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Review

Ambient Nanoparticles ($PM_{0.1}$) Mapping in Thailand

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Abstract: Nanoparticles (NPs), nanoaerosols (NAs), ultrafine particles (UFPs), and $PM_{0.1}$ (diameters $\leq$ 0.1 µm or 100 nm) are used interchangeably in the field of atmospheric studies. This review article summarizes recent research on $PM_{0.1}$ in Thailand. The review involved peer-reviewed papers that appeared in the Scopus and the Web of Science databases and included the most recently published articles in the past 10 years (2013–2022). $PM_{0.1}$ mainly originate from combustion processes such as in motor vehicles. The highest mass concentration of $PM_{0.1}$ occurs during the dry season, in which open fires occur in some regions of Thailand. The northern area of the country has higher $PM_{0.1}$ mass concentrations, followed by the central and southern areas. Carbonaceous nanoaerosols are produced during normal periods, and the proportions of organic to elemental carbon and char to soot suggest that these originate from motor vehicles. However, in haze periods, biomass fires can also produce carbon-containing particles. $PM_{0.1}$ pollution from local and cross-border countries also needs to be considered. The overall conclusions reached will likely have a beneficial long-term impact on achieving a blue sky over Thailand through the development of coherent policies and managing new air pollution challenges and sharing knowledge with a broader audience.

Keywords: biomass burning; motor vehicles; nanoaerosols; nanoparticles; ultrafine particles; $PM_{0.1}$; health risks; local sources; transboundary; Thailand

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1. Introduction of Impact of $PM_{0.1}$

Ambient particulate matters (PMs), which are strongly associated with harmful aspects concerning human health [1,2] and global warming, have recently appeared [3] and have attracted considerable interest regarding environmental pollution in many countries. PMs can be categorized into three modes, which include coarse particles (diameter between 2.5 and 10 μm), fine particles (with a diameter between 0.1 to 2.5 μm), and ultrafine particles (diameters $\leq$ 0.1 μm or 100 nm) [4,5]. The coarse category is primarily generated from attrition processes, namely, mechanical abrasion, the re-suspension of road and soil dust, volcanic eruptions, and sea spray [6]. On the other hand, fine and ultrafine mode particles evolve mainly from combustion processes, e.g., biomass burning, motor vehicle exhaust, coal combustion, and chemical processes in the atmosphere [7,8].

Nanoparticles (NPs), nanoaerosols (NAs), ultrafine particles (UFPs), and $PM_{0.1}$ are interchangeably used depending on the subject area [9], but there are slight differences among these particles. The most common nanoparticles are mainly incidentally and unintentionally generated and are suspended in the atmosphere [8,10]. The term nanoaerosols is used to refer to a broader coverage, including environmental and engineered nanoparticles. In addition, toxicologists refer to particle size as ultrafine, fine, and coarse particles to specify their danger to cells and human health [11,12]. The latest definition is $PM_{0.1}$, which typically refers to solid particles with at least one dimension smaller than 0.1 μm or 100 nm [13] and is always used in atmospheric pollution studies. Therefore, nanoparticles, nanoaerosols, ultrafine particles, and $PM_{0.1}$ are commonly used in the scientific fields but depend on the subject matter areas.

In the past decade, smaller particles ($PM_{2.5}$ or, predominantly, $PM_{0.1}$) are likely to be a human health risk problem [8,14]. Airborne PM is linked to increased mortality and morbidity in humans [15]. There is considerable evidence to show that PMs harm the respiratory, nervous, and cardiovascular systems [16–18]. Smaller particles (UFPs) have a large surface area and strong absorption/adsorption capability for various airborne contaminants. UFPs can carry both various hazardous chemical compounds, such as polycyclic aromatic hydrocarbons (PAHs) and heavy metals [19–22], and airborne pathogens such as bacteria, fungi, and viruses [22,23].

Southeast Asia (SEA) has been a source of PM pollution for the last decades, affecting countries in and countries outside the region [24,25]. The transport plume of Indonesian forest fires affects air quality in Singapore, Malaysia, Brunei, and southern Thailand [25–28]. Moreover, recent studies suggest that fine particles from open biomass burning plumes are transported from northern Southeast Asia (SEA) to East Asia (EA), including southeastern China, the South China Sea, and southern Taiwan, during the dry season [29–31]. In Thailand, the effect of the migration of polluted air masses is vital on a multi-provincial scale (100–200 km) [32].

The particulate matter (PM) pollution observed in Thailand and Southeast Asian countries is related to studies of the PM_{10} and $PM_{2.5}$ fractions and, to a slight extent, on the ground monitoring and satellite detection of $PM_{1.0}$ [33–37]. However, information on the status and characteristics of $PM_{0.1}$ and emission sources is still ongoing and only limited information is currently available. Only a few studies have appeared concerning the level and sources of airborne NPs between different locations [32,38,39]. This work gathered current papers on all aspects of atmospheric UFPs in Thailand. Over 100 refereed papers in the Web of Sciences and Scopus databases were examined for this study and were used to integrate this knowledge base. The keywords searched included "$PM_{0.1}$, ultrafine particles, nanoparticles, nanoaerosols, haze pollution, health effects, Thailand". The work covered publications in this area that have appeared in the past 10 years, from 2013 to 2022, and included the following topics:

1. Introduction to the impact of $PM_{0.1;}$
2. Recent studies of $PM_{0.1}$ particles in Thailand;
3. Health concerns regarding $PM_{0.1}$ particles in Thailand;
4. Challenges to the study of $PM_{0.1}$ particles in Thailand;

5. Options and recommendations for $PM_{0.1}$ in Thailand;
6. Conclusions.

2. Recent Studies of $PM_{0.1}$ in Thailand

2.1. $PM_{0.1}$ Particle Mass Concentration and Particle Number Concentration

The $PM_{0.1}$ levels in ambient air are usually extensively measured by particle number concentration (PNC) due to their minuscule size in addition to mass concentration [40]. No standards for airborne $PM_{0.1}$ have been adopted in Thailand. Thailand's National Ambient Air Quality Standards recently established parameters for six air pollutants that are deemed the highest priority to protect public health, including PM (TSP, PM_{10}, $PM_{2.5}$), O_3, CO, SO_2, NO_2, and lead (Pb) (Table 1). The six criteria for pollutants are classified into health risk levels based on criteria defined by Thailand's Air Quality and Noise Management Bureau, Pollution Control Department, and Ministry of Natural Resources and Environment. This is the current standard as of 2022; particulate pollution is a severe and increasing problem for Thailand. The Pollution Control Department announced in 2022 [41] that it will decrease Thailand's National Ambient Air Quality of 24 h $PM_{2.5}$ concentration to 37.5 $\mu g/m^3$ in 2023. This is because of human health concerns about smaller particles in the recent decade.

Table 1. Thailand's National Ambient Air Quality Standards.

Pollutants	Time Period	Concentration
TSP (PM_{100})	Annual	100 $\mu g/m^3$
	24 h	330 $\mu g/m^3$
PM_{10}	Annual	50 $\mu g/m^3$
	24 h	120 $\mu g/m^3$
$PM_{2.5}$	Annual	15 $\mu g/m^3$
	24 h	50 $\mu g/m^3$
O_3	8 h	140 $\mu g/m^3$ (0.07 ppm)
	1 h	200 $\mu g/m^3$ (0.10 ppm)
CO	8 h	10,260 $\mu g/m^3$ (9 ppm)
	1 h	3420 $\mu g/m^3$ (30 ppm)
NO_2	Annual	57 $\mu g/m^3$ (0.03 ppm)
	1 h	320 $\mu g/m^3$ (0.17 ppm)
SO_2	Annual	100 $\mu g/m^3$ (0.04 ppm)
	24 h	300 $\mu g/m^3$ (0.12 ppm)
	1 h	78,000 $\mu g/m^3$ (0.3 ppm)
Lead (Pb)	Monthly	1.50 mcg/m^3

Moreover, according to the new guidelines on air quality by the World Health Organization (WHO) (2021) [42], the suggested mean annual concentration for PM_{10} was 200 $\mu g/m^3$ in 2005 and the mass concentration for 2021 moved to 150 $\mu g/m^3$. The 24 h concentration was updated from 50 $\mu g/m^3$ in 2005 to 45 $\mu g/m^3$. Furthermore, in 2005, the highest recommended average $PM_{2.5}$ annual mass concentration was 10 $\mu g/m^3$; the 2021 revision reduced that number by half, to just 5 $\mu g/m^3$. The 24 h level changed from 25 $\mu g/m^3$ in 2005 to 15 $\mu g/m^3$. The WHO was confident that there was insufficient information to provide guidelines for other types of PM, including elemental and black carbon, sand and dust storm particles, and $PM_{0.1}$ particles. The WHO does not create a set of best practices for managing those pollutants, even though it recommends further study into their risks and methods for mitigation.

In European countries, the Condensation Particle Counter (CPC) is a standard method for measuring nanoparticles [43]. However, the ambient nanoparticle standard for all emission types is still limited. Only the gasoline and diesel emission standard representing the non-volatile particle of diameter >23 nm has been defined (the Solid Particle Number > 23 nm method (SPN23)) [44]. Surface area and particle number are appropriate for measuring minor mass concentrations of $PM_{0.1}$ in most atmospheres [16]. NPs are commonly

measured as particle number concentration (PNC), representing more than 85% of the total $PM_{2.5}$ particle number [45]. In contrast, it contributes only slightly (10–20%) to the total PM concentration.

Table 2 shows the $PM_{0.1}$ mass concentration at each sampling site in Thailand. The first sampling of NPs in Thailand started during 2014–2015 in Bangkok and Chiang Mai. Chiang Mai had the highest $PM_{0.1}$ level in Thailand based on the sampling period during 2014–2015 up to 25.2 ± 4.7 μg/m^3. Bangkok, the capital city of Thailand, is one of the megacities in SEA with high concentrations of residents and traffic congestion. Many studies have concluded that the particulate pollution in the Bangkok metropolitan region (BMR) is mainly from land transportation [46–49]. The mass concentration of $PM_{0.1}$ in the BMR ranges from 7.7–18.9 μg/m^{3,} a number that is higher than that in Western countries such as those of Europe and the USA; however, it is in the same range as other Asian megacities such as Shanghai [50]. The levels of $PM_{0.1}$ particles in southern Thailand are comparatively low compared with other types; cities in Thailand range from 1.9 ± 0.6 (normal)–14.2 ± 10.0 (haze) μg/m^3. Interestingly, $PM_{0.1}/PM_{2.5}$ is the highest in Chiang Mai, Thailand. It is well known that Chiang Mai has been confronted with air pollution in almost every dry season from January to mid-April. $PM_{2.5}$ concentrations are augmented every dry season (January–April), which starts around mid-January and reaches its peak in March before decreasing by April. The primary source of worsening air pollution during the dry season in these areas was open burning, such as forest fires and crop residue burning [32]. Considering that the ultrafine particles from biomass burning are so high is in general agreement with laboratory experiments, in which nanoparticles account for up to 30% of the total particle mass concentration [51].

Table 2. Ambient $PM_{0.1}$ concentrations (μg/m^3) and $PM_{0.1}/PM_{2.5}$ ratio at different locations in Thailand.

Location	Site Description	Sampling Time	$PM_{0.1}$	$PM_{2.5}$	$PM_{0.1}/PM_{2.5}$ Ratio	References
Chiang Mai	Suburban	September 2014–June 2015	25.2 ± 4.7	77.5 ± 23.8	0.33 ± 0.03	[32]
	Suburban	March–April 2016	16.5	-	-	[52]
Pathumtani	Suburban	October 2019 (wet)	13.5 ± 0.8	55.1 ± 4.6	0.25 ± 0.06	[24]
		January–February 2020 (dry)	18.9 ± 4.0	73.4 ± 16.3	0.26 ± 0.04	
Bangkok	Urban	July 2014–June 2015	14.5 ± 4.7	66.4 ± 17.2	0.23 ± 0.09	[32]
	Urban	March–April 2016	11.9	-	-	[52]
	Urban	November 2014–October 2015	15.0 ± 2.4	-	-	[53]
	Urban	May 2016–April 2017	14.8 ± 2.0	-	-	[54]
	Urban—traffic	March–April 2016	7.7	-	-	[52]
Songkhla	Suburban	September–October 2015	14.2 ± 10.0	73.7 ± 49.8	0.19	[26]
		August–October 2017	1.9 ± 0.6	12.9 ± 0.8	0.15	
	Suburban	March–April 2016	10.9	-	-	[52]
	Suburban	January–December 2018	10.2 ± 2.2	57.8 ± 4.7	0.18 ± 0.05	[55]
	Suburban	January–August 2019	10.4 ± 1.2	-	-	[25]
	Suburban	January–December 2018	8.4 ± 1.9	-	-	[28]

In the BMR, the $PM_{0.1}/PM_{2.5}$ ratio is around 0.23 [32]. Motor vehicles account for smaller particles in this area, and the ratio slightly increases to 0.26 during the dry season, indicating that some biomass burning episodes produce $PM_{0.1}$ [24]. Hat Yai, Songkhla province, is an economic city in the south of Thailand. A previous study showed that the primary particulate pollutants in Hat Yai are caused by biomass combustion from the rubber industry [56] because southern Thailand is different from the other regions of Thailand. The economic crop in the region is oil palm and para-rubber, which are produced in plantations in the south of Thailand [57,58]. However, $PM_{0.1}$ in the southern part of Thailand is lower than in other parts due to less frequent open biomass burning fires in the area. The $PM_{0.1}/PM_{2.5}$ ranges from 0.15 to 0.19 depending on the transboundary particulate effects that increase the mass concentration [26,55].

2.2. Carbonaceous Nanoaerosol

The most significant portion of airborne PM is carbon-containing materials with various physical and chemical characteristics, which account for around 20–50% of the mass concentration of PMs [59,60]. The PM-bound total carbon (TC) can be divided into two types, including organic carbon (OC) and black carbon (BC) or elemental carbon (EC). BC and EC are used interchangeably depending on the analytical method being used [61,62]. Brown carbon (BrC) was recently discovered with light absorption characteristics similar to atmospheric aerosols [63]. BrC is a non-soot organic carbon aerosol that is produced from bioaerosols, tar, and humic-like substances (HULIS) [64,65]. BC is mainly emitted by high-temperature combustion processes (diesel and gasoline exhausts, coal combustion, and biomass burning) [66,67]. BrC is primarily emitted by biomass burning. BC and BrC are the two most crucial light-absorbing substances in atmospheric aerosols [68]. In contrast, OC is a light-scattering material that is mainly generated from biomass fires, coal combustion, motor vehicles, and secondary chemical processes in the atmosphere [69,70]. The Intergovernmental Panel on Climate Change (IPCC) predicted that EC would lead to a direct global radiative forcing of around +0.2 Wm^{-2} [71]. In contrast, OC was produced at around the same magnitude [72]. Therefore, the primary emissions of BC clearly have global warming potential and can influence the hydrological cycle [73]. Primary pollutants, including BC and OC, include an atmospheric photochemical activity and can produce secondary organic aerosols (SOA) and ozone (O_3), creating an even more complicated effect [74].

Information concerning OC and EC is crucial in estimating the impact of PMs and our understanding of the source and strength of these pollutants. EC can be divided into char-EC and soot-EC [75]. Char consists of the residue remaining after burning solid residue. Soot, however, is different from the physical and chemical properties of the source materials after the high-temperature condensation of hot gases during the combustion process [76]. The ratio of Char-EC and Soot-EC varies depending on the main sources and can be used to categorize the origin of this material. Only a small number of studies have reported on the pattern for Thailand's carbonaceous nanoaerosols (OC and EC) [24,25,32,55]. Brown carbon (BrC) in nanoaerosols, which affects the splitting between OC and EC via a thermal-optical protocol, has not been studied so far in Thailand. A reliable method for detecting BrC plays a vital role in accurately estimating carbonaceous nanoaerosols [77]. The effect on regional and global warming is highly uncertain due to carbonaceous aerosols that are emitted into the atmosphere. This is because the distribution of carbon fractions varies with the time and location, which basically contributes to the chemical, physical, and optical characteristics of carbon components in PMs. Accordingly, information on carbonaceous nanoaerosols is vital in terms of assessing their radiative effects on global warming. Only limited studies of carbon components and spatial and temporal variations in Thailand have appeared, particularly of the nano-scale ambient particles related to carbon components.

2.3. Carbon Characteristics of OC, EC, Char-EC, and Soot-EC

The ratios of OC/EC can be used to classify the exact emission sources of carbonaceous particulate matter. Ratios for diesel exhaust, coal burning, and biomass combustion are different. Biomass burning has a higher ratio, while the OC/EC ratios for fossil burning results are lower [78]. The ratio of OC to EC for biomass combustion is higher (~6–8) [79] and that from fossil fuel is lower (<1) [80]. The characteristics of emission sources of carbon fractions include diesel exhaust (OC/EC ~0.1–0.8) [70], biomass combustion (OC/EC ~4–6) [33,81], and long-range transport/aged aerosol (OC/EC ~12) [82]. On the other hand, OC/EC depends on three factors for appropriately categorizing the source of the emission. The three factors include the primary emission source, the deposition rate, and secondary organic aerosols (SOA) [55,70]. Table 3 shows the average seasonal concentration of OC, EC, Char-EC, Soot-EC ($\mu g/m^3$), and OC/EC and Char-EC/Soot-EC ratios in different locations in Thailand. A high concentration of carbon species was found in Chiang Mai (2014–2015) [32]; the dry season is longer than the wet season. However, in Songkhla (2019) [55], the wet season is longer than the dry season. The OC/EC ratio in Thailand is

typically higher than 2.0, except in the wet season in Pathumtani. The ratios of OC/EC are usually used to diagnose the source of an organic aerosol [32,70]. However, the high OC/EC in many $PM_{0.1}$ particles suggests that secondary organic carbon is vital in this area. The lower ratio represents the influence of local transportation in Thailand [24,25].

Table 3. Seasonal average of OC, EC (μg/m^3), and OC/EC ratio as well as Char-EC, Soot-EC (μg/m^3), and Char-EC/Soot-EC ratio at different locations in Thailand.

Location	Season	OC (μg/m^3)	EC (μg/m^3)	OC/EC (-)	Char-EC (μg/m^3)	Soot-EC (μg/m^3)	Char-EC/ Soot-EC (-)	References
Chiang Mai	Wet–2014	2.34 ± 0.82	0.51 ± 0.14	5.62 ± 1.22	0.23 ± 0.11	0.29 ± 0.07	0.80 ± 0.51	[32]
	Dry—2015	4.97 ± 1.46	1.51 ± 0.66	3.29 ± 0.67	0.96 ± 0.58	0.54 ± 0.13	1.78 ± 0.66	
Pathumtani	Wet—2019	0.86 ± 0.17	0.58 ± 0.17	1.50 ± 0.18	0.24 ± 0.08	0.34 ± 0.08	0.70 ± 0.09	[24]
	Dry—2020	2.05 ± 0.45	0.93 ± 0.41	2.49 ± 0.89	0.39 ± 0.32	0.54 ± 0.14	0.69 ± 0.46	
Bangkok	Wet—2014	0.78 ± 0.34	0.31 ± 0.08	2.57 ± 1.10	0.11 ± 0.03	0.20 ± 0.05	0.52 ± 0.57	[32]
	Dry—2015	2.31 ± 0.58	0.58 ± 0.13	4.47 ± 1.46	0.26 ± 0.10	0.32 ± 0.04	0.77 ± 0.24	
Bangkok	Wet—2016	3.45 ± 0.70	1.39 ± 0.43	2.59 ± 0.55	0.43 ± 0.15	0.97 ± 0.30	0.45 ± 0.09	[54]
	Dry—2017	2.60 ± 0.83	0.61 ± 0.14	4.43 ± 1.79	0.27 ± 0.09	0.35 ± 0.06	0.77 ± 0.23	
Songkhla	Wet—2019	4.90 ± 0.90	1.85 ± 0.50	2.70 ± 0.70	0.43 ± 0.10	1.40 ± 0.10	0.30 ± 0.20	[25]
	Dry—2019	1.60 ± 0.20	0.66 ± 0.10	2.42 ± 0.51	0.15 ± 0.10	0.50 ± 0.10	0.33 ± 0.20	
Songkhla	Pre-monsoon—2018	1.22 ± 1.01	0.34 ± 0.14	3.00 ± 1.41	0.08 ± 0.04	0.25 ± 0.13	0.35 ± 0.19	[55]
	Monsoon—2018	0.42 ± 0.21	0.14 ± 0.07	3.15 ± 0.81	0.04 ± 0.03	0.12 ± 0.05	0.34 ± 0.29	
	Dry—2018	0.44 ± 0.22	0.18 ± 0.12	2.75 ± 1.10	0.05 ± 0.03	0.14 ± 0.09	0.37 ± 0.17	

Unlike the OC/EC ratio, the char-EC/soot-EC ratio differs from each source; it is frequently possible to identify the sources [83]. Only two factors can affect the char/soot ratio: the primary emission source and particle deposition by scavenging. A higher proportion of char/soot (generally >1.0) is suggestive of biomass fires; char contributes to the total EC levels. In contrast, char/soot <1.0 suggests that emissions from diesel engines are an essential contributor to the total EC concentrations [32,84]. The Char-EC/Soot-EC ratios in nanoparticles in Thailand are almost constant and less than 1.0 in both the wet and dry seasons, suggesting that motor vehicles are a key source of $PM_{0.1}$ particles in Thailand. However, only in Chiang Mai during the dry season, the Char-EC content and Char-EC/Soot-EC were increased and higher than 1.0 because of open biomass burning to smaller particles [32,55,70]. Therefore, the $PM_{0.1}$ particles represent diesel engine emissions, although sensitive to biomass emissions in Thailand, e.g., the Chiang Mai area, which is recognized to have airborne particulate pollution from biomass burning for a long time [85,86]. Moreover, the increased Char-EC content and Char-EC/Soot-EC ratio should be studied in detail in future studies for the accuracy of carbonaceous nanoaerosols in Thailand and elsewhere.

2.4. $PM_{0.1}$ Derived from Biomass Burning

In SEA, haze has occurred nearly every year during the dry season [85,86]. These haze episodes generated PM that was derived from biomass combustion in the past decade [24,33]. Forest fires and slash and burn in agricultural areas are typical methods for removing biomass residues in SEA [87]. Research reports addressed the high PM concentration that is released from open biomass fires in Thailand [86,88,89]. Hata et al. (2014) [51] reported, based on chamber experiments, that biomass fuel combustion releases around 80% of all sub-micron particles and nanoparticles of approximately 30% of the total particles. Similarly, open biomass fires during a haze episode in northern Thailand revealed that more than 60% of the total PM is smaller than $PM_{1.0}$ [32]. The size distribution of PM released from open fires depends on fuel type, moisture content, and excess air during combustion [90,91].

Biomass burning is a significant contributor to the production of ambient particles. As reported by Hata et al. (2014) [51], in chamber experiments, biomass solid fuel combustion accounted for more than 30% of the biomass burning and that the particle mass concentration was smaller than <100 nm. However, in the atmospheric environment, $PM_{0.1}$ particles are contained in the ambient atmosphere due to anthropogenic activities and natural sources or chemical processes. Therefore, determining the actual emission sources under ambient conditions is not an easy task. Phairuang et al. (2021) [53] reported on the source apportionment of $PM_{0.1}$ particles in Bangkok. They found that around 10% of the ambient nanoparticles in Bangkok during haze episodes came from biomass fires. However, $PM_{0.1}$ particles, primarily derived from motor vehicle emissions, are also strongly affected by forest fires in the north of Thailand [32]. Hence, this activity has an important influence on the quality of ambient air during the dry season. As a result, the main emission sources of $PM_{0.1}$ are both natural and anthropogenic. Figure 1 shows the morphology of ambient nanoparticles from Chiang Mai, Thailand, as observed in scanning electron microscope (SEM) analysis [92]. The particles from near emission sources during strong biomass fires represent particles in the ultrafine mode (Dp < 100 nm).

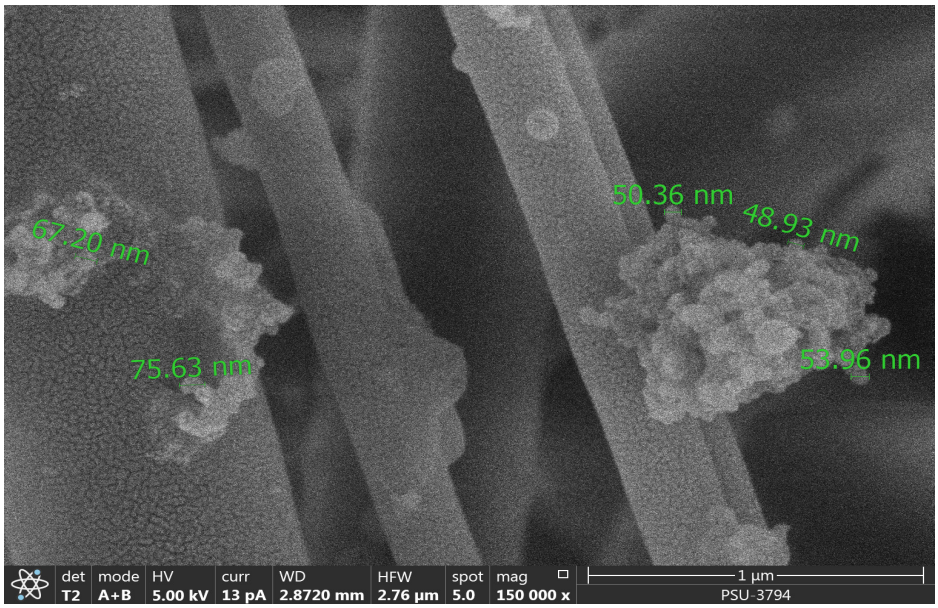

Figure 1. SEM images of atmospheric nanoparticles in Chiang Mai, Thailand, in the year 2015 (forest fires dominated as emission sources during the dry season) [92].

3. Health Concerns of $PM_{0.1}$ in Thailand

Smaller particles, especially nano-size particles, are recognized as being detrimental to human health due to their small size, chemical makeup, and the fact that they accumulate in ambient conditions [8]. Evidence collected in the past decade makes it clear that $PM_{0.1}$

affects public health. The Health Effects Institute (HEI) [14] suggests that the $PM_{0.1}$ data on health risk assessment are still an ongoing study and it cannot conclude or decide on policy making for the control of ambient $PM_{0.1}$ worldwide. However, health risks, such as oxidative stress and inflammatory damage, may result from human exposure to atmospheric $PM_{0.1}$ through inhalation [8,10].

In the same manner, studies of $PM_{0.1}$ in Thailand make it clear that there are health effects from these particles. Only a few studies have appeared on health risk assessment from $PM_{0.1}$ as related to the chemical composition of these particles. Chomanee et al. (2020) [26] reported on a health risk assessment of nanoparticle-bound PAHs in southern Thailand during a period of transboundary particulate pollution. It is known that the lower SEA suffers from the effects of large peat-land fires during the dry season, around July–September, almost every year. This research suggests that the health effects from carcinogenic PAHs during a strong haze period are higher than normal, by around 2–5 times. Public health concerns in this region should focus on smaller particles in some periods from cross-border pollution that depend on the intensity of emission sources, wind speed, wind direction, and meteorology during those periods.

Similarly, Phairuang et al. (2022) [28] reported on the year-long health effects of $PM_{0.1}$-bound trace elements in southern Thailand in 2018. They found that the health risk from hazardous components is generally highly recognized during the pre-monsoon season. Toxic elements from peat-land fires that are transported from other sources to southern Thailand depend on the speed and direction of the wind. Cross-border particulate pollution must be investigated in more detail, with emphasis on the origin and health concerns during haze episodes in this region. During the normal period, the primary emission sources of $PM_{0.1}$ are land transportation [25].

In other parts of Thailand, our knowledge of the health risks from $PM_{0.1}$ related to the chemical components remains limited. Phairuang et al. (2021) [53] reported that the health risk assessment from $PM_{0.1}$-bound metals in Bangkok, Thailand, was substantial during a smog haze period. $PM_{0.1}$-bound elements in Bangkok differ with the season but are generally related to road transport emissions. It is well known that in the Bangkok Metropolitan Region air quality worsens during periods of heavy traffic congestion [32,47,49]. There is general agreement that the production of $PM_{0.1}$ worldwide is derived from motor vehicles in urban areas [40,50]. Diesel and benzene engines are the primary sources of ambient nanoparticles in mega-cities [93,94]. However, open biomass burning, e.g., forest fires, crop waste, and grass burning, significantly contribute to $PM_{0.1}$ during intense haze episodes in many countries [5,32]. Most studies have concluded that inhaled airborne $PM_{0.1}$ has adverse effects on human health. Data of relationships between $PM_{0.1}$ and sickness are limited. It appears that we are not fully aware of the life-threatening hazards of ambient NPs in air pollution from biomass fires on human health in Thailand.

4. Challenges in Studies of $PM_{0.1}$ in Thailand

In the past decade, Thailand has been faced with particulate pollution almost yearly. In particular, in the dry season, emissions from open fires and meteorological conditions can temporarily affect the particle concentration [85,95]. Phairuang et al. (2019) [32] examined the influence of biomass fires on air quality in Thailand, i.e., Bangkok and Chiang Mai, in a case study of size-fractionated particulate matter ranging from small to nano-sized. The influence of biomass burning strongly affects ambient $PM_{0.1}$ in Bangkok, although many reports have suggested that the main contribution of $PM_{2.5}$ in BMR is from motor vehicles [47,49]. On the other hand, $PM_{0.1}$ is ubiquitous in the atmospheric environment in the northern part of Thailand during the dry season, as in Chiang Mai, the economic city in the northern part of Thailand. This is a new challenge in the studies of biomass burning, especially crop waste burning and woodland fires in agricultural countries, to understand the production of ambient nanoparticles [5,32,55]. The apportionment of the sources of $PM_{0.1}$ is very limited in Thailand due to the small amount of mass and chemical composition. Moreover, a recent study of particle size distribution in Bangkok

by Panyametheekul et al. (2022) [96] found that the particle number concentration of samples collected from three locations in Bangkok revealed that up to 90% of the $PM_{0.1}$ was produced in comparison with other sizes. Consequently, in the case of $PM_{0.1}$, both the number and mass particle concentration are subjects that need to be examined in terms of air quality management in Thailand's land based on heavy particulate pollution in the past decade.

It is generally assumed that $PM_{0.1}$ particles are highly toxic substances compared to larger particles because they have a vast surface area per volume that can carry and absorb hazardous chemicals such as heavy metals, carbon components, and carcinogenic PAHs [8]. In the past decade, strong evidence has appeared to suggest that $PM_{2.5}$ and PM_{10} induce human illness, including respiratory symptoms, cardiovascular effects, and chronic obstructive pulmonary disease (COPD), which contribute to mortality and morbidity [97–100]. This is especially true in northern Thailand, which experiences particulate pollution almost yearly. Many reports have revealed that the smoke haze episodes induce more people to visit hospitals in the north of Thailand [101,102]. However, there is no evidence of risks to health from nanoaerosols. Although the northern part of Thailand, during the dry season, has a high mass concentration of $PM_{0.1}$ particles [32], the relationship and epidemiological survey of ultrafine particles and health effects still underestimate human public health due to insufficient information concerning the source, characteristics, and abundance of such small particles.

5. Option and Recommendations concerning $PM_{0.1}$ in Thailand

5.1. Evaluation of $PM_{0.1}$: Present Status and Characteristics, Comparison between Sites

Airborne particles can migrate over long distances and can cross the borders between countries and regions on a global scale. $PM_{2.5}$ can be transported in the atmosphere for an extended period, change its properties via further chemical reactions [103,104], and can change into fine or coarse particles, known as secondary particles. The effectiveness of the secondary formation of particles suggests that it is more significant than primary formation in that they can contain both hazardous chemicals and are easily carried in the atmosphere [105,106]. For monitoring carbonaceous compounds in suburban areas compared to urban areas in Thailand, it was found that the average concentrations of ambient carbonaceous compounds in a suburban area (Klong Luang, Pathumtani, Thailand) were higher than that in an urban area (Bangkok Metropolitan Region (BMR)) [106,107].

However, information on the long-range transport of ambient nanoparticles continues to be limited. Collecting $PM_{0.1}$ from cities in Thailand and other countries during a high smoke episode and comparing and examining cross borders among cities and countries are needed if we are to develop a better understanding of the impact of atmospheric $PM_{0.1}$. Building a monitoring network through monitoring ambient nanoaerosols is a priority in studying $PM_{0.1}$ in Thailand. Phairuang et al. (2019) [32] reported that the transport of ambient $PM_{0.1}$ in Thailand can cover a distance of around 100–200 km. Nevertheless, Inerb et al. (2022) [25] reported that during intense forest fire episodes in lower southern Asia, the nanoparticles produced from peat-land fires could be transported around 800 km from Indonesia to the southern part of Thailand. High international collaboration and links between climate and air pollution policies should be compulsory to control small particles' ambient air quality effects. Therefore, a monitoring network to discuss the contribution of near emission sources and possible transboundary transportation continues to be a challenge. There has only been one monitoring network to study ambient nanoaerosols in East and Southeast Asia, namely, the East Asia Nanoparticle Monitoring Network (EA-Nanonet). The EA-Nanonet was established in 2013 to monitor the emission of nanoparticles and their characteristics, transport, and behavior in many East and Southeast Asian countries, including Japan, China, Thailand, Vietnam, Malaysia, Indonesia, and Cambodia [108].

5.2. Information on $PM_{0.1}$ Emission Sources

$PM_{0.1}$ is a small particle that is produced both naturally and by humans, primarily from combustion processes and chemical reactions in the atmosphere [8,10]. In the past decade, nanoparticles were generally produced from diesel engines and contained a high level of carbon and metal. The emission inventory (EI) of $PM_{0.1}$ particles and chemical relationships has not been extensively studied in Thailand. However, some information on emission factors (EF) from solid biomass burning in Thailand has appeared [90,91]. Interestingly, other emission sources, e.g., coal combustion, motor vehicles, power plants, and non-combustion sources, are still lacking in Thailand. Moreover, particle number concentration (PNC), which usually measures a smaller particle, is still lacking in Thailand. There is a vast gap in emission inventories due to a lack of EFs and other default values that are needed to calculate the accuracy of EI.

5.3. Summary of Facts on $PM_{0.1}$ for Policy Making

Ambient $PM_{0.1}$, both number and mass concentration in the ambient air, comes from various sources and influences human health via personal exposure. An inventory of $PM_{0.1}$ should be seriously addressed. This is scientific information to support policy makers in the near future. It cannot be ignored that the higher the concentration of small particles is, the higher the amount of heavy metal or other toxic materials will be. Developing a standard or even guidelines for a reasonable value for public health is needed. Further, we need to understand the origins, transportation, transformation (new particles), and effects on public health of ambient $PM_{0.1}$ to identify appropriate procedures to resolve the problem sustainably. The production of new particulate aerosols possibly increases with an increase in the concentration of UFPs under conditions of high relative humidity (RH) above 70%, especially in tropical countries. UFPs should then be an indicator to convince decision makers of the need for policy making. Summarizing ambient nanoparticles will help develop clean air policies in Thailand.

6. Conclusions

The study of ambient $PM_{0.1}$ particles in Thailand has been ongoing for a decade and is focused on particle mass concentration, the characteristics of the carbon contained by these particles, and the health effects of these particles. The health-related effects of ambient $PM_{0.1}$ have not resulted in support for air quality management in Thailand and also most of the Asian countries because, unlike coarse and fine particles, of a lack of this type of information. Evaluations of $PM_{0.1}$, the present status, characteristics, and comparison between sites play an important role in atmospheric systems. Local sources and transboundary ultrafine particulate pollution should be considered for future studies. Other chemical substances in $PM_{0.1}$ have not been studied extensively in Thailand. They could, however, also be an essential factor in air pollution, which merits future study in a more detailed investigation into the nature and health-related effects. As a result, summarizing factual information concerning $PM_{0.1}$ for policy making will fill the gap until more in-depth studies of ambient particulate matter can be carried out. This promises to have a long-term impact on achieving a blue sky over Thailand through coherent policies and management.

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