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Original Research

Spatio-Temporal Distribution of Particulate Matter (PM_{10} and $PM_{2.5}$) Concentrations in Urban Subway Station – A Case of Nanning in China

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Abstract

Particulate matter is one of the primary air pollutants in urban subway stations. Characteristics of particulate matter concentration is specific due to the heterogeneity of subway system in each city. The spatio-temporal distribution of particulate matter (PM_{10} and $PM_{2.5}$) concentrations in a typical urban subway station of Nanning city was analyzed. PM_{10} and $PM_{2.5}$ concentrations of winter were both significantly higher than those of spring, summer and autumn ($P<0.001$). PM_{10} and $PM_{2.5}$ concentrations of station were significantly higher than those of the ground control ($P<0.001$). PM_{10} and $PM_{2.5}$ concentrations of ticket office were significantly higher than those of platform, security checkpoint and passageway ($P<0.001$). PM_{10} and $PM_{2.5}$ levels of station during the rush hour were significantly higher than those during the non-rush hour ($P<0.001$). There is a positive correlation between PM (PM_{10} and $PM_{2.5}$) levels and passenger flow of station. The results indicated that the spatio-temporal distribution of PM (PM_{10} and $PM_{2.5}$) level may be ascribed to seasonal factor, passenger flow, and layout structure of station respectively. The findings of this study therefore make them possible to be the part of preliminary foundation of subway-related standards improvement for airborne particulate matter in the future.

Keywords: subway, station, particulate matter, concentration, distribution

Introduction

With the growing demand of green and efficient urban transportation, subway systems, by reducing gasoline consumption and providing rapid and affordable transportation, have been rapidly developed in last decades. The number of subway riders in metropolitan cities has continuously increased over recent years. Subway system is carrying the largest commuters daily in urban metropolises around the world [1-2]. By 2019, more than 50 countries and 160 cities worldwide have subway systems, which have

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over 15000 km mileage in operation and transport about 68 billion riders per year [3]. According to the Statistics and Analysis Report of Urban Rail Transit of China [4], By the end of 2019, there are 40 cities in China have subway systems, which have over 5000 km mileage in operation and transport about 23 billion riders per year. From 2013 to 2019, China's annual average investment in transportation infrastructure stands at more than 280 billion dollars. Local governments and urban planners have realized the importance of rail transit system such as subway in improving air quality and traffic conditions. At present, China is the country with the longest operating mileage and the largest commuters of subway in the world. Although the high efficiency, green transport, safety and large-scaled passenger capacity brought by subway system, one environmental health risk was observed that air pollutants may accumulate in confined space of subway station. There have been reports that the concentrations of air pollutants in underground station are higher than the outside ambient levels [5-7]. Subway station is a confined space that promotes the air pollutants entering from the outside atmosphere in addition to those generated inside. The growing body of literature has reported that various air pollutants were observed in subway stations and detected exceeding the stipulated standards [8-14]. As high ridership volumes are confined in such enclosed spaces, passengers who were exposed to these air pollutants may suffer health risks such as pulmonary dysfunction [15], cardiovascular diseases and cancer. This has become of a particular public concern [16-18].

Airborne particulate matter has been identified as one of the primary air pollutant in the subway station [19-21]. Particulate matter levels were reported in subway systems of many other countries and cities like Mexico, Milan and Barcelona [22-25]. Very high levels of particulates matter were reported in London and Stockholm's subway stations, which were even 30~40 times higher than the reference limits recommended by World Health Organization [26-27]. Furthermore, studies also proposed that the constituents of subway particulate, including heavy metals such as Manganese, Chromium, Nickel, and Cuprum [28-31], can induce negative health effects like oxidative stress in lung tissues, gene toxicity, excess cancer mortality and endocrine diseases on human bodies [32-34]. A previous study also demonstrated that subway particulate was approximately 8 times more genotoxic than street particulate and induced 4 times oxidative stress in cultured human lung cells [35]. Despite time spent in subway was comparatively short, a rough estimate of an important part of exposure caused by commuting via subway preliminary indicated that the exposure to particulate matter increased a lot [36].

Generally, subway particulate exposure is specific due to the heterogeneity of subway system in each city. Field study should be taken into account so that more specific data could be produced regarding local subway-related exposure. Nanning, a regional center and an opening city that plays key role in the communication between China and Southeast Asia, is the city with a population of more than eight million people in southern China. At the end of 2020, there are 5 subway lines and 104 subway stations in Nanning and the total mileage of the subway Network in operation was 128 km. It is estimated that the Nanning subway system carries over 270 million passengers per year. The objective of this study was to investigate the distributions of airborne particulate matter (PM_{10} and $PM_{2.5}$) concentrations in typical urban subway station, a case of urban subway station in Nanning, and to improve the information of field study about the particulate matter of subway station that can be used to help define the ideal or optimum environment of urban subway station. The findings are expected to help step towards healthy subway and facilitate sustainable operation of subway in future.

Materials and Methods

Sampling Site

We selected six underground stations from two subway lines for monitoring. To ensure the representativeness of typical urban station, all of the chosen stations locate in downtown area and main residential areas. The stations are equipped with the central mechanical ventilation system. In each station, we selected four passenger activity areas included passageway, ticket office, security checkpoint and platform as sampling sites because of these sites are the necessary path nodes for passengers. According to the national standard of the Examination methods for public places-Part 2: Chemical pollutant (GB/T 18204.2-2013), the sampling points at these areas located at a height of 1.5 meters were selected to avoid air inlets and outlets from the ventilation and air condition facilities and minimize inconvenience to passengers. Each sampling point was required with an air monitoring area over 1000 m^2. In addition, ground control sampling site was situated about 10 meters adjacent to the ground entrance of each station for the comparative assessment of indoor subway pollution levels.

Sampling Methods

This study was performed from April 2019 to January 2020. The measurement was carried out during four seasons included winter (monitoring in January 2020), spring (monitoring in April 2019), summer (monitoring in August 2019) and autumn (monitoring in November 2019). The monitoring was implemented three times a day for three consecutive workdays during each season (corresponding month). We selected three sampling time periods on each workday consisted of morning rush hour (7:00-8:00), non-rush hour

(10:00-11:00), and evening rush hour (18:00-19:00) for comparing the results of rush hours and non-rush hours. Mass concentration of $PM_{2.5}$ and PM_{10} were recorded simultaneously at each time. In addition, the relationship between PM levels and passenger flow was analyzed in this study.

$PM_{2.5}$ and PM_{10} were sampled and measured by PM sampler Dust-Trak 8532 Aerosol Detector (TSI, USA). Its detection sensitivity was 1μg/m^3. The instrument combines the function of photometer and optical particle counter. All instruments were seriously zero-calibrated before each measurement. Sampling flow rate was set at 3.0L/min. The instruments were fixed on tripods measuring 1.5 meters in height, which corresponded to the breathing zone of people. The instruments were kept off the places with strong air current, such as air inlets and outlets of the ventilation and air condition facilities, and kept at least 1 meter away from walls. During sampling time periods of each day, the measurement was carried out in the time of 7:00-8:00, 10:00-11:00 and 18:00-19:00 respectively. Mass concentration of PM_{10} and $PM_{2.5}$ were recorded at the same time. The data was transferred to a computer after measurement and dealt with using statistical software such as SPSS.

Statistical Analysis

Based on the normal distribution of PM concentration ($p>0.05$) by Shapiro-Wilk Statistical test, mean value was used to describe the average value. All the data was shown in mean±standard deviation (SD). Consequently, mean values are employed for comparison with PM concentrations in different sampling sites and time periods. SPSS version 16.0 (SPSS Inc., Chicago) was applied for the statistical analysis. Different mass concentration of PM among sampling sites and time periods were analyzed for their statistical significance by One-way ANOVA and Student-Newman-Keuls multiple comparison. To evaluate the relationship between PM concentrations and passenger flow, Bivariate correlations analysis (Pearson's correlation coefficient test) was performed. A significance level of p value as 0.05 was used.

Results and Discussion

PM Concentrations in Different Seasons

There are significant differences in the concentration levels of PM_{10} and $PM_{2.5}$ among different seasons. As seen in Table 1, as for station, PM_{10} and $PM_{2.5}$ concentrations of winter were both significantly higher than those of spring, summer and autumn ($P<0.001$). Additionally, as for ground control, PM_{10} and $PM_{2.5}$ concentrations of winter were also significantly higher than those of spring, summer and autumn ($P<0.001$).

PM Concentrations at Different Time Periods

Three different time periods consisted of morning rush hour (7:00-8:00), non-rush hour (10:00-11:00), and evening rush hour (18:00-19:00) during three consecutive work days for monitoring. As seen in Table 2, PM_{10} concentration in the evening rush hour was significantly higher than those in the morning rush hour and non-rush hour ($P<0.001$). $PM_{2.5}$ concentrations in the rush hour (morning and evening) were all significantly higher than that in the non-rush hour ($P<0.001$). PM_{10} and $PM_{2.5}$ concentrations of ground control varied with different measuring time but did not appear significant difference ($P>0.05$).

PM Concentrations in Different Sites of Station

In this study, four sites of each station included passageway, ticket office, security checkpoint, platform and ground control of outdoor environment were monitored for PM_{10} and $PM_{2.5}$ concentrations. As seen in Fig. 1, PM_{10} and $PM_{2.5}$ concentrations of passageway, ticket office, security checkpoint and platform were all significantly higher than those of the ground control ($P<0.001$). As for the comparison with PM concentrations among different sites of internal station, we found that PM_{10} and $PM_{2.5}$ concentrations of ticket office were significantly higher than those of platform, security checkpoint and passageway ($P<0.001$).

Table 1. PM concentrations in different seasonsa

Seasons	Station		Ground control	
	$PM_{2.5}$ (μg/m^3)	PM_{10} (μg/m^3)	$PM_{2.5}$ (μg/m^3)	PM_{10} (μg/m^3)
Winter (January)	81±12	184±19	59±8	143±10
Spring (April)	77±8	160±17	52±5	106±9
Summer (August)	74±10	164±18	54±8	110±10
Autumn (November)	75±8	179±18	51±6	127±8
P-*value*	<0.001	<0.001	<0.001	<0.001

[a] The comparison by use of One-way ANOVA and Student-Newman-Keuls multiple comparison.

Table 2. PM concentrations at three different time periods [a].

Time periods	Station		Ground control	
	$PM_{2.5}$ (μg/m³)	PM_{10} (μg/m³)	$PM_{2.5}$ (μg/m³)	PM_{10} (μg/m³)
Non-rush hour	71±8	164±19	52±7	120±18
Morning rush hour	77±9	170±19	53±8	118±17
Evening rush hour	82±9	181±20	56±8	125±17
P-*value*	<0.001	<0.001	0.087	0.066

[a] The comparison by use of One-way ANOVA andStudent-Newman-Keulsmultiple comparison.

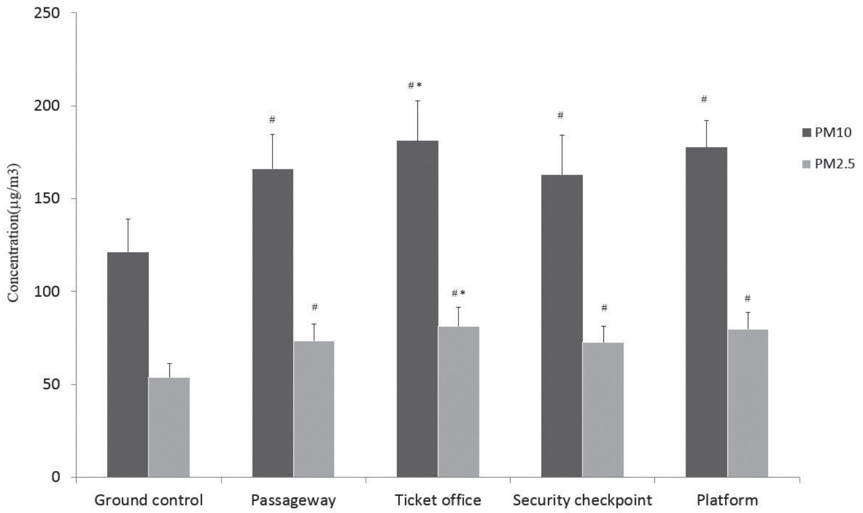

Fig. 1. PM concentrations in different sites of station (Note: The comparison by use of One-way ANOVA and Student-Newman-Keuls multiple comparison. □ Significant P-value□0.001, compared to ground comtrol value; □Significant P-value□0.001, compared to all other four sites (ground comtrol, passageway, security checkpoint and platform) value.)

Relationship between PM Levels and Passenger Flow

Passenger flow data of morning rush hour (7:00-8:00), non-rush hour (10:00-11:00) and evening rush hour (18:00-19:00) was obtained from station ticket system. Relationship between particulate matter concentrations and passenger flow was explored in this study. As seen in Table 3, the results showed that the correlation coefficient (r) between particulate matter concentration and passenger flow was statistically significant ($P< 0.001$). As shown in Fig. 2, there is a positive correlation between particulate matter (PM_{10} and $PM_{2.5}$) levels and passenger flow of station.

In this study, the average concentrations of PM_{10} and $PM_{2.5}$ of station were about three times higher than those of air quality standard recommended by WHO guideline (50 μg/m³ for PM_{10}, 25 μg/m³ for $PM_{2.5}$). Although passengers are exposed to subway station environment for a short time, the exposure may induce harmful or dissatisfactory effects on their health. The exposure to particulate matter in subway station has become of a health concern.

PM_{10} and $PM_{2.5}$ concentrations varied with different seasons was observed in this study. PM_{10} and $PM_{2.5}$ concentrations of winter were significantly higher than those of spring, summer and autumn. This seasonal concentration variation may be related to atmospheric pollution that is more common in winter [37-38]. In this study, we also observed that PM_{10} and $PM_{2.5}$ concentrations of ground environment in winter were higher than those in other seasons. Subway stations are generally connected with the external atmospheric

Table 3. Correlation coefficient between PM levels and passenger flow [a].

Monitoring indicators	Correlation coefficient (r)	P-*value*
PM_{10}	0.801	<0.001
$PM_{2.5}$	0.713	<0.001

[a] The correlation coefficient between PM levels and passenger flow was calculated by use of Bivariate correlations analysis (Pearson's correlation coefficient test)

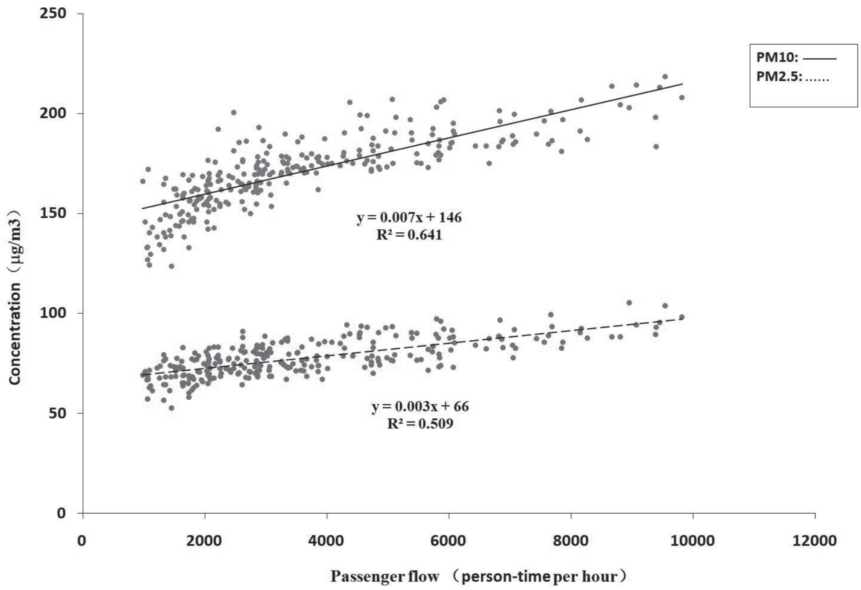

Fig. 2. Correlation between particulate matter (PM_{10} and $PM_{2.5}$) concentration and passenger flow.

environment through the entrance and exit of the station, fresh air pavilion and other channels. During a large time scale such as seasons, atmospheric particles to some extent could apparently affect the concentration of particulate matter in the station.

In this study, PM_{10} and $PM_{2.5}$ concentrations of station in the rush hour were significantly higher than that in the non-rush hour. Particulate matter concentration varied with different time period has also been reported in other city subway stations [39-40]. The reason for this temporal distribution is probably related to the passenger flow. The correlation between particulate matter concentration and passenger flow was analyzed in the current study. The results showed that both PM_{10} and $PM_{2.5}$ concentrations were positively correlated with passenger flow, and the correlation was statistically significant. The passenger flow may be a influence factor of particulate matter concentration in station. Subway station is an underground confined space environment with lacking of natural ventilation. Such architecture feature would promote the air pollutants entering from the outside atmosphere in addition to those generated inside when the passenger flow increased significantly. Activities of subway passenger can also induce re-suspension of particles in addition to carrying particles into the station from the outside atmosphere [41-42]. Some studies have revealed that human activities can lead to the secondary suspension of particles, which was considered as an important source related to airborne particle concentration of indoor environment [43-44]. In addition, the result of ground control showed that PM_{10} and $PM_{2.5}$ concentrations of outside station did not display significant difference among different time periods of a day. This may suggest that the fluctuation of particulate matter concentration of internal station had little correlation with the air quality of outside station during a small time scale of a day. The present study in Nanning provided specific data to indicate that not like the effects of seasonal concentration variation of atmospheric particle, atmospheric particle concentration in a day does not seem to influence the temporal fluctuation of concentration of station significantly. There is a variation when comparing current results with those of other city subway systems [45]. This may due to the heterogeneity of subway system in each city, such as the differences in design of the stations, the system age, the passenger density, the ventilation systems, and other factors.

In this study, the particulate matter concentrations in subway station displayed a spatial distribution. The PM_{10} and $PM_{2.5}$ concentrations of station were significantly higher than that of the ground control. Several studies have also shown that the particulate matter concentration of internal station is generally higher than that of outdoor environment [46-47]. This may be attributed to the underground confined space environment of subway station. Particularly, high passenger volume and lacking of natural ventilation in this confined space could aggravate the accumulation of particulate matter.

Among the four monitoring sites of internal station, the particulate matter concentration of ticket office area was the highest, followed by that of platform. Particulate matter concentrations of passageway and security checkpoint were similar and lowest. The reason for this spatial distribution is probably related to the layout structure of subway station. Ticket office installed with ticket vending machine was set at both two ends of station hall. Many passengers gathered here to buy tickets. The fresh air outlets of the ventilation and air condition system are distributed at the middle of the station hall's ceiling. The position of ticket office is far away from fresh air outlets. Consequently, the relative small volume of fresh air flow with low velocity may not purify the air effectively, which may result in the high level of particulate matter [48]. The platform is where passengers get on and off the subway train. Due to the abrasion and wear of rail tracks and wheels caused by the passage of the trains as well as to the braking system, the train tunnel outside the screen door of the platform is a source of particulate matter in the station. Because of piston wind effect, particulate matter generated from tunnel can be brought into the platform area when the trains passing through the platform [49]. This may increase the particulate matter level of the platform. A study in Seoul subway station showed that the highest concentrations of airborne PM_{10} and $PM_{2.5}$ were observed in platform. Another study in Shanghai subway station also showed that the PM_{10} concentrations of platform were significantly higher than that of station hall. The position of security checkpoint is in the middle of station hall close to fresh air outlets. Due to high volume of fresh air flow in this region, the fresh air flow can purify the air effectively, and therefore this region has relative low level of particulate matter. The passageway is close to the entrance and exit of the station, and is the transition region between external ground environment and internal station. The relative low particulate matter concentrations of passageway may be attributed to natural ventilation that generated by air convection from external ground.

As for passenger related activity areas of subway station, the spatial distribution of airborne particulate matter concentrations occurred in different areas of station was also reported by other studies. In the current study, we investigated airborne particulate matter concentrations of passenger activity areas such as passageway, ticket office, security checkpoint and platform in more detail because of these areas are the necessary path nodes and important places of particle exposure for passengers in subway station. We found that ticket office area and platform have relative high level of particulate matter while relative low level of particulate matter was found in passageway and security checkpoint areas. If we compare these results with previous other studies measuring the concentrations of particulate matter, there is a variation among respective results. This could be explained by differences in the monitoring conditions such as measurement place, time, and layout structure of subway station, air filter unit efficiency and the year of construction of each subway station. In addition, seasonal condition s may not be excluded.

As for airborne particulate matter, although many countries and regions have established their own standards or guidelines so as to protect public health, these standards are more applicable to outdoor ambient air above ground and plays limited role in assessing environment of urban subway station. There is a great vacancy in urban subway station standards for airborne particulate matter. Meanwhile, several defects were found in the current standards related to subway station, such as incomplete information and poor pertinence to subway station environment. Despite of some similarity with outdoor ambient particulate matter exposure, subway station shows quite a difference in passengers exposure during their subway commuting. The standards regarding ambient air quality above ground are hardly to serve as reference for the situations of subway station. Comparing with above ground environment, some factors such as underground confined space environment, varied passenger flow related to specific time periods, layout structure of station, and seasonal condition could bring about the heterogeneity of subway station in respect of particulate matter and other substances exposure. Additionally, differences between subway and aboveground particle concentration, composition and size distribution further limit the value of comparisons to outdoor particulate matter guidelines. Therefore, field studies are commonly deployed for characterization of subway stations. Data obtained from these field studies could then serve for the evaluation of subway station. The meanings of present study, as a case of field study, was providing more specific data about spatio-temporal distribution to evaluate subway particulate matter exposure and helping to establish or revise the standards related to subway in the future. While in the field of subway environment research, there will be more demand for field studies to create more abundant data. In addition, more field studies, in a wide range of cities, are also needed.

Conclusions

With the aim to contribute to a healthy subway environment, field studies conducted in subway stations are needed. As the first step to investigate the characteristics of PM in urban subway station, the present field study draws attention to the spatio-temporal distribution of particulate matter (PM_{10} and $PM_{2.5}$) in the stations. We have monitored the concentration of PM_{10} and $PM_{2.5}$ in different places of station during different time periods and seasons. The results of the current study provided specific data of particulate matter levels in typical urban subway stations of Nanning city. The findings revealed that seasonal variation of atmospheric particle concentration could apparently affect the particulate matter concentration of station. In addition, there is a positive correlation between PM (PM_{10} and $PM_{2.5}$) levels and passenger flow of subway station. Passenger flow is the important factor affecting the PM (PM_{10} and $PM_{2.5}$) level of subway station. The temporal and spatial distribution of particulate matter (PM_{10} and $PM_{2.5}$) level may be ascribed to seasonal factor, passenger flow and layout structure of station respectively.

These results would help us to better understand particulate matter exposure and its related influence factors in subway station. The findings therefore make them possible to be the part of preliminary foundation of subway-related standards establishment and revision.

In fact, at present, only a few countries and regions worldwide have established standards for subway particulate matter exposure. Although many other countries and regions such as United State and China mainland has promulgated some standards related to particulate matter for atmospheric environment, the relevant standards can hardly match with the variability of the subway station. Therefore, more specific data of subway came from field study needs to be collected and analyzed. Moreover, the present study could be used as reference to take effective policy measures. The findings of this study could remind the public to emphasize the issues of urban subway station environment. Based on this study, it is recommended to adopt some protective solutions to reduce health risks of subway station environments. For instance, passengers should raise self-protection awareness, such as wearing particle-proof masks. Subway managers should pay more attention to the health of station staff. Besides, the plan to control subway particulate matter pollution is required, such as utilizing high-efficiency air filter units, optimizing structure design of subway station, strengthening the management of passenger flow, and so on. Finally, this study provided specific data of spatio-temporal distribution of particulate matter (PM_{10} and $PM_{2.5}$) in typical urban subway station. However, more details related to particulate matter of subway station should be further studied, and more steps should be taken to reduce particulate exposure and improve air quality of subway station so as to build a healthy and friendly environment and ensure the health for subway passengers.

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Conflict of Interest

The authors declare no conflict of interest.

References

1. DYBWAD M., GRANUM PE., BRUHEIM P., BLATNY JM. Characterization of airborne bacteria at an underground subway station. Applied and Environmental Microbiology, **78**, 1917, **2012.**
2. FAN H., LI X., DENG J., DA G., YAO M. Time-dependent size-resolved bacterial and fungal aerosols in Beijing subway. Aerosol and Air Quality Research, **17** (3), 799, **2017**.
3. HAN BM., CHEN JH., YANG YJ. Statistical analysis of urban rail transit operation in the world in 2019: A review. Urban Rapid Rail Transit, **33** (01), 4, **2020**.
4. China Association of Metros. Statistics and Analysis Report of Urban Rail Transit. Available online: http://www.camet.org.cn. (accessed on 1/July/**2020**)
5. CAO SJ., KONG X R., LI L., ZHANG W., YE ZP., DENG Y. An investigation of the $PM_{2.5}$ and NO_2 concentrations and their human health impacts in the metro subway system of Suzhou, China. Environmental Science-Processes&Impacts, **19**, 666, **2017**.
6. MINGUILLÓNA MC., RECHEA C., MARTINS V., AMATO F., DE MIGUEL E., CAPDEVILA M., CENTELLES S.,QUEROL X., MORENO T. Aerosol sources in subway environments. Environmental Research, **167**, 314, **2018**.
7. CARTENI A., CASCETTA F., CAMPANA S. Underground and ground-level particulate matter concentrations in an Italian metro system. Atmospheric Environment, **101**, 328, **2015**.
8. MARTINS V., MORENO T., MINGUILLÓN MC., VAN DROOGE BL., RECHE C., AMATO F., DE MIGUEL E., CAPDEVILA M., CENTELLES S., QUEROL X. Origin of inorganic and organic components of $PM_{2.5}$ in subway stations of Barcelona, Spain. Environmental Pollution, **208**, 125, **2016**.
9. MARTINS V., MORENO T., MENDES L., Eleftheriadis K., Diapouli E., Alves CA., Duarte M., DE MIGUEL E., CAPDEVILA M., QUEROL X., MINGUILLÓN MC. Factors controlling air quality in different European subway systems. Environmental Research, **146**, 35, **2016**.
10. GONG Y., WEI Y., CHENG J., JIANG T., CHEN L., XU B. Health risk assessment and personal exposure to Volatile Organic Compounds (VOCs) in metro carriages – a case study in Shanghai, China. Science of the Total Environment, **574**, 1432, **2017**.
11. CHANG L., CHONG WT., WANG X., PEI F., ZHANG X., WANG T., WANG C., PAN S. Recent progress in research on PM2.5 in subways. Environmental Science-Processes&Impacts, **23** (5), 642, **2021**.
12. WEN Y., LENG J., SHEN X., HAN G., SUN L., YU F. Environmental and Health Effects of Ventilation in Subway Stations: A Literature Review. International Journal of Environmental Research and Public Health, **17** (3), 1084, **2020**.
13. TRIADÓ-MARGARIT X., VEILLETTE M., DUCHAINE C., TALBOT M., AMATO F., MINGUILLÓN MC., MARTINS V., DE MIGUEL E., CASAMAYOR EO., MORENO T. Bioaerosols in the Barcelona subway system. Indoor Air, **27** (3), 564, **2017**.
14. CHEN YY., SUNG FC., CHEN ML., MAO IF., LU CY. Indoor air quality in the metro system in north Taiwan. International Journal of Environmental Research and Public Health, **13**, 1200, **2016**.
15. KARIISA M., FORAKER R., PENNELL M., BUCKLEY T., WILKINS JRI. Short-and long-term effects of ambient ozone and fine particulate matter on the respiratory health of chronic obstructive pulmonary disease subjects. Archives of Environmental & Occupational Health, **70** (1), 56, **2015**.
16. BUONANNO G., STABILE L., MORAWSKA L. Personal exposure to ultrafine particles: The influence of time-activity patterns. Science of the Total Environment, **468**, **2014**.
17. GUSEVA CANU I., CRÉZÉ C., HEMMENDINGER M., BEN RAYANA T., BESANÇON S., JOUANNIQUE V.,

DEBATISSE A., WILD P., SAUVAIN JJ., SUÁREZ G., HOPF NB. Particle and metal exposure in Parisian subway: Relationship between exposure biomarkers in air, exhaled breath condensate, and urine. International Journal of Hygiene and Environmental Health, **237**, 113837, **2021**.

18. SUMANASEKARA S., JAYASINGHE C. Alternative techniques to improve indoor environmental quality. Journal of Green Building, **13**, 19, **2018**.
19. LUGLIO DG., KATSIGEORGIS M., HESS J., KIM R., ADRAGNA J., RAJA A., GORDON C., FINE J., THURSTON G., GORDON T., VILCASSIM MJR. $PM_{2.5}$ Concentration and Composition in Subway Systems in the Northeastern United States. Environmental Health Perspectives, **129** (2), 27001, **2021**.
20. JI W., LI X., WANG C. Composition and exposure characteristics of $PM_{2.5}$ on subway platforms and estimates of exposure reduction by protective masks. Environmental Research, **197**, 111042, **2021**.
21. YONGIL L., YOUNG-CHUL L., TAESUNG K., JIN SEOK C., DUCKSHIN P. Sources and Characteristics of Particulate Matter in Subway Tunnels in Seoul, Korea. International Journal of Environmental Research and Public Health, **15** (11), 2534, **2018**.
22. MUGICA-ÁLVAREZ V., FIGUEROA-LARA J., ROMERO-ROMO M., SEPULVE DA -SANCHEZ J., LOPEZ-MORENO T. Concentrations and properties of airborne particles in the Mexico City subway system. Atmospheric Environment, **49**, 284, **2012**.
23. COLOMBI C., ANGIUS S., GIANELLE V., LAZZARINI M. Particulate matter concentrations, physical characteristics and elemental composition in the Milan underground transport system. Atmospheric Environment, **70**, 166, **2013**.
24. MORENO T., PÉREZ N., RECHE C., MARTINS V., MIGUEL E., CAPDEVILA M., CENTELLES S., MINGUILLÓN MC., AMATO F., ALASTUEY A., QUEROL X., GIBBONS W. Subway platform air quality: assessing the influences of tunnel ventilation, train piston effect and station design. Atmospheric Environment, **92**, 461, **2014**.
25. QUEROL X., MORENO T., KARANASIOU A., RECHE C., ALASTUEY A., VIANA M., FONT O., GIL J., DE MIGUEL E., CAPDEVILA M. Variability of levels and composition of PM10 and PM2.5 in the Barcelona metro system. Atmospheric Chemistry and Physics, **12** (11), 5055, **2012**.
26. JOHANSSON C., JOHANSSON PK. Particulate matter in the underground of Stockholm. Atmospheric Environment, **37** (3), 3, **2003**.
27. SEATON A., CHERRIE J., DENNEKAMP M., DONALDSON K., HURLEY J.F., TRAN C.L. The London underground: dust and hazards to health. Occupational and Environmental Medicine, **62**, 355, **2005**.
28. FIGUEROA-LARA J.J., MURCIA-GONZÁLEZ J.M., GARCÍA-MARTÍNEZ R., ROMERO-ROMO M., TORRES RODRÍGUEZ M., MUGICA-ÁLVAREZ V. Effect of platform subway depth on the presence of Airborne $PM_{2.5}$, metals, and toxic organic species. Journal of Hazardous Materials, **377**, 427, **2019.**
29. SPAGNOLO AM., OTTRIA G., PERDELLI F., CRISTINA ML. Chemical characterisation of the coarse and fine particulate matter in the environment of an underground railway system: cytotoxic effects and oxidative stress-a preliminary study. International Journal of Environmental Research and Public Health, **12** (4), 4031, **2015**.
30. LOXHAM M., NIEUWENHUIJSEN M.J. Health effects of particulate matter air pollution in underground railway systems - a critical review of the evidence. Particle and Fibre Toxicology, **16** (1), 12, **2019**.
31. LU SL., LIU DY., ZHANG W.CH., LIU PW., FEI Y., GU Y., WU MH., YU S., YONEMOCHI S., WANG XJ. Physico-chemical characterization of PM 2.5 in the microenvironment of Shanghai subway. Atmospheric Research, **153**, 543, **2015**.
32. TAO F., GONZALEZ-FLECHA B., KOBZIK L. Reactive oxygen species in pulmonary inflammation by ambient particulates. Free Radical Biology and Medicine, **35** (4), 327, **2003**.
33. PUN VC., KAZEMIPARKOUHI F., MANJOURIDES J., SUH HH. Long-Term PM2.5 exposure and respiratory, cancer, and cardiovascular mortality in older US adults. American Journal Of Epidemiology, **186** (8), 961, **2017**.
34. LIM C.C., HAYES R.B., AHN J., SHAO Y.Z., SILVERMAN D.T., JONES R.R., GARCIA C., THURSTON G.D. Association between long-term exposure to ambient air pollution and diabetes mortality in the US. Environmental Research, **165**, 330, **2018**.
35. KARLSSON H.L., NILSSON L., MOLLER L. Subway particles are more genotoxic than street particles and induce oxidative stress in cultured human lung cells. Chemical Research In Toxicology, **18**, 19, **2005**.
36. POSSELT K.P., NEUBERGER M., KÖHLER D. Fine and ultrafine particle exposure during commuting by subway in Vienna. Wiener Klinische Wochenschrift, **131** (15-16), 374, **2019**.
37. KWON S., JEONG W., PARK D., KIM K., CHO K.H. A multivariate study for characterizing particulate matter (PM_{10}, $PM_{2.5}$, and PM1) in Seoul metropolitan subway stations, Korea. Journal of Hazardous Materials, **297**, 295, **2015**.
38. FURUYA K., KUDO Y., OKINAGA K., YAMUKI M., TAKAHASHI S., ARAKI Y., HISAMATSU Y. Seasonal variation and their characterization of suspended particulate matter in the air of subway stations. Journal of Trace and Microprobe Techniques, **19** (4), 469, **2001**.
39. ZHANG X., JIN Y., WANG XB., GAO JH., SUN XD., SHI-DA W., WEI L. Distributions of pm_ (10) and pm_ (2.5) in two shanghai metro stations. Journal of Environmental and Occupational Medicine, **31** (7), 534, **2014**.
40. WANG B.Q., LIU J.F., REN Z.H., CHEN R.H. Concentrations, properties, and health risk of $PM_{2.5}$ in the Tianjin City subway system. Environmental Science and Pollution Research International, **23** (22), 22647, **2016**.
41. XIONG XQ., LI YX., ZHAO A., WANG H., PAN XC. PM(2.5) concentrations in subway cars in beijing and related awareness of subway passengers. Journal of Environmental and Occupational Medicine, **35** (7), 583, **2018**.
42. NIEUWENHUIJSEN M.J., GÓMEZ-PERALES J.E., COLVILE R.N. Levels of particulate air pollution, its elemental composition, determinants and health effects in metro systems. Atmospheric Environment, **41**, 7995, **2007**.
43. THATCHER T.L., LAYTON D.W. Deposition, resuspension, and penetration of particles within a residence. Atmospheric Environment, **29** (13), 1487, **1995**.
44. ZHAO B., CHEN J.J., LI X.T., CHEN X. Source, effect and distribution of indoor particulate matter. Journal of Environmental Health, **22** (1), 65, **2005**.
45. WOO S.H., KIM J.B., BAE G.N., HWANG M.S., TAHK G.H., YOON H.H., KWON S.B., PARK D., YOOK S.J.

Size-dependent characteristics of diurnal particle concentration variation in an underground subway tunnel. Environmental Monitoring and Assessment, **190** (12), 740, **2018**.
46. KIM K.Y., KIM Y.S., ROH Y.M., LEE C.M., CHI N.K. Spatial distribution of particulate matter (PM_{10} and $PM_{2.5}$) in Seoul Metropolitan Subway stations. Journal of Hazardous Materials, **154**, 440, **2008**.
47. PARK J.H., SON Y.S., KIM K.H. A review of traditional and advanced technologies for the removal of particulate matter in subway systems. Indoor Air, **29** (2), 177, **2019**.
48. HU Z.Y. Theoretical Analysis and Numerical Simulation Study of Particle Pollution in Subway Environment [MD Thesis]. Xi'an University of Architecture and Technology, Xi'an, China, **2014**.
49. MORENO T., RECHE C., MINGUILLÓN M.C., CAPDEVILA M., DE MIGUEL E., QUEROL X. The effect of ventilation protocols on airborne particulate matter in subway systems. Science of the Total Environment, **584/585**, 1317, **2017**.