A review of ambient nanoparticles ($PM_{0.1}$) in South East Asian cities: biomass and fossil burning impacts

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Abstract: $PM_{0.1}$ (particles diameter ≤ 0.1 μm), nanoparticles (NPs), and ultrafine particles (UFPs), were interchangeably used in the scientific communities. $PM_{0.1}$ originated from both natural and human sources. However, investigations of $PM_{0.1}$ and its effects on the environment, visibility, and human health risk to understand the levels of air pollution, sources, and impacts in South East Asia (SEA) countries continue to be lacking. The concentration of $PM_{0.1}$ in most SEA countries are much worse than those in western countries environment. A further motivation of this reviewed article is to provide a critical synthesis of the current knowledge and study of ambient $PM_{0.1}$ in SEA cities. The main influence of characteristics of $PM_{0.1}$ appears to be local sources including biomass burning and motor vehicles. Continuous monitoring of $PM_{0.1}$ in terms of both mass and number concentration should be further understood. A critical review is of great importance to facilitating air pollution control policies and predicting the behavior of $PM_{0.1}$ in SEA.

Keywords; Health Risk, Ultrafine Particles, Nanoparticles, South East Asia, Biomass burning

1. Introduction

Particulate matters (PM) have a complex component, including acids (such as nitrates and sulfates), organic chemicals, and heavy metals, some of these components have a hazard for human health [1]. Especially, smaller particles down to nano-size range mainly come from human sources, contain extremely hazardous components like heavy metals, carbon components, and polycyclic aromatic hydrocarbons (PAHs) [2]. PM had a wide range of particle size and can be categorized into three modes: coarse particles ($PM_{10\text{-}2.5}$; aerodynamic diameter between 2.5 and 10 μm), fine particles ($PM_{2.5}$; predominantly in accumulation mode, aerodynamic diameter

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range from 0 to 2.5 μm), and ultrafine particles ($PM_{0.1}$; nucleation mode, aerodynamic diameter smaller than 0.1 μm, or 100 nm) [1-2]. $PM_{0.1}$, ultrafine particles (UFPs), and nanoparticles (NPs) are interchangeably used in scientific society [3]. NPs are commonly used in representing particles from engineer-material that release to the environment. At the same time, other researcher groups use different names. For instance, toxicologists typically use ultrafine, fine, and coarse modes, and monitoring organizations i.e., the United States Environmental Protection Agency (US.EPA) uses $PM_{0.1}$, PM_1, $PM_{2.5}$, and PM_{10} refer the atmospheric particulate matter [4]. In the recent decade, it has been found that $PM_{0.1}$ poses the most risks to human health effects [5-6]. It is not enough information on the status and characteristics of atmospheric $PM_{0.1,}$ and their emission sources remain incomplete currently. Because $PM_{0.1}$ is challenging to study due to its tiny sizes, high chemical reactivity, and rapid changes [6-7].

The data on physical, optical, and chemical characteristics in $PM_{0.1}$ are scarce worldwide including all South-East Asian (SEA) countries, where in the past decades have been the dominant contributors of PMs into the atmosphere [8-11]. Several research publications have been investigated the size distribution of atmospheric particles bounded chemicals in various countries around SEA due to environmental damage and health effects. [10-11]. Atmospheric PMs in SEA countries are presently based on the concentrations of PM_{10} and $PM_{2.5}$ as well as to a slight area on PM_1 (sub-micron particle) [10, 12-13]. Several studies based on satellite remote sensing, ground-based observing, and mathematical modeling techniques revealed that aerosol plume during smoke-haze exceeded the national standard of SEA countries, which has a very high value compared to the World Health Organization (WHO) or other countries standard [14]. A recent study in Thailand and neighboring countries displayed that $PM_{0.1}$ represented approximately 10-15% of total suspended particulates (TSP) in ambient air [11, 15-17].

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The status and characteristics of ambient $PM_{0.1}$ have not been compared between different locations. In addition, the other chemical compositions in $PM_{0.1}$ are so far poorly studied in Asia. All these available data from $PM_{0.1}$ in western countries i.e., Europe and the United States of America (USA), are more progressive [18-20]. However, the data in SEA city environments are still separate in detail. Consequently, the motivation of this review is to recognize the recent data, sources, and knowledge gap in $PM_{0.1}$ emission and exposure levels. The authors discuss the recent situation of $PM_{0.1}$ study in Asian developing countries in a case study of SEA to better understanding and future perspective of ambient $PM_{0.1}$. This review collects the recent research papers on all aspect of PMs in SEA. Over 100 peer-reviewed journals in Scopus and ISI database was used to analyze and integrate to synthesis and group in this paper. The term and keywords was used to search including "$PM_{0.1,}$ biomass burning, ultrafine particles, haze pollution, health effects, emission inventory, and clean air policies. The synthesis reviewed article prefers to use the recent publish in 6 years from 2016 - 2021.

2. $PM_{0.1}$ mass concentration in South East Asia atmosphere

The PMs are separated into three modes according to particle size, i.e., coarse, fine, and ultrafine modes [21]. The ultrafine ($PM_{0.1}$) fractions in the ambient particulate matter (PM) have a very low particle mass concentration but a huge number of particles [7]. Most particles by numbers lie below 0.1 µm (100 nm) and there are in $PM_{0.1}$. However, their concentration in terms of mass per volume is very low. No standards for ambient $PM_{0.1}$ or UFPs have been adopted in Asian countries. The European Committee for standardization announced that Condensation Particle Counter (CPC) is a standard protocol to measure ambient UFPs [22]. However, only the emission standard for diesel and gasoline-direct injection engine road vehicles

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must meet a type-approval of UFPs for non-volatiles particles of > 23 nm diameter (The Solid Particle Number > 23 nm method; SPN23) [23]. According to a very small amount and mass concentration, the most widely used to measure UFPs is particle number concentration (PNC). The estimated concentration based on 10 µg/m^3 in $PM_{2.5}$ found that $PM_{2.5}$ 1 particle/cm^3 equal to $PM_{0.02}$ (< 20 nm) 2.4 x 10^6 particle/cm^3, or PM_{10} 1 particle/cm^3 similar to UFPs 1.0 x 10^6 particle/cm^3 [6, 24]. The number concentration and surface area are suitable to measure UPFs small amount of mass concentration in the past decades [2, 6].

The average $PM_{0.1}$ mass concentration in SEA is progressive in the past decade (Table 1). The preliminary study of ambient $PM_{0.1}$ in SEA and publish in an international peer-review journal is based on a study in Thailand during 2014-2105 [11]. The $PM_{0.1}$ mass concentration in Bangkok and Chiang Mai, Thailand be 14.80 ± 1.99 and 25.21 ± 4.73 µg/m^3, respectively. Bangkok is a capital city in Thailand and one of the densest populated cities in Asia. The high episode in $PM_{0.1}$ particles in Chiang Mai is recognized to arise from open biomass fires in the dry season (Jan-May). In Thailand, $PM_{0.1}$ concentration in Pathumtani, one of the Bangkok Metropolitan Region (BMR) areas, is also elevated mass concentration in both wet and dry seasons [15]. In another study in Hat Yai, southern Thailand [16], $PM_{0.1}$ was 10.17 ± 2.23 µg/m^3 representing PM concentrations lower than other parts of Thailand. Moreover, as Zhao et al. (2016) [25] reported, compare $PM_{0.1}$ concentration during the dry season (Mar-Apr 2016) in many cities, including Chiang Mai, Bangkok, Songkhla, Riau, Ho Chi Minh City, Phnom Penh, Kuala Lumpur. The study found that mass concentration (µg/m^3) decreased in the order, Phnom Penh (18.9) > Chiang Mai (16.5) > Hanoi (15.4) > Ho Chi Minh City (13.1) > Riau (12.4) > North Bangkok (11.9) > Hat Yai (10.9) > Kuala Lumpur (9.3) > Bangkok (7.7). The higher mass concentration in Upper SEA countries than lower SEA countries due to the dry season during

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that period that the open biomass burning has been reported by several researchers [26-27]. PMs concentrations were increased every dry season (February-April) which start to increase at around the beginning of February and reached its peak in March before decreasing by mid-April [11]. The main emission source of PMs worsening during the dry season in these areas was identified as open biomass burning including forest fire and crop residue burning [15, 27]. The above mentioned corresponded with the accumulated number of fire hotspots location that was high in the dry season and low in the wet season. Each hotspot/active fire location represents the center of approximately 1 km pixel flagged as containing one or more actively burning hotspots/fires within that pixel [10]. Generally, $PM_{0.1}$ was a key identifier of diesel exhaust and it was sensitive to open biomass burning in this area [11].

Moreover, ambient $PM_{0.1}$ in Vietnam and Indonesia is very progressive. In Indonesia, the study by Amin et al. (2019) and Putri et al. (2021) [28-29] suggested that the $PM_{0.1}$ mass concentration in the dry season is higher than the wet season in all monitoring sites. In addition, the mass concentrations by different monitoring sites have a concentration as follows, urban > suburban > rural. In Vietnam, many studies of $PM_{0.1}$ in Hanoi, the capital city in Vietnam, are more progressive than other SEA cities [17, 30-34]. The results show that various mass concentrations in different environments in Hanoi ranged from 1 to 17 $\mu g/m^3$.

Table 1 Mass concentration of $PM_{0.1}$ at difference locations in Asian Environment

Location	Site description	Period	Concentration ($\mu g/m^3$)
Pathumtani, Thailand	Suburban	Oct 2019	13.47 ± 0.79
	Suburban	Jan-Feb 2020	18.88 ± 3.99
Hat Yai, Thailand	Mixed	Jan-Dec 2018	10.17 ± 2.23
Hat Yai, Thailand	Mixed	Mar-April 2016	10.9

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North Bangkok, Thailand	Urban-traffic	Jul 2014 - Jun 2015	14.80 ± 1.99
North Bangkok, Thailand	Urban-traffic	Mar-April 2016	11.9
Bangkok, Thailand	Urban-traffic	Mar-April 2016	7.7
Chiang Mai, Thailand	Suburban	Sep 2014 - Jun 2015	25.21 ± 4.73
Chiang Mai, Thailand	Suburban	Mar-April 2016	16.5
Riau, Indonesia	Urban	Mar-April 2016	12.4
North Sumatra, Indonesia	Urban-traffic	Feb 2019	13.10 ± 3.80
	Rural-volcano	Mar 2019	7.10 ± 2.50
	Industry Area	Feb-Mar 2019	16.80 ± 4.00
	School Environment	Feb 2019	15.90 ± 1.60
Padang, Indonesia	Rural	Mar 2018	5.36
		Aug 2018	5.57
Muaro Jambi, Indonesia	Suburban	Mar 2018	9.20
		Aug 2018	9.61
Pekanbaru, Indonesia	Urban	Mar 2018	10.92
		Aug 2018	15.16
Hanoi, Vietnam	Mixed	Aug-Dec 2015	5.36 - 5.79
	Urban-traffic	Aug-Dec 2015	6.06 - 11.90
Hanoi, Vietnam	Mixed	Nov-Dec 2015	5.44 ± 2.03
Hanoi, Vietnam	Mixed	Jul-Aug 2015	1.47 ± 0.54
	Mixed	Mar 2016	1.71 ± 0.61
Hanoi, Vietnam	Mixed	Mar-April 2016	15.4
Hanoi, Vietnam	Residential Area	Jan 2019	8.74
		Apr-May 2019	5.28
Hanoi, Vietnam	Suburban 1 (Rice burning)	Nov 2019	6.50 ± 2.2 0
	Suburban 2 (Rice burning)	Nov 2019	11.50 ± 3.90
Hanoi, Vietnam	School Environment	Nov 2019 – Jan 2020	17.07 ± 3.70
Phnom Penh, Cambodia	Urban-traffic	Mar-April 2016	13.1
	Urban	Mar-April 2016	18.9
Kuala Lumpur, Malaysia	Suburban	Mar-April 2016	9.3

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Instead, the mass concentrations are very low in western countries. Venecek et al. (2019) [19] studied regional $PM_{0.1}$ concentrations in 39 cities across the USA and found that $PM_{0.1}$ levels exceed 2 $\mu g/m^3$ during summer pollution episodes. Conversely, the annual average mass concentration of $PM_{0.1}$ is very low, below 1 $\mu g/m^3$. Moreover, the United Kingdom (UK) described that the mass concentration of $PM_{0.1}$ based on the estimated fraction of PM_{10} in each emission source is as follows; production process, non-road transportations, agriculture, industrial off-road mobile machinery, transformation industries, energy combustion, combustion in industries as well as waste incineration (15%, 14%, 9%, 9%, 8%, 7% and 4 %, respectively) [35]. $PM_{0.1}$ are mostly measured in terms of particle number concentrations (PNC) due to the very low mass concentrations in all cities around the western part of the world [18].

3. Sources and Characteristics of $PM_{0.1}$ in South East Asia

Regarding the natural sources, primary $PM_{0.1}$ is mainly generated by forest fires, while lesser fractions come from maritime aerosols and volcanic eruptions [2]. On the other hand, anthropogenic sources of $PM_{0.1}$ include transportation (on- and off-road vehicles, diesel engines, airplanes, and shipping), industrial combustion processes including biomass burning and waste incineration, cigarette smoking, and meat cooking [6]. Therefore, the main emission sources of $PM_{0.1}$ are both natural and anthropogenic sources. Figure 1. shows the morphology of atmospheric nanoparticles from Chiang Mai, Thailand, as observed in the scanning electron microscope (SEM) analysis.

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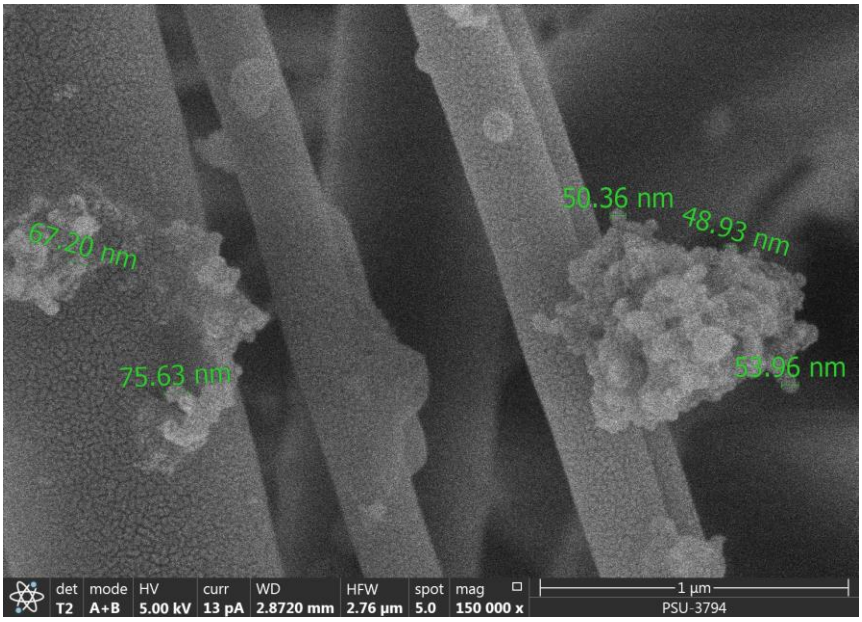

Figure 1. SEM images of atmospheric nanoparticles from Chiang Mai, Thailand, year 2015 (forest fires dominated as emission sources during the dry season)

Most studies of the primary emission source of $PM_{0.1}$ in Asia are related to road vehicles [36-38]. In an urban area, traffic is the major source of $PM_{0.1}$ emissions. Diesel engines dominate $PM_{0.1}$ in mega-cities, including Shanghai, China [39], Hanoi, Vietnam [17] and Bangkok, Thailand [11]. Diesel engines have an emission factor about two times of magnitude higher than gasoline engines [40]. On the other hand, as Kumar et al. (2013) [5], the forest fires emitted particles dominate over traffic emissions, and the size distribution peaks at approximately 120 nm for a fresh aerosol plume. In addition, the recent study by Phairuang et al. (2019a) [11] states that open biomass burning in central and northern Thailand dominated the release of carbon materials into the atmosphere. The $PM_{0.1}$ particles, primarily derived from motor vehicle emissions, are also strongly affected by open biomass burning in the upper part of Thailand. Hence this activity is a significant factor affecting air quality during the dry season. Similarly, ambient $PM_{0.1}$ study in Hanoi, Vietnam, showed that high mass concentrations of $PM_{0.1}$ were

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detected during rice straw burning periods [17]. However, some possibly important sources, such as domestic wood burning, are poorly quantified in Asian countries [41-42].

The chemical composition study in NPs is still limited, especially in ambient $PM_{0.1}$ particles. However, there have been a few publications from sources related to NPs and chemical composition. For instance, polycyclic aromatic hydrocarbons (PAHs) dominate PM sources' emission components [41, 43-44]. Most PAHs emissions are generated from incomplete combustion of natural and human sources, including vehicle exhaust, biomass burning, industrial activities, and coal combustion. Hata et al. (2014) [41] studied the characteristics of NPs emitted from biomass fuels burning in Asia. The result displayed that approximately 30% of the biomass fuels burning smoke had a mass down to a range of < 100 nm. Additionally, PM smaller than 0.43 μm significantly contributed to their toxicity of PAHs and the fraction of Water-soluble Organic Carbon (WSOC). In the same manner, Chomanee et al. (2018) [42] studied the PAHs in smoke particles released from the fuelwood (para-rubber) combustion. This result displays that the ultrafine ($PM_{0.07}$) smoke particles comprised the highest number of PAHs and Benzo[a]pyrene-Toxic Equivalence Quotient (BaP-TEQ). The major fraction of NPs had the largest emission of toxicity per unit PM mass comparing to fine and coarse PM. In addition, the recent study during the biomass open burning episode in western Thailand suggested that Toxicity equivalent (BaP-TEQ) and the mutagenic equivalent (MEQ-BaP) concentrations during the biomass open burning episode were considerably higher than those in the non-smoke episode in $PM_{2.5}$ [45]. This is an important point to concentrated on smaller particles, especially NPs on any emission sources due to a lack of reliable information on the sources and magnitudes in Asian countries.

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Secondary $PM_{0.1}$ aerosols are mainly generated from atmospheric photochemical of gaseous precursors and by condensation of semi-volatile vapors [46]. Such new particle formation can occur during low relative humidity and wind speed at low pre-existing particle surface area and high global radiation [47]. Reche et al. (2011) [48], described that new particle formation in an urban area in Europe during warmer and sunny climates as an important contributor to air pollution. In SEA, Thuy et al. (2018) [17] stated that Secondary Organic Carbon (SOC) is more dominant in smaller particles than in larger particles; and the SOC in $PM_{0.1}$ contributes up to 42.7% of the OC level in Hanoi, Vietnam. The secondary atmospheric $PM_{0.1}$ in the Asian environment remains poorly understood.

4. Health concerns of $PM_{0.1}$

$PM_{0.1}$ has strongly believed very high toxic properties, because there has a high surface area that can absorb many poisonous substances. After they penetrate the human organ systems, allowing translocation and interactions to a human body organ and highly potential deeply into circular systems via respiratory mechanism [49-51]. The World Health Organization (WHO, 2013) [52] suggested that the epidemiological data of $PM_{0.1}$ are very too scarce to estimate or to use as a policy-making for air quality control management of $PM_{0.1.}$ The Health Effects Institute (HEI, 2013) [53] reflected that the ongoing evidence did not convincingly support the suggestion that $PM_{0.1}$ alone can account for important conducts for the adverse effects that have been associated with atmospheric pollutants such as $PM_{2.5}$ and PM_{10} [54-55].

In health risk assessment, toxicity equivalent concentration (TEQs), calculations based on toxic equivalent factors (TEFs), can be used to estimate health risks associated with PAHs [56]. High concentrations of PMs containing PAH's are well-known to consequence in symptoms, i.e.,

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eye irritation, diarrhea, vomiting, and nausea [56-57]. The detrimental effects of PAHs hang on the mechanism of exposure. Benzo[a]pyrene (BaP) is the well-known PAH to cause cancer on a laboratory scale resulting long term exposure [57]. The BaP-TEQ is a widely used indicator to estimate the exposure to PAHs to human health [42]. On the other hand, there have been limited studies on the characteristics of $PM_{0.1}$ and toxic PAHs in the Asian environment. Moreover, it is vital to note, that finer particles are a more significant source of carcinogenic properties and cause more human health consequences than larger particles due to their higher surface area that can absorb many toxic elements.

Guan et al. (2016) [58] studied in China, they found that increasing 10 μg/m³ in $PM_{2.5}$ from any emission sources have been linked to a 3.1% increase in the risk of hospitalization as well as a 2.5% rise in mortality. Crippa et al. (2016) [59], reported the short-term exposure to agricultural residue burning and peat-land fires in heavy haze episodes in 2015 from Indonesia might have caused 11,880 excess mortalities. The studies have stated the adverse effect of inhaled atmospheric $PM_{0.1}$ on human health to continue lacking in SEA. Three are still limited information between $PM_{0.1}$ and disease. However, there have not become fully aware of the critical hazardous of $PM_{0.1}$ in the air pollution on human health [2-4].

5. Challenges study in $PM_{0.1}$

1. 5.1 Evaluation of $PM_{0.1}$

2. The present status and characteristics, comparison between cities and countries need assessments of events and long-range transportation. For instance, Southeast Asia (SEA) has been a source of PM pollutants affecting countries within and outside this region [60]. The transport of plumes from Indonesian forest fires affects Singapore, Malaysia, Brunei, and

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southern Thailand [16, 61]. United States Environmental Protection Agency (US-EPA) has mentioned that PM is one of the criteria pollutants that is the most widespread health threat. PM is the generic term used for these types of air pollutants, consisting of complex mixtures of solid or liquid droplets or both suspended in the breathing air, which vary in size and composition [62]. According to the criteria of particle size, most SEA countries had been designated that $PM_{2.5}$ was a criteria pollutant. However, $PM_{0.1}$ is more concerned about health impact than larger PM sizes. Accordingly, the sources, abundance, chemical compositions and migration of $PM_{0.1}$ between regions and countries need further studies.

3. 5.2 Information on $PM_{0.1}$ emission sources

The Emission Inventory (EI) of $PM_{0.1}$ is subject to very high mass and particle number emission uncertainties. There are very scarce emission factors (EFs) of methodologies for estimating $PM_{0.1}$ emissions in available official EI guidebooks. EFs on $PM_{0.1}$ number, mass, a mass of chemicals should be studied in more detail. Samae et al. (2021, 2022) [63-64] reported the first EFs from solid biomass combustion in Thailand including 11 types of biomass (*Avicennia alba* Blume, *Xylocarpus moluccensis*, *Rhizophora mucronata*, bagasse, sugarcane leaves, corn residue, rice straw, rice stubble, palm fiber, palm kernel, and rubberwood). The $PM_{0.1}$ mass concentration is very low, approximately 1–8% of total PM. Emission factors of particle size < 0.1 μm were in the range of 0.11-0.28 g kg^{-1}. There is not complete EI of $PM_{0.1}$ in Asia due to a lack of information on EFs and other parameters [11, 65]. Knowledge of the EFs of $PM_{0.1}$ is fundamental to the development of strategies for pollution control and air quality management.

5.3 Development and application of new $PM_{0.1}$ tools

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5.3.1 Measurements of atmospheric particles are inherently more complex than other gases-phase pollutants. The new technology to size-classified PMs down to $PM_{0.1}$ is also vital to study the physical and chemical characteristics of ambient $PM_{0.1}$ [66-67]. For example, the inertial filter (IF) technology to collect various size fractions, including nano-particles, in a short sampling period will be important to gather the ambient $PM_{0.1}$[68-71]. The artifacts due to the evaporation of semi-volatiles should be much smaller than those of conventional types of nanoparticle samplers, e.g., low-pressure impactors and Nano-MOUDI [72-73].

5.3.2 A High-Volume $PM_{0.1}$ air sampler for toxicity evaluation will be able to evaluate dynamic health risks. Retention or removal of semi-volatile particles for $PM_{0.1}$ can be volatilized within the sampling system, because of their large specific surface area. Considering $PM_{0.1}$ related to chemical compositions with minimal artifacts during air sampling caused by the degradable characteristics of chemicals and semi-volatile is also a crucially important issue [74]. The High-Volume $PM_{0.1}$ will improve the $PM_{0.1}$ instrument toward 1) understanding ambient $PM_{0.1}$ based on various chemicals in $PM_{0.1}$ collected with high time resolution, 2) risk assessment using a large amount of $PM_{0.1}$ collected by the tool [75]. Hence, there is a need for tools to collect more significant amounts of $PM_{0.1}$ in a short period with minimal artifacts.

5.3.3 The $PM_{0.1}$ real-time sensors in the internet of things (IoT) monitoring network (big data) will play an important role in understanding the $PM_{0.1}$ plume migration and transportation, with temporal variations by geo-specific location [76-77]. The real-time and IoT sensor for PMs monitoring has been a vital tool, potentially becoming an integral part of air quality monitoring and management, especially during the haze episode of intensive biomass burning smoke in the Asian environment [78].

5.4 Summarizing facts on $PM_{0.1}$ for policy-making

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Future research on $PM_{0.1}$ needs to focus on intervention, classification, and quantification of mass and number concentrations with mixed emission sources at ambient and personal levels to detrimental human health effects. The environmental quality standard regarding $PM_{0.1}$ in Asian countries is only focused on mass concentrations. The future precise study particle types and size govern $PM_{0.1}$ will fulfill the research gaps, perspectives and emerging challenges for $PM_{0.1}$ policymaking in Asia.

6. Conclusion

Future studies on atmospheric nanoparticles in Asia should focus on the abundance, sources, distribution and temporal and spatial variations of $PM_{0.1}$ in urban and rural Asian environments. The exposure to $PM_{0.1}$ should be quantified to understand the exposure of nano-size particles in humans. Continuous monitoring of $PM_{0.1}$ in terms of both mass and number concentration should be further understood. Future research on $PM_{0.1}$ needs to focus on the identification and quantification of $PM_{0.1}$ particles. Finally, better knowledge about the physicochemical characteristics of $PM_{0.1}$ generated by various emission sources in the Asian environment will help fill the gap about air quality policies and management in this region.

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8. Conflict of interest

The authors declare no conflict of interest.

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