

Disclaimer/Publisher's Note: The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.

Review

Ambient Nanoparticles (PM_{0.1}) Mapping in Thailand

Worradorn Phairuang ^{1,2*}, Suthida Piriayakarnsakul 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 Chetiyankornkul ¹¹, Sirima Panyametheekul ^{12,13}, Muhammad Amin ^{1,14}, Mitsuhiro 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: pworradorn@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 $25.2 \pm 4.7 \mu\text{g}/\text{m}^3$. 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 [46,47,48,49]. The mass concentration of PM_{0.1} in the BMR ranges from $7.7 - 18.9 \mu\text{g}/\text{m}^3$ 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) $\mu\text{g}/\text{m}^3$. 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 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 ($\mu\text{g}/\text{m}^3$) 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	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	
	Urban	Jul 2014 - Jun 2015	14.5 ± 4.7	66.4 ± 17.2	0.23 ± 0.09	[7]
Bangkok	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 $\text{PM}_{0.1}/\text{PM}_{2.5}$ 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 $\text{PM}_{0.1}$ [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, $\text{PM}_{0.1}$ in the southern part of Thailand is lower than in other parts due to less frequent open biomass-burning fires in the area. The $\text{PM}_{0.1}/\text{PM}_{2.5}$ 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 $+0.2 \text{ W m}^{-2}$ [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) [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 ($\mu\text{g}/\text{m}^3$) 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) [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 $\text{PM}_{0.1}$ 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 $\text{PM}_{0.1}$ 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 $\text{PM}_{0.1}$ 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 ($\mu\text{g}/\text{m}^3$) and OC/EC ratio as well as Char-EC, Soot-EC ($\mu\text{g}/\text{m}^3$) and Char-EC/Soot-EC ratio at different locations in Thailand.

Location	Season	Char-					
		OC ($\mu\text{g}/\text{m}^3$)	EC ($\mu\text{g}/\text{m}^3$)	OC/EC (-)	Char-EC ($\mu\text{g}/\text{m}^3$)	Soot-EC ($\mu\text{g}/\text{m}^3$)	EC/ Soot-EC (-)
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
	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 ± 0.7	1.50 ± 1.18	0.24 ± 0.08	0.34 ± 0.08	0.70 ± 0.9
	Dry - 2020	2.05 ± 0.45	0.93 ± 1	2.49 ± 0.89	0.39 ± 0.32	0.54 ± 0.4	0.69 ± 0.6

Bangkok	Wet - 2014	0.78 ± 0.	0.31 ± 0.0	2.57 ± 1.	0.11 ± 0.	0.20 ± 0.0	0.52 ± 0.5	[7]
		34	8	10	03	5	7	
Bangkok	Dry - 2015	2.31 ± 0.	0.58 ± 0.1	4.47 ± 1.	0.26 ± 0.	0.32 ± 0.0	0.77 ± 0.2	[54]
		58	3	46	10	4	4	
Songkhla	Wet - 2016	3.45 ± 0.	1.39 ± 0.4	2.59 ±	0.43 ±	0.97 ±	0.45 ±	[33]
		70	3	0.55	0.15	0.30	0.09	
Songkhla	Dry - 2017	2.60 ±	0.61 ±	4.43 ±	0.27 ±	0.35 ±	0.77 ±	[55]
		0.83	0.14	1.79	0.09	0.06	0.23	
Songkhla	Wet - 2019	4.90 ± 0.	1.85 ± 0.5	2.70 ± 0.	0.43 ± 0.	1.40 ± 0.1	0.30 ± 0.2	[33]
		90	0	70	10	0	0	
Songkhla	Dry - 2019	1.60 ± 0.	0.66 ± 0.1	2.42 ± 0.	0.15 ± 0.	0.50 ± 0.1	0.33 ± 0.2	[55]
		20	0	51	10	0	0	
Songkhla	Pre-monsoon - 2018	1.22 ±	0.34 ±	3.00 ±	0.08 ±	0.25 ±	0.35 ±	[55]
		1.01	0.14	1.41	0.04	0.13	0.19	
Songkhla	Monsoon - 2018	0.42 ±	0.14 ±	3.15 ±	0.04 ±	0.12 ±	0.34 ±	[55]
		0.21	0.07	0.81	0.03	0.05	0.29	
Songkhla	Dry - 2018	0.44 ±	0.18 ±	2.75 ±	0.05 ±	0.14 ±	0.37 ±	[55]
		0.22	0.12	1.10	0.03	0.09	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. Phairaung 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 (D_p < 100 nm).

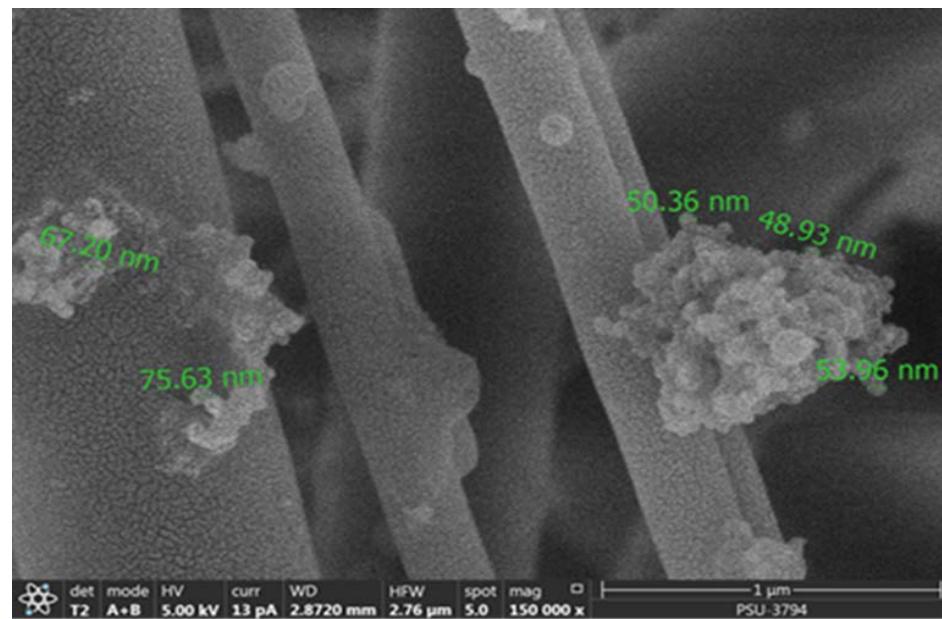


Figure 1. SEM images of atmospheric nanoparticles from Chiang Mai, Thailand, in the year 2015 (forest fires dominated as emission sources during the dry season).

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 PM₁₀ 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 2013 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.

Contributions: All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by Office of the Permanent Secretary, Ministry Higher Education, Science, Research and Innovation in Thailand (Grant No. RGNS 63-253). Moreover, this research work was partially supported by JICA-JST SATREPS, JSPS KAKENHI 21H03618, and Sumitomo Foundation, Japan.

Institutional Review Board Statement: Not applicable

Informed Consent Statement: Not applicable

Data Availability Statement: Not applicable

Acknowledgments: The authors acknowledge the contribution of members of the East Asia Nanoparticle Monitoring Network (EA-Nanonet) for field sampling and laboratory work. Moreover, the authors also wish to thank Dr. Milton S. Feather for improving the English in this manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Adam, M.G., Tran, P.T., Bolan, N., & Balasubramanian, R. (2021). Biomass burning-derived airborne particulate matter in Southeast Asia: A critical review. *Journal of Hazardous Materials*, 407, 124760.
2. Amnuaylojaroen, T., Inkom, J., Janta, R., & Surapipith, V. (2020). Long-range transport of southeast asian pm2.5 pollution to northern Thailand during high biomass burning episodes. *Sustainability*, 12(23), 10049.
3. Othman, M., Latif, M.T., Hamid, H. H.A., Uning, R., Khumsaeng, T., Phairuangs, W., & Lung, S.C.C. (2022). Spatial-temporal variability and health impact of particulate matter during a 2019–2020 biomass burning event in Southeast Asia. *Scientific Reports*, 12(1), 1-11.
4. Vejpongsa, I., Suvachittanont, S., Klinklan, N., Thongyen, T., Veres, M., & Szymanski, W.W. (2017). Deliberation between PM₁ and PM_{2.5} as air quality indicators based on comprehensive characterization of urban aerosols in Bangkok, Thailand. *Particuology*, 35, 1-9.
5. Nuthammachot, N., Phairuangs, W., & Stratoulias, D. (2019). Estimation of carbon emission in the ex-mega rice project, Indonesia based on SAR satellite images. *Appl. Ecol. Environ. Res*, 17(2).
6. Amin, M., Putri, R.M., Handika, R.A., Ullah, A., Goembira, F., Phairuangs, W., ... & Furuuchi, M. (2021). Size-Segregated Particulate Matter Down to PM_{0.1} and Carbon Content during the Rainy and Dry Seasons in Sumatra Island, Indonesia. *Atmosphere*, 12(11), 1441.
7. Phairuangs, W., Suwattiga, P., Chetiyankornkul, T., Hongtieab, S., Limpaseni, W., Ikemori, F., ... & Furuuchi, M. (2019). The influence of the open burning of agricultural biomass and forest fires in Thailand on the carbonaceous components in size-fractionated particles. *Environmental Pollution*, 247, 238-247.
8. Putri, R.M., Amin, M., Suciari, T.F., Faisal, M.A.F., Auliani, R., Ikemori, F., ... & Furuuchi, M. (2021). Site-specific variation in mass concentration and chemical components in ambient nanoparticles (PM_{0.1}) in North Sumatra Province-Indonesia. *Atmospheric Pollution Research*, 12(6), 101062.

9. Li, Z., Tang, Y., Song, X., Lazar, L., Li, Z., & Zhao, J. (2019). Impact of ambient PM_{2.5} on adverse birth outcome and potential molecular mechanism. *Ecotoxicology and Environmental Safety*, 169, 248-254.
10. Yang, L., Zhang, H., Zhang, X., Xing, W., Wang, Y., Bai, P., ... & Tang, N. (2021). Exposure to atmospheric particulate matter-bound polycyclic aromatic hydrocarbons and their health effects: A review. *International journal of environmental research and public health*, 18(4), 2177.
11. Lee, D., Wang, S.Y.S., Zhao, L., Kim, H.C., Kim, K., & Yoon, J.H. (2020). Long-term increase in atmospheric stagnant conditions over northeast Asia and the role of greenhouse gases-driven warming. *Atmospheric Environment*, 241, 117772.
12. Bulot, F.M., Johnston, S.J., Basford, P.J., Easton, N.H., Apetroaie-Cristea, M., Foster, G.L., & Loxham, M. (2019). Long-term field comparison of multiple low-cost particulate matter sensors in an outdoor urban environment. *Scientific reports*, 9(1), 1-13.
13. Thuy, N.T.T., Dung, N.T., Sekiguchi, K., Thuy, L.B., Hien, N.T.T., & Yamaguchi, R. (2018). Mass concentrations and carbonaceous compositions of PM_{0.1}, PM_{2.5}, and PM₁₀ at Hanoi, Vietnam urban locations. *Aerosol and Air Quality Research*, 18(7), 1591-1605.
14. Skuland, T., Grytting, V. S., Låg, M., Jørgensen, R. B., Snilsberg, B., Leseman, D. L., ... & Refsnes, M. (2022). Road tunnel-derived coarse, fine and ultrafine particulate matter: physical and chemical characterization and pro-inflammatory responses in human bronchial epithelial cells. *Particle and fibre toxicology*, 19(1), 1-20.
15. Deng, L., Hao, C., Luo, Y., Yang, P., & Wu, B. (2022). Effect of air and exhaust gas dilutions on ultra-fine particulate emissions in different combustion modes. *Science of The Total Environment*, 843, 156865.
16. Schraufnagel, D. E. (2020). The health effects of ultrafine particles. *Experimental & molecular medicine*, 52(3), 311-317.
17. Phairuang, W., Amin, M., Hata, M., & Furuuchi, M. (2022). Airborne Nanoparticles (PM_{0.1}) in Southeast Asian Cities: A Review. *Sustainability*, 14(16), 10074.
18. Kwon, H. S., Ryu, M. H., & Carlsten, C. (2020). Ultrafine particles: unique physicochemical properties relevant to health and disease. *Experimental & molecular medicine*, 52(3), 318-328.
19. Oberdörster, G., Sharp, Z., Atudorei, V., Elder, A., Gelein, R., Kreyling, W., & Cox, C. (2004). Translocation of inhaled ultrafine particles to the brain. *Inhalation Toxicology*, 16(6-7), 437-445.
20. Yang, M., Jalava, P., Hakkarainen, H., Roponen, M., Leskinen, A., Komppula, M., ... & Dong, G.H. (2022). Fine and ultrafine airborne PM influence inflammation response of young adults and toxicological responses in vitro. *Science of The Total Environment*, 836, 155618.
21. Marval, J., & Tronville, P. (2022). Ultrafine particles: A review about their health effects, presence, generation, and measurement in indoor environments. *Building and Environment*, 108992.
22. HEI. Understanding the health effects of ambient ultrafine particles. In HEI Perspectives HEI Review Panel on Ultrafine Particles; Health Effects Institute: Boston, MA, USA, 2013.
23. Vohra, K., Vodonos, A., Schwartz, J., Marais, E. A., Sulprizio, M. P., & Mickley, L. J. (2021). Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: Results from GEOS-Chem. *Environmental Research*, 195, 110754.
24. Chen, Q., Wang, Q., Xu, B., Xu, Y., Ding, Z., & Sun, H. (2021). Air pollution and cardiovascular mortality in Nanjing, China: evidence highlighting the roles of cumulative exposure and mortality displacement. *Chemosphere*, 265, 129035.
25. Nakharutai, N., Traisathit, P., Thongsak, N., Supasri, T., Srikummoon, P., Thumronglaohapun, S., ... & Chitapanarux, I. (2022). Impact of Residential Concentration of PM_{2.5} Analyzed as Time-Varying Covariate on the Survival Rate of Lung Cancer Patients: A 15-Year Hospital-Based Study in Upper Northern Thailand. *International Journal of Environmental Research and Public Health*, 19(8), 4521.
26. Thiankhaw, K., Chattipakorn, N., & Chattipakorn, S. C. (2022). PM_{2.5} exposure in association with AD-related neuropathology and cognitive outcomes. *Environmental Pollution*, 292, 118320.
27. Arias-Pérez, R. D., Taborda, N. A., Gómez, D. M., Narvaez, J. F., Porras, J., & Hernandez, J. C. (2020). Inflammatory effects of particulate matter air pollution. *Environmental Science and Pollution Research*, 27(34), 42390-42404.
28. Kim, K. H., Kabir, E., & Kabir, S. (2015). A review on the human health impact of airborne particulate matter. *Environment international*, 74, 136-143.
29. Schraufnagel, D.E., Balmes, J.R., Cowl, C.T., De Matteis, S., Jung, S. H., Mortimer, K., ... & Wuebbles, D. J. (2019). Air pollution and noncommunicable diseases: A review by the Forum of International Respiratory Societies' Environmental Committee, Part 2: Air pollution and organ systems. *Chest*, 155(2), 417-426.
30. Shao, L.Y., Wang, W.H., Xing, J.P., Li, W.J., Niu, H.Y., Hou, C., Tang, S.S. (2018). Physicochemical characteristics and effects of airborne particles: Research progress and prospects. *Earth Sci. 43 (5)*, 1691-1708.
31. Han, Y.P., Li, L., Wang, Y., Ma, J. W., Li, P.Y., Han, C., Liu, J.X. (2021). Composition, dispersion, and health risks of bioaerosols in wastewater treatment plants: a review. *Front. Environ. Sci. 15*, 38.
32. Boongla, Y., Chanonmuang, P., Hata, M., Furuuchi, M., & Phairuang, W. (2021). The characteristics of carbonaceous particles down to the nanoparticle range in Rangsit city in the Bangkok Metropolitan Region, Thailand. *Environmental Pollution*, 272, 115940.
33. Inerb, M., Phairuang, W., Paluang, P., Hata, M., Furuuchi, M., & Wangpakapattanawong, P. (2022). Carbon and Trace Element Compositions of Total Suspended Particles (TSP) and Nanoparticles (PM_{0.1}) in Ambient Air of Southern Thailand and Characterization of Their Sources. *Atmosphere*, 13(4), 626.

34. Chomanee, J., Thongboon, K., Tekasakul, S., Furuuchi, M., Dejchanchaiwong, R., & Tekasakul, P. (2020). Physicochemical and toxicological characteristics of nanoparticles in aerosols in southern Thailand during recent haze episodes in lower southeast Asia. *Journal of Environmental Sciences*, 94, 72-80.

35. Cush, K., Koh, K., & Saikawa, E. (2021). Impacts of biomass and garbage burning on air quality in South/Southeast Asia. In *Biomass Burning in South and Southeast Asia* (pp. 3-20). CRC Press.

36. Phairuang, W., Inerb, M., Hata, M., & Furuuchi, M. (2022). Characteristics of trace elements bound to ambient nanoparticles (PM_{0.1}) and a health risk assessment in southern Thailand. *Journal of Hazardous Materials*, 425, 127986.

37. Huang, K., Fu, J. S., Lin, N. H., Wang, S. H., Dong, X., & Wang, G. (2019). Superposition of Gobi dust and Southeast Asian biomass burning: The effect of multisource long-range transport on aerosol optical properties and regional meteorology modification. *Journal of Geophysical Research: Atmospheres*, 124(16), 9464-9483.

38. Xing, L., Bei, N., Guo, J., Wang, Q., Liu, S., Han, Y., ... & Li, G. (2021). Impacts of biomass burning in peninsular Southeast Asia on PM_{2.5} concentration and ozone formation in Southern China During Springtime—A case study. *Journal of Geophysical Research: Atmospheres*, 126(22), e2021JD034908.

39. Zhang, L., Ding, S., Qian, W., Zhao, A., Zhao, S., Yang, Y., ... & Wang, Z. (2022). The Impact of Long-Range Transport of Biomass Burning Emissions in Southeast Asia on Southern China. *Atmosphere*, 13(7), 1029.

40. De Jesus, A. L., Rahman, M. M., Mazaheri, M., Thompson, H., Knibbs, L. D., Jeong, C., ... & Morawska, L. (2019). Ultrafine particles and PM_{2.5} in the air of cities around the world: Are they representative of each other?. *Environment international*, 129, 118-135.

41. Pollution Control Department (2022). National Thailand Ambient Air Quality Standards. Available online <https://www.pcd.go.th/laws/26439>

42. World Health Organization. (2021). WHO global air quality guidelines: particulate matter (PM_{2.5} and PM₁₀), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. World Health Organization. <https://apps.who.int/iris/handle/10665/345329>. License: CC BY-NC-SA 3.0 IGO

43. CEN/TS 16976:2016; Ambient Air-Determination of the Particle Number Concentration of Atmospheric Aerosol. European Committee for Standardization: Brussels, Belgium, 2016

44. Giechaskiel, B., Lahde, T., Suarez-Bertoa, R., Clairotte, M., Grigoratos, T., Zardini, A., Perujo, A., Martini, G. (2018). Particle number measurements in the European legislation and future JRC activities. *Combust. Engines*, 174, 3–16.

45. Hinds, W. C., & Zhu, Y. (2022). *Aerosol technology: properties, behavior, and measurement of airborne particles*. John Wiley & Sons.

46. Chavanaves, S., Fantke, P., Limpaseni, W., Attavanich, W., Panyametheekul, S., Gheewala, S. H., & Prapaspong, T. (2021). Health impacts and costs of fine particulate matter formation from road transport in Bangkok Metropolitan Region. *Atmospheric Pollution Research*, 12(10), 101191.

47. Choochay, C., Pongpiachan, S., Tipmanee, D., Suttinun, O., Deelaman, W., Wang, Q., ... & Cao, J. (2020). Impacts of PM_{2.5} sources on variations in particulate chemical compounds in ambient air of Bangkok, Thailand. *Atmospheric Pollution Research*, 11(9), 1657-1667.

48. Kanjanasiranont, N., Butburee, T., & Peerakiatkhajohn, P. (2022). Characteristics of PM₁₀ Levels Monitored in Bangkok and Its Vicinity Areas, Thailand. *Atmosphere*, 13(2), 239.

49. Narita, D., Oanh, N. T. K., Sato, K., Huo, M., Permadi, D. A., Chi, N. N. H., ... & Pawarmart, I. (2019). Pollution characteristics and policy actions on fine particulate matter in a growing Asian economy: The case of Bangkok Metropolitan Region. *Atmosphere*, 10(5), 227.

50. Ding, X., Kong, L., Du, C., Zhanzakova, A., Wang, L., Fu, H., ... & Cheng, T. (2017). Long-range and regional transported size-resolved atmospheric aerosols during summertime in urban Shanghai. *Science of the Total Environment*, 583, 334-343.

51. Hata, M., Chomanee, J., Thongyen, T., Bao, L., Tekasakul, S., Tekasakul, P., ... & Furuuchi, M. (2014). Characteristics of nanoparticles emitted from burning of biomass fuels. *Journal of Environmental Sciences*, 26(9), 1913-1920.

52. Zhao, T.; Hongtieab, S.; Hata, M.; Furuuchi, M.; Dong, S.; Phairuang, W.; Ge, H.; Zhang, T. Ambient nanoparticles characterization by East and Southeast Asia nanoparticle monitoring network. In *Proceedings of the 9th Asian Aerosol Conference*, Kanazawa, Japan, 24–26 June 2015.

53. Phairuang, W., Suwattiga, P., Hongtieab, S., Inerb, M., Furuuchi, M., & Hata, M. (2021). Characteristics, sources, and health risks of ambient nanoparticles (PM_{0.1}) bound metal in Bangkok, Thailand. *Atmospheric Environment*: X, 12, 100141.

54. Phairuang, W., Hongtieab, S., Suwattiga, P., Furuuchi, M., & Hata, M. (2022). Atmospheric Ultrafine Particulate Matter (PM_{0.1})-Bound Carbon Composition in Bangkok, Thailand. *Atmosphere*, 13(10), 1676.

55. Phairuang, W., Inerb, M., Furuuchi, M., Hata, M., Tekasakul, S., & Tekasakul, P. (2020). Size-fractionated carbonaceous aerosols down to PM_{0.1} in southern Thailand: Local and long-range transport effects. *Environmental Pollution*, 260, 114031.

56. Chomanee, J., Tekasakul, S., Tekasakul, P., & Furuuchi, M. (2018). Effect of irradiation energy and residence time on decomposition efficiency of polycyclic aromatic hydrocarbons (PAHs) from rubber wood combustion emission using soft X-rays. *Chemosphere*, 210, 417-423.

57. Office of Agricultural Economics (OAE), 2020. Agricultural Statistic in Thailand, 2019. Bangkok, Thailand.

58. Phairuang, W., Tekasakul, P., Hata, M., Tekasakul, S., Chomanee, J., Otani, Y., & Furuuchi, M. (2019). Estimation of air pollution from ribbed smoked sheet rubber in Thailand exports to Japan as a pre-product of tires. *Atmospheric Pollution Research*, 10(2), 642-650.

59. Samiksha, S., Kumar, S., & Sunder Raman, R. (2021). Two-year record of carbonaceous fraction in ambient PM_{2.5} over a forested location in central India: temporal characteristics and estimation of secondary organic carbon. *Air Quality, Atmosphere & Health*, 14(4), 473-480.

60. Zioła, N., Banasiak, K., Jabłońska, M., Janeczek, J., Błaszczał, B., Klejnowski, K., & Mathews, B. (2021). Seasonality of the Airborne Ambient Soot Predominant Emission Sources Determined by Raman Microspectroscopy and Thermo-Optical Method. *Atmosphere*, 12(6), 768.

61. Rana, A., Jia, S., & Sarkar, S. (2019). Black carbon aerosol in India: A comprehensive review of current status and future prospects. *Atmospheric Research*, 218, 207-230.

62. Zhang, Z. W., Shahpoury, P., Zhang, W., Harner, T., & Huang, L. (2022). A new method for measuring airborne elemental carbon using PUF disk passive samplers. *Chemosphere*, 299, 134323.

63. Pani, S. K., Lee, C. T., Griffith, S. M., & Lin, N. H. (2022). Humic-like substances (HULIS) in springtime aerosols at a high-altitude background station in the western North Pacific: Source attribution, abundance, and light-absorption. *Science of The Total Environment*, 809, 151180.

64. Tang, J., Wang, J., Zhong, G., Jiang, H., Mo, Y., Zhang, B., ... & Zhang, G. (2021). Measurement report: Long-emission-wavelength chromophores dominate the light absorption of brown carbon in aerosols over Bangkok: impact from biomass burning. *Atmospheric Chemistry and Physics*, 21(14), 11337-11352.

65. Wonaschütz, A., Hitzenberger, R., Bauer, H., Pouresmaeil, P., Klatzer, B., Caseiro, A., & Buxbaum, H. (2009). Application of the integrating sphere method to separate the contributions of brown and black carbon in atmospheric aerosols. *Environmental science & technology*, 43(4), 1141-1146.

66. Cui, M., Xu, Y., Yu, B., Yan, C., Li, J., Zheng, M., & Chen, Y. (2023). Experimental simulation characterizes carbonaceous matter emitted from residential coal and biomass combustion. *Atmospheric Environment*, 293, 119447.

67. Malmborg, V., Eriksson, A., Gren, L., Török, S., Shamus, S., Novakovic, M., ... & Pagels, J. (2021). Characteristics of BrC and BC emissions from controlled diffusion flame and diesel engine combustion. *Aerosol Science and Technology*, 55(7), 769-784.

68. Runa, F., Islam, M., Jeba, F., & Salam, A. (2022). Light absorption properties of brown carbon from biomass burning emissions. *Environmental Science and Pollution Research*, 29(14), 21012-21022.

69. Hallquist, M., Wenger, J. C., Baltensperger, U., Rudich, Y., Simpson, D., Claeys, M., ... & Wildt, J. (2009). The formation, properties, and impact of secondary organic aerosol: current and emerging issues. *Atmospheric chemistry and physics*, 9(14), 5155-5236.

70. Amin, M., Handika, R. A., Putri, R. M., Phairuang, W., Hata, M., Tekasakul, P., & Furuuchi, M. (2021). Size-segregated particulate mass and carbonaceous components in roadside and riverside environments. *Applied Sciences*, 11(21), 10214.

71. Houghton, J. T., Ding, Y. D. J. G., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., ... & Johnson, C. A. (Eds.). (2001). *Climate change 2001: the scientific basis: contribution of Working Group I to the third assessment report of the Intergovernmental Panel on Climate Change*. Cambridge university press.

72. Kelesidis, G.A., Bruun, C.A., & Pratsinis, S.E. (2021). The impact of organic carbon on soot light absorption. *Carbon*, 172, 742-749.

73. Gustafsson, Ö., & Ramanathan, V. (2016). Convergence on climate warming by black carbon aerosols. *Proceedings of the National Academy of Sciences*, 113(16), 4243-4245.

74. Irei, S., Takami, A., Sadanaga, Y., Nozoe, S., Yonemura, S., Bandow, H., & Yokouchi, Y. (2016). Photochemical age of air pollutants, ozone, and secondary organic aerosol in transboundary air observed on Fukue Island, Nagasaki, Japan. *Atmospheric Chemistry and Physics*, 16(7), 4555-4568.

75. Han, Y., Chen, Y., Feng, Y., Shang, Y., Li, J., Li, Q., & Chen, J. (2022). Existence and formation pathways of high-and low-maturity elemental carbon from solid fuel combustion by a time-resolved study. *Environmental Science & Technology*, 56(4), 2551-2561.

76. Falk, J., Korhonen, K., Malmborg, V. B., Gren, L., Eriksson, A. C., Karjalainen, P., ... & Kristensen, T. B. (2021). Immersion freezing ability of freshly emitted soot with various physico-chemical characteristics. *Atmosphere*, 12(9), 1173.

77. Zhang, Y., Peng, Y., Song, W., Zhang, Y. L., Ponsawansong, P., Prapamontol, T., & Wang, Y. (2021). Contribution of brown carbon to the light absorption and radiative effect of carbonaceous aerosols from biomass burning emissions in Chiang Mai, Thailand. *Atmospheric Environment*, 260, 118544.

78. Singh, G. K., Choudhary, V., Rajeev, P., Paul, D., & Gupta, T. (2021). Understanding the origin of carbonaceous aerosols during periods of extensive biomass burning in northern India. *Environmental Pollution*, 270, 116082.

79. Tao, J., Zhang, Z., Zhang, L., Huang, D., & Wu, Y. (2021). Quantifying the relative importance of major tracers for fine particles released from biofuel combustion in households in the rural North China Plain. *Environmental Pollution*, 268, 115764.

80. Yang, H. H., Dhital, N. B., Wang, L. C., Hsieh, Y. S., Lee, K. T., Hsu, Y. T., & Huang, S. C. (2019). Chemical characterization of fine particulate matter in gasoline and diesel vehicle exhaust. *Aerosol and Air Quality Research*, 19(6), 1349-1449.

81. Thumanu, K., Pongpiachan, S., Ho, K. F., Lee, S. C., & Sompongchaiyakul, P. (2009). Characterization of organic functional groups, water-soluble ionic species and carbonaceous compounds in PM₁₀ from various emission sources in Songkhla Province, Thailand. *WIT Trans. Ecol. Environ.*, 123, 295-306.

82. Saarikoski, S., Timonen, H., Saarnio, K., Aurela, M., Järvi, L., Keronen, P., ... & Hillamo, R. (2008). Sources of organic carbon in fine particulate matter in northern European urban air. *Atmospheric chemistry and physics*, 8(20), 6281-6295.

83. Guo, Y. (2015). Carbonaceous aerosol composition over northern China in spring 2012. *Environmental Science and Pollution Research*, 22(14), 10839-10849.

84. Han, Y. M., Chen, L. W., Huang, R. J., Chow, J. C., Watson, J. G., Ni, H. Y., ... & Cao, J. J. (2016). Carbonaceous aerosols in megacity Xi'an, China: Implications for comparison of thermal/optical protocols. *Atmospheric Environment*, 132, 58-68.

85. Moran, J., Nasuwan, C., & Poocharoen, O.O. (2019). A review of the haze problem in Northern Thailand and policies to combat it *Environmental Science & Policy*, 97, 1-15.

86. Phairuang, W., Hata, M., & Furuuchi, M. (2017). Influence of agricultural activities, forest fires and agro-industries on air quality in Thailand. *Journal of Environmental Sciences*, 52, 85-97.

87. Janta, R., Sekiguchi, K., Yamaguchi, R., Sopajaree, K., Plubin, B., & Chetiyankornkul, T. (2020). Spatial and temporal variations of atmospheric PM₁₀ and air pollutants concentration in upper Northern Thailand during 2006-2016. *Applied Science and Engineering Progress*, 13(3), 256-267.

88. Punsompong, P., Pani, S. K., Wang, S. H., & Pham, T. T. B. (2021). Assessment of biomass-burning types and transport over Thailand and the associated health risks. *Atmospheric Environment*, 247, 118176.

89. Vongruang, P., & Pimonsree, S. (2020). Biomass burning sources and their contributions to PM10 concentrations over countries in mainland Southeast Asia during a smog episode. *Atmospheric Environment*, 228, 117414.

90. Samae, H., Tekasakul, S., Tekasakul, P., & Furuuchi, M. (2021). Emission factors of ultrafine particulate matter (PM<0.1μm) and particle-bound polycyclic aromatic hydrocarbons from biomass combustion for source apportionment. *Chemosphere*, 262, 127846.

91. Samae, H., Tekasakul, S., Tekasakul, P., Phairuang, W., Furuuchi, M., & Hongtieab, S. (2022). Particle-bound organic and elemental carbons for source identification of PM< 0.1 μm from biomass combustion. *Journal of Environmental Sciences*, 113, 385-393.

92. Kumar, P., Morawska, L., Birmili, W., Paasonen, P., Hu, M., Kulmala, M., Harrison, R.M., Norford, L., & Britter, R (2014). Ultrafine particles in cities. *Environmental International*, 66, 1-10.

93. Kumar, P., Pirjola, L., Ketzel, M., & Harrison, R.M. (2013). Nanoparticle emissions from 11 non-vehicle exhaust sources—a review. *Atmospheric Environment*, 67, 252-277.

94. Kliengchuay, W., Worakhunpiset, S., Limpanont, Y., Meeyai, A. C., & Tantrakarnapa, K. (2021). Influence of the meteorological conditions and some pollutants on PM₁₀ concentrations in Lamphun, Thailand. *Journal of Environmental Health Science and Engineering*, 19(1), 237-249.

95. Panyametheekul S., Kangwansupamonkon W., Anuchitchanchai O., & Pongkiatkul P. (2022). Final report "Research Program on Integrated Technology for mitigating PM_{2.5}: A case study in Bangkok Metropolitan Region (BMR)". National Research Council Fund. September 2022.

96. Ahmad, M., Manjantrarat, T., Rattanawongsa, W., Muensri, P., Saenmuangchin, R., Klamchuen, A., ... & Panyametheekul, S. (2022). Chemical Composition, Sources, and Health Risk Assessment of PM_{2.5} and PM₁₀ in Urban Sites of Bangkok, Thailand. *International Journal of Environmental Research and Public Health*, 19(21), 14281.

97. Fold, N.R., Allison, M.R., Wood, B.C., Thao, P.T., Bonnet, S., Garivait, S., ... & Pengjan, S. (2020). An assessment of annual mortality attributable to ambient PM_{2.5} in Bangkok, Thailand. *International Journal of Environmental Research and Public Health*, 17(19), 7298.

98. Pothirat, C., Chaiwong, W., Liwsrisakun, C., Bumroongkit, C., Deesomchok, A., Theerakittikul, T., ... & Phetsuk, N. (2021). The short-term associations of particular matters on non-accidental mortality and causes of death in Chiang Mai, Thailand: a time series analysis study between 2016-2018. *International journal of environmental health research*, 31(5), 538-547.

99. Thao, N. N. L., Pimonsree, S., Prueksakorn, K., Thao, P. T. B., & Vongruang, P. (2022). Public health and economic impact assessment of PM2.5 from open biomass burning over countries in mainland Southeast Asia during the smog episode. *Atmospheric Pollution Research*, 13(6), 101418.

100. Uttajug, A., Ueda, K., Oyoshi, K., Honda, A., & Takano, H. (2021). Association between PM₁₀ from vegetation fire events and hospital visits by children in upper northern Thailand. *Science of The Total Environment*, 764, 142923.

101. Uttajug, A., Ueda, K., Seposo, X. T., Honda, A., & Takano, H. (2022). Effect of a vegetation fire event ban on hospital visits for respiratory diseases in Upper Northern Thailand. *International journal of epidemiology*, 51(2), 514-524.

102. Dahari, N., Muda, K., Latif, M. T., & Hussein, N. (2021). Studies of atmospheric PM_{2.5} and its inorganic water-soluble ions and trace elements around Southeast Asia: a review. *Asia-Pacific Journal of Atmospheric Sciences*, 57(2), 361-385.

103. Tham, J., Sarkar, S., Jia, S., Reid, J. S., Mishra, S., Sudiana, I. M., ... & Liya, E. Y. (2019). Impacts of peat-forest smoke on urban PM_{2.5} in the Maritime Continent during 2012–2015: Carbonaceous profiles and indicators. *Environmental Pollution*, 248, 496-505.

104. Feng, X.L., Sfao, L.Y., Xi, C.X., Jones, T., Zhang, D.Z., Beru Be, K. (2020). Particle-induced oxidative damage by indoor size-segregated particulate matter from coal-burning homes in the Xuanwei lung cancer epidemic area, Yunan Province, China. *Chemosphere* 256, 127058.

105. Huo, M., Sato, K., Kim Oanh, N.T., Mettasithikorn, M., Leamlaem, M., Permadi, D.A., Narita, D., Garivait, H., Laogul, W. & Akimoto, H. (2022). Chemical characteristics and deposition amounts of carbonaceous species and inorganic ions in precipitation in the Bangkok metropolitan Region. *Atmospheric Environment*, 291, 119393.
106. Rao, L.F., Zhang, L.Y., Wang, X.Z., Xie, T.T., Zhou, S.M., Lu, S.L., Liu, X.C., Lu, H., Xiao, K., Wang, W.Q., Wang, Q.Y. (2020). Oxidative potential induced by ambient particulate matters with acellular assays: a review. *Various Technol. Environ. Pollut. Control* 8, 1410.
107. Hata, M., Furuuchi, M., Dong, S., Phairuang, W., Ge, H., Zhang, T. et al. (2015). Ambient nanoparticles characterization by East and Southeast Asia nanoparticle monitoring network. In *Proceedings of the 9th Asian Aerosol Conference*, Kanazawa, Japan, June 24-26.