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Review

Ambient Nanoparticles (PM_{0.1}) Mapping in Thailand

Worradorn Phairuang ^{1,2*}, Suthida Piriyaakarnsakul ³, Muanfun Inerb ⁴, Surapa Hongtieab ¹, Thunyapat Thongyen ⁵, Jiraporn Chomanee ⁶, Yaowatat Boongla ⁷, Phuchiwan Suriyawong ⁸, Hisam Samae ⁸, Phuvasa Chanonmuang ⁹, Panwadee Suwattiga ¹⁰, Thaneeya Chetianukornkul ¹¹, Sirima Panyametheekul ^{12,13}, Muhammad Amin ^{1,14}, Mit-suhiko Hata ¹ and Masami Furuuchi ^{1,4}

¹ Faculty of Geosciences and Civil Engineering, Institute of Science and Engineering, Kanazawa University, Kanazawa, Ishikawa, 920-1192, Japan; spm.ztp@gmail.com (S.H.); muhammadamiin2020@gmail.com (M.A.); hata@se.kanazawa-u.ac.jp (M.H.); mfuruch@staff.kanazawa-u.ac.jp (M.F.)

² Department of Geography, Faculty of Social Sciences, Chiang Mai University, Muang, Chiang Mai, 50200, Thailand; worradorn@gmail.com (W.P.)

³ Office of National Higher Education Science Research and Innovation Policy Council, Bangkok 10330, Thailand; suthida@nxpo.or.th (S.P.)

⁴ Faculty of Environmental Management, Prince of Songkla University, Hat Yai, Songkhla, 90110, Thailand; muanfun.in@gmail.com (M.I.)

⁵ Department of Environmental Technology and Management, Faculty of Environment, Kasetsart University, Bangkok 10900 Thailand; thunyapat.t@ku.ac.th (T.P.)

⁶ Department of Basic Science and Mathematics, Faculty of Science, Thaksin University, Muang, Songkhla, 90000 Thailand; chomanee_j@yahoo.co.th (J.C.)

⁷ Department of Sustainable Development Technology, Faculty of Science and Technology, Thammasat University, Rangsit Campus, Pathumtani, 12121, Thailand; yaowatat@gmail.com (Y.B.)

⁸ Research Unit for Energy, Economic, and Ecological Management (3E), Science and Technology Research Institute, Chiang Mai University, Chiang Mai, 50200 Thailand; pooshewan@gmail.com (P.S.); hisam_01@hotmail.com (H.S.)

⁹ Expert Centre of Innovative Clean Energy and Environment, Thailand Institute of Scientific and Technological Research (TISTR), Klong-Luang, Pathumtani, 12120, Thailand; phuvasa@tistr.or.th (P.C.)

¹⁰ Department of Agro-Industrial, Food and Environmental Technology, Faculty of Applied Science, King Mongkut's University of Technology North Bangkok, Bangkok, 10800, Thailand; panwadee.s@sci.kmutnb.ac.th (P.S.)

¹¹ Department of Biology, Faculty of Science, Chiang Mai University, Muang, Chiang Mai, 50200, Thailand; thaneeya.s@cmu.ac.th (T.C.)

¹² Department of Environmental Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok 10330, Thailand; sirima.p@chula.ac.th (S.P.)

¹³ Thailand Network Center on Air Quality Management: TAQM, Chulalongkorn University, Bangkok 10330, Thailand

¹⁴ Faculty of Engineering, Maritim University of Raja Ali Haji, Tanjung Pinang, Kepulauan Riau 29115, Indonesia

* Correspondence: pworrador@se.kanazawa-u.ac.jp; worradorn@gmail.com

Abstract: Nanoparticles (NP), Nanoaerosols (NA), ultrafine particles (UFP), and PM_{0.1} (particles with a diameter $\leq 0.1 \mu\text{m}$ or 100 nm) are interchangeably used in the field of atmospheric studies. PM_{0.1} are emitted from both natural and anthropogenic sources. The main emission sources of PM_{0.1} are combustion processes, including biomass and fossil fuel. Moreover, secondary formation via atmospheric photochemical reactions can also occur depending on meteorological conditions and the suspended pollutant species. Identifying the physical and chemical characteristics and spatial and temporal variations is vital in terms of understanding the effect of NPs on the environment, the global climate, and human health risks. This review article summarizes recent research on PM_{0.1} in Thailand. The review involves peer-reviewed papers from Scopus and the Web of Science databases, and includes the most recently published articles in the past ten years (2013–2022). UFPs mainly come from the combustion processes such as motor vehicles. The high mass concentration of PM_{0.1} that occurs during the dry season in which open fires depend on the specific region of Thailand. Particulate pollution from local and cross-border countries also needs to be considered in terms of the concentrations of ambient nanoparticles. 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

1. Introduction

The particulate matter (PM) pollution observed in Thailand and Southeast Asian countries is related to studies of the PM₁₀ and PM_{2.5} fractions and, to a slight extent, on ground monitoring and satellite detection in PM_{1.0} [1,2,3,4,5]. 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 [6,7,8]. This review article gathers 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, and Thailand”. The review article covers publications in this area that have appeared in the past 10 years, from 2013 to 2022, and includes the following topics;

1. Introduction
2. Background and impact of PM_{0.1}
3. Recent studies of PM_{0.1} in Thailand
4. Health concerns regarding PM_{0.1} in Thailand
5. Challenges to the study of PM_{0.1} in Thailand
6. Options and recommendations for PM_{0.1} in Thailand

2. Background and impact of PM_{0.1}

Ambient particulate matter (PM), which is strongly associated with harmful aspects concerning human health [9,10] and global warming have recently appeared [1,11] and has attracted considerable interest regarding environmental pollution in many countries. PM can be categorized into three modes, which include coarse particles (diameter between 2.5 and 10 μm), fine particles with diameter between 0.1 to 2.5 μm), and ultrafine particles (diameters $\leq 0.1 \mu\text{m}$, or 100 nm) [12,13]. 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 [14]. 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 [15,16].

Nanoparticles (NP), nanoaerosols (NA), ultrafine particles (UFP), and PM_{0.1} are interchangeably used depending on the subject area [17], but there are slight differences among these particles. The most common nanoparticles are mainly incidentally and unintentionally generated and are suspended in the atmosphere [16,18]. 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 [19,20]. 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 [18,21], 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 [17,22]. Airborne PM is linked to increased mortality and morbidity in humans [23]. There is considerable evidence to show that PMs harm the respiratory, nervous, and cardiovascular systems [24,25,26]. 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 [27,28,29,30] and airborne pathogens such as bacteria, fungi, and viruses [31].

Southeast Asia (SEA) has been a source of PM pollution for the last decades, affecting countries and countries outside the region [32,33]. The transport plume of Indonesian forest fires affects air quality in Singapore, Malaysia, Brunei, and southern Thailand [34,35,36]. 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 [37,38,39]. In Thailand, the effect of the migration of polluted air masses is vital on a multi-provincial scale (100-200 km) [7].

3. Recent studies of PM_{0.1} in Thailand

3.1. 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, PM₁₀, PM_{2.5}), O₃, CO, SO₂, NO₂, and lead (Pb) and (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, Ministry of Natural Resources and Environment in Thailand. This is the current standard as of 2022; particulate pollution is a severe and increasing problem for the Thailand. The pollution Control Department announced that (2022) [41] will decrease Thailand’s National Ambient Air Quality of 24 hours PM_{2.5} concentration to 0.375 mg/m³ in 2023. This is because of human health concerns about smaller particles in the recent decade.

Moreover, according to the new guidelines on air quality of the World Health Organization (WHO) (2021) [42], the suggested mean annual concentration for PM₁₀ was 0.02 mg/m³ in 2005, and the mass concentration for 2021 moved to 0.015 mg/m³. The 24-hour concentration was updated from 0.05 mg/m³ in 2005 to 0.045 mg/m³. Furthermore, in 2005, the highest recommended average PM_{2.5} annual mass concentration was 0.01 mg/m³, and the 2021 revision reduces that number by half, to just 0.005 mg/m³. The 24-hour level changed from 0.025 mg/m³ in 2005 to 0.015 mg/m³. 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 1. National Thailand Ambient Air Quality Standards.

Pollutants	Time Period	Concentration
TSP (PM ₁₀₀)	Annual	0.10 mg/m ³
	24 hours	0.33 mg/m ³
PM ₁₀	Annual	0.05 mg/m ³
	24 hours	0.12 mg/m ³
PM _{2.5}	Annual	0.015 mg/m ³
	24 hours	0.05 mg/m ³
O ₃	8 hours	0.14 mg/m ³ (0.07 ppm)
	1 hour	0.20 mg/m ³ (0.10 ppm)
CO	8 hours	10.26 mg/m ³ (9 ppm)
	1 hour	34.2 mg/m ³ (30 ppm)
NO ₂	Annual	0.057 mg/m ³ (0.03 ppm)
	1 hour	0.32 mg/m ³ (0.17 ppm)
SO ₂	Annual	0.10 mg/m ³ (0.04 ppm)
	24 hours	0.30 mg/m ³ (0.12 ppm)
	1 hour	780 mg/m ³ (0.3 ppm)
Lead (Pb)	Monthly	1.50 mcg/m ³

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,

Thailand. Chiang Mai has the highest PM_{0.1} level in Thailand based on the sampling period during 2014-2015 up to 25.2 ± 4.7 µg/m³. 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 [46,47,48,49]. The mass concentration of PM_{0.1} in the BMR ranges from 7.7 - 18.9 (µg/m³) a number that is higher than that in western countries such as 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/m³. 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 reached 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 [7]. 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/m³) 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	Sep 2014 - Jun 2015	25.2 ± 4.7	77.5 ± 23.8	0.33 ± 0.03	[7]
	Suburban	Mar - Apr 2015	16.5	-	-	[52]
Pathumtani	Sururban	Oct 2019 (wet)	13.5 ± 0.8	55.1 ± 4.6	0.25 ± 0.06	[32]
		Jan - Feb 2020 (dry)	18.9 ± 4.0	73.4 ± 16.3	0.26 ± 0.04	
Bangkok	Urban	Jul 2014 - Jun 2015	14.5 ± 4.7	66.4 ± 17.2	0.23 ± 0.09	[7]
	Urban	Mar - Apr 2015	11.9	-	-	[52]
	Urban	Nov 2014 - Oct 2015	15.0 ± 2.4	-	-	[53]
	Urban	May 2016 - Apr 2017	14.8 ± 2.0	-	-	[54]

Songkhla	Urban-traffic	Mar - Apr 2015	7.7	-	-	[52]
	Suburban	Sep - Oct 2015	14.2 ± 10.0	73.7 ± 49.8	0.19	[34]
		Aug - Oct 2017	1.9 ± 0.6	12.9 ± 0.8	0.15	
	Suburban	Mar - Apr 2015	10.9	-	-	[52]
	Suburban	Jan - Dec 2018	10.2 ± 2.2	57.8 ± 4.7	0.18 ± 0.05	[55]
	Suburban	Jan - Aug 2019	10.4 ± 1.2	-	-	[33]
	Suburban	Jan - Dec 2018	8.4 ± 1.9	-	-	[36]

In the BMR, the PM_{0.1}/PM_{2.5} ratio is around 0.23. 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} [32]. 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 [34,55].

3.2. Carbonaceous Nano-aerosol

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 (O₃), 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) [7,32,33,55,70]. 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]. Therefore, only limited studies of carbon components and spatial and

temporal variation in Thailand have appeared, particularly of the nano-scale ambient particles related to carbon components.

3.3. 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 (ug/m³) 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) [7]; the dry season is longer than the wet season. But, 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 [7,32,33,70]. 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 [32,33].

Unlike the OC/EC ratio, the char-EC/soot-EC ratio differs from each source, and 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, and char contributes to the total EC levels. In contrast, char/soot < 1.0 suggests that emission from diesel engine is an essential contributor to the total EC concentrations [7,84]. 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 [7,55,70]. 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 nano-aerosol in Thailand and elsewhere.

Table 3. Seasonal average of OC, EC (ug/m³) and OC/EC ratio as well as Char-EC, Soot-EC (ug/m³) and Char-EC/Soot-EC ratio at different locations in Thailand.

Location	Season	OC (ug/m ³)	EC (ug/m ³)	OC/EC (-)	Char-EC (ug/m ³)	Soot-EC (ug/m ³)	Char- EC/ Soot-EC (-)	Refer- ence
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	[7]
		4.97 ± 1.46	1.51 ± 0.66	3.29 ± 0.67	0.96 ± 0.58	0.54 ± 0.13	1.78 ± 0.66	
	Dry - 2015	0.86 ± 0.17	0.58 ± 0.07	1.50 ± 0.18	0.24 ± 0.08	0.34 ± 0.08	0.70 ± 0.09	[32]
		2.05 ± 0.45	0.93 ± 0.1	2.49 ± 0.89	0.39 ± 0.32	0.54 ± 0.4	0.69 ± 0.6	

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 ± 0.07	[7]
	Dry - 2015	2.31 ± 0.58	0.58 ± 0.13	4.47 ± 1.46	0.26 ± 0.10	0.32 ± 0.04	0.77 ± 0.04	
Bangkok	Wet - 2016	3.45 ± 0.70	1.39 ± 0.3	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 ± 0.5	2.70 ± 0.70	0.43 ± 0.10	1.40 ± 0.1	0.30 ± 0.0	[33]
	Dry - 2019	1.60 ± 0.20	0.66 ± 0.1	2.42 ± 0.51	0.15 ± 0.10	0.50 ± 0.1	0.33 ± 0.0	
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	

3.4 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 [1,32]. 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 [2,86,88,89]. 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} [7]. 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) [92] 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. Although, PM_{0.1} particles, primarily derived from motor vehicle emissions, are also strongly affected by forest fires in the north of Thailand [7]. 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. The particles from near emission sources during strong biomass fires represent particles in the ultrafine mode (Dp < 100 nm).

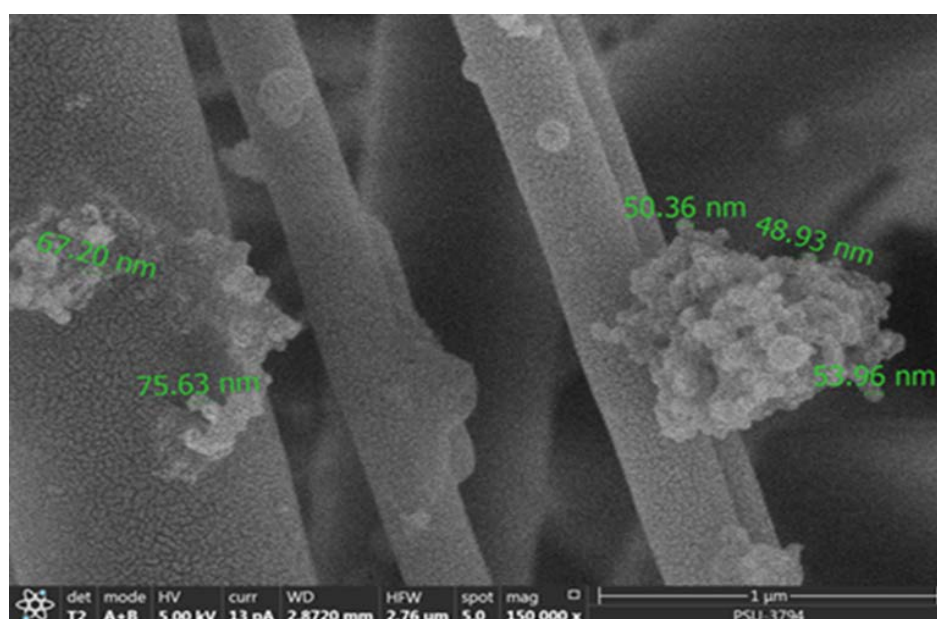


Figure 1. SEM images of atmospheric nanoparticles from Chiang Mai, Thailand, in the year 2015 (forest fires dominated as emission sources during the dry season).

4. 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 [18]. Evidence collected in the past decade makes it clear that PM_{0.1} affects public health. The Health Effects Institute (HEI) [22] suggests that the PM_{0.1} data on health risk assessment is still an ongoing study and 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 [16,18].

In the same manner, studies of PM_{0.1} study 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) [34] 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) [36] 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 high 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 [33].

In other parts of Thailand, our knowledge of the health risks from PM_{0.1} related to the chemical components remain 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, that 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 [92,93]. 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 [7,13,94]. 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.

5. 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 [85,94]. Phairuang et al. (2019) [7] 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, like Chiang Mai, the economic city in the northern part of Thailand. This is a new challenge in studies of biomass burning, especially crop waste burning and woodland fires in agricultural countries, to understand the production of ambient nanoparticles [13,32,33,55]. 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, in a recent study of particle size distribution in Bangkok by Panyametheekul et al. (2022) [95], they found that the particle number concentration of samples collected from 3 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 [16]. 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, Chronic Obstructive Pulmonary Disease (COPD), and of which contribute to mortality and morbidity [96,97,98,99]. 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 [100,101]. However, there is no evidence of risks to health from nano-aerosols. Although the northern part of Thailand, during the dry season, has a high mass concentration of $PM_{0.1}$ particles [7]. 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.

6. Option and recommendation of $PM_{0.1}$ in Thailand

6.1. Evaluation of $PM_{0.1}$: Present status and characteristics, comparison between sites

Airborne particles can migrate over long distances and can cross the border 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 [1,102,103], 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 [104,105]. 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) were higher than that in urban (Bangkok Metropolitan Region: BMR) [106].

However, information on the long-range transport of ambient nanoparticles continues to be limited. Collecting $PM_{0.1}$ between 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 nano-aerosol is a priority in studying $PM_{0.1}$ in Thailand. Phairuang et al. (2019) [7] 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) [33] 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. 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 the east and southeast Asia, namely, the East Asia Nanoparticle Monitoring Network (EA-Nanonet). The EA-Nanonet was established in 2103 to monitor the emission of nanoparticles, their characteristics, transport, and behavior in many East and South-East Asia countries, including Japan, China, Thailand, Vietnam, Malaysia, Indonesia, and Cambodia [107].

6.2. Information on $PM_{0.1}$ emission sources

$PM_{0.1}$ is a small particle that is produced both naturally and human-made, primarily from combustion processes and chemical reactions in the atmosphere [16,18]. In the past decade, nanoparticles have been generally been 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 have 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) that 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.

6.3. 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 policymakers in the near future. It cannot be ignored that the higher the concentration of small particles, 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 the need for and to improve policymaking. Summarizing ambient nanoparticles will help develop clean air policies in Thailand.

7. Conclusions

The study of ambient PM_{0.1} 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 related health effects. In some typical cities in Thailand, studies of nanoparticles have mainly focused on mass concentrations during high episodes. The physical, chemical, and optical characteristics of PM_{0.1} continue to be challenging. Primary and secondary emission sources will be the main thrust of future research. The influence on air quality, atmosphere, and public health is still unclear regarding smaller particles in Thailand. The health effects of ambient PM_{0.1} have not resulted in convincing support for air quality management in Thailand because of a lack of this type of information, unlike coarse and fine particles. 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 study. Very few countries are monitoring PM_{0.1} due to the complex routes for their formation and levels of estimation, and different measures to reduce the formation of PM_{0.1} are being implemented. As a result, summarizing facts on PM_{0.1} for policy-making will fill the gap in studies of ambient particulate matter and will have a long-term impact on achieving a blue sky over Thailand through coherent policies and management.

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