Environment International 107 (2017) 33–46

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Review article

Air quality inside subway metro indoor environment worldwide: A review

Bin Xu*, Jinliang Hao

State Key Laboratory of Pollution Control and Resource Reuse, Tongji University, Shanghai 200092, China
Department of Environmental Engineering, Tongji University, Shanghai 200092, China

ARTICLE INFO

Keywords:
Air quality
Metro environment
Air pollutant
Particulate matter
Volatile organic compounds

ABSTRACT

The air quality in the subway metro indoor microenvironment has been of particular public concern. With specific reference to the growing demand of green transportation and sustainable development, subway metro systems have been rapidly developed worldwide in last decades. The number of metro commuters has continuously increased over recent years in metropolitan cities. In some cities, metro system has become the primary public transportation mode. Although commuters typically spend only 30–40 min in metros, the air pollutants emitted from various interior components of metro system as well as air pollutants carried by ventilation supply air are significant sources of harmful air pollutants that could lead to unhealthy human exposure. Commuters' exposure to various air pollutants in metro carriages may cause perceivable health risk as reported by many environmental health studies. This review summarizes significant findings in the literature on air quality inside metro indoor environment, including pollutant concentration levels, chemical species, related sources and health risk assessment. More than 160 relevant studies performed across over 20 countries were carefully reviewed. These comprised more than 2000 individual measurement trips. Particulate matters, aromatic hydrocarbons, carbonyls and airborne bacteria have been identified as the primary air pollutants inside metro system. On this basis, future work could focus on investigating the chronic health risks of exposure to various air pollutants other than PM, and/or further developing advanced air purification unit to improve metro in-station air quality.

1. Introduction

Air pollutant exposure has been extensively studied and approved to be a vital cause of increased perceivable health risk (Pope and Dockery, 2006; Dockery et al., 1993; Araki et al., 2010). Indoor microenvironment was identified as the primary source of human exposure to various air pollutants due to the long time people spent every day (Klepeis et al., 2000). Recently, with the rapid development of subway metro system worldwide, human exposure to air pollutants and the related health risk assessment inside metro indoor environment have become of a significant public concern.

Metro transit, by avoiding congestion and reducing gasoline consumption, is providing rapid and affordable transportation to urban communities in > 60 countries. The number of metro commuters has continuously increased over recent years in metropolitan cities. In some cities, metro system has become the primary public transportation mode. For example, Shanghai, as a prosperous and densely populated city, has one of the largest urban metro traffic systems in the world. Daily ridership averaged 9 million in 2015 and reached a record of about 11.3 million on March 11th, 2017.

With such large population of metro riders, metro systems not only need to provide the economic benefits, but also a safe and healthy environment for both passengers and workers. Since metro system infrastructures and operation condition varied significantly at different countries, this review summarized the findings from previous literature according to different geographic divisions (Asia, America, Europe, others). For all continents, the metro air research work always began from the measurement of pollutant exposure level and the identification of pollutant chemical speciation. In the previous literature, particulate matters, aromatic hydrocarbons, carbonyls and airborne bacteria have been identified as the primary air pollutants in the metro air. Then, the influence of ventilation on metro air quality were generally investigated, and mitigation measures to reduce air pollutant concentrations were developed and evaluated. It was reported that some factors may affect air pollutant exposure levels in metro carriages, including service time, ventilation quality, passenger numbers, platform screen doors and driving conditions, etc. (K.Y. Kim et al., 2008; Kim et al., 2011; Mugica-Álvarez et al., 2012a; Moreno et al., 2014a; Hernández-Castillo et al., 2014a; Martins et al., 2015a; Zhang et al., 2012; Shiohara et al., 2005a). Recent studies, especially in Europe, paid more and more

---

* Corresponding author at: Department of Environmental Engineering, Tongji University, Shanghai 200092, China.
E-mail address: binxu@tongji.edu.cn (B. Xu).

http://dx.doi.org/10.1016/j.envint.2017.06.016
Received 29 March 2017; Received in revised form 27 May 2017; Accepted 20 June 2017

attention on the health risk from exposure to metro air pollutants. To examine this issue more carefully, this structured review of the literature was conducted to characterize air pollutants, discuss possible determinants, introduce health implications, and suggest future research inside metro indoor environment. Over 160 relevant articles were selected and reviewed.

2. Asia

Asian metro system in urban area was relatively new and developed very fast following to the formation of metropolitan cities in last decade. As the population of people and automobile increased in metropolitan area, metro was recognized as a sufficient solution to road traffic congestion and urban air quality deterioration. Metro indoor air quality was then received increasing public attentions. To date, > 80 articles on the topic of pollutant species, their sources and concentrations, control measures have been published regarding to Asian metro system. Research interests and focus varied with different national regulations and stages of development. Current air quality studies in Asian metro system focused too much on the assessment of pollutant concentration or people exposure levels. Excessive measurements were conducted under the similar conditions. Most of the studies were conducted in East Asia area. The measurement results and information were summarized in Table 1.

2.1. Air pollutants

Various air pollutants were observed in the metro environment, which is mainly ascribed to the emissions from rails, wheels, catenaries, brake pads, pantographs, and infiltration from out-station polluted air (Kang et al., 2008; Park et al., 2014). The difference of metro system designs led to a large variation in occurrence of air pollutants species, levels and hence personal exposure levels. At the beginning, vehicular exhaust emission was recognized as a primary air pollutant source and studied extensively in the Asian metro system. Chan et al. (1999) conducted a comprehensive survey to evaluate commuter exposure to air pollutants inside different commuting microenvironments in Hong Kong. Hong Kong metro system served about 21% of the public transport passengers. Three individual lines namely Tsuen Wan line, Kwun Tong line and Island line were operated mostly on underground tracks. Traffic-related pollutants, e.g. CO, NOx, THC (Total Hydro Carbon) and O_3 were used as the target pollutants. It was found that all the air pollutant concentrations inside metro were comparable to the other transit modes, although it was enclosed from road atmosphere. The same group also examined the commuter's exposure to respirable suspended PM and VOCs while commuting in eight public transportation modes. The PM_{10} concentration ($\sim 50\ \mu g\ m^{-3}$) inside metro was found the lowest (Chan et al., 2002a). The VOCs concentrations ($3.0–3.8\ \mu g\ m^{-3}$) inside metro was ranked the second place after the roadway transport cabins (Lau and Chan, 2003). The PM and VOCs exposure levels of metro commuters in Hong Kong were lower than those in most overseas cities. The heterogeneity of passenger exposure in different transit microenvironments were then studied in Hong Kong. Traffic-related pollutants were found larger variations than $PM_{2.5}$ across different microenvironments. The lowest average $PM_{2.5}$ concentrations were observed in the metro platform air (F. Yang et al., 2015). An independent approach unravelling the bacterial diversity within the Hong Kong metro system was used. It was found that microbial diversities and assemblages varied depending on architectural characteristics, nearby outdoor microbiomes, and connectedness with other lines (Leung et al., 2014). After Hong Kong, dozens of measurement campaigns were conducted all over the Asian metropolitan cities.

Li et al. (2006) and Li et al. (2007) measured the concentrations of CO_2, CO, TVOC, TSP (Total Suspended Particle), PM_{10}, $PM_{2.5}$, PM_1, benzene, toluene and xylene in Beijing metro transit system. Only CO showed significant seasonal variations (greater in winter than in summer). The concentrations of TVOC, TSP and PM_{10} were significantly higher during rush hours than during regular hours. The in-train concentrations of VOC species were mainly influenced by the ambient pollutant concentrations; while the in-train concentration of CO_2 was mainly influenced by the number of passengers. Exposure to fine particles as well as particulate PAHs (Polycyclic Aromatic Hydrocarbons) in three transportation modes (walking, metro and bus) were examined in Beijing. The lowest median $PM_{2.5}$ mass concentration ($56.9\ \mu g\ m^{-3}$) and particle number concentrations ($2.2 \times 10^4\ cm^{-3}$) were observed in metro system (Yan et al., 2015). The characteristics of carbonyl compounds were investigated for taxi, bus and metro in Beijing. Metros energized by electricity without exhaust had the lowest levels with total concentrations of $98.5 \pm 26.3\ \mu g\ m^{-3}$ (Pang and Mu, 2007). Compared to PM and VOCs, high culturable bacteria ($12{,}639\ CFU\ m^{-3}$) and fungi ($1806\ CFU\ m^{-3}$) concentrations were observed for the metro system, respectively (Dong and Yao, 2010).

Different from Beijing, most of the previous studies in Shanghai focused on the PM exposure levels in metro system. The mean levels of PM_1, $PM_{2.5}$, and PM_{10} were observed at 231 ± 152, 287 ± 177, and $366 \pm 193\ \mu g\ m^{-3}$, respectively (Ye et al., 2010; Xu et al., 2013; Qiao et al., 2015a; Xu et al., 2016). Commuters' real-time exposure to PM and BC (Black Carbon) by several common travel modes (bus, walking, cycling, taxi and subway) were measured. The average PM_1 exposure levels and inhalation doses during commuting were $122 \pm 77\ \mu g\ m^{-3}$ and $28.6 \pm 25.9\ \mu g$ for metro trips (Yu et al., 2012). The average BC exposure concentrations and inhalation doses during commuting were $9.43 \pm 2.89\ \mu g\ m^{-3}$ and $0.95 \pm 0.29\ \mu g$ for metro trips, respectively (Li et al., 2015). Measurements were conducted to assess PM levels, chemical compositions, morphology and mineralogy. Newer underground metro system showed lower PM pollution than the old aboveground system, which was likely attributable to the advanced ventilation setup and air filter. Fe, Mn, Cr, Cu, Sr, Ba and Pb concentrations in all of the metro lines were significantly higher than those in the urban ambient air, implicating that these metals may be associated with the metro systems operation (Guo et al., 2014; Lu et al., 2015). Fe was observed as the most abundant metal element, following by Ca, Al, Mg, Mn, Zn, Cu, Cr, Ni, Pb and Hg (Qiao et al., 2015b). Only a few studies measured VOCs concentrations inside metro system in Shanghai. The exposure levels of in-train VOCs (benzene, toluene, ethylbenzene, xylene, styrene, formaldehyde, acetaldehyde, acetone and acrolein) were strongly dependent on service time of metro trains, passenger numbers and driving conditions (Gong et al., 2017). The total carbonyl concentrations of in-train were about 1.4–2.5 times lower than in stations. Most carbonyls concentrations were much higher in the morning rush hour than in other time (Feng et al., 2010).

Other than Hong Kong, Beijing, Shanghai, there has not been a large number of relevant research in other Chinese cities. Only a few field measurements intermittently reported the metro indoor air quality in those cities. Chan et al. (2002b) and Chan et al. (2003) examined commuter exposure to respirable PM (PM_{10} and $PM_{2.5}$), CO, and VOCs in various public transport environments (metro, bus and taxi) in Guangzhou. For all the measured pollutants, the exposure levels in metro were noticeably lower than those in the roadway transports. The exposure levels measured in evening peak hours were slightly higher than those in afternoon non-peak hours. The metro air quality assessment in Tianjin showed the average concentration of the $PM_{2.5}$ was $151.43\ \mu g\ m^{-3}$ inside the metro train during rush hours (Wang et al., 2016). $PM_{2.5}$ concentrations on the platform were higher than those inside train. The highest element in $PM_{2.5}$ samples was Fe with the level at $17.55\ \mu g\ m^{-3}$ (Wang et al., 2016). In Taipei metro system, experimental results demonstrated that PM levels inside trains ($8–68\ \mu g\ m^{-3}$) and on platforms ($7–100\ \mu g\ m^{-3}$) were lower than those measured for other metro systems worldwide (Cheng et al., 2008; Cheng and Lin, 2010). The same group later extended the investigation to more metro lines as Taipei metro system developed. Measurement results showed that PM_{10}, $PM_{2.5}$ and CO_2 levels inside metro trains travelling

Table 1
Summary of the air pollutant measurements in Asia.

City	Metro built year	Measurement year	Pollutant species	Average concentration	Instrument	Reference
Hong Kong	1979	1995–1996	CO, NO_X	1500, 205 ppb	Correlation CO Analyzer (Model 48, Thermo Environmental Instruments Inc., USA); NO-NO_2-NOx Analyzer (Model 42, Thermo Environmental Instruments Inc., USA)	(Chan et al., 1999)
		2014	PM_{10}, $PM_{2.5}$	120, 10.2 $\mu g\ m^{-3}$	DustTrak (Model 8520, TSI Inc., USA); Condensation particle counter (CPC, TSI Inc., USA)	(Chan et al., 2002a; F. Yang et al., 2015)
		2014	Microbiome	N/A	Portable sample pumps (SKC Inc., USA)	(Leung et al., 2014)
Beijing	1969	2004	TVOC	0.3 ppm	TVOC monitor (Phocheck 5000, Ion science Inc., United Kingdom)	(Li et al., 2006)
			TSP, PM_{10}, $PM_{2.5}$, PM_1	166, 108, 36.9, 14.7 $\mu g\ m^{-3}$	Dustmate fume and dust detector (Turnkey Instruments Ltd., United Kingdom)	(Li et al., 2006; Li et al., 2007)
			Benzene, toluene and xylene	13.7,12.4,4.1 $\mu g\ m^{-3}$	GC (N/A)	(Li et al., 2006)
		2005	Carbonyl compounds	98.5 $\mu g\ m^{-3}$	HPLC (HP1050, Hewlett Packard Co., USA)	(Pang and Mu, 2007)
		2007	Bacteria, fungi	12,639, 1806 CFU m^{-3}	BioSampler (Becton, Dickson and Company, USA)	(Dong and Yao, 2010)
		2011	PAHs	50.3 ng m^{-3},	GC–MS (7890A-5975C Agilent Inc., USA)	(Yan et al., 2015)
Shanghai	1993	2008	PM_1, $PM_{2.5}$, PM_{10}	231, 287, 366 $\mu g\ m^{-3}$	DustTrak (Model 8532, TSI Inc., USA)	(Ye et al., 2010; Xu et al., 2013; Qiao et al., 2015a; Guo et al., 2014; Lu et al., 2015; Juraeva et al., 2016)
		2008	Carbonyl compounds	24 $\mu g\ m^{-3}$	GC–MS (5973 N, Agilent Inc., USA)	(Zhang et al., 2012; Feng et al., 2010)
		2015	Black Carbon	9.43 $\mu g\ m^{-3}$	Black Carbon monitors (Model AE-51, Magee Scientific Co., USA)	(Li et al., 2015)
Guangzhou	1997	2002	$PM_{2.5}$, PM_{10}	55, 44 $\mu g\ m^{-3}$	DustTrak (Model 8520, TSI Inc., USA)	(Chan et al., 2002b)
		2000	VOCs	60.5 $\mu g\ m^{-3}$	GC–MS (5972 GC/MSD, Hewlett-Packard Development Co., USA)	(Chan et al., 2003)
Tianjin	1984	2015	$PM_{2.5}$	151.4 $\mu g\ m^{-3}$	Fine particle separating devices (PEM-2000-25AA, SKC Inc., USA)	(Wang et al., 2016)
Taipei	1996	2011	PM_{10}, $PM_{2.5}$	58, 32 $\mu g\ m^{-3}$	Particle monitors (BAM 1020 beta, Met One Inc., USA)	(Cheng et al., 2008; Cheng and Lin, 2010; Cheng and Yan, 2011; Cheng, 2012; Chen et al., 2016; Liu et al., 2015)
Seoul	1971	2007–2008	PM_{10}, $PM_{2.5}$	150, 118.2 $\mu g\ m^{-3}$	Mini-volume air sampler (Model PAS 201, Air Metrics., USA)	(K.Y. Kim et al., 2008; Park et al., 2014; Yu et al., 2004; Park and Ha, 2008; Kwon et al., 2008; J.C. Kim et al., 2008; Jung et al., 2010; Jung et al., 2012; Byeon et al., 2015; Kwon et al., 2015; Y. Kim et al., 2010; Y.S. Kim et al., 2010; M.J. Kim et al., 2012; Kang et al., 2013; Oh et al., 2012; Liu and Yoo, 2015; Yong et al., 2011; K.H. Kim et al., 2012; Son et al., 2014a; Han et al., 2014; Kwon et al., 2016; J.B. Kim et al., 2014)
		2005	Chemical compositions	Fe (70%)	Environmental scanning electron microscope (S-3500N, Hitachi Co., Japan)	(Kang et al., 2008)
		2007	Fungi	N/A	One-stage viable particulate cascade impactor (Model 10-800, Andersen Inc., USA)	(Kim et al., 2011; Cho et al., 2006)
		2015	Bacteria, fungi	210, 75 CFU m^{-3}	Air Sampler (17G9, Gilian Product Sensidyne, Inc., USA)	(Hwang et al., 2010; Sung et al., 2016; Naddafi et al., 2011)
		2006	VOCs	146.7 $\mu g\ m^{-3}$	GC–MS (HP-6890, Hewlett-Packard Development Co., USA)	(Lee et al., 2011; Son et al., 2011)
Tokyo	1927	2004	Fungi	342 CFU m^{-3}	Air Sampler (MAir T, Millipore Co., USA)	(Kawasaki et al., 2010)
		1997	TSP	90 $\mu g\ m^{-3}$	Air sampler (GilAir-5 Gillian Corp., USA) with a polycarbonate Nuclepore filter	(Furuya et al., 2001)
Tehran	1986	2011	Fungi	1210 CFU m^{-3}	BioStage single-stage cascade impactor (N/A)	(Kamani et al., 2014; Hoseini et al., 2013)
Delhi	2002	2012	$PM_{2.5}$	78 $\mu g\ m^{-3}$	DustTrak (Model 8533, TSI Inc., USA)	(Goel et al., 2015)
St. Petersburg	1935	2007	Bacteria, fungi	2236, 205 CFU m^{-3}	Passive air sampler (N/A)	(Bogomolova and Kirtsideli, 2009)

underground were approximately 20–50% higher than those in aboveground (Cheng and Yan, 2011; Cheng, 2012). A comprehensive measurement campaign was then conducted to measure the metro indoor air pollutants, including humidity, temperature, CO, CO_2, formaldehyde (HCHO), TVOCs, O_3, PM_{10} and $PM_{2.5}$, bacteria and fungi, in Taipei. The concentrations of CO, CO_2 and HCHO were under the limits in the standards. However, TVOCs levels, bacterial levels, and PM_{10} and $PM_{2.5}$ concentrations exceeded the stipulated standards. Increased air change rates in each station might reduce the exposure to bacteria and CO_2 (Chen et al., 2016).

As one of the earliest metro system in Asia, the indoor air quality in Seoul metro system was studied extensively. Yu et al. (2004) evaluated asbestos exposure among Seoul metropolitan metro workers and identified possible sources of asbestos exposure, including gaskets, ceiling boards, ceiling materials, and dust settled inside ducts. In 2008, a series of studies reported the concentrations of PM_{10}, $PM_{2.5}$, CO_2 and CO inside trains and platforms. The results showed that PM_{10} levels inside metro exceeded the Korean indoor air quality standard by 37–83% (Park and Ha, 2008). On the other hand, some found the average PM_{10} level in the metro trains were below the limit in the standards for cabins (Kwon et al., 2008; J.C. Kim et al., 2008). To clearly identify sources of metro particles, PM samples were characterized by a single-particle analytical technique (particle electron probe X-ray microanalysis). Particles with relative abundances of 75–91% Fe-containing, indicating that metro particles were generated from wheels and brakes (Jung et al., 2010). Chemical composition of particles was then examined in more details. Fe-containing particles and Soil/road dust particles accounted for 69% and 18% of $PM_{2.5–1.0}$ in PM samples, with minor fractions of Mg, Al, Si, Ca, S, and C (Jung et al., 2012; Byeon et al., 2015). The relationship between PM concentration and multivariate factors were analyzed using statistical methods. The station depth and number of trains passing through stations were found to be the determinants on PM levels (Kwon et al., 2015). To capture the multivariate and periodic characteristics of all the air samples, a predictive monitoring and diagnosis system using a lifting technique was developed, which can identify the contributions of various pollution sources (Y. Kim et al., 2010; Y.S. Kim et al., 2010; M.J. Kim et al., 2012; Kang et al., 2013; Oh et al., 2012; Liu and Yoo, 2015). Measurements were performed to assess the levels of fungi concentration in metro stations in Seoul. The airborne fungi concentrations measured during the morning and evening rush hours were significantly higher than those measured during non-rush hours. High concentrations of fungi were observed in the settled dust samples, indicating that the settled dust may be the main source of airborne fungi (Cho et al., 2006). Concentrations of total airborne bacteria were detected up to 4997 CFU m^{-3}, with a geometric mean of 191 CFU m^{-3}. It was found that bacterial aerosol concentration in the metro systems varied throughout the seasonal transitions (Hwang et al., 2010). They increased by more than three times from spring to summer, and decreased by more than two times from fall to winter (Heo and Lee, 2015). There was a significant correlation between culturable airborne fungi and various environmental factors, including the presence of platform screen doors, temperature, relative humidity, and number of passengers (Sung et al., 2016). VOCs were investigated and found below the limit in national standard (Lee et al., 2011).

Besides China and South Korea, a number of studies were conducted in Tokyo, Japan, Tehran, Iran, Delhi, India and St. Petersburg, Russia. In Tokyo metro system, the PM mass concentration showed seasonal variations, and was higher in December and October than in March and June. The elements that were observed at high concentrations were Fe, Ba, Cu and Ca (Furuya et al., 2001). It was also found that there was a positive correlation between airborne particles and fungi, but not correlation between humidity and fungi (Kawasaki et al., 2010). The PM and bacterial contamination in Tehran metro system was investigated. Maximum and minimum bacterial contamination levels were 1073 CFU m^{-3} and 242 CFU m^{-3}, respectively. The average concentrations of PM_{10} and $PM_{2.5}$ were found at 94.4 ± 26.3 and 52.3 ± 16.5 μg m^{-3} (Kamani et al., 2014). Fourteen bacterial species and genera were found with the dominant species of *Staphylococcus*, *Micrococcus* and *Bacillus* (Naddafi et al., 2011; Hoseini et al., 2013). Measurements of $PM_{2.5}$ exposures were conducted in various transport microenvironments in Delhi. The metro PM concentrations were ~20% greater than the ambient but were still lower than most of other transport modes (Goel et al., 2015). The fungal and bacterial aerosols in four St. Petersburg metro stations were examined over a 4-month period. Fifty fungal species were found, among which were *Acremonium*, *Aspergillus*, *Cladosporium* and *Penicillium*. The fungal air propagules number increased significantly in spring at all the stations (Bogomolova and Kirtsideli, 2009).

2.2. Ventilation

Indoor air quality in metro systems was greatly influenced by the ventilation systems. Efficient ventilation systems could maintain indoor air quality and reduce the pollutant entry from outdoor atmosphere. To date, most of the relevant studies were conducted in South Korea. Measurement of natural ventilation rate in Seoul metro system was performed. The dilution factor by natural ventilation was found to be approximately 35% along all the measured metro lines (Kwon et al., 2010). The mechanical ventilation performance in the metro tunnel was then investigated using commercial-available ANSYS CFX software by solving Reynolds-averaged Navier-Stokes equations. The numerical results were validated with experimental results. It was found that the average velocity of the airflow in the shaft increased when the velocity of the air-curtain increased (Juraeva et al., 2016). The PM concentration was reduced significantly in the tunnel when the air-curtain and train-wind were operated. The results suggested an optimum connecting location of the ventilation shafts to maximize the ventilation efficiency (Juraeva et al., 2013). A ventilation system of connecting ducts and installing the guide vanes on both sides of the ducts was found effective from the modelling results (Juraeva et al., 2015). A predictive model was proposed to estimate both the PM concentration and the energy usage of the ventilation system. The comparison results with other prediction models showed that the proposed model can decrease 20% prediction error of PM concentration in platform (Lee et al., 2015). Besides South Korea, a few studies were conducted in China. Yuan and You (Yuan and You, 2007) reported a two-equation turbulence model that can be used to predict velocity field and temperature field influenced by the ventilation system in the station. The piston effects influenced by draught relief shaft was examined in Taipei metro system. It was found that the length of draught relief shaft was an important design parameter for efficient air exchange by piston effects for underground metro systems (Lin et al., 2008). Based on a numerical analysis using computational fluid dynamics (CFD) method, Wu et al. (Wu et al., 2013) reported that a metro system with two shafts rather than that with one shaft could significantly improve air exchange efficiency. For the one-shaft system, it worked better with the shaft at the train-arrival side rather than at train departure side.

2.3. Mitigation measures

Several mitigation measures were developed and applied to reduce pollutant levels in the metro system. South Korean researchers conducted most of the investigation in this field. Platform screen doors (PSD) was recognized as an efficient measure to improve the metro air quality. It showed that airborne bacteria concentrations at the stations without PSD was higher than those with PSD (Hwang et al., 2010). A multivariate statistical approach, called statistical hypothesis testing, was developed to determine the effect of the installation of a PSD system (Yong et al., 2011). The concentrations of PM_{10} and $PM_{2.5}$ were measured continuously before and after the PSD system was installed. The mean PM_{10} concentration in the later period (after PSD

Table 2
Summary of the air pollutant measurements in America.

City	Metro built year	Measurement year	Pollutant species	Average concentration	Instrument	Reference
Newark	1907	1977	Chemical composition	N/A.	A six-stage suspended particle fractionating sampler (Model 2354, Research Appliance Company, USA)	(Trattner et al., 1977)
Boston	1897	1989–1990	VOCs	12.5 μg m^{-3}	GC-FID (HP 5890, Hewlett Packard Co., USA)	(Chan et al., 1993)
Washington D.C.	1976	1999	PM	10^6 particles m^{-3}	Optical aerosol counter (Model 237A, Met One Inc., USA)	(Birenzvige et al., 2003)
New York City	1907	2013	Microorganisms	N/A	Fluid impinger (Omni 3000, InnovaPrep LLC, USA)	(Robertson et al., 2013)
		1999	Fe, Cr, Mn	500, 84, 240 ng m^{-3}	HR-ICP-MS (N/A)	(Chillrud et al., 2004; Chillrud et al., 2005; Grass and Family, 2010)
		2007–2008	$PM_{2.5}$	30.6 μg m^{-3}	Personal monitor (AM510 SidePakTM, TSI Inc., USA)	(Morabia et al., 2009; Wang and Gao, 2011; Vilcassim et al., 2014)
Los Angeles	1990	2012	PM	27,500 particles cm^{-3}	Particle counter (Model 3007, TSI Inc., USA)	(Houston et al., 2016)
		2010	PM_{10}, $PM_{2.5}$	78.0, 56.7 μg m^{-3}	DustTrak (Model 8520 TSI Inc., USA)	(Kam et al., 2011a; Kam et al., 2013)
		2011	PAHs	93 μg m^{-3}	Air pollution monitors (PAS 2000 CE, EcoChem Inc., USA)	(Houston et al., 2013)
Mexico City	1969	2002	$PM_{2.5}$, PM_{10}	78.0, 126 μg m^{-3}	Gravimetric analysis (DataRAM, MIE Inc., United Kingdom)	(Gómez-Perales et al., 2004; Mugica-Álvarez et al., 2012b; Vallejo et al., 2004)
		2002	Benzene	4 ppb	GC/FID (DKK Corporation, Japan)	(Gómez-Perales et al., 2004)
		2002	VOCs	22.2 μg m^{-3}	GC–MS (HP6890-HP5973, Hewlett Packard Co., USA)	(Shiohara et al., 2005a)
		2010–2011	Fungi, bacteria	284, 415 CFU m^{-3}	Two-stage multiorifice cascade impactors (Lot 1280573, Becton–Dickinson and Company, USA)	(Hernández-Castillo et al., 2014a)
Montreal	1966	2003	Manganese	32 ng m^{-3}	Pumps equipped with Teflon filters AirCon-2 (Gillian Corp., USA)	(Boudia et al., 2006)
Buenos Aires	1913	2005–2006	TSP	211 μg m^{-3}	Pumps equipped with Millipore polycarbonate HTTP 0037 filters (Gillian Corp., USA)	(Murruni et al., 2009)
		2005–2006	Fe, Zn, Cu	86, 0.08, 0.8 μg m^{-3}	PIXE technique developed at the TANDAR Laboratory accelerator facility of the National Commission of Atomic Energy	(Murruni et al., 2009)
Santiago	1975	2011–2012	$PM_{2.5}$	16.9 μg m^{-3}	DustTrak (Model 8532, TSI Inc., USA)	(Suárez et al., 2014)

installation) was significantly reduced by 16–30% compared to the earlier period (K.H. Kim et al., 2012; Son et al., 2014a; Han et al., 2014). The change of PM size distribution in a metro station with PSD installed was investigated. It was found that the inflow of coarse mode particles from the tunnel seemed unavoidable with PSD alone. A combination of PSD and ventilation that can block fine PM inflow was more effective (Kwon et al., 2016). Other than PSD, a newly developed metro in-train air purifier was installed on the ceilings of the carriages and the effectiveness was evaluated. It was found that the PM_{10} concentrations in two metro lines decreased from 132.8 to 112.2 μg m^{-3} (15.5% efficiency) and from 154.4 to 114.2 μg m^{-3} (26.0% efficiency), respectively (J.B. Kim et al., 2014). Efficiency of adsorbents purification for the removal of VOC and NO_2 in an underground metro station was evaluated. The performance of higher contents of granular activated carbon was better than that of higher contents of the constructed carbon. When the purifier was applied to the metro ventilation system, the removal efficiencies were found to be 75% and 85% for NO_2 and VOC, respectively (Son et al., 2011). Li and You (2011) evaluated a ventilation system integrated with PSD during the transition season and winter. The results showed that it met the indoor air quality requirements and saved energy consumption. Also, an innovative PSD system with controllable slits was introduced, aiming to improve traditional PSD and automatic platform gates system. Compared with the traditional PSD system, the new environmental control system met air quality requirements and the energy consumption was reduced by using optimized opening and operating programs (Z. Yang et al., 2015). In the newly built metro platforms, PSDs have been frequently installed in recent years.

2.4. Health assessment

Compared to above-mentioned studies, metro air quality research related to health assessment was much less in Asia. Recently, passenger health risk assessment based on a non-Gaussian dynamic sensor validation method was developed in metro systems (M.J. Kim et al., 2014). A dynamic independent component analysis based on iterative reconstruction algorithm was proposed to restore the faults to normal measurements and validated with the experimental data. The measurement results in previous studies assumed that (1) the measured pollutant concentrations follow an identical Gaussian distribution, and (2) current data of the pollutant concentrations were statistically independent of past ones. However, the pollutant concentrations measured from the underground environments were correlated, which meant they followed a non-Gaussian distribution. Therefore, M.J. Kim et al. (2014) proposed a new sensor fault validation model with health risk assessment of indoor air quality and applied to the data obtained from the underground metro station at Seoul Metro, Korea for taking non-Gaussianity and dynamics of the air pollutant concentrations into account. A comprehensive indoor air quality index was used to determine the influence of sensor reliability on passengers' health risk inside the metro station. The results showed that it can more accurately validate sensor faults than conventional methods and produce an improved indoor air quality level in the metro station (M.J. Kim et al., 2014). The association between traffic-related air pollution and adverse cardiovascular effects for different commuting modes (metro, bus, car, and walking) was studied with 120 young, healthy subjects in Taipei. It was found that decreases in the heart rate variability indices were associated with increased levels of $PM_{2.5}$. The effects of $PM_{2.5}$ on cardiovascular endpoints were the lowest in the metro mode (Liu et al., 2015).

3. America

As the metro system was built very early in America, the study on air quality in American metro environment began many decades ago. Although the number of research paper is less than that in Asia, there have still been > 20 articles published. Different from Asia, research interests and attentions were more focused on species and health related issues instead of control measures. Although the air pollutant species and their potential health effects were well investigated, the mitigation measures were barely studied in American metro system. Most of the studies were conducted in the United States of America. The measurement results and information were summarized in Table 2.

3.1. Air pollutants

As early as 1977, the chemical composition of PM in Newark metro air were determined. Several inorganic constituents (e.g. sulfate, nitrate, bromate and silica) were found. The possible sources of the pollutants were recognized as the emissions from automobiles, power plants, incineration, braking operations and track-wheel abrasion of the metro trains (Trattner et al., 1977). Then, many studies were conducted in the northeast of USA. In Boston, the concentrations of six gasoline-related VOCs: benzene, toluene, ethylbenzene, m-/p-xylene, o-xylene and formaldehyde in four different commuting modes (driving, metro, walking, and biking) were compared. The VOCs concentration in metro system was relatively low. However, high VOCs exposure might occur due to long commuting time underground (Chan et al., 1993). In Washington D.C., biological and nonbiological aerosols in a metro environment were characterized using UV (UltraViolet) fluorescence and PCR (Polymerase Chain Reaction). Only a small fraction of the total PM (typically < 1%) were found as biological aerosols. The total number concentration of PM exhibited a diurnal cycle that depended on the station usage. The most common element in the PM was Fe. Sodium chloride was prevalently observed in the PM mass (Birenzvige et al., 2003). In New York City (NYC), measurement campaign was conducted to determine sources, levels, and exposure pathways of Fe, Mn, and Cr. It was found that personal samples had much higher concentrations of Fe, Mn, and Cr than home indoor and ambient samples, which indicated that Fe dust in the NYC metro system was the dominant source of airborne exposures to Fe, Mn, and Cr (Chillrud et al., 2004; Chillrud et al., 2005). The composition and diversity of microorganisms associated with bioaerosols in NYC metro environment were then measured. The bacterial composition was relatively simple: only 26 taxonomic families made up 75% of the sequences. Identifiable bacterial sequences were composed of soil, environmental water, and human skin commensal bacteria (Robertson et al., 2013). To study the health risks and benefits associated with using public buses and metros rather than car, the magnitude and variance of personal exposure to $PM_{2.5}$ for transportation by car, metro, or walking were assessed. Total $PM_{2.5}$ exposures did not differ among car, metro, and walking. Exposure to $PM_{2.5}$ appeared to be higher for the metro (19.6 μg m^{-3} min) than for the car (13.1 μg m^{-3} min) (Morabia et al., 2009). Travelers exposure to fine PM was assessed in terms of mass and number concentrations across various transportation micro-environments in NYC. The highest exposure occurred at underground metro stations and onboard metro trains (Wang and Gao, 2011). BC and $PM_{2.5}$ concentrations in selected metro stations were measured. Real time BC concentrations ranged from 5 to 23 μg m^{-3}, with 1 min average peaks larger than 100 μg m^{-3}, while real time $PM_{2.5}$ levels ranged from 35 to 200 μg m^{-3} (Vilcassim et al., 2014).

Besides northeast of USA, many related studies were conducted in California. An extensive sampling campaign was conducted in 2010 to measure PM concentrations in two lines of the Los Angeles metro system. The average PM_{10} concentrations at station platforms and inside the train were 78.0 μg m^{-3} and 31.5 μg m^{-3}, respectively. It suggested that local emissions (i.e., vehicular traffic, road dust, operation of trains) were the main sources of airborne PM for the metro system (Kam et al., 2011a). The same research group then performed a comprehensive PM chemical analysis including total and water-soluble metals, inorganic ions, elemental and organic carbon, and organic compounds. It showed that, among all the elements, Fe makes up to

27% and 32% of gravimetric mass in coarse PM and fine PM, respectively. Reactive oxygen species activity was strongly correlated with water-soluble Fe, Ni, and OC (Kam et al., 2011b). The exposure to particle-bound PAH across transportation microenvironments was characterized with twenty four adult residents carrying a portable air pollution monitor for a total of 96 days. Average PAH concentrations were the lowest while travelling in public transportation (61–124 ng m^{-3}) compared to other travelling modes (Houston et al., 2013). They also monitored the PM number concentrations and noise levels on 17 station platforms in the Los Angeles metro system. It was found that PM number concentrations were about 2000 particles cm^{-3} higher at open platform than standing under a shade canopy, but the noise levels were significantly lower at open platform compared to under canopy (Houston et al., 2016).

Mexico City is another city with many metro air quality assessments in America. Survey studies measured commuters' exposure to $PM_{2.5}$, CO, benzene, and the chemical composition of $PM_{2.5}$ on different routes and transport modes in Mexico City. The concentrations of all pollutants were observed lower in metro than other transportation modes at all the time (Gómez-Perales et al., 2004). Concentrations of $PM_{2.5}$ were observed between 60 μg m^{-3} and 93 μg m^{-3} in the metro that were 6% larger than outside concentrations. Greater Fe, Cu, Ni, Cr and Mn concentrations were found in the metro samples as compared to the PM in ambient PM samples by up to 2.6 times (Mugica-Álvarez et al., 2012b). Later, a study that focused on describing the personal exposure to $PM_{2.5}$ during their daily activities was conducted. A total of forty healthy volunteers carried $PM_{2.5}$ personal monitors during 13 h and registered their activities in a written diary. Among all the environments, the highest concentration (106.2 μg m^{-3}) occurred in the metro (Vallejo et al., 2004). The commuters' VOCs exposure levels were also investigated in Mexico City. Benzene, toluene, ethylbenzene, m/p-xylene, and formaldehyde were measured in various transport modes: car, microbus, bus, and metro. The results showed that the average concentrations of all chemicals inside cars and microbuses were statistically higher than in metro trains (Shiohara et al., 2005b). An aerobiological study were carried out to assess airborne bacterial and fungi concentrations, as well as their relationship with several factors, such as depth of the station, sampling site, temperature, and relative humidity. Fifty-seven fungi and sixty-one bacteria colonies were found. Concentration levels of bacteria (1–484 CFU m^{-3}) and fungi (51–715 CFU m^{-3}) inside metro were higher than outdoors by up to 8 times. Most of bacteria were identified as Gram-positive nonsporulating short bacillus, while the most abundant fungi were identified as *Aspergillus*, *Penicillium*, and *Alternaria* (Hernández-Castillo et al., 2014b).

There were some studies regarding to the metro air quality other than USA and Mexico. Mn concentrations in the underground metro air were measured in Montreal, Canada. Low levels of Mn in respirable and total PM were found, with averages of 18 and 32 μg m^{-3}, respectively (Boudia et al., 2006). In the Buenos Aires underground metro system, TSP samples were collected and analyzed by using the PIXE (Particle Induced X-ray Emission) technique. PM concentrations were found to be between 152 μg m^{-3} and 270 μg m^{-3}, which were about 3 times larger than those in urban ambient air. The most enriched element in samples was Fe, the levels of which ranged from 36 to 86 μg m^{-3} (Murruni et al., 2009). Personal exposure to PM (fine and Ultrafine Particles, UFP) in different transport modes (bicycle, bus, car and metro) was measured in a busy assigned route in downtown Santiago, Chile. $PM_{2.5}$ and UFP exposure in metro were 16.9 μg m^{-3} and 8400 particles cm^{-3}, respectively (Suárez et al., 2014).

3.2. Ventilation

Compared to Asian studies, ventilation and mitigation measures were not paid much attention in America. A realistic computational fluid dynamics approach was developed to simulate airflow in metro tunnels and stations. The dispersion and transport of pollutants though the stations were simulated by correlating to the airflow dynamics (Camelli et al., 2014).

3.3. Mitigation measures

The effectiveness of magnetic filters on removing PM from a metro tunnel was evaluated. It was found that PM removal efficiency increased as fan frequency increased. Maximum removal efficiency of PM_{10} (52%), $PM_{2.5}$ (46%), and PM_1 (38%) were observed at 60 Hz fan frequency (Son et al., 2014b).

3.4. Health assessment

The health related assessment was studied much more than that in Asia. In NYC, average personal Mn and Cr exposure concentrations were observed much lower than the United States Occupational Safety and Health Administration's Permissible Exposure Limit (PEL) guideline concentrations (Mn = 5 mg m^{-3}; Cr = 1 mg m^{-3}, average level for 8 h). To investigate the potential for health effects of exposure at these levels, a pilot study of personal exposures to Fe dust with biomarkers of metal exposure, oxidative stress, and DNA damage in blood and urine samples was conducted. Urinary isoprostane concentrations were significantly correlated with the number of years working in the metro system, and were detected at higher concentrations in metro workers than in bus drivers or office workers (Grass and Family, 2010). In Mexico City, the measurement results suggested that, for comparable commuting durations, metro commuters passengers were exposed to lower levels of VOC than car and microbus. The lifetime carcinogenic risk from commuting by metro was $1.3–1.7 \times 10^{-5}$ (Shiohara et al., 2005a). In Los Angeles, the composition and estimated lung cancer risk of $PM_{2.5}$ for five differential commute environments were compared. Metals associated with stainless steel, e.g. Fe, Cr, and Mn, were elevated for the metro environment, which most likely originated from abrasion processes between the rail and brakes. Lung cancer risk due to inhalation of PAHs was calculated. Results showed that lung cancer risk for the metro is 3.8 and 4.5 times lower than driving on freeways and busy roadways (Kam et al., 2013).

4. Europe

Similar to America, the air quality in European metro environment was investigated very early. Since there were metro systems in many cities, the relevant studies were conducted in many countries. Over 50 papers were selected to summarize the findings. Most of research interests and attentions focused on species and health related issues. The measurement results and information were summarized in Table 3.

4.1. Air pollutants

In 1998, six London metro stations were sampled for the bacteria and fungal. The numbers of fungi found in most of the samples were approaching 150 CFU m^{-3} (Gilleberg et al., 1998). Measurements of personal exposure to $PM_{2.5}$ in various transport microenvironments (bicycle, bus, car and metro) were conducted in central London. Mean exposure levels (247.2 μg m^{-3}) in London metro system were 3–8 times higher than the on-road transport modes (Adams et al., 2001). Personal exposure to PM_5 and the number, shape, size distribution and elemental composition of collected PM were assessed using computer-controlled scanning electron microscopy and energy dispersive X-ray detection. The most PM were Fe/Si particles with the average Fe concentration at 22.8% and the Si concentration at 17.4% together with C, Ca and K (Sitzmann et al., 1999). Since the UFP fraction that may contribute significantly to PM number concentrations and surface area, the chemistry of $PM_{0.1}$ was measured using coupled plasma mass spectrometry and ion chromatography. The results showed similar metal-rich concentrations as the coarse and fine fractions. Scanning electron

Table 3
Summary of the air pollutant measurements in Europe.

City	Metro built year	Measurement year	Pollutant species	Average concentration	Instrument	Reference
London	1863	1996	Fungi	125 CFU m^{-3}	Biosampler (Biotest Inc., Germany)	(Gilleberg et al., 1998)
		1996	$PM_{2.5}$	892.8 μg m^{-3}	N/A	(Adams et al., 2001; Sitzmann et al., 1999)
Barcelona	1924	2013	PM_1, PM_3, PM_{10}	67, 165, 183 μg m^{-3}	IAQ monitor (Model 7525, TSI Inc., USA)	(Martins et al., 2015a; Moreno et al., 2015a; Querol et al., 2012; Moreno et al., 2014b; Minguillón et al., 2012; Martins et al., 2016a; Martins et al., 2016b; Moreno et al., 2015b; Moreno et al., 2017; Martins et al., 2015b)
Milan	1964	1996	Fungi	N/A	N/A	(Picco and Rodolfi, 2000)
		2010	UFP, PM_{10}, $PM_{2.5}$, PM_1	1.3×10^4 particles cm^{-3}, 147.7, 91.1, 36.7 μg m^{-3}	Condensed particle counter (P-Trak, TSI Inc., USA); optical particle counter (OPC, DustMonit Contec., Italy)	(Ozgen et al., 2016)
Italian cities	1964	2006	PM_{10}, $PM_{2.5}$	217, 53 μg m^{-3}	PM air sampling device (Aerocet 531, Met One Inc., USA)	(Cartenì et al., 2015; Ripanucci et al., 2006; Perrino et al., 2015)
Lisbon	1959	2014	$PM_{2.5}$, PM_{10}	13, 40 μg m^{-3}	DustTrak (Model 8530, TSI Inc., USA)	(Ramos et al., 2015)
Berlin	1902	1995	PAHs	19.7 ng m^{-3}	HPLC (N/A)	(Fromme et al., 1998)
Frankfurt	1902	2013	PM_{10}, $PM_{2.5}$, PM_1	77, 44, 23 μg m^{-3}	Laser aerosol spectrometer (PLA spectrometer, Grimm Aerosol Technik, Germany)	(Gerber et al., 2014)
Paris	1900	2007	Chemical composition	Fe (41.8%)	N/A	(Bachoual et al., 2007; Tokarek and Bernis, 2006)
Stockholm	1950	2000	$PM_{2.5}$, PM_{10}	139, 390 μg m^{-3}	N/A	(Johansson and Johansson, 2003; Midander et al., 2012)
Helsinki	1982	2004	$PM_{2.5}$	53 μg m^{-3}	Particle counter (FH62 I-R Eberline Instruments GmbH Inc., Germany)	(Aarnio et al., 2005)
Norway	1966	2010	Bacteria	N/A	High-volume air sampler (SASS 3100, Research International Inc., USA)	(Dybwad et al., 2012)
Prague	1974	2004	PM_{10}, $PM_{2.5}$, PM_1	164.3, 93.9, 44.8 μg m^{-3}	DustTrak (Model 8520, TSI Inc., USA)	(Braniš, 2006; Cusack et al., 2015)
Budapest	1894	2007	PM_{10}, Fe	155 μg m^{-3}, 40%	Tapered-element oscillating microbalance (Model 1400a, Rupprecht and Patashnick, USA)	(Dura and Szalay, 2007; Salma, 2007; Salma et al., 2009)
Athens	2000	2013	PM_1, $PM_{2.5}$, PM_{10}	40, 100, 400 μg m^{-3}	IAQ monitor (Model 3016 Lighthouse Inc., USA)	(Assimakopoulos et al., 2013; Barmparesos et al., 2016)
Istanbul	1910	2007	PM_{10}	200 μg m^{-3}	Air sampler (Model 20-800, Anderson ACFM, USA)	(Şahin et al., 2012; Onat and Stakeeva, 2014; Onat and Stakeeva, 2013)

microscopy showed that the coarse fraction of underground PM had a morphology indicative of generation by abrasion, absent for fine and ultrafine particulates (Loxham et al., 2013).

Barcelona was another European city with many metro air quality research. The personal exposure to inhalable pollutants during bus, metro, tram and walking journeys were compared. Average number concentrations of PM in 10–300 nm size were lowest using metro trains ($< 2.5 \times 10^4$ particles cm^{-3}) (Moreno et al., 2015a). A high resolution air quality monitoring campaign (PM, CO_2 and CO) was conducted on differently designed station platforms in the Barcelona metro system. Different size-fractioned PM concentrations varied significantly (PM_1:6–128 μg m^{-3}, PM_3:16–314 μg m^{-3}, and PM_{10}:33–332 μg m^{-3}). CO concentrations were found very low (< 1 ppm) and CO_2 averages range from 371 to 569 ppm (Querol et al., 2012). Indoor air quality and passenger exposure in the Barcelona metro, focusing on PM levels and their metal contents, were evaluated. The $PM_{2.5}$ levels (11–32 μg m^{-3}) inside the trains in summer were the lowest among worldwide metro systems due to the air conditioning system working in all carriages (Moreno et al., 2014b). A source apportionment analysis found that metro was a significant source for exposures to Fe, Mn, Cu and Ba (Minguillón et al., 2012; Martins et al., 2016b). Besides, $PM_{2.5}$ could also comprise of carbonaceous aerosol, crustal matter, secondary inorganic compounds, insoluble sulfate and halite, PAHs, nicotine, levoglucosan and aromatic musk compounds (Martins et al., 2016a). The results showed different chemical profiles for each station, but was always dominated by Fe. $PM_{2.5}$ source included rails, wheels, catenaries, brake pads and pantographs. Particle generation process was recognized as mechanical wear at the brake–wheel and wheel–rail interfaces. Magneticmetallic flakes and splinters were released and underwent progressive atmospheric oxidation from metallic iron to magnetite and maghemite (Moreno et al., 2015b).

Many metro air quality studies were also conducted in Italy. The viable or culturable airborne fungi were investigated inside two Milan metro stations. Four dominant genera, *Cladosporium*, *Penicillium*, *Epicoccum* and *Alternaria*, were found in the station air (Picco and Rodolfi, 2000). Measurement results in Naples metro system showed that the average PM_{10} concentrations measured in the underground station platforms range between 172 and 262 μg m^{-3}, which were 2–14 times higher than outdoors (Cartenì et al., 2015). Then, PM_{10}, respirable fraction, respirable combustible dust, and the organic, metallic, siliceous, and fibrous components were investigated in Rome metro system. PM concentration in the tunnels and platforms was three times higher than that at the entrances to the underground metro stations. Silica sand in the train braking system caused a dispersion of quartz in the air in percentages varying from 5% to 14% (Ripanucci et al., 2006). In Milan, UFPs, PM_{10}, $PM_{2.5}$, PM_1 exposure levels for four transport modes (i.e., walking, cycling, car, and metro) were measured. The metro mode was characterized with the highest PM_{10}, $PM_{2.5}$, PM_1 mass concentrations, which were respectively about 2–4 times higher than other modes (Ozgen et al., 2016). In Milan metro system, an extensive measurement campaign was conducted to investigate PM_{10} concentrations, physical and elemental composition, origins, and source contributions. Average PM_{10} concentrations between 105 and 283 μg m^{-3} were observed at the platform level. Fe, Ba, Sb, Mn and Cu, likely originating from mechanical processes, accounted for most of the PM_{10} mass at the platform level. Wheel, brake and track wear were found to contribute 40–73% of total PM_{10} mass and electric cable wear (Cu and Zn oxides) 2%–3% (Colombi et al., 2013; Perrino et al., 2015).

Besides London, Barcelona and Milan, the metro air quality studies were also conducted in some Western European cities. In Lisbon, PM_{10} and $PM_{2.5}$ concentrations were measured and compared across different microenvironments, e.g. walking, bus, mini-bus, tram and metro. The metro train presented the highest $PM_{2.5}$ inhalation (Ramos et al., 2015). In Berlin, a comparison between metro and car exposures showed significantly higher concentrations of PAHs in the metro train (Fromme et al., 1998). In Frankfurt, it was found the WHO limits for PM_{10} and $PM_{2.5}$ were exceeded at nearly all times at underground stations, subterranean metro stations and subterranean shopping arcades (Gerber et al., 2014). In Paris, the average PM_{10} and $PM_{2.5}$ concentrations in metro system were approximately 5–30 times higher than those measured in Paris streets. PM levels were influenced by the rate at which train and people passed through the station (Raut et al., 2009).

There were also some measurements studies in Northern Europe. The concentrations of PM_{10} and $PM_{2.5}$ were measured at metro stations in central Stockholm. The results showed that PM_{10} concentrations at two subterranean stations were far exceeding the outdoor limit value (Gustafsson et al., 2012). The average PM_{10} and $PM_{2.5}$ concentrations were 470 and 260 μg m^{-3}, which were 5 and 10 times higher than those measured on the busiest streets in central Stockholm (Johansson and Johansson, 2003). A large number concentration of nano-sized particles, at a mean concentration of 12,000 particles cm^{-3}, were observed. Several volatile and semi-volatile organic compounds, carcinogenic aromatic compounds and traces of flame retardants were found on metro particle size fractions of PM_{10} and $PM_{2.5}$ (Midander et al., 2012). $PM_{2.5}$ and particle number concentrations were also monitored in the Helsinki metro system. The average daytime $PM_{2.5}$ concentrations were 47 ± 4 and 60 ± 18 μg m^{-3} at the two underground metro stations. The most enriched element in $PM_{2.5}$ samples was still Fe, with the concentration of 29 ± 7 μg m^{-3} at the underground metro station. Other enriched elements included Mn, Cr, Ni, and Cu (Aarnio et al., 2005). In Norway, the airborne bacterial was characterized (concentration level, diversity, and virulence- and survival-associated properties) at a metro station. A total of thirty-seven different genera were identified, with the majority genera: *Bacillus*, *Micrococcus*, and *Staphylococcus*. It suggested that anthropogenic sources were major contributors to airborne bacteria at metro stations (Dybwad et al., 2012).

Measurements were also conducted in Middle Europe. In Prague metro system, PM_{10} concentration inside the metro trains was recorded two times larger than the ambient outdoor concentrations (Braniš, 2006). PM concentrations were substantially increased in the coarse fraction when the metro was in operation. PM was highly enriched with Fe, especially in the coarse fraction, comprising 46% of PM_{10} (Cusack et al., 2015). In Budapest, the concentrations of PM_{10}, $PM_{2.5}$ and TSP were measured. PM_{10} pollution was 2–3 times higher in the metro station than that in the street. PM pollution level was not influenced by the depth of the platforms (Dura and Szalay, 2007). In metro air, Fe, Mn, Ni, Cu, and Cr concentrations were 10 times higher than in outdoor air. Fe accounted for 40% and 46% of the $PM_{10–2.0}$ and $PM_{2.0}$ masses, respectively. Mechanical wear and friction of electric conducting rails and bow sliding collectors were identified as the primary sources (Salma, 2007; Salma et al., 2009).

In Eastern Europe, metro air quality studies were mostly conducted in Athens and Istanbul. In Athens, TVOCs, PM_{10}, $PM_{2.5}$, PM_1 as well as temperature and relative humidity were simultaneously monitored in the metro trains (Assimakopoulos et al., 2013). All of the pollutants concentrations presented their peak values during the morning rush hours. Mean PM_1, $PM_{2.5}$ and PM_{10} concentrations at the deeper and most crowded station reached 18.7, 88.1 and 320.8 μg m^{-3}, which were 3–10 time greater than those in ambient air (Barmparesos et al., 2016). A series of measurements were conducted in Istanbul. The relative abundance of Fe-containing PM collected in the metro stations was 3.5–8 times higher than in the Istanbul atmosphere (Şahin et al., 2012). The average daytime $PM_{2.5}$ concentrations (49.3 to 181.7 μg m^{-3}) were higher than the ambient air $PM_{2.5}$ standard. However, compared to other transportation modes (bus, car and walking), the lowest average $PM_{2.5}$ concentration was measured inside metro trains (Onat and Stakeeva, 2014; Onat and Stakeeva, 2013). Recently, a sampling campaigns were conducted to assess and compare the air quality at three South European subway systems (Barcelona, Athens and Oporto). Fe was still the most abundant element, accounting for 29–43% of the total $PM_{2.5}$ mass. It was found that the

$PM_{2.5}$ concentrations varied significantly among the European metro systems likely due to distinct station, tunnel designs and ventilation systems. Lowest $PM_{2.5}$ concentrations were observed with the low frequency of the trains when air conditioning system was operating properly (Martins et al., 2016c).

4.2. Ventilation

The effects of ventilation conditions and station design on metro air quality were investigated in the Barcelona metro system. PM levels were doubled if tunnel ventilation was switched off. PM was accumulated at one end of the platform rather than in the middle. To maintain good air quality, narrow platforms served by single-track tunnels should be equipped with forced tunnel ventilation. The air quality in the stations with spacious double-track tunnels were not greatly affected when tunnel ventilation was switched off (Moreno et al., 2014a).

4.3. Mitigation measures

The new metro lines with PSDs showed lower $PM_{2.5}$ concentrations than those in the conventional system. PM concentrations inside the trains were generally lower than those on the platforms due to the air conditioning systems with air filters (Martins et al., 2015a). In Paris, an electrostatic precipitator prototype was installed to remove PM in the metro air. The results showed that this process was efficient. With twenty filters installed, the initial particle concentration (230 $\mu g\ m^{-3}$) was reduced to 135 $\mu g\ m^{-3}$ (Tokarek and Bernis, 2006).

4.4. Health assessment

Health assessment related to metro air pollutants were much better studied in Europe than in Asia and America. Swedish researchers have conducted most of the relevant studies in this field. A randomized crossover study investigated responses of the respiratory system to Stockholm metro air in asthmatics and healthy individuals. Oxylipins were sampled in the distal lung as an indicator of shifts in lipid mediators in association with exposure to metro air compared to ambient air. Significant changes were observed in eight metabolites of linoleic- and α-linolenic acid. A reduced anti-inflammatory response was observed in asthmatics following exposure to metro air, whereas oxylipin levels were increased in healthy individuals following exposure to metro air (Lundström et al., 2011). There used to be a hypothesis that metro PM would be more potentially inducing lung cancer or the relative risk of myocardial infarction than PM in ambient air due to the larger metal content in metro air. A cohort study was conducted to determine if metro PM were more toxic to DNA in lung cells than PM from ambient air. The study gave some evidence that the lung cancer incidence and the relative risk of myocardial infarction were not increased among the metro drivers compared to other transport and communication workers in Stockholm (Gustavsson et al., 2008; Bigert et al., 2007). However, PM was identified as the major pollutant to induce inflammatory and toxicity. After exposure to a metro environment for 2 h, a statistically significant increase in fibrinogen and regulatory white blood cell was observed (Nyström et al., 2010). The genotoxicity and the ability to induce inflammatory mediators of different PM types (metro, street, wood and diesel combustion, etc.) were investigated and compared. Measurement results showed that all PM caused DNA damage and those from the metro caused more damage than the other PM most likely due to redox-active Fe (Karlsson et al., 2006). To investigate the mechanisms behind the genotoxicity of metro PM, the cause of mitochondrial depolarization and to form intracellular reactive oxygen species was studied. PM collected from a metro station were most potent to induce lipid peroxidation, arachidonic acid release, and formation of reactive oxygen species (Lindbom et al., 2007). Since highly reactive surfaces of magnetite PM can cause rise to oxidative stress, the metro particles with magnetite as the main component showed greater genotoxicity due to high intracellular reactive oxygen species (Karlsson et al., 2008; Karlsson et al., 2005).

Two toxicological indicators of oxidative activity: ascorbic acid oxidation and glutathione oxidation, showed low oxidative potential of $PM_{2.5}$ samples in the Barcelona metro system. Results illustrated that metro PM toxicity was related to the presence of metallic trace elements such as Cu and Sb sourced from brakes and pantographs (Moreno et al., 2017). The dose of the inhaled PM in the human respiratory tract was estimated using the dosimetry model ExDoM. The lowest amount of the inhaled PM was deposited in the tracheobronchial tree (4%), whereas the deposition was much larger in the alveolar-interstitial region (10%) and extrathoracic region (68%) (Martins et al., 2015b). In UK, the toxic effects of metro PM on the mucus-covered airway epithelial cell cultures was studied. Monolayer and mucociliary air-liquid interface cultures of primary bronchial epithelial cells were exposed to various size-fractionated metro PM. It was found that metro PM exposure increased interleukin-8 release from primary bronchial epithelial cells, but was diminished in mucus-secreting cultures. Intracellular PM was observed within vesicles, mitochondria, and free in the cytosol. Although the mucous layer appeared to confer some protection against metro PM, primary bronchial epithelial cells detected PM and led to an antioxidant response (Loxham et al., 2015). A comprehensive study was performed to evaluate the biological effects of metro PM in the Paris metro system. Cell viability, production of cellular and lung proinflammatory cytokines, and mRNA were measured in exposed mice macrophages. Metro PM, comprising of large Fe content, induced a time- and dose-dependent increase in tumor necrosis factor and macrophage inflammatory protein production. Metro PM induced an increased expression of matrix metalloproteases and heme oxygenase both in vitro and in vivo, which indicated PM from the meto system caused transient biological effects (Bachoual et al., 2007).

5. Others

Besides Asia, America and Europe, there were only a few studies that reported the air quality and its health effect inside metro system in Egypt. Metro commuters recorded the lowest pollutant levels for all VOC pollutants comparing to other travel mode groups: car, bus, bicycle and walking (Chertok et al., 2004; Knibbs and Dear, 2010). *Cladosporium*, *Penicillium* and *Aspergillus* were found the most dominant fungi inside Cairo metro system. Concentrations of the biological PM were higher in the underground stations than those in the surface stations (Awad, 2002).

6. Conclusions

This review summarizes major findings reported in literature on air quality inside metro system, including air pollutant concentrations, chemical species, related sources, mitigation measures and potential health effects. In different countries, research interests and focus varied, which may have led to different reporting and more difficult to compare results between metro systems. However, there were still some common grounds provided by the previous literature. Some measurement results showed that air pollutants observed inside metro system were relatively low compared to other transportation modes. Throughout the world, PM was always identified as the primary pollutant in the metro air. Fe was found as the most dominant element in the metro PM. Mechanical wear at the brake–wheel and wheel–rail interfaces were commonly recognized as the primary PM source in the metro air. As for the gaseous pollutants, benzene, toluene, ethylbenzene, xylene, styrene, formaldehyde, acetaldehyde, acetone and acrolein were mostly found in the metro air. Service time of metro system, frequency of passing train, ventilation mode and airflow rate, the age and air-tightness of the metro train, interior materials, the number of passengers and the ambient pollution level outside the metro stations were identified as the key determinants that could play important roles of influencing the metro air quality. The concentrations of aromatic VOCs in new metro carriage were 1–2 times lower than that in the old ones, as higher quality paintings were used in new trains. Less air circulation and ventilation inside underground carriage was likely the reason of higher VOCs levels than the above-ground track. To reduce the exposure levels of air pollutants, PSDs, air purifier unit, high-efficiency air filter seemed to be effective measures. Among these measures, PSDs have been frequently installed in the newly built metro platforms worldwide. To better evaluate the effectiveness of these mitigation measures, more field assessments were necessary to compare the air pollutant concentrations before/after the installation. Metro PM showed genotoxicity and ability to induce inflammatory due to large magnetite component. According to the acceptable level proposed by the World Health Organization (1×10^{-6}–1×10^{-5}), the life carcinogenic risk of commuters by subway was sometimes above the acceptable level.

On this basis, future work could focus on investigating the chronic health risks of exposure to various air pollutants other than PM and/or further developing advanced air purification unit to improve metro in-station air quality.

Declaration of conflict of interests

The authors declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

Acknowledgement

This material is based on the work partially supported by the National Science Foundation of China [Grant number 51208372] and the National Key Research and Development Program of China (GEFC10-15). The author would like to thank Yu Gong for collecting literature files and information for the review.

References

Aarnio, P., Yli-Tuomi, T., Kousa, A., Mäkelä, T., Hirsikko, A., Hämeri, K., Räisänen, M., Hillamo, R., Koskentalo, T., Jantunen, M., 2005. The concentrations and composition of and exposure to fine particles ($PM_{2.5}$) in the Helsinki subway system. Atmos. Environ. 39, 5059–5066.

Adams, H.S., Nieuwenhuijsen, M.J., Colvile, R.N., Mcmullen, M.A., Khandelwal, P., 2001. Fine particle ($PM_{2.5}$) personal exposure levels in transport microenvironments, London, UK. Sci. Total Environ. 279, 29–44.

Araki, A., Kawai, T., Eitaki, Y., Kanazawa, A., Morimoto, K., Nakayama, K., Shibata, E., Tanaka, M., Takigawa, T., Yoshimura, T., 2010. Relationship between selected indoor volatile organic compounds, so-called microbial VOC, and the prevalence of mucous membrane symptoms in single family homes. Sci. Total Environ. 408, 2208–2215.

Assimakopoulos, M.N., Dounis, A., Spanou, A., Santamouris, M., 2013. Indoor air quality in a metropolitan area metro using fuzzy logic assessment system. Sci. Total Environ. 449, 461–469.

Awad, A.H.A., 2002. Environmental study in subway metro stations in Cairo, Egypt. J. Occup. Health 44, 112–118.

Bachoual, R., Boczkowski, J., Goven, D., Amara, N., Tabet, L., On, D., Leçonmalas, V., Aubier, M., Lanone, S., 2007. Biological effects of particles from the Paris subway system. Chem. Res. Toxicol. 20, 1426–1433.

Barmparesos, N., Assimakopoulos, V.D., Assimakopoulos, M.N., Tsairidi, E., 2016. Particulate matter levels and comfort conditions in the trains and platforms of the Athens underground metro. AIMS Environ. Sci. 3, 199–219.

Bigert, C., Klerdal, K., Hammar, N., Gustavsson, P., 2007. Myocardial infarction in Swedish subway drivers. Scand. J. Work Environ. Health 33, 267–271.

Birenzvige, A., Eversole, J., Seaver, M., Francesconi, S., Valdes, E., Kulaga, H., 2003. Aerosol characteristics in a subway environment. Aerosol Sci. Technol. 37, 210–220.

Bogomolova, E., Kirtsideli, I., 2009. Airborne fungi in four stations of the St. Petersburg underground railway system. Int. Biodeterior. Biodegrad. 63, 156–160.

Boudia, N., Halley, R., Kennedy, G., Lambert, J., Gareau, L., Zayed, J., 2006. Manganese concentrations in the air of the Montreal (Canada) subway in relation to surface automobile traffic density. Sci. Total Environ. 366, 143–147.

Braniš, M., 2006. The contribution of ambient sources to particulate pollution in spaces and trains of the Prague underground transport system. Atmos. Environ. 40, 348–356.

Byeon, S.H., Willis, R., Peters, T.M., 2015. Chemical characterization of outdoor and subway fine ($PM_{(2.5–1.0)}$) and coarse ($PM_{(10–2.5)}$) particulate matter in Seoul (Korea) by computer-controlled scanning electron microscopy (CCSEM). Int. J. Environ. Res. Public Health 12, 2090–2104.

Camelli, F.E., Byrne, G., Löhner, R., 2014. Modeling subway air flow using CFD. Tunn. Undergr. Sp. Tech. 43, 20–31.

Cartenì, A., Cascetta, F., Campana, S., 2015. Underground and ground-level particulate matter concentrations in an Italian metro system. Atmos. Environ. 101, 328–337.

Chan, C., Spngler, J.D., Ozkaynak, H., Lefkopoulou, M., 1993. Commuter exposure to VOCs in Boston, Massachusetts. J. Air Waste Manage. Assoc. 12, 1594–1600.

Chan, L.Y., Chan, C.Y., Qin, Y., 1999. The effect of commuting microenvironment on commuter exposures to vehicular emission in Hong Kong. Atmos. Environ. 33, 1777–1787.

Chan, L.Y., Lau, W.L., Lee, S.C., Chan, C.Y., 2002a. Commuter exposure to particulate matter in public transportation modes in Hong Kong. Atmos. Environ. 36, 3363–3373.

Chan, L.Y., Lau, W.L., Zou, S.C., Cao, Z.X., Lai, S.C., 2002b. Exposure level of carbon monoxide and respirable suspended particulate in public transportation modes while commuting in urban area of Guangzhou, China. Atmos. Environ. 36, 5831–5840.

Chan, L.Y., Lau, W.L., Wang, X.M., Tang, J.H., 2003. Preliminary measurements of aromatic VOCs in public transportation modes in Guangzhou, China. Environ. Int. 29, 429–435.

Chen, Y.Y., Sung, F.C., Chen, M.L., Mao, I., Lu, C.Y., 2016. Indoor air quality in the metro system in north Taiwan. Int. J. Environ. Res. Public Health 13, 1200–1210.

Cheng, Y.H., 2012. Comparisons of PM_{10}, $PM_{2.5}$, particle number, and CO_2 levels inside metro trains between traveling in underground tunnels and on elevated tracks. Aerosol Air Qual. Res. 12, 879–891.

Cheng, Y.H., Lin, Y.L., 2010. Measurement of particle mass concentrations and size distributions in an underground station. Aerosol Air Qual. Res. 10, 22–29.

Cheng, Y.H., Yan, J.W., 2011. Comparisons of particulate matter, CO, and CO_2 levels in underground and ground-level stations in the Taipei mass rapid transit system. Atmos. Environ. 45, 4882–4891.

Cheng, Y.H., Lin, Y.L., Liu, C.C., 2008. Levels of PM_{10} and $PM_{2.5}$ in Taipei rapid transit system. Atmos. Environ. 42, 7242–7249.

Chertok, M., Voukelatos, A., Sheppeard, V., Rissel, C., 2004. Comparison of air pollution exposure for five commuting modes in Sydney-car, train, bus, bicycle and walking. Health Promot. J. Austr. 15, 63–67.

Chillrud, S.N., Epstein, D., Ross, J.M., Sax, S.N., Pederson, D., Spengler, J.D., Kinney, P.L., 2004. Elevated airborne exposures of teenagers to manganese, chromium, and iron from steel dust and New York City's subway system. Environ. Sci. Technol. 38, 732–737.

Chillrud, S.N., Grass, D., Ross, J.M., Coulibaly, D., Slavkovich, V., Epstein, D., Sax, S.N., Pederson, D., Johnson, D., Spengler, J.D., 2005. Steel dust in the New York City subway system as a source of manganese, chromium, and iron exposures for transit workers. J. Urban Health 82, 33–42.

Cho, J.H., Hee, M.K., Paik, N.W., 2006. Temporal variation of airborne fungi concentrations and related factors in subway stations in Seoul, Korea. Int. J. Hyg. Environ. Health 209, 249–255.

Colombi, C., Angius, S., Gianelle, V., Lazzarini, M., 2013. Particulate matter concentrations, physical characteristics and elemental composition in the Milan underground transport system. Atmos. Environ. 70, 166–178.

Cusack, M., Talbot, N., Ondráček, J., Minguillón, M.C., Martins, V., Klouda, K., Schwarz, J., Ždímal, V., 2015. Variability of aerosols and chemical composition of PM_{10}, $PM_{2.5}$ and PM_1 on a platform of the Prague underground metro. Atmos. Environ. 118, 176–183.

Dockery, D.W., Pope, C.A., Xu, X., Spengler, J.D., Ware, J.H., Fay, M.E., Ferris Jr., B.G., Speizer, F.E., 1993. An association between air pollution and mortality in six US cities. New Engl. J. Med. 329, 1753–1759.

Dong, S., Yao, M., 2010. Exposure assessment in Beijing, China: biological agents, ultrafine particles, and lead. Environ. Monit. Assess. 170, 331–343.

Dura, G., Szalay, B., 2007. Particle exposure through the indoor air environment. Nato Sci. Peace Secur. 271–276.

Dybwad, M., Granum, P.E., Bruheim, P., Blatny, J.M., 2012. Characterization of airborne bacteria at an underground subway station. Appl. Environ. Microbiol. 78, 1917–1929.

Feng, Y., Mu, C., Zhai, J., Li, J., Zou, T., 2010. Characteristics and personal exposures of carbonyl compounds in the subway stations and in-subway trains of Shanghai, China. J. Hazard. Mater. 183, 574–582.

Fromme, H., Oddoy, A., Piloty, M., Krause, M., Lahrz, T., 1998. Polycyclic aromatic hydrocarbons (PAH) and diesel engine emission (elemental carbon) inside a car and a subway train. Sci. Total Environ. 217, 165–173.

Furuya, K., Kudo, Y., Okinaga, K., Yamuki, M., Takahashi, S., Araki, Y., Hisamatsu, Y., 2001. Seasonal variation and their characterization of suspended particulate matter in the air of subway stations. J. Trace Microprobe Tech. 19, 469–485.

Gerber, A., Bohn, J., Groneberg, D.A., Schulze, J., Bundschuh, M., 2014. Airborne particulate matter in public transport: a field study at major intersection points in Frankfurt am Main (Germany). J. Occup. Med. Toxicol. 9, 13–16.

Gilleberg, S.B., Faull, J.L., Graeme-Cook, K.A., 1998. A preliminary survey of aerial biocontaminants at six London underground stations. Int. Biodeterior. Biodegrad. 41, 149–152.

Goel, R., Gani, S., Guttikunda, S.K., Wilson, D., Tiwari, G., 2015. On-road $PM_{2.5}$ pollution exposure in multiple transport microenvironments in Delhi. Atmos. Environ. 123, 129–138.

Gómez-Perales, J.E., Colvile, R.N., Nieuwenhuijsen, M.J., Fernández-Bremauntz, A., Gutiérrez-Avedoy, V.J., Páramo-Figueroa, V.H., Blanco-Jiménez, S., Bueno-López, E., Mandujano, F., Bernabé-Cabanillas, R., 2004. Commuters' exposure to $PM_{2.5}$, CO, and benzene in public transport in the metropolitan area of Mexico City. Atmos. Environ. 38, 1219–1229.

Gong, Y., Wei, Y., Cheng, J., Jiang, T., Chen, L., Xu, B., 2017. Health risk assessment and personal exposure to Volatile Organic Compounds (VOCs) in metro carriages—a case study in Shanghai, China. Sci. Total Environ. 574, 1432–1438.

Grass, D.S., Family, R.F., 2010. Airborne particulate metals in the New York City subway: a pilot study to assess the potential for health impacts. Environ. Res. 110, 1–11.

Guo, L., Hu, Y., Hu, Q., Lin, J., Li, C., Chen, J., Li, L., Fu, H., 2014. Characteristics and chemical compositions of particulate matter collected at the selected metro stations of Shanghai, China. Sci. Total Environ. 496C, 443–452.

Gustafsson, M., Blomqvist, G., Swietlicki, E., Dahl, A., Gudmundsson, A., 2012. Inhalable railroad particles at ground level and subterranean stations – physical and chemical properties and relation to train traffic. Transport Res D-Tr E. 17, 277–285.

Gustavsson, P., Bigert, C., Pollán, M., 2008. Incidence of lung cancer among subway drivers in Stockholm. Am. J. Ind. Med. 51, 545–547.

Han, H., Lee, J.Y., Jang, K.J., 2014. Effect of platform screen doors on the indoor air environment of an underground subway station. Indoor Built Environ. 24, 8092–8097.

Heo, K.J., Lee, B.U., 2015. Seasonal variation in the concentrations of culturable bacterial and fungal aerosols in underground subway systems. J. Aerosol Sci. 92, 122–129.

Hernández-Castillo, O., Mugica-Álvarez, V., Castañeda-Briones, M.T., Murcia, J.M., García-Franco, F., Briseño, Y.F., 2014a. Aerobiological study in the Mexico City subway system. Aerobiologia 30, 357–367.

Hernández-Castillo, O., Mugica-Álvarez, V., Castañeda-Briones, M.T., Murcia, J.M., García-Franco, F., Briseño, Y.F., 2014b. Aerobiological study in the Mexico City subway system. Aerobiologia 30, 357–367.

Hoseini, M., Jabbari, H., Naddafi, K., Nabizadeh, R., Rahbar, M., Yunesian, M., Jaafari, J., 2013. Concentration and distribution characteristics of airborne fungi in indoor and outdoor air of Tehran subway stations. Aerobiologia 29, 355–363.

Houston, D., Wu, J., Yang, D., Jaimes, G., 2013. Particle-bound polycyclic aromatic hydrocarbon concentrations in transportation microenvironments. Atmos. Environ. 71, 148–157.

Houston, D., Dang, A., Wu, J., Chowdhury, Z., Edwards, R., 2016. The cost of convenience; air pollution and noise on freeway and arterial light rail station platforms in Los Angeles. Transport Res D-Tr E. 49, 127–137.

Hwang, S.H., Yoon, C.S., Ryu, K.N., Paik, S.Y., Cho, J.H., 2010. Assessment of airborne environmental bacteria and related factors in 25 underground railway stations in Seoul, Korea. Atmos. Environ. 44, 1658–1662.

Johansson, C., Johansson, P.Å., 2003. Particulate matter in the underground of Stockholm. Atmos. Environ. 37, 3–9.

Jung, H.J., Kim, B.W., Ryu, J.Y., Maskey, S., Kim, J.C., Sohn, J., Ro, C.U., 2010. Source identification of particulate matter collected at underground subway stations in Seoul, Korea using quantitative single-particle analysis. Atmos. Environ. 44, 2287–2293.

Jung, H.J., Kim, B., Malek, M.A., Koo, Y.S., Jung, J.H., Son, Y.S., Kim, J.C., Kim, H., Ro, C.U., 2012. Chemical speciation of size-segregated floor dusts and airborne magnetic particles collected at underground subway stations in Seoul, Korea. J. Hazard. Mater. 213, 331–340.

Juraeva, M., Ryu, K.J., Jeong, S.H., Song, D.J., 2013. Influence of mechanical ventilation-shaft connecting location on subway tunnel ventilation performance. J. Wind Eng. Ind. Aerodyn. 119, 114–120.

Juraeva, M., Ryu, K.J., Jeong, S.H., Song, D.J., 2015. Effect of guide vanes on recovering uniform flow in a ventilation duct in an existing twin-track subway tunnel. J. Mech. Sci. Technol. 29, 251–258.

Juraeva, M., Ryu, K.J., Jeong, S.H., Song, D.J., 2016. Influences of the train-wind and air-curtain to reduce the particle concentration inside a subway tunnel. Tunn. Undergr. Sp. Tech. 52, 23–29.

Kam, W., Cheung, K., Daher, N., Sioutas, C., 2011a. Particulate matter (PM) concentrations in underground and ground-level rail systems of the Los Angeles metro. Atmos. Environ. 45, 1506–1516.

Kam, W., Ning, Z., Shafer, M.M., Schauer, J.J., Sioutas, C., 2011b. Chemical characterization and redox potential of coarse and fine particulate matter (PM) in underground and ground-level rail systems of the Los Angeles Metro. Environ. Sci. Technol. 45, 6769–6776.

Kam, W., Delfino, R.J., Schauer, J.J., Sioutas, C., 2013. A comparative assessment of $PM_{2.5}$ exposures in light-rail, subway, freeway, and surface street environments in Los Angeles and estimated lung cancer risk. Environ. Sci. Process. Impacts 15, 234–243.

Kamani, H., Hoseini, M., Seyedsalehi, M., Mahdavi, Y., Jaafari, J., Safari, G.H., 2014. Concentration and characterization of airborne particles in Tehran's subway system. Environ. Sci. Pollut. R. 21, 7319–7328.

Kang, S., Hwang, H., Park, Y., Kim, H., Ro, C.U., 2008. Chemical compositions of subway particles in Seoul, Korea determined by a quantitative single particle analysis. Environ. Sci. Technol. 42, 9051–9057.

Kang, O.Y., Liu, H., Kim, M.J., Kim, J.T., Wasewar, K.L., Yoo, C.K., 2013. Periodic local multi-way analysis and monitoring of indoor air quality in a subway system considering the weekly effect. Indoor Built Environ. 22, 77–93.

Karlsson, H.L., Nilsson, L., Möller, L., 2005. Subway particles are more genotoxic than street particles and induce oxidative stress in cultured human lung cells. Chem. Res. Toxicol. 18, 19–23.

Karlsson, H.L., Ljungman, A.G., Lindbom, J., Möller, L., 2006. Comparison of genotoxic and inflammatory effects of particles generated by wood combustion, a road simulator and collected from street and subway. Toxicol. Lett. 165, 203–211.

Karlsson, H.L., Holgersson, Å., Möller, L., 2008. Mechanisms related to the genotoxicity of particles in the subway and from other sources. Chem. Res. Toxicol. 21, 726–731.

Kawasaki, T., Kyotani, T., Ushiogi, T., Izumi, Y., Lee, H., Hayakawa, T., 2010. Distribution and identification of airborne fungi in railway stations in Tokyo, Japan. J. Occup. Health 52, 186–193.

Kim, K.Y., Kim, Y.S., Roh, Y.M., Lee, C.M., Kim, C.N., 2008. Spatial distribution of particulate matter (PM_{10} and $PM_{2.5}$) in Seoul metropolitan subway stations. J. Hazard. Mater. 154, 440–443.

Kim, J.C., Sohn, J.R., Min, Y.K., Son, Y.S., 2008. Particulate behavior in subway airspace. Asian J. Atmos. Environ. 2, 54–59.

Kim, Y., Kim, M., Lim, J., Kim, J.T., Yoo, C., 2010. Predictive monitoring and diagnosis of periodic air pollution in a subway station. J. Hazard. Mater. 183, 448–459.

Kim, Y.S., Kim, J.T., Kim, I.W., Kim, J.C., Yoo, C., 2010. Multivariate monitoring and local interpretation of indoor air quality in Seoul's metro system. Environ. Eng. Sci. 27, 721–731.

Kim, K.Y., Kim, Y.S., Kim, D., Kim, H.T., 2011. Exposure level and distribution characteristics of airborne bacteria and fungi in Seoul metropolitan subway stations. Ind. Health 49, 242–248.

Kim, M.J., Sankararao, B., Kang, O.Y., Kim, J.T., Yoo, C.K., 2012. Monitoring and prediction of indoor air quality (IAQ) in subway or metro systems using season dependent models. Energ. Buildings 46, 48–55.

Kim, K.H., Ho, D.X., Jeon, J.S., Kim, J.C., 2012. A noticeable shift in particulate matter levels after platform screen door installation in a Korean subway station. Atmos. Environ. 49, 219–223.

Kim, J.B., Kim, S., Lee, G.J., Bae, G.N., Cho, Y., Park, D., Lee, D.H., Kwon, S.B., 2014. Status of PM in Seoul metropolitan subway cabins and effectiveness of subway cabin air purifier (SCAP). Clean Techn. Environ. Policy 16, 1193–1200.

Kim, M.J., Liu, H., Kim, J.T., Yoo, C.K., Kim, M.J., Kim, J.T., 2014. Evaluation of passenger health risk assessment of sustainable indoor air quality monitoring in metro systems based on a non-Gaussian dynamic sensor validation method. J. Hazard. Mater. 278C, 124–133.

Klepeis, N.E., Nelson, W.C., Ott, W.R., Robinson, J.P., Tsang, A.M., Switzer, P., Behar, J.V., Hern, S.C., Engelmann, W.H., 2000. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. J. Expo. Anal. Environ. Epidemiol. 11, 231–252.

Knibbs, L.D., Dear, R.J.D., 2010. Exposure to ultrafine particles and $PM_{2.5}$ in four Sydney transport modes. Atmos. Environ. 44, 3224–3227.

Kwon, S.B., Cho, Y., Park, E.Y., 2008. Study on the indoor air quality of Seoul metropolitan subway during the rush hour. Indoor Built Environ. 17, 361–369.

Kwon, S.B., Cho, Y., Park, E.Y., 2010. Measurement of natural ventilation rate in Seoul metropolitan subway cabin. Indoor Built Environ. 19, 366–374.

Kwon, S.B., Jeong, W., Park, D., Kim, K.T., Cho, K.H., 2015. A multivariate study for characterizing particulate matter (PM_{10}, $PM_{2.5}$, and PM_1) in Seoul metropolitan subway stations, Korea. J. Hazard. Mater. 297, 295–303.

Kwon, S.B., Namgung, H.G., Jeong, W., Park, D., Jin, K.E., 2016. Transient variation of aerosol size distribution in an underground subway station. Environ. Monit. Assess. 188, 1–11.

Lau, W.L., Chan, L.Y., 2003. Commuter exposure to aromatic VOCs in public transportation modes in Hong Kong. Sci. Total Environ. 308, 143–155.

Lee, C.M., Kim, Y.S., Nagajyoti, P.C., Park, W., Kim, K.Y., 2011. Pattern classification of volatile organic compounds in various indoor environments. Water Air Soil Pollut. 215, 329–338.

Lee, S., Min, J.K., Kim, J.T., Chang, K.Y., 2015. In search for modeling predictive control of indoor air quality and ventilation energy demand in subway station. Energ. Buildings 98, 56–65.

Leung, M.H., Wilkins, D., Li, E.K., Kong, F.K., Lee, P.K., 2014. Indoor-air microbiome in an urban subway network: diversity and dynamics. Appl. Environ. Microbiol. 80, 6760–6770.

Li, G.Q., You, S.J., 2011. A new system to reduce air pollution in metro platform. Procedia Environ Sci 11, 1454–1458.

Li, T.T., Bai, Y.H., Liu, Z.R., Liu, J.F., Zhang, G.S., Li, J.L., 2006. Air quality in passenger cars of the ground railway transit system in Beijing, China. Sci. Total Environ. 367, 89–95.

Li, T.T., Bai, Y.H., Liu, Z.R., Li, J.L., 2007. In-train air quality assessment of the railway transit system in Beijing: a note. Transport Res D-Tr E. 12, 64–67.

Li, B., Lei, X.N., Xiu, G.L., Gao, C.Y., Gao, S., Qian, N.S., 2015. Personal exposure to black carbon during commuting in peak and off-peak hours in Shanghai. Sci. Total Environ. 524, 237–245.

Lin, C.J., Chuah, Y.K., Liu, C.W., 2008. A study on underground tunnel ventilation for piston effects influenced by draught relief shaft in subway system. Appl. Therm. Eng. 28, 372–379.

Lindbom, J., Gustafsson, M., Blomqvist, G., Dahl, A., Gudmundsson, A., Swietlicki, E., Ljungman, A.G., 2007. Wear particles generated from studded tires and pavement induces inflammatory reactions in mouse macrophage cells. Chem. Res. Toxicol. 20, 937–946.

Liu, H., Yoo, C., 2015. A robust localized soft sensor for particulate matter modeling in Seoul metro systems. J. Hazard. Mater. 305, 209–218.

Liu, W.T., Ma, C.M., Liu, I.J., Han, B.C., Chuang, H.C., Chuang, K.J., 2015. Effects of commuting mode on air pollution exposure and cardiovascular health among young adults in Taipei, Taiwan. Int. J. Hyg. Environ. Health 218, 319–323.

Loxham, M., Cooper, M., Gerlofsnijland, M.E., Cassee, F.R., Davies, D., Palmer, M.R., Teagle, D.A.H., 2013. Physicochemical characterization of airborne particulate matter at a mainline underground railway station. Environ. Sci. Technol. 47, 3614–3622.

Loxham, M., Morganwalsh, R.J., Cooper, M.J., Blume, C., Swindle, E.J., Dennison, P.W., Howarth, P.H., Cassee, F.R., Teagle, D.A.H., Palmer, M.R., 2015. The effects on bronchial epithelial mucociliary cultures of coarse, fine, and ultrafine particulate matter from an underground railway station. Toxicol. Sci. 145, 98–107.

Lu, S., Liu, D., Zhang, W., Liu, P., Fei, Y., Gu, Y., Wu, M., Yu, S., Yonemochi, S., Wang, X., 2015. Physico-chemical characterization of $PM_{2.5}$ in the microenvironment of Shanghai subway. Atmos. Res. 153, 543–552.

Lundström, S.L., Levänen, B., Nording, M., Klepczynskanyström, A., Sköld, M., Haeggström, J.Z., Grunewald, J., Svartengren, M., Hammock, B.D., Larsson, B.M., 2011. Asthmatics exhibit altered oxylipin profiles compared to healthy individuals after subway air exposure. PLoS One 6, e23864.

Martins, V., Moreno, T., Minguillón, M.C., Amato, F., De, M.E., Capdevila, M., Querol, X., 2015a. Exposure to airborne particulate matter in the subway system. Sci. Total Environ. 511, 711–722.

Martins, V., Minguillón, M.C., Moreno, T., Querol, X., Miguel, E.D., Capdevila, M., Centelles, S., Lazaridis, M., 2015b. Deposition of aerosol particles from a subway microenvironment in the human respiratory tract. J. Aerosol Sci. 90, 103–113.

Martins, V., Moreno, T., Mendes, L., Eleftheriadis, K., Diapouli, E., Alves, C.A., Duarte, M., Miguel, E.D., Capdevila, M., Querol, X., 2016a. Factors controlling air quality in different European subway systems. Environ. Res. 146, 35–46.

Martins, V., Moreno, T., Minguillón, M.C., van Drooge, B.L., Reche, C., Amato, F., De, M.E., Capdevila, M., Centelles, S., Querol, X., 2016b. Origin of inorganic and organic components of PM$_{2.5}$ in subway stations of Barcelona, Spain. Environ. Pollut. 208, 125–136.

Martins, V., Moreno, T., Mendes, L., Eleftheriadis, K., Diapouli, E., Alves, C.A., Duarte, M., Miguel, E.D., Capdevila, M., Querol, X., 2016c. Factors controlling air quality in different European subway systems. Environ. Res. 146, 35–46.

Midander, K., Elihn, K., Wallén, A., Belova, L., Karlsson, A.K., Wallinder, I.O., 2012. Characterisation of nano- and micron-sized airborne and collected subway particles, a multi-analytical approach. Sci. Total Environ. 427, 390–400.

Minguillón, M.C., Schembari, A., Triguero-Mas, M., Nazelle, A.D., Dadvand, P., Figueras, F., Salvado, J.A., Grimalt, J.O., Nieuwenhuijsen, M., Querol, X., 2012. Source apportionment of indoor, outdoor and personal PM$_{2.5}$ exposure of pregnant women in Barcelona, Spain. Atmos. Environ. 59, 426–436.

Morabia, A., Amstislavski, P.N., Mirer, F.E., Amstislavski, T.M., Eisl, H., Wolff, M.S., Markowitz, S.B., 2009. Air pollution and activity during transportation by car, subway, and walking. Am. J. Prev. Med. 37, 72–77.

Moreno, T., Pérez, N., Reche, C., Martins, V., Miguel, E.D., Capdevila, M., Centelles, S., Minguillón, M.C., Amato, F., Alastuey, A., 2014a. Subway platform air quality: assessing the influences of tunnel ventilation, train piston effect and station design. Atmos. Environ. 92, 461–468.

Moreno, T., Pérez, N., Reche, C., Martins, V., Miguel, E.D., Capdevila, M., Centelles, S., Minguillón, M.C., Amato, F., Alastuey, A., 2014b. Subway platform air quality: assessing the influences of tunnel ventilation, train piston effect and station design. Atmos. Environ. 92, 461–468.

Moreno, T., Reche, C., Rivas, I., Cruz, M.M., Martins, V., Vargas, C., Buonanno, G., Parga, J., Pandolfi, M., Brines, M., 2015a. Urban air quality comparison for bus, tram, subway and pedestrian commutes in Barcelona. Environ. Res. 142, 495–510.

Moreno, T., Martins, V., Querol, X., Jones, T., Amato, F., Capdevila, M., De, M.E., Centelles, S., Gibbons, W., 2015b. A new look at inhalable metalliferous airborne particles on rail subway platforms. Sci. Total Environ. 505, 367–375.

Moreno, T., Kelly, F.J., Dunster, C., Oliete, A., Martins, V., Reche, C., Minguillón, M.C., Amato, F., Capdevila, M., Miguel, E.D., 2017. Oxidative potential of subway PM$_{2.5}$. Atmos. Environ. 148, 230–238.

Mugica-Álvarez, V., Figueroa-Lara, J., Romero-Romo, M., Sepúlveda-Sánchez, J., López-Moreno, T., 2012a. Concentrations and properties of airborne particles in the Mexico City subway system. Atmos. Environ. 49, 284–293.

Mugica-Álvarez, V., Figueroa-Lara, J., Romero-Romo, M., Sepúlveda-Sánchez, J., López-Moreno, T., 2012b. Concentrations and properties of airborne particles in the Mexico City subway system. Atmos. Environ. 49, 284–293.

Murruni, L.G., Solanes, V., Debray, M., Kreiner, A.J., Davidson, J., Davidson, M., Vazquez, M., Ozafran, M., 2009. Concentrations and elemental composition of particulate matter in the Buenos Aires underground system. Atmos. Environ. 43, 4577–4583.

Naddafi, K., Jabbari, H., Hoseini, M., Nabizadeh, R., 2011. Investigation of indoor and outdoor air bacterial density in Tehran subway system. Iran J. Environ. Health 8, 121–132.

Nyström, A.K., Svartengren, M., Grunewald, J., Pousette, C., Rödin, I., Lundin, A., Sköld, C.M., Eklund, A., Larsson, B.-M., 2010. Health effects of a subway environment in healthy volunteers. Eur. Respir. J. 36, 240–248.

Oh, T., Kim, M., Lim, J., Kang, O., Shetty, K., Rao, B., Yoo, C.K., Park, J., Kim, J., 2012. A real-time monitoring and assessment method for calculation of total amounts of indoor air pollutants emitted in subway stations. J. Air Waste Manage. Assoc. 62, 517–526.

Onat, B., Stakeeva, B., 2013. Personal exposure of commuters in public transport to PM$_{2.5}$ and fine particle counts. Atmos. Pollut. Res. 4, 329–335.

Onat, B., Stakeeva, B., 2014. Assessment of fine particulate matters in the subway system of Istanbul. Indoor Built Environ. 23, 574–583.

Ozgen, S., Ripamonti, G., Malandrini, A., Ragettli, M.S., Lonati, G., 2016. Particle number and mass exposure concentrations by commuter transport modes in Milan, Italy. AIMS Environ. Sci. 3, 168–184.

Pang, X., Mu, Y., 2007. Characteristics of carbonyl compounds in public vehicles of Beijing city: concentrations, sources, and personal exposures. Atmos. Environ. 41, 1819–1824.

Park, D.U., Ha, K.C., 2008. Characteristics of PM$_{10}$, PM$_{2.5}$, CO$_2$ and CO monitored in interiors and platforms of subway train in Seoul, Korea. Environ. Int. 34, 629–634.

Park, D., Lee, T., Hwang, D., Jung, W., Lee, Y., Cho, K.C., Kim, D., Lee, K., 2014. Identification of the sources of PM$_{10}$ in a subway tunnel using positive matrix factorization. J. Air Waste Manage. Assoc. 64, 1361–1368.

Perrino, C., Marcovecchio, F., Tofful, L., Canepari, S., 2015. Particulate matter concentration and chemical composition in the metro system of Rome, Italy. Environ. Sci. Pollut. R. 22, 9204–9214.

Picco, A.M., Rodolfi, M., 2000. Airborne fungi as biocontaminants at two Milan underground stations. Int. Biodeterior. Biodegrad. 45, 43–47.

Pope, C.A., Dockery, D.W., 2006. Health effects of fine particulate air pollution: lines that connect. J. Air Waste Manage. Assoc. 56, 709–742.

Qiao, T., Xiu, G., Zheng, Y., Yang, J., Wang, L., 2015a. Characterization of PM and microclimate in a Shanghai subway tunnel, China. Procedia Eng. 102, 1226–1232.

Qiao, T., Xiu, G., Zheng, Y., Yang, J., Wang, L., Yang, J., Huang, Z., 2015b. Preliminary investigation of PM$_1$, PM$_{2.5}$, PM$_{10}$ and its metal elemental composition in tunnels at a subway station in Shanghai, China. Transport Res D-Tr E. 41, 136–146.

Querol, X., Moreno, T., Karanasiou, A., Reche, C., Alastuey, A., Viana, M., Font, O., Gil, J., Miguel, E.D., Capdevila, M., 2012. Variability of levels and composition of PM$_{10}$ and PM$_{2.5}$ in the Barcelona metro system. Atmos. Chem. Phys. 12, 253–261.

Ramos, M.J., Vasconcelos, A., Faria, M., 2015. Comparison of particulate matter inhalation for users of different transport modes in Lisbon. Transp. Res. Procedia 10, 433–442.

Raut, J.C., Chazette, P., Fortain, A., 2009. Link between aerosol optical, microphysical and chemical measurements in an underground railway station in Paris. Atmos. Environ. 43, 860–868.

Ripanucci, G., Grana, M., Vicentini, L., Magrini, A., Bergamaschi, A., 2006. Dust in the underground railway tunnels of an Italian town. J. Occup. Environ. Hyg. 3, 16–25.

Robertson, C.E., Baumgartner, L.K., Harris, J.K., Peterson, K.L., Stevens, M.J., Frank, D.N., Pace, N.R., 2013. Culture-independent analysis of aerosol microbiology in a metropolitan subway system. Appl. Environ. Microbiol. 79, 3485–3493.

Şahin, Ü.A., Onat, B., Stakeeva, B., Ceran, T., Karim, P., 2012. PM$_{10}$ concentrations and the size distribution of Cu and Fe-containing particles in Istanbul's subway system. Transport Res D-Tr E. 17, 48–53.

Salma, I., 2007. Time-resolved mass concentration, composition and sources of aerosol particles in a metropolitan underground railway station. Atmos. Environ. 41, 8391–8405.

Salma, I., Pósfai, M., Kovács, K., Kuzmann, E., Homonnay, Z., Posta, J., 2009. Properties and sources of individual particles and some chemical species in the aerosol of a metropolitan underground railway station. Atmos. Environ. 43, 3460–3466.

Shiohara, N., Fernández-Bremauntz, A.A., Jiménez, S.B., Yanagisawa, Y., 2005a. The commuters' exposure to volatile chemicals and carcinogenic risk in Mexico City. Atmos. Environ. 39, 3481–3489.

Shiohara, N., Fernández-Bremauntz, A.A., Jiménez, S.B., Yanagisawa, Y., 2005b. The commuters' exposure to volatile chemicals and carcinogenic risk in Mexico City. Atmos. Environ. 39, 3481–3489.

Sitzmann, B., Kendall, M., Watt, J., Williams, I., 1999. Characterisation of airborne particles in London by computer-controlled scanning electron microscopy. Sci. Total Environ. 241, 63–73.

Son, Y.S., Kang, Y.H., Chung, S.G., Park, H.J., Kim, J.C., 2011. Efficiency evaluation of adsorbents for the removal of VOC and NO$_2$ in an underground subway station. Asian J. Atmos. Environ. 5, 113–120.

Son, Y.S., Jeon, J.S., Lee, H.J., Ryu, I.C., Kim, J.C., 2014a. Installation of platform screen doors and their impact on indoor air quality: Seoul subway trains. J. Air Waste Manage. Assoc. 64, 1054–1061.

Son, Y.S., Dinh, T.V., Chung, S.G., Lee, J.H., Kim, J.C., 2014b. Removal of particulate matter emitted from a subway tunnel using magnetic filters. Environ. Sci. Technol. 48, 2870–2876.

Suárez, L., Mesías, S., Iglesias, V., Silva, C., Cáceres, D.D., Ruizrudolph, P., 2014. Personal exposure to particulate matter in commuters using different transport modes (bus, bicycle, car and subway) in an assigned route in downtown Santiago, Chile. Environ. Sci. Process. Impacts 16, 1309–1317.

Sung, H.H., Jang, S., Park, W.M., Park, J.B., 2016. Concentrations and identification of culturable airborne fungi in underground stations of the Seoul metro. Environ. Sci. Pollut. R. 23, 1–7.

Tokarek, S., Bernis, A., 2006. An exemple of particle concentration reduction in Parisian subway stations by electrostatic precipitation. Environ. Technol. 27, 1279–1287.

Trattner, R.B., Kimmel, H.S., Perna, A.J., Lee, M., 1977. Infrared analysis of the chemical composition of particulates in subway air. Spectrosc. Lett. 10, 699–717.

Vallejo, M., Lerma, C., Infante, O., Hermosillo, A.G., Riojasrodriguez, H., Cárdenas, M., 2004. Personal exposure to particulate matter less than 2.5 lm in Mexico City: a pilot study. J. Expo. Anal. Environ. Epidemiol. 14, 323–329.

Vilcassim, M.J.R., Thurston, G.D., Peltier, R.E., Gordon, T., 2014. Black carbon and particulate matter (PM$_{2.5}$) concentrations in New York City's subway stations. Environ. Sci. Technol. 48, 14738–14745.

Wang, X., Gao, H.O., 2011. Exposure to fine particle mass and number concentrations in urban transportation environments of New York City. Transport Res D-Tr E. 16, 384–391.

Wang, B.Q., Liu, J.F., Ren, Z.H., Chen, R.H., 2016. Concentrations, properties, and health risk of PM$_{2.5}$ in the Tianjin City subway system. Environ. Sci. Pollut. Res. Int. 23, 1–11.

Wu, Y., Gao, N., Wang, L., Wu, X., 2013. A numerical analysis of airflows caused by train-motion and performance evaluation of a subway ventilation system. Indoor Built Environ. 23, 854–863.

Xu, B., Cui, P., Xu, H., Chen, H., Lin, Y., 2013. Commuter exposure to particle matter and carbon dioxide inside high-speed rail carriages. Transport Res D-Tr E. 20, 1–6.

Xu, B., Yu, X., Gu, H., Miao, B., Wang, M., Huang, H., 2016. Commuters' exposure to PM$_{2.5}$ and CO$_2$ in metro carriages of Shanghai metro system. Transp. Res. D-Tr E 47, 162–170.

Yan, C., Zheng, M., Yang, Q., Zhang, Q., Qiu, X., Zhang, Y., Fu, H., Li, X., Zhu, T., Zhu, Y., 2015. Commuter exposure to particulate matter and particle-bound PAHs in three transportation modes in Beijing, China. Environ. Pollut. (Barking, Essex: 1987) 204, 199–206.

Yang, F., Kaul, D., Wong, K.C., Westerdahl, D., Sun, L., Ho, K.F., Tian, L., Brimblecombe, P., Ning, Z., 2015. Heterogeneity of passenger exposure to air pollutants in public transport microenvironments. Atmos. Environ. 109, 42–51.

Yang, Z., Su, X., Ma, F., Yu, L., Wang, H., 2015. An innovative environmental control system of subway. J. Wind Eng. Ind. Aerodyn. 147, 120–131.

Ye, X., Lian, Z., Jiang, C., Zhou, Z., Chen, H., 2010. Investigation of indoor environmental quality in Shanghai metro stations, China. Environ. Monit. Assess. 167, 643–651.

Yong, S., Abtin, A., Kim, J.T., Kumar, D., Chang, K.Y., 2011. Statistical evaluation of indoor air quality changes after installation of the PSD system in Seoul's metro. Indoor Built Environ. 20, 187–197.

Yu, I.J., Yoo, C.Y., Chung, Y.H., Han, J.H., Yhang, S.Y., Yu, G.M., Song, K.S., 2004. Asbestos exposure among Seoul metropolitan subway workers during renovation of subway air-conditioning systems. Environ. Int. 29, 931–934.

Yu, Q., Lu, Y., Xiao, S., Shen, J., Li, X., Ma, W., Chen, L., 2012. Commuters' exposure to PM_1 by common travel modes in Shanghai. Atmos. Environ. 59, 39–46.

Yuan, F.D., You, S.J., 2007. CFD simulation and optimization of the ventilation for subway side-platform. Tunn. Undergr. Sp. Tech. 22, 474–482.

Zhang, Y., Li, C., Wang, X., Guo, H., Feng, Y., Chen, J., 2012. Rush-hour aromatic and chlorinated hydrocarbons in selected subway stations of Shanghai, China. J. Environ. Sci. 24, 131–141.