Received: 25 September 2018 | Revised: 7 December 2018 | Accepted: 8 December 2018

DOI: 10.1111/ina.12532

REVIEW ARTICLE

WILEY

A review of traditional and advanced technologies for the removal of particulate matter in subway systems

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Funding information
National Research Foundation of Korea, Grant/Award Number: NRF-2018R1D1A3B07040617; National Research Foundation; Ministry of Education, Grant/Award Number: NRF-2016R1E1A1A01940995

Abstract

The pollution status of particulate matter (PM) in a subway system and technological trends in their reduction were discussed in this study. The levels of $PM_{2.5}$ and PM_{10} are generally found to be higher in the underground platforms and tunnels than those in the outdoor air. It has also been reported that the composition of fine dust in the subway consists of various substances including heavy metals (like Fe), carbonaceous matter, and solvent extractable organic matter (SEOM). It was confirmed that subway dust was created mainly by wearing on wheels, rails, and brakes. In addition, the concentration of PM in such environment was influenced not only by internal factors (eg, operating conditions of trains and ventilation systems, number of passengers, and the structure of subway stations) but also by outside factors (eg, ambient air concentration). Up to now, various techniques (ventilation fans, platform screen doors (PSDs), magnetic filters, small jet fans, artificial intelligent ventilation systems, hybrid filters, etc) have been studied to reduce PM in underground subway systems. In this study, we reviewed the air quality of major subway stations with the focus on PM and relevant technologies for its reduction.

KEYWORDS

energy saving, particulate matter, platform screen doors, PM_{10}, $PM_{2.5}$, subway system

1 | INTRODUCTION

Due to the rapid civilization and increase in urban population density, the demand for public transportation services has been increasing continuously. The subway system is one of the most popular public transportation systems, with low price and accurate operating time. Currently, the subway systems are operating to provide fast and reasonable transportation in urban communities in more than 60 countries. As such, the number of subway commuters has steadily been increasing in metropolitan areas.[1] In particular, the subway system represented 59.3% of public transportation in Seoul, Korea in 2016. In fact, in 2016, the daily average number of public commuters decreased by 0.7% (or 94 000 people) relative to the previous year (total of about 13.49 million people) in Seoul. Although the number of bus users decreased by 108 000 (1.9%), that of subway users increased by 14 000 (0.2%).[2] Therefore, now more than ever, it is necessary to provide a safe and healthy environment for passengers and workers, including strict air quality management. However, indoor air quality (IAQ) in the subway is in a serious state because most subway platforms are located underground and the floating population rapidly increases during rush hours.

The subway is unique in that it has a source of internal particulate matter (PM) in an enclosed space.[3] It is known that the PM in subway systems is generated by the movement of trains and passengers and is accumulated inside.[4-11] In addition, it has been reported that in most of the world's subway system, indoor air quality tends to be worsened due to the increase in the inadequate ventilation and the number of passengers and subway.[2,12] In addition, since most of the subway platforms constructed in recent years are located underground, pollution in subway environment is projected to be more serious with time. It was also reported that the pollution level of underground platforms and tunnels is affected not only by external factors such as air pollutant inflow of outside air (ground vehicle exhaust gas) but also by internal factors such as train-induced wind and wear on rails and wheels which serve as the main cause of increased contamination.[2,12-15] The pollutants generated by the wear of brakes, wheels, and rails in the tunnel cause more serious problems to the human body due to their harmfulness. According to the previous research by Kalsson et al,[16] the PM generated from the subway is about eight times more genotoxic and four times more likely to cause oxidative stress in lung cells than PM in the outside air. These authors also reported that all PM from the subway can cause DNA damage by redoxactive iron, which is mostly (60%-70%) in the form of magnetite (Fe_3O_4). Additionally, various PMs emitted from underground subway systems were reported to have cytotoxic and inflammatory potential and transient biological effects with their toxicity caused by such factors as the high content of iron compounds.[17-20] Iron-containing compounds such as magnetite (Fe_3O_4), hematite (α-Fe_2O_3), maghemite (γ-Fe_2O_3), and iron (Fe) metal are known to make up most PM contents originating in a subway system to adversely affect the human health.[16,21-25]

In light of environmental significance of PM in subway system, diverse studies have been conducted all over the world. However, most of them have focused on the concentration and composition of PM and other pollutants in subway systems. In particular, the study on subway PM has been made exclusively toward its pollution levels. However, in order to manage the PM levels in subway more efficiently, it is important not only to characterize PMs but also to develop methods of their removal. Various techniques for reducing subway PM (such as ventilation fans, platform screen doors, magnetic filters, jet fans, artificial intelligent ventilation, modified dust collectors, hybrid filters, etc) have been introduced and applied in actual field locations. Nevertheless, technology needed for the reduction and control of subway PM has not been thoroughly reviewed to date. Therefore, in this review paper, the present situation and characteristics of PM pollution in subway platform in major cities around the world were assessed along with the causes of subway PM generation and the correlation with the outside air. In addition, the health effects of PM on pedestrians and workers were also investigated. Finally, we review the basic information regarding the existing technologies for the reduction and control of PM in subway systems along with the more updated advanced technologies.

Practical Implication

- The construction and utilization of subway system are increasing due to the concentration of population by urbanization all over the world.
- As a result, the interest in the health of subway passengers and workers has increased.
- Particularly, the concentration of particulate matter (PM) in the subway system is reported to be higher than the outdoor air.
- Therefore, in this study, we reviewed the conventional technologies for reducing subway PM and the new technologies developed to overcome the problems of existing technologies.

2 | PARTICULATE MATTER IN SUBWAY SYSTEMS

2.1 | Levels of particulate matter

The severity of PM pollution in subway stations and tunnels has been recognized since the 1990s, and many studies of the problem have been conducted worldwide. In particular, researches have been carried out to measure pollution levels of $PM_{2.5}$ (particulate matter 2.5 μm or less in diameter), PM_{10} (particulate matter 10 μm or less in diameter), and other pollutants in major cities with the rise of health hazards due to PM. Table 1 lists the results of concentration measurements of PM in major cities in the world. The concentration of subway PM was 7-731 μg/m^3 for $PM_{2.5}$ and 10-1500 μg/m^3 for PM_{10}, and it was confirmed that concentration of PM exists in a wide range depending on the place of measurement.

When comparing results of previous studies, it was found that the PM levels were considerably different in the presence of various factors, such as the depth of the tunnel, the tunnel design, the length of the underground section, operating conditions, the presence of platform screen doors (PSDs), and the train's ventilation system.[26-32] It is also known that the PM generated by the subway operation is caused by mechanical phenomena (such as wear due to friction and scratching between the rail and wheels, and between the pantograph and the subway trains) and is floated by the train-induced wind.[1-8]

Most of the literature reported that the concentrations of PM during weekdays were higher than those during weekends. The reason for this is that the number of passengers and the frequency of trains passing are higher during the weekdays due to commuters going to and from work, and thus the PM concentration increases rapidly on those days. Many researchers reported that $PM_{2.5}$ concentrations in the weekday are about 20% to 50% higher than on weekends.[5,6,9-12] Martins et al[29] also reported that the source of $PM_{2.5}$ was related to the train's operation because the average concentration of $PM_{2.5}$ during the times the trains were in operation was higher than the average over the entire day. A more detailed analysis was done on the PM concentration in Shanghai subway during day times, and it was found that PM concentration at Friday afternoon was the highest among a week.[13,14]

From four stations in Barcelona, Spain, differences in $PM_{2.5}$ levels between warmer and colder temperature conditions were investigated.[31] Accordingly, the levels of $PM_{2.5}$ during the cold period were higher than those during warmer period. This is because ventilation systems were more intensively activated to control the air quality in subway platforms during the warmer periods. We could find similar results for the season in the results of studies conducted by Braniš[10] and Querol et al.[33]

TABLE 1 Particulate matter (PM) concentration in subways of major cities in the world

Ref	Metro built year	Measurement year	Location	Particle size	Sampling site	Concentration (μg/m^3)
30	1869, 2000(under)	2014	Athens, Greece	$PM_{2.5}$	Subway platform	68.3
	1924	2013-2014	Barcelona, Spain	$PM_{2.5}$		58.3
33	1924	2011	Barcelona, Spain	$PM_{2.5}$	Station platform (PSDs)	41 (22-60)
				PM_{10}		134 (77-192)
				$PM_{2.5}$	Station platform	125 (102-148)
				PM_{10}		346 (289-403)
				$PM_{2.5}$	Train	21 (16-26)
				PM_{10}		65 (49-81)
29	1924	2013-2014	Barcelona, Spain	$PM_{2.5}$	Platform	48 (12-154)
					Train	32.7 (11-99)
31	1924	2013-2014	Barcelona, Spain	$PM_{2.5}$	subway platform (warmer)	35.8 (20.7-51.5)
					subway platform (colder)	65 (32-93.2)
82	1981	2004	Beijing, China	$PM_{2.5}$	Underground Inner subway	112.6 ± 42.7
				PM_{10}		324.8 ± 125.5
83	1897	2001	Boston, USA	$PM_{2.5}$	Train	65 (36-104)
25	1896	2006	Budapest, Hungary	PM_{10}	Underground	180 (85-234)
					Underground	155 (25-322)
84	1913	2005-2006	Buenos Aires, Argentina	$PM_{2.5}$	Platform	152-270
85	1968	2013	Frankfurt, Germany	$PM_{2.5}$	Station platform	59 (–85)
				PM_{10}		101 (–166)
86	1997	2001	Guangzhou, China	$PM_{2.5}$	Compartment	44 ± 11
				PM_{10}	Compartment	55 ± 14
8	1982	2004	Helsinki, Finland	$PM_{2.5}$	Underground	47 (±4) and 60 (±18)
					Inner subway	21 (±4)
						60 (23-103)
87	1979	1999-2000	Hong Kong, China	$PM_{2.5}$	Compartment	21-68 (39 ± 9)
				PM_{10}	Compartment	21-68 (39 ± 9)
88	1875	2007	Istanbul, Turkey	PM_{10}	Station platform	170 (72-294)
89	1875	2007	Istanbul, Turkey	$PM_{2.5}$	Underground	49.3-181.7
					Station platform	105 (20-421)
					Train	71 (46-161)
90	1863	1999	London, UK	$PM_{2.5}$	Underground	247.2 (105.3-371.2)
						157.3 (12.2-263.5)
20	1863	2003	London, UK	$PM_{2.5}$	Station platform	270-480
					Inner subway	130-200
				PM_{10}	Station platform	1000-1500
					Inner subway	
				$PM_{2.5}$	Train	170 (118-201)

(Continues)

TABLE 1 (Continued)

Ref	Metro built year	Measurement year	Location	Particle size	Sampling site	Concentration (μg/m^3)
91	1993, 2000 (red line)	2010	Los Angeles, USA	$PM_{2.5}$	Station	56.7 ± 11.3
					Train	24.2 ± 6.9
				PM_{10}	Station	78.0 ± 16.5
					Train	31.5 ± 10.8
				Coarse PM	Station	21.3 ± 5.6
					Train	7.3 ± 6.4
92	1969	2003	Mexico city, Mexico	$PM_{2.5}$	Train	38 (8-68)
24	1969	2007	Mexico city, Mexico	$PM_{2.5}$	subway platform	60-93
				PM_{10}		88-145
27	1964	2012	Milan, Italy	PM_{10}	Station platform	188 (137-239)
37	1993	2014	Napoli, Italy	$PM_{2.5}$	Station platform	45-60
				PM_{10}		172-262
				$PM_{2.5}$	Train	18-36
				PM_{10}		58-138
49	1904	2001	New York, USA	$PM_{2.5}$	Platform	62
				$PM_{2.5}$	train	62
93	1904	2004-2005	New York, USA	$PM_{2.5}$	Underground	56 ± 95
94	1904	2010	New York, USA	$PM_{2.5}$	Train	40 (34-44)
					Platform	68 (60-77)
11	1900, 1999 (Magenta station)	2006	Paris, France	$PM_{2.5}$	Underground station platform (rush hours)	93
					Underground station platform (normal hours)	61
				PM_{10}	Underground station platform (rush hours)	320
					Underground station platform (normal hours)	200
30	2002	2014	Porto, Portugal	$PM_{2.5}$		83.7
10	1974	2004	Prague, Czech	PM_{10}	Underground	103
				PM_{10}	Train	114 (24-218)
95	1955	2005	Rome, Rome	PM_{10}	Underground	407 (71-877)
4	1974	2004	Seoul, Korea	$PM_{2.5}$	platform	129 (81.6-176.3)
				PM_{10}		359 (171.3-480.1)
				$PM_{2.5}$	Train	126 (115-136)
				PM_{10}		312 (29-356)
96	1974		Seoul, Korea	$PM_{2.5}$	Underground station and ground stations	105.4 ± 14.4-121.7 ± 16.1
				PM_{10}		123 ± 6.6-145.3 ± 12.8
				$PM_{2.5}$	Platform	105
					Train	117
13	1974	2008	Seoul, Korea	$PM_{2.5}$	Platform	66 (39-129)
				PM_{10}		116 (76-164)
				$PM_{2.5}$	Platform (PSD installation)	58.1 (20.4-166)
				PM_{10}		97.2 (37.1-247)

(Continues)

TABLE 1 (Continued)

Ref	Metro built year	Measurement year	Location	Particle size	Sampling site	Concentration (μg/m^3)
32	1974	2014-2015	Seoul, Korea	$PM_{2.5}$	Platform	64
				PM_{10}		108.4
28	1993		Shanghai, China	$PM_{2.5}$	Platform	231 ± 152(80-623)
				$PM_{2.5}$		287 ± 177(98-731)
				PM_{10}		366 ± 193(81-975)
97	1993	2013	Shanghai, China	$PM_{2.5}$	Station platform	352
				PM_{10}		457
72,74	1993	2013	Shanghai, China (Line A)	$PM_{2.5}$	Tunnel	57 ± 30(5-137)
				PM_{10}		69 ± 34(6-156)
	1993	2013	Shanghai, China (Line B)	$PM_{2.5}$		61 ± 45(13-190)
				PM_{10}		71 ± 46(14-234)
41	1993	2012	Shanghai, China	$PM_{2.5}$	Platform	49.17 ± 19.7-66.15 ± 25.20
9	1950	2000	Stockholm, Sweden	$PM_{2.5}$	Platform	165-258 (34-388)
				PM_{10}		302-469 (59-722)
16	1950		Stockholm, Sweden	PM_{10}	Platform	357
98	1968	2009	Sydney, Australia	$PM_{2.5}$	Train	36
99	1995	2007	Taipei	$PM_{2.5}$	Platform	7-100
				PM_{10}		11-137
				$PM_{2.5}$	Train	8-68 or 40 (22-71)
				PM_{10}		10-97 or 31 (19-51)
5	1999	2011	Tehran, Iran	$PM_{2.5}$	Underground station platform	52.3 (23.7-85.3)
				PM_{10}		94.4(32.5-126.2)

The effect of external PM_{10} concentration was observed to have the greatest effect on the PM concentration in the subway platform.[32] In addition, it was confirmed that the PM concentration increases with the depth of the subway station. Colombi et al[27] also reported that the PM_{10} concentration tends to increase as the subway station becomes smaller and deeper. It is assumed that the reason for the high PM concentration in these circumstances is that contact with outside air becomes difficult. Martins et al[31] suggested that high PM concentrations in small subway stations (those with a single narrow tunnel and one rail track) are due to less efficient dispersion of air pollutant. Similar results were obtained by Moreno et al.[34,35] They reported that the average PM concentration in such small stations was higher than that of a wider tunnel and two rail tracks separated by a middle wall among the conventional stations (without PSDs). In a single narrow tunnel, the concentration of PM_{10} on the platform is maximized by the fact that the air pollutants are blown into the tunnel due to piston wind occurring just before the train arrives.[34] Wang et al[36] also reported that the concentrations of PM in the platform were affected by the piston effect. They found that the piston effect caused the $PM_{2.5}$ and PM_1 concentrations in the subway to increase by 9% and 8%, respectively. However, the results they obtained were different from those found in previous literature. Because of this piston effect, the side-type platform ($PM_{2.5}$ mean concentration at front, meddle, and rear: 73.1, 64.9, and 75.7 μg/m^3) and the island-type platform (50.0, 43.5, and 53.0 μg/m^3) have high PM concentrations on the front and rear of the platform, and the PM concentration in the center of the platform is relatively low. On the other hand, in the case of the stacked-type platform (one direction train), the $PM_{2.5}$ average concentration at the rear was higher (27.5, 26.9, and 39.7 μg/m^3). Therefore, it is deemed appropriate to design a one direction type platform to minimize PM of the platform caused by the piston effect.

Platform screen doors have been constructed between the platform and the tunnel in subway stations to maintain the safety of passengers. And, it is also used to distinctly improve indoor air quality in the platforms.[15-18] It is a system that prevents the tunnel air from entering the platform. It has been reported that the average concentration of $PM_{2.5}$ in the platform can be reduced by 50% or more by the use of PSDs,[34] which are widely used in the most recently installed subways. In South Korea, PSDs are installed in most subway stations, and details of their effectiveness will be covered in the following section, 3B.

In general, the PM concentration in the train is lower than in the platform.[2,7,19-23] This is due to the operation of an air-conditioning system equipped with an air filter inside the train.[29] On the other hand, Carteni et al[37] confirmed that when the subway passes through the underground tunnel with the windows open, the PM concentration in the train increases due to the inflow of outside air by turbulence. In contrast, at the ground level, clean air flows into the subway and the PM concentration decreases. They also reported

TABLE 2 Comparison of filtration performances obtained using single-layer and double-layer PM_{10} filter installed in Seoul Metro, Korea[61]

	Fabric panel Filter (single-layer filter)	Fabric panel + electret pleated filter (double-layer filter)
Filter efficiency (%)	69	80
Average platform PM_{10} concentration (μg/m^3)	38	22
Filtration cost		
Installation cost ($/time)	65	315
Replacement cost ($/time)	50	600
Waste filter disposal cost ($/time)	123	665
Replacement times (time/year)	24	6
Total filtration cost ($/year)	5775	7486

that the turbulence caused by the operation of the train causes PM resuspension, which greatly increases the PM concentration of the platform. Similar results were observed in the metro system in Athens. In the case of the Athens subway, the carriage windows are usually open, and it was confirmed that when the subway passes through a tunnel between stations, the levels of $PM_{2.5}$ increase by a factor of three over the average concentration of $PM_{2.5}$ in the subway system.[30]

2.2 | Component

The most important feature of subway PM is that its large fraction occurs in the underground system by itself.[35] Therefore, the PM of the subway is mainly caused by mechanical phenomena, such as abrasion and friction of rails, wheels and brake pad systems, abrasion due to friction between the pantograph and power supply facilities, and dust caused by working inside the tunnels.[1,3,4,7,8,13,24-26] Various studies confirmed that the main component of subway PM is Fe, which consists of various trace metals, such as Ca, Al, Mg, Mn, Zn, Cu, Cr, Ni, Pb, and Hg. Fe is primarily caused by mechanical phenomena, such as wear and friction. After that, it is known that Fe reacts with oxygen in the atmosphere and floats by train-induced wind in the form of various iron oxides, such as Fe_3O_4, α-Fe_2O_3, and γ-Fe_2O_3, in subway platforms and tunnels.[3] Colombi et al[27] also reported that Fe, Mn, Sb, and Ba oxide, generated by the wear of wheels, rails, and brakes, account for about 40%-73% of PM_{10}, and Cu and Zn oxide, formed by wear of electric cables, account for 2%-3% of PM_{10}. In addition, Jung et al[38] confirmed that the amount of aerosol particles containing iron components accounted for 75%-85% of the total amount of particles. A similar result is also confirmed by Seaton et al[20], who found that about 67% of the $PM_{2.5}$ in the London subway consists of iron oxide. Trace metals found in subway platforms and tunnels were also induced by mechanical wear and friction in the brake or power supply materials, which followed various component distributions in each of the manufactured materials.[2,11,19,27-29]

On the other hand, carbonaceous were also found in the subway platforms and tunnels by many researchers.[2,3,11,30] Martins et al[30] found that total carbon (TC), with a combination of elemental carbon (EC) and organic carbon (OC), was the second highest component in the subway platform, following the Fe concentration of $PM_{2.5}$. This was an unexpected result because there was no combustion source in the subway system, which was driven by electrical force. As a source of TC, the authors suggested the diesel train driven by nighttime maintenance workers and wear of C-bearing brake pads and current supply materials. Gustafsson et al[39] also reported that EC is caused by abrasion of pantograph and brake, and that OC is generated by running diesel trains, as well as lubricants used to minimize rail wear.

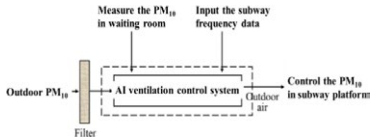
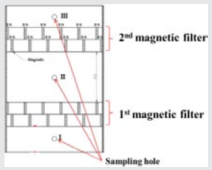
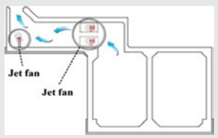
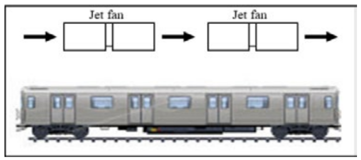
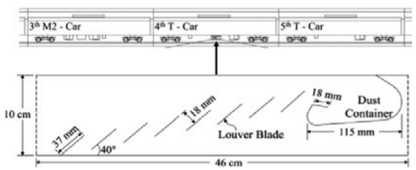
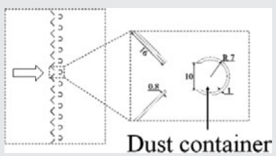
It was reported that the contents of solvent extractable organic matter (SEOM), including n-alkanes and polycyclic aromatic hydrocarbons (PAHs) in the subway space, were 30% higher than in outdoor air, implying that toxic organic compounds are present at considerable levels in the subway environment.[24,40] Furthermore, Martins et al[31] confirmed that organic compounds, such as PAHs, were detected at the subway station. It was observed that the concentration of PAHs was high in the cold period and in the traditional subway station. In addition, aromatic musk compounds (methyl dihydrojasmonate and galaxolide) were also found for the first time.

2.3 | Health effects

As mentioned above, there are various pollutants in the subway system. Therefore, the air quality in the subway system is considered to be more harmful to the human body than outdoor air. Seaton et al[20] reported that subway PM is more toxic than outdoor airborne particles and is similar in toxicity to weld dust. It is known that the high iron content of PM in the subway environment contributes greatly to toxicity.[16] Additionally, the formation of reactive oxygen species (ROS) by iron-rich particles (or other trace metals such as Cu) can harm human lungs.[41]

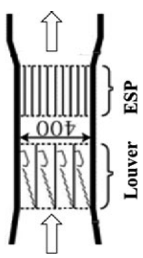
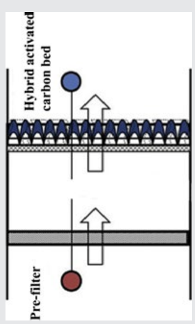
The toxicity level of subway PM was investigated with respect to human health.[16] Accordingly, the genotoxic effect and the potential of lung cell oxidative stress (as a causative agent) for the subway PM were eight and four times higher than those of outdoor PM. It is also reported that fine dusts generated in the subway contain various heavy metal components. Soluble transition metals, such as Co, Cu, Fe, Mn, V, and Zn, are involved in various metabolic and signaling pathways and are related to DNA damage and oxidative stress.[42,43]

TABLE 3 Schematic diagram and feature of advanced technologies developed for subway PM reduction

Advanced technology	Schematic diagram	Removal efficiency (%) $PM_{2.5}$	Removal efficiency (%) PM_{10}	Technical features	References
AI ventilation system				Artificial intelligence control of ventilation fan considering environmental factors such as outdoor and train operation Reduce energy consumption while improving subway environment	52,69-71,100
Magnetic filter		46	52	Magnet filter is efficient for subway PM collection with large amount of Fe	26
		90	95	Improved removal efficiency as the number of magnet layers increases	75
				Use permanent magnet and metal net without external power	76
Jet fan					
Case. 1				Improved subway air by applying to old tunnels that depend on natural ventilation. The concentration of PM_{10} decreased by about 6 μg/m^3 per 10 000 CMH	52,58,101
Case. 2		$PM_{2.0}$:66-85	96-98	Improved ventilation by installing jet pens on top of underground tunnels Removing PM by attaching a filter to the jet fan	
Power-free and hybrid dust collection train					
Louver dust collector				Removing subway PM by installing power-free dust collector under the trailer car Using only train-induced wind force without using additional power The louver collector is simple in appearance, with low pressure drop, and utilizing inertial properties of particles At the normal speed range (5-65 km/h), the cutoff size of the louver collector is about 5-10 μm	79
Baffle dust collector				The baffle collector changes the airflow to increase the inertia of the suspended particles The cutoff size of the inhaled particles at 70 km is 7.8 μm	78

(Continues)

TABLE 3 (Continued)

Advanced technology	Schematic diagram	Removal efficiency (%)		Technical features	References
		$PM_{2.5}$	PM_{10}		
Hybrid dust collector		>65	>85	High dust collection efficiency over a wide flow rate range Hybrid dust collector adapting to change of flow rate when moving between subway station and station. Combines the advantages of an inertial dust collector and an electrostatic precipitator	80
Hybrid filter				Hybrid filter capable of removing NO_2 and VOCs as well as PM	81

Also, soluble particulate matter, such as metals, may be absorbed into the bloodstream and cause inflammation or heart problem.[24]

It was reported that commuters are exposed daily to the subway atmosphere due to repeated subway use, which can lead to cumulative or chronic health effects.[29] In addition, sensitive groups, such as children, elderly people, and people who have respiratory illnesses can be greatly influenced by brief exposure to the subway environment.[25] Exposure to particulate matters, such as PM_{10} and $PM_{2.5}$, can adversely affect respiratory and cardiovascular health. Additionally, it is reported that as the particle size decreases, the ability to penetrate into the lower airways will increase.[44] Nguyen et al[45] also reported that subway PM inhalation affects the heart and lungs and can cause serious health problems. These particles have been reported to increase the risk of respiratory-related diseases, such as irregular heartbeat, vascular disorders, lung cancer, arrhythmias, chronic obstructive pulmonary disease, asthma exacerbation, and cardiovascular-related diseases.[46,47]

According to a result provided by Oh et al,[48] long-term exposure to heavy metals in PM_{10} and $PM_{2.5}$ of underground subway stations has increased the likelihood of carcinogenesis. However, there is a lack of epidemiological evidence to date that the subway PM has a direct impact on the health of workers and commuters. Chillrud et al[49] concluded that the health effects of PM inhalation levels were unknown in the metal dust exposure environment of subway workers and commuters in New York. It was also concluded that there was no apparent increase in the risk of lung cancer among train operators in the Stockholm subway system.[21] However, as subway PM is to exert harmful effects on human health, many techniques have been developed and applied for its reduction.

3 | TRADITIONAL TECHNOLOGY

To solve problems induced by the subway PM, diverse methods (such as ventilation, filtration, and a dust collection train) have been developed and applied. However, traditional technologies have many limitations, like high operating costs, low removal efficiency, etc

3.1 | Ventilation fan

To improve indoor air quality, natural ventilation is still used for ventilation of the tunnel and platform in some old places. The natural ventilation is the use of train-induced wind to naturally vent air in the tunnel without the use of other mechanical forces.[50] This natural wind is generated by the piston effect of a train moving through a tunnel. The train passing through the tunnel has a double effect—pushing the air in front and suctioning the air from the rear with a negative vortex pressure. These piston winds can ventilate the platform without mechanical forced ventilation.[34] Thus, optimal use of the piston effect can provide significant energy savings.[51] Moreno et al[34] investigated the PM concentration in the platform according to the presence or absence of mechanical ventilation systems to determine the effect of this piston effect. As a result, it was confirmed that the PM_{10} level of narrow platforms with single-track tunnels were doubled when the ventilation system was turned off. Therefore, they reported that the air quality in this spatially confined type of station is extremely dependent on the presence of forced mechanical tunnel ventilation (FMTV). In contrast, in the case of a wider station (with double tracks), the air quality was improved without FMTV, resulting in significant energy savings. Meanwhile, the presence of FMTV did not affect the particle size ratio. Martins et al[29] also reported that using only natural ventilation created by the piston effect, it would be difficult to obtain good air quality in subway systems.

It has been reported that the efficiency of this effect is lower than that of the forced ventilation using a fan.[50] However, in the case of forced ventilation, appropriate use and management are necessary to solve civil complaints caused by noise, aging, improper design, and high operating costs.[26] To solve this problem, it is necessary to improve the old ventilation system and to operate it properly. As an example, Son et al[12] proved that the PM_{10} concentration in the tunnel can be kept below 150 $\mu g/m^3$ (indoor air quality standard in Korea) by operating the appropriate ventilation system. Hong[52] also reported that the concentration of PM_{10} in the tunnel decreased by 6 $\mu g/m^3$ per 10 000 CMH (Cubic Meter Hour) as the air volume of the ventilation fan increased. Further, the concentration of PM decreased sharply when the airflow exceeded 300 000 CMH. According to this study, the concentration of PM_{10} can be maintained at 150~170 $\mu g/m^3$, if the air volume is 340 000 CHM.

In the subway systems of Paris and Barcelona, ventilation of the subway station for air quality is accounting for about one-third of the overall energy consumption.[34,53] Rigaut et al[53] proposed an energy system concept that shows comparable air quality while reducing the energy consumption of the ventilation system. The concept is a battery system that stores the braking energy of a train and an energy management system that controls energy flow and ventilation air flow in a short period of time. They compared stochastic dynamic programming (SDP)-based algorithms with model predictive control (MPC) ones. As a result, it was reported both yield energy and money operating savings of the order of one-third compared to current management practices, concluding that SDP is the best choice. In addition, the height of the supply air vents should be raised in order to introduce clean air.[26] Accordingly, it is estimated that the air supply ventilation system installed in parks and green areas can reduce the indoor air pollution level in the subway space by introducing a supply of clean air.[50] On the other hand, ventilation systems can cause another problem. Contaminated air in the tunnel is discharged either naturally or forcibly into the atmosphere, which affects not only the pedestrians around the ventilation but the occupants living near the ventilation.[26] Therefore, further studies on the reduction of pollutant discharged through the ventilation should be performed.

3.2 | Platform screen doors

The recently built subway stations have installed and operated platform screen doors (PSDs). The PSDs were installed to improve passenger safety and indoor air quality in the station. Air quality in the platform was improved as a result. This means that the fine dust that is rescattered by the train entering the platform from the tunnel is blocked by the PSDs.[13,22] Kim et al[13] confirmed that the PM_{10} concentration in the platform was reduced by 16% with operating the PSDs. In addition, Jung et al[54] reported that iron-containing particles generated from the tunnel were significantly reduced in the platform after the PSDs were installed.[22] Martins et al[29] suggested that the recent concentration of PM in the new subways with PSDs is lower than in the conventional systems because of the low frequency of train operation and station design as well as the advanced ventilation system. These results demonstrate that the installation of PSDs has a clear effect on the reduction of fine dust concentration in the platform.

On the other hand, the concentration of PM in underground tunnels is increasing due to PSDs.[12,55] This is because the PM that has spread from the tunnel to the platform due to the train-induced wind and natural ventilation remains is kept in the tunnel by the PSDs.[50] Additionally, Son et al[26] confirmed that the PM_{10} levels in the train increased to 29.9%-103% after the installation of PSDs. They also confirmed that PSDs strictly limit air flow diffusion between the tunnel and platform through correlation analysis between PM_{10} and $PM_{2.5}$.

3.3 | Washing and dust collection train

Tunnel washing to reduce subway fine dust was tested in the Taiwan Rapid Transit System (TRTS). Chen et al[56] reported that the tunnel was cleaned using a high-pressure (pressure range: 50-195 bars) washing vehicle, and the nozzle was used to clean the tunnel wall. The washing vehicle cleared the tunnel section between one station and the next. On the first day after washing, the concentration of fine dust was increased because of the evaporation of the sewage containing residual particles remaining on the bottom of tunnel after washing. However, the PM concentration decreased on the second day. Three and a half months after tunnel washing, the PM_{10} level was found to have decreased by 46.1%, and after 2 months, the concentration of $PM_{2.5}$ was found to have decreased by 28.7%. They reported that the mechanism of the continuous reduction of PM_{10} concentration after washing was due to the porous material on the tunnel wall (which provided a deposition sink for aerosol particles) or the filter effects of the air-conditioning system. However, it was confirmed that the fine aerosols having a particle size smaller than $PM_{2.5}$ had a relatively little affected by tunnel cleaning. In addition, it is necessary to prevent rescattering through appropriate treatment of sewage to increase the effectiveness of the tunnel washing. They also proposed that additional research would be needed to determine the exact cause of the reduction of fine dust by tunnel washing.

In order to reduce the fine dust of the subway, the sprinkler train and the dust collection train are operated periodically during times when the regular subway trains are not operating. At this time, if electric power, which is the power source of subway trains, is cutoff, then sprinklers and dust collectors should operate their own power such as diesel or battery. In the case of tunnel sprinkling, the dust that has accumulated on the tunnel floor is periodically washed into the drainage system using a sprinkler, and the dust that has accumulated in the tunnel is removed through the high-pressure sprinkler operation once or twice annually. Using tunnel sprinkling, metal particles are rapidly precipitated, and thus the effect of removing fine dust is high. However, the washing train can only be operated for a short time at night and the process is not economical efficient because of water costs, water transportation costs, and labor costs.[57] In addition, water cleaning is highly likely to redisperse fine dust due to train and worker movements when the air is dry.[58] On the other hand, Kim et al[59] reported that the washing train did not have a significant effect on the concentration of PM_{10}, even on the day of operation.

The dust suction train traps dust by using an air discharge nozzle, and at the same time, it sucks in six suction ports before and after the air discharge unit to collect dust.[60] It was reported that the dust suction trains can treat not only PM from the track but coarse trash, such as plastic bags, cans, and cigarette butts. However, the dust suction train is expensive, and the operation and cleaning time are limited, since it can only operate after the operating time of regular trains.

3.4 | Filtration

The concentration of subway fine dust can be reduced by filtration. Kim et al[61] investigated the removal efficiency of subway PM and filtration cost using two PM_{10} filters (Table 2). The removal efficiency of the PM_{10} was 80% for the double-layer filter and 69% for the single-layer filter. However, the filtration cost increased by 65%. Since the average concentrations of PM_{10} (38 and 22 μg/m^3, respectively) for both single and dual filters are appropriate levels that meet management standards, the single-layer filter is economical and reasonable.

The Paris Transport Authority (PTA) used an electrostatic precipitator to treat subway fine dust in Paris.[62] Using a prototype electrostatic precipitator (with 20 filters installed) at the closed station, they could confirm that the initial concentration of 230 μg/m^3 was reduced to 135 μg/m^3. However, after 1 year, the efficiency of the electrostatic precipitator was reduced by 15%, so it is necessary to periodically clean the precipitation cartridge.

Li et al[63] and Li and Jo[64] have proposed a new type of thin, fine-bundle filter (TFBF). The existing subway filter is a nonwoven fiber filter made of polypropylene, whereas the TFBE filter is composed of an electrically charged thin fiber bundle. The TFBE filter results in a low pressure drop due to low packing density, which can have a positive impact on energy consumption and filter life. It was confirmed that TFBE filters in subway MVAC (mechanical ventilation and air-conditioning) systems were effective primarily for particles larger than 1 μm. Although the dust collection efficiency was low during the initial period, the filtration efficiency improved continuously until the dust collection was completed. Li and Jo[64] (2010) also compared the dust collection efficiencies of subway dusts of PPF (polypropylene filter), FBF (fiber bundle-type filter), and FF (fibrous filter). As a result, it was confirmed that FBF is most suitable for subway MVAC in terms of fine dust collection and pressure drop. However, it is also pointed out that the unstable collection efficiency for large particles and the increase in penetration over time are the main drawbacks of FBF. The Seoul subway operates air-conditioning facilities using pre-filter grade fiber filters, which are relatively inexpensive and easy to maintain.[65,66] However, the pre-filter is not efficient in controlling the air quality in the underground space because the collection efficiency at the early stage of replacement is very low. In order to compensate for the decrease in the initial collection efficiency, Park et al[66] compared the filter efficiency and the pressure drop by combining the conventional filter with various electrostatic filters, such as electret filter (EF), electret bundle filter (EBF), and electret plated filter (EPF). As a result, it was confirmed that the combination of pre-filter and EPF showed the best dust collecting efficiency (85% for PM_{10} and 55% for $PM_{2.5}$). This technique is a useful method for improving the efficiency of the collection of subway dust while maintaining an existing air-conditioning system. Similar results were obtained by Jo et al.[67] Field tests using a combination of pre-filter and EPF have shown that this filtration system can improve collection efficiency without a significant increase in flow resistance. Kim et al[68] also reported that the use of a two-stage filter structure (pre-filter and EPF) can maintain the collection efficiency at around 80% and improve environmental benefits over existing systems.

4 | ADVANCED TECHNOLOGY

4.1 | Artificial intelligent ventilation system

Operating the trains and the ventilation systems in a subway system requires a lot of energy consumption.[69] In Beijing, the amount of energy consumed in an underground station during the day is 9500 kWh, of which about 64% is used in the ventilation system (heating, ventilating, and air-conditioning (HVAC) system).[70] Therefore, various methods using artificial intelligence and automatic control systems have been tried to reduce the energy consumption of the subway ventilation system,[31,32,34] as represented in Table 3. The technologies using a ventilation fan have been studied in conjunction with the methods using the time schedule and artificial intelligence, which is outside the limitations of the conventional manual type operation.[26] It was reported that the control of a ventilation fan can improve the air quality of the subway and reduce the operating cost at the same time by considering environmental factors, such as outdoor air and train operation.[50] In addition, a method of predicting indoor air quality in the subway platform using an artificial neural network technique and operating the ventilation facility has been investigated.[71] Kim et al[61] proposed a new indoor air quality (IAQ) ventilation system that takes into account the outdoor atmosphere to control the PM_{10} concentration in the platform. If outdoor air is heavily contaminated by particulate matters, the indoor air quality can get worse when the outside air enters the underground platform through the ventilation system. Therefore, an IAQ ventilation system is used to determine whether the platform ventilation system is operating by measuring outdoor air quality (PM_{10} concentration). It was reported that this system can improve platform PM_{10} levels and save on ventilation energy consumption more than manual ventilation systems.

4.2 | Magnetic filter

Most of the dust in the subway is composed of iron particles generated by iron rail and wheel wear.[1,6,15,20,72] According to the results of research by Jung et al,[22,54] 98%-100% of the subway fine dust is magnetic and 77.3%-86.9% of the PM collected in tunnels is composed of iron particles. It was also confirmed that Fe-containing particle and soil/road dust particles account for 69% and 18% of $PM_{2.5\text{-}1.0}$.[22,73] Some studies attempted to remove subway PM using electromagnets and permanent magnets by using features of subway PM with high Fe concentration.[18,33,74] Son et al[26] reported that when using a double magnet filter, the fine dust removal efficiencies were 52%, 46%, and 38% for PM_{10}, $PM_{2.5}$, and PM_1, respectively. They confirmed that the removal efficiency of the fine dust is determined by the number of layers of the magnet filter and the frequency of the ventilation fan. In addition, it was found that the fine dust trapping stability of the magnet filter is improved as the number of magnet filter layers increases from a single layer (relative standard deviation (RSD): 10.9%-24.5%) to a double layer (RSD: 3.2%-5.8%). Park et al[75] tried to remove fly ash particles with a magnetic filter using a permanent magnet. The target fine dust is fly ash dust emitted from the thermal power plant, and the Fe content is high, as in the subway dust. This Fe is mainly composed of ferromagnetic materials, such as Fe_2O_3 and Fe_3O_4. The amount of collected fly ash increased with the permanent magnet strength, and it was confirmed that 95% of PM_{10} and 90% of $PM_{2.5}$ could be removed at 3000 gauss. Choi et al[76] also reported that the use of permanent magnets and metal mesh has advantages, such as that it does not require an external power supply and can selectively capture iron-containing particles.

For the magnetic filter, maintenance is generally performed using high pressure spray. However, in case of the magnetic filter, it may be difficult to exhaust the iron-based dust, if the magnetic filter has a very high magnetic force. Therefore, it is essential to develop a filter system in which magnetic properties can be realized only at desired times.

4.3 | Jet fan

Tunnels that depend on natural ventilation have a limit in pollutant discharge compared to those that use forced ventilation. Therefore, in order to solve such a problem, a method of operating a small jet fan with a train-induced wind has been actively studied.[35,36,77] This technique is a method to improve the ventilation by moving the underground air to the outside by installing a small jet fan in a natural ventilation hole.[52] As the air volume of jet fan increased, the concentration of the internal PM_{10} decreased, and it was confirmed that the concentration of PM_{10} decreased by about 6 μg/m^3 per 10 000 CMH (cubic meter per hour). Hong[52] also measured the change in concentration in the subway over time and suggested ways to keep it below the PM management concentration limit and save power consumption at the same time. Additionally, they proposed a method to improve ventilation by adding a turbulent effect to the air inside the underground tunnels using natural ventilation aided by a powerful jet fan. A filter was installed in the front or rear portion of the jet fan to perform forced filtration to improve the ventilation and to remove fine dust. The jet fan filter system can remove 96%-98% of PM_{10}, but it has been confirmed that the smaller the particle size, the lower the collection efficiency. It was reported that the jet fan method can improve the air inside the subway tunnel by improving the ventilation.

4.4 | Power-free and hybrid dust collection train

It is known that the subway PM is intensively formed in the space under the trailer car due to the friction between the train wheels and the subway rail while the train is running in the tunnel. Therefore, in order to effectively remove PM produced from subway trains, it is necessary to install a PM removal system in the space under the trailer.[78] To reduce the level of PM in the subway tunnel, Sim et al[78] proposed a method of attaching a baffle dust collector to the bottom of a subway train, rather than improving the ventilation system. A baffle collector is a device that changes the air flow to increase the inertia of the suspended dust particles and collect them in the baffle. Sim et al[78] analyzed the air flow around the baffle dust collector and predicted the amount of air entering the collector in relation to the train speed. As a result, the air flow rate to the baffle dust collector at a constant train speed of 70 km/hour was about 2.1% higher than the air flow rate in the low-speed section of 10 km/hour. In addition, the cutoff size of particles captured at a speed of 70 km/hour was determined to be 7.8 μm.

The fine dust of the subway tunnel has a wide particle size distribution. A study on a louver collecting device targeting coarse particles (PM_{10}) was conducted by Sim et al.[79] The louver dust collector was considered to be suitable for removing dust in the space below the subway train traveling at high speed because of its simple appearance, low pressure drop, and the fact that it utilizes inertial properties of particles. Through numerical analysis, the authors estimated the cutoff size of louver dust collector to about 5-10 μm at the normal speed range (5-65 km/hour).

Since the subway changes speed when moving from station to station, there must be a dust collecting device that adapts to the flow rate change. Woo et al[80] developed a hybrid-type dust collector that combines an inertial dust collector and an electric dust collector. Inertial dust collectors have the advantage of the fact that the flow resistance is small and the dust collecting efficiency is as large as that of the filter for particles of a size over 1 μm. The electric dust collector has a very high dust collecting efficiency if there is little flow resistance, but the dust collecting efficiency sharply decreases when the flow speed is high. Therefore, the performance of the hybrid type dust collector that compensates for the disadvantages of the two dust collectors was tested in the wind tunnel, and the fine dust collection amount was confirmed by attaching it to the actual train. The PM_{10} removal efficiency of the hybrid dust collector was 85% or more, and the $PM_{2.5}$ removal efficiency was 65% or more at 5 m/s flow rate.

4.5 | Hybrid filter

Studies on the removal from the air supply of not only PM but NO_2 and VOCs have been carried out.[12,81] Among these studies, various active carbon methods have been performed. Son et al[81] introduced a technology for controlling NO_2 concentration in the underground platform to <50 ppb (which is the indoor air quality standard for multi-use facilities in Korea) and reducing energy consumption by using hybrid-activated carbon and an automatic control system.[81]

5 | CONCLUSION

In this study, the concentration and characteristics of PM pollution in subway systems of major cities in the world were surveyed. Information on various attempts and studies made to resolve the PM problem was also reviewed. The concentration levels of PM in the subway air were generally higher than those of the outside air. Further, the internal factors, such as abrasion between track and wheel, were the most significant contributors to its pollution. Since PM containing a large amount of Fe is toxic enough to cause adverse health effects (eg, respiratory diseases), it is necessary to properly manage the air quality of the subway. To solve the subway PM problem, ventilation system, PSD, washing/dust collection train, and filtration technology have been generally used. However, in case of conventional ventilation equipment, improvement is urgently required due to the potential problems of deterioration and operation costs. The PSDs are effective for reducing the concentration of PM in the platform, although they have the potential to cause greater stagnation of the PM in the tunnel. Therefore, the technique for reducing PM in the tunnel systems should also be developed simultaneously. Washing and dust collection trains can remove subway dust directly, but they are economically inefficient with limited cleaning time. There is also an economic burden because filter technology also requires periodic filter replacement.

In order to solve the problems of these existing technologies, researchers have suggested various technologies. In particular, it is being attempted to simultaneously achieve PM reduction and energy saving by using an automatic control system and artificial intelligence technology. In addition, technologies such as magnetic filters and power-free and hybrid dust collection trains are being developed to increase removal efficiency and maximize economic efficiency. However, because these various subway PM control researches are still on the scale of a laboratory or pilot, more research needs to be done to maximize efficiency.

ACKNOWLEDGEMENTS

This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2018R1D1A3B07040617). This study was also supported by a grant from the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (2016R1E1A1A01940995).

CONFLICT OF INTEREST

The authors declare they have no competing financial interest.

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How to cite this article: Park J-H, Son Y-S, Kim K-H. A review of traditional and advanced technologies for the removal of particulate matter in subway systems. *Indoor Air*. 2019;29:177–191. https://doi.org/10.1111/ina.12532