ in the tunnel will enter the carriage through the cracks and the fresh air system when the train is moving, and can improve the air quality inside by improving the airtightness of the carriage and filtering the fresh air (Xu and Hao 2017; Kim et al. 2013).

Many scholars are more concerned about $PM_{2.5}$ concentrations in the platform than the hall floor because passengers spend time waiting for the train, and sometimes the concentrations at the platform are higher than the hall due to the direct connection with the tunnel. However, Fig. 6 shows that inhalation in the platform was not prominent

Fig. 5 Trips under two outdoor concentrations. **a** T1 at outdoor $PM_{2.5}$ concentrations of 20–30 µg/m^3 (50 µg/m^3 is Chinese standard value for indoor $PM_{2.5}$ concentrations (State Administration for Market Regulation & Administration, 2022)). **b** T2 at outdoor $PM_{2.5}$ concentrations of 120–180 µg/m.^{3}



(a) T1 at outdoor $PM_{2.5}$ concentrations of 20-30 μg/m³ (50 μg/m³ is Chinese standard value for indoor $PM_{2.5}$ concentrations (State Administration for Market Regulation & Administration, 2022))



(b) T2 at outdoor $PM_{2.5}$ concentrations of 120-180 μg/m³

compared to the hall and channel. There may be two reasons for this: first, the tested platform was equipped with PSD, which blocks most of the $PM_{2.5}$ from the tunnel. Figure 5 also showed that there was no obvious difference between the $PM_{2.5}$ concentration at the platform and the hall. On the other hand, passengers in the hall were actively walking, and an increased heart rate leads to a higher breathing rate. On the platform, passengers stand or sit waiting for the train with light intensity, and their heart rate is also reduced, resulting in a significant drop in breathing rate (Tan et al. 2017).

The results showed that $PM_{2.5}$ in the entrance channels cannot be ignored, especially when outdoor air quality is poor. $PM_{2.5}$ inhalation in the channel accounted for 10–36% of the total commute. The channel was affected both by the internal and external environments of the station. Due to its long narrow and multi-turn structure, $PM_{2.5}$ from the tunnel and outside easily enters the channel and

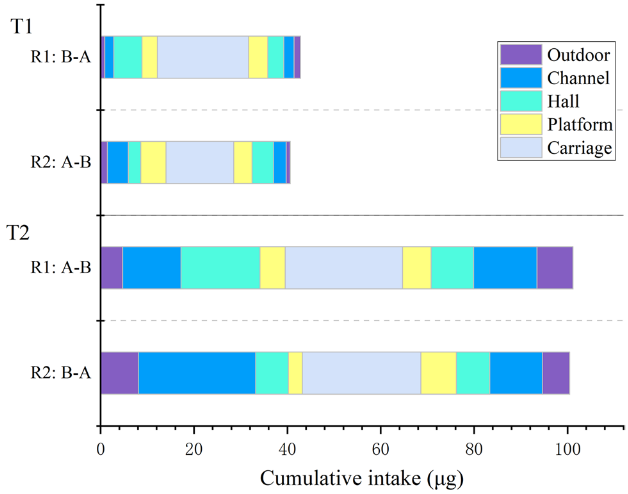


Fig. 6 Cumulative $PM_{2.5}$ inhalation in different trips

is resuspended by piston wind and passengers walking. On the other hand, when passengers are walking or going up and down the stairs, their breathing rate will increase and lead to more inhalation. In some studies, air curtains can be installed at subway entrance to reduce the ingress of outdoor particles (Chen et al. 2021), and adding filters or removal dust devices to the ventilation system, or installing flexible air dust removal equipment, may help reduce the $PM_{2.5}$ concentration.

Inhalation depends on not only the $PM_{2.5}$ concentration in the exposed space, but also exposure time and the breathing rate associated with activity intensity. The cumulative inhalation calculated in this paper was much higher than in the Singapore Metro (8.9 μg) under the same respiratory rate at all stages (Tan et al. 2017) due to the longer commuting time and higher $PM_{2.5}$ concentrations. In mega cities with longer average subway commutes of more than 1 h, the cumulative inhalation may be higher, such as in Beijing and Shanghai.

Due to the lack of real-time $PM_{2.5}$ exposure concentrations of staff in the work area, the average $PM_{2.5}$ concentration is used here to estimate the daily $PM_{2.5}$ inhalation of staff. As shown in Sect. 3.2, the $PM_{2.5}$ concentrations in the subway station workspace did not change with concentrations outdoors or in the station public area, and there was little difference in concentrations between working rooms. Therefore, it is assumed that the $PM_{2.5}$ concentration in the work area does not vary with time during the working hours of the day, and the average $PM_{2.5}$ concentration in the five working rooms is taken as the exposure concentration of the staff in the work area. To estimate the daily $PM_{2.5}$ inhalation of staff in the work area, the average $PM_{2.5}$ concentration, human respiration rate and exposure time were substituted into Formula 2. The average concentration of the five working rooms in Fig. 2 under two outdoor conditions was 57.83 μg/m^3. The activity intensity of staff in the working area was similar to that of passengers in the carriage, so their respiratory rate was selected as 18.5 L/min from Table 2. The exposure time was eight hours, according to normal working rules. Finally, the daily $PM_{2.5}$ intake of staff in the subway work area was 513.53 μg. Although the $PM_{2.5}$ concentration in the work rooms was lower than in public areas, inhalation was much higher than passenger commuters by 5 to 12 times. This estimate reflects that air quality in the work area is worrying. At present, there have been few studies on $PM_{2.5}$ in subway work areas and they have only tested concentrations. Future studies will need to learn more about particulate matter in the workplace through continuous monitoring of concentrations, their chemical compositions and impacts on human health. Compared with public areas, work areas are smaller and more stable, which makes it easier to control internal air quality. There are some mitigation measures that can be considered, such as placing household air purifiers in working rooms, or installing high-efficiency filtration modules in the ventilation system.

To reduce $PM_{2.5}$ inhalation, it is very important for subway stations to improve internal air quality and take protective measures for passengers and staff members. Setting up dust removal equipment or adjusting ventilation strategies in subway stations are all positive measures to control air pollutants. Since the COVID-19 pandemic, passengers and staff in public transportation in China have been required to wear masks for the health and safety of themselves and others. This can reduce the infection rate of the virus and also reduces the inhalation of particulate matter. Masks have a greater impact on the respiratory rate: a study has shown that the filtration efficiencies of N95 masks and surgical masks for particles >300 nm are $99.9 \pm 0.1\%$ and $99.6 \pm 0.1\%$, respectively, and for particles <300 nm are $85 \pm 15\%$ and $76 \pm 22\%$, respectively (Konda et al. 2020). Wearing a mask can also effectively reduce the exposure of metal elements in air particles in subway stations (Ji et al. 2021).

Study limitations

This study provides the first understanding of $PM_{2.5}$ concentration levels and personnel inhalation in the selected urban subway stations. $PM_{2.5}$ concentrations in the subway public areas were strongly influenced by the outdoor environment, but $PM_{2.5}$ concentrations in the work areas were rarely influenced by the outdoors, which may be related to the ventilation conditions. Although the fresh air systems in both areas were turned off during the test period, the public areas could be naturally ventilated with the outdoors, while the work areas were not connected to the outdoor environment. The data obtained only represent the winter condition and cannot determine the variation of $PM_{2.5}$ concentration in other seasons. The fresh air system in the subway station is closed in the winter, but it is open in the spring and autumn, and the air volume may be adjusted. In future studies, a whole year's monitoring of $PM_{2.5}$ concentrations in subway stations is needed to understand the changes under different ventilation strategies in different seasons.

$PM_{2.5}$ inhalation by passengers and staff in the subway environment was estimated based on short-term inland $PM_{2.5}$ concentrations, commuting time, and inhalation rate. To provide a more comprehensive understanding of $PM_{2.5}$ inhalation by passengers and staff in the subway environment, commuting activities should be recorded under more scenarios, such as different seasons and time periods, and by different ages and genders. In addition, real-time heart rate monitoring of the measured personnel to calculate their inhalation rate using Eq. 3 would also provide a more accurate picture of inhalation. Compared with passengers, workers are exposed to the subway environment for a longer time and may inhale more $PM_{2.5}$, but due to objective conditions, this study was not able to monitor real-time $PM_{2.5}$ exposure concentration of workers during a working day, which is also one of our concerns in future research.

Conclusion

To address the limited knowledge of existing studies on $PM_{2.5}$ in work areas and $PM_{2.5}$ inhalation by exposed personnel in the subway station, this paper provides the two-week field data on $PM_{2.5}$ concentrations in four subway stations in Changchun, China, and the cumulative inhalation of $PM_{2.5}$ by passengers and workers was calculated. The results showed that $PM_{2.5}$ concentrations in the workrooms were less affected by the outdoor environment, and were maintained at about 60 μg/m^3, which exceeded the Chinese indoor air quality standards (GB/T 18,883–2022). $PM_{2.5}$ concentrations in subway public areas increased with the outdoor concentrations. Corresponding mitigation measures should be adopted to reduce particulate matter concentrations in subway stations under various situations, considering factors like local air quality changes and subway station ventilation systems. When outdoor air quality is good, more outdoor air should be brought in to dilute the internal polluted air, such as by turning on the fresh air system in the work area; conversely, when the outdoor air quality is poor, the air exchange between the station and the outside should be reduced, and internal air filtration should be enhanced.

When the outdoor $PM_{2.5}$ concentration was 20–30 μg/m^3 and 120–180 μg/m^3, the cumulative inhalation of passengers for a single commute was 42 μg and 100 μg respectively. The greatest proportion of $PM_{2.5}$ inhalation occurred in the carriage, at 25–40% of total inhalation, not only because of the longer exposure time, but also because of the higher particulate matter concentrations there. The air quality in the entrance channel and the hall is also worthy of attention, where passengers are likely to inhale more particulate matter than on the station platform. Compared with passengers, workers are exposed to the subway environment for a longer time and inhale more $PM_{2.5}$ in workplaces, averaging 513.53 μg per day. Besides placing air purifiers in the room to improve air quality, workers should take protective measures, such as wearing masks with higher filtration efficiency and having regular physical examinations.

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Data availability The data and materials can be available on request.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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