Carbon and Trace Element Compositions of Total Suspended Particles (TSP) and Nanoparticles (PM\textsubscript{0.1}) in Ambient Air of Southern Thailand and Characterization of Their Sources

Muanfun Inerb \(^{1}\), Worradorn Phairuang \(^{2,3,*}@\), Phakphum Paluang \(^{3}\), Mitsuhiko Hata \(^{2}\), Masami Furuuchi \(^{1,2}\) and Prasit Wangpakapattanawong \(^{4}\)

Abstract: The concentration of total suspended particles (TSP) and nanoparticles (PM\textsubscript{0.1}) over Hat Yai city, Songkhla province, southern Thailand was measured in 2019. Organic carbon (OC) and elemental carbon (EC) were evaluated by carbon aerosol analyzer (IMPROVE-TOR) method. Thirteen trace elements including Al, Ba, K, Cu, Cr, Fe, Mg, Mn, Na, Ni, Ti, Pb, and Zn were evaluated by ICP-OES. Annual average TSP and PM\textsubscript{0.1} mass concentrations were determined to be 58.3 ± 7.8 and 10.4 ± 1.2 µg/m\(^3\), respectively. The highest levels of PM occurred in the wet season with the corresponding values for the dry seasons being lower. The averaged OC/EC ratio ranged from 3.8–4.2 (TSP) and 2.5–2.7 (PM\textsubscript{0.1}). The char to soot ratios were constantly less than 1.0 for both TSP and PM\textsubscript{0.1}, indicating that land transportation is the main emission source. A principal component analysis (PCA) revealed that road transportation, industry, and biomass burning are the key sources of these particles. However, PM arising from Indonesian peatland fires causes an increase in the carbon and trace element concentrations in southern Thailand. The findings make useful information for air quality management and strategies for controlling this problem, based on a source apportionment analysis.

Keywords: air quality management; biomass burning; carbon; PCA; PM\textsubscript{0.1}; trace elements

1. Introduction

Airborne particulate matter (PM), which is thought to be strongly associated with adverse human health effects [1,2] and global warming [3,4] has recently become a subject of great interest. Studies of PM in Thailand and Asian countries are currently based on measurements of PM\textsubscript{10} and PM\textsubscript{2.5} through ground-based monitoring and mathematical modeling [5–11]. However, data on the abundance, sources, monthly distribution together with seasonal variations in the concentrations of carbon and elements in the nano-size range (PM\textsubscript{0.1}; particles of diameter ≤ 0.1 µm or 100 nm) and total suspended particles (TSP) remain scarce in developing countries, including Thailand and its neighboring countries [12–14].

Particle-bound total carbon (TC) can be separated into two types, i.e., organic carbon (OC) and elemental carbon (EC) or black carbon (BC) [15]. The term BC is loosely equivalent to EC liable on the analytical method being used [16,17]. The distribution of carbon portions, which basically represent the chemical, optical, and physical appearances of carbon material in PM, varies with time and location [18–20]. Knowledge of carbon...
composition in atmospheric PM is also vital for identifying emission sources and control measures for PM and carbon-containing materials, the two main causes of air pollution and global warming [21,22].

In addition, particle-bound trace elements have important effects regarding human health. The toxic elements increase both carcinogenic and non-carcinogenic risk assessments in humans [23–25]. Although they represent a small share of the total mass concentration of PM, trace elements are of particular concern because that have a health risk to humans [23,26,27]. Concerning elements, Mn, Al, and Fe are characteristically found in the crust earth, whereas Cu, Cr, Pb, and Zn are resulting from anthropogenic sources [5,13]. Inhaling toxic elements including Cd, Zn, Cr, Pb, and Ni could be harmful to human health, causing various diseases, particularly cancer [28–30].

To the best of the authors’ knowledge, only a few limited studies of the distribution of PM$_{0.1}$ and carbon material in Thailand are reported [12,16]. Previous studies reported only data on OC/EC in the upper part of Thailand and did not report information on the contribution and source apportionment for the PM$_{0.1}$ fraction. Moreover, information concerning particle-bound trace elements in the PM$_{0.1}$ fraction is still lacking in Thailand. Receptor modeling, e.g., principal component analyses (PCA) has been used to identify the emission sources of chemical species in the PM$_{10}$ and PM$_{2.5}$ fractions in Thailand [7,24], although PCA continues to be lacking in PM$_{0.1}$ fraction in Thailand.

Like other cities in Thailand and other Southeast Asian countries, the economy of Hat Yai has grown rapidly in recent years. The city of Hat Yai also suffers from air pollution. Thus, the objectives of this study were (1) to investigate the characteristics of atmospheric OC, EC, and metals in the PM$_{0.1}$ and TSP fractions, (2) to determine the emission sources by PCA, and (3) to identify the possible sources of this pollution in Hat Yai city, the economic capital of the Songkhla province. These relationships would be valuable for identifying potential emission sources in the area and could lead to better air quality management leading to a sustainable city and society.

2. Methodology

2.1. Sampling Site

Hat Yai is an economic city in the southern part of Thailand, covering an area of approximately 852.8 square kilometers and with a population of around 0.6 million. The key economic activities of Hat Yai are related to farming production, i.e., palm oil and para-rubber [31,32]. PM$_{0.1}$ and TSP samples were collected on the top floor of an 8-floor building, which is part of the Faculty of Engineering, Prince of Songkla University (PSU; 7°00′21.8″ N 100°30′08.6″ E). The site is located approximately 30 m above ground level, and is not expected to be influenced by ground-level activities. The monitoring station is located at a distance of approximately 4 km from the commercial area, where household and transportation are not dense. Figure 1 shows the monitoring site in this study. During the monitoring periods, detailed weather information was collected, including relative humidity, rainfall, temperature, pressure, and wind speed was also carefully measured, as shown in Table 1. The weather in southern Thailand can be separated into two seasons depending on the monsoons, namely, a dry season from January to April, and a wet season (or monsoon season) from May to December [33].
Figure 1. Location of sampling site, in Hat Yai, Songkhla, southern Thailand; Prince of Songkla University (PSU).

Table 1. Meteorological parameters during different sampling times.

| Sampling Period | Temperature (°C) | RH (%) | Wind Speed (m/s) | Pressure (hPa) | Rainfall (mm) |
|----------------|-----------------|--------|-----------------|----------------|--------------|
| Jan–April, 2019 | 24.7–28.3 (26.8) | 65–82 (74) | 0.98–1.84 (1.40) | 913–1009 (977) | 28.6–215.8 (117.9) |
| May–Aug, 2019   | 27.0–28.3 (27.9) | 77–81 (78) | 0.75–1.26 (0.99) | 975–1008 (1000) | 75.4–245.2 (153.2) |

2.2. Cascade Sampler for PM$_{0.1}$ and High-Volume Sampler for TSP

For the air sampling, PM$_{0.1}$ samples were collected on quartz fiber filters (QFF) (2500 QAT-UP, Pall Corp., pure quartz, size 55 mm, New York, NY, USA) using a PM$_{0.1}$ cascade sampler that operated at a flow rate of 40 L/min. Samples were collected for periods of 48 hrs. from January to August 2019. Samples were collected for two consecutive days in each week of each month. A total of 32 PM$_{0.1}$ samples were collected and examined in this study. Moreover, TSP was collected with a portable high-volume sampler (Shibata, Japan). The high-volume sampler contained an air inlet at 500 L/min (2500 QAT-UP, Pall Corp., pure quartz, size 110 mm, New York, NY, USA). To confirm the mass concentration, non-repeated ANOVA was performed for determining the mass concentrations of TSP and PM$_{0.1}$ evaluated at the sampling site, and significant differences ($p < 0.05$) were found between seasons. The annual averaged TSP and PM$_{0.1}$ concentrations were computed by dividing the mass of all the monthly averaged TSP and PM$_{0.1}$ by the volume of the air they were taken from.

For TSP sampling, 24-h samples were collected from January to August 2019. Samples were collected four times per month, in parallel with PM$_{0.1}$ samples. A total of 32 TSP samples were collected in this study. QFFs were weighed twice before and after sampling. Before weighing, QFFs were pre-baked in an electric furnace at 350 °C for 1 h to eliminate possible carbon impurities [19,20]. QFFs were balanced for 48 h in a PM$_{2.5}$ chamber with
Atmosphere 2022, 13, 626

a controlled relative humidity of 35 ± 5% as well as a temperature of 21.5 ± 1.5 °C [18]. Travel blank filters were also arranged to decrease the effect of any contamination, i.e., the adsorption of volatile organic components during sampling and filter transportation. All filters that were used were stored at a temperature below −20 °C in a freezer until chemical analysis [30].

2.3. Carbon Analysis Method

Carbon compositions in the PM were determined using a Carbon Aerosol Analyzer (Model 5L, Sunset Laboratory, Tigard, OR, USA) at Kanazawa University, Japan and the measures followed the Interagency Monitoring of Protected Visual Environments-Thermal/Optical Reflectance (IMPROVE-TOR method) [34]. QFF sample parts were punched using a 15 mm × 10 mm rectangular cutter before the carbon analysis. Briefly, four OC fractions OC1, OC2, OC3, and OC4 at temperature 120 °C, 250 °C, 450 °C, and 550 °C were analyzed in a 100% helium (He) atmosphere, while the EC fractions EC1, EC2, and EC3 at temperature 550 °C, 700 °C and 800 °C were measured in O2 (2%) and He (98%) carrier gas. Additionally, the pyrolyzed organic carbon fraction (PyC) was determined at 550 °C between the split time of EC and OC [16,17]. OC and EC are defined respectively as follows: OC = OC1 + OC2 + OC3 + OC4 + PyC as well as EC = EC1 + EC2 + EC3-PyC.

Moreover, Char-EC refers to EC1-PyC and Soot-EC is EC2 + EC3 [15]. In the following studies, char, soot, and char/soot ratios were used as indices of the influence of biomass combustion and fossil fuel together with OC, EC, and OC/EC ratios [19]. The quality assurance (QA) and quality control (QC) were calibrated with blank filters and a reference standard. The calibration standard for the carbon analysis was TC, as analyzed by sucrose (C12H22O11) (196-00015, Wako Pure Chemical Industries, Ltd., Osaka, Japan). Minimum detection limits (MDLs) were determined by blank filters. The averaged MDL values of OC and EC in PM0.1 (n = 3) in blank filters were 0.2 and 0.2 µg/m3, as well as those in TSP (n = 3) were 0.2 and 0.1 µg/m3, respectively. The blank filters month was subtracted from the samples for correction of the carbon species in each month.

2.4. Trace Elements Analysis

All samples were determined for 13 trace elements including Al, Ba, Cu, Na, Ni, K, Cr, Mg, Ti, Fe, Mn, Zn, and Pb. The trace element concentrations were measured by an inductively coupled plasma optical emission spectrometer (ICP-OES; PerkinElmer, AVIO 500) at Prince of Songkla University, Thailand. Briefly, one half of the QFF was cut into small pieces and immersed in 2 mL of 65% HNO3 for 1 h, in a water bath at a temperature of 95 °C. Then, the 0.5 mL of 30% H2O2 was added for 30 min [30]. The samples were allowed to cool to room temperature, filtered through Whatman No.1 paper, and then diluted to obtain a 10 mL solution [23]. The procedure for the extraction and analysis of trace elements followed the US-EPA method 6010D (SW-846) and the US-EPA method IO-3.1 (compendium of methods for the determination of inorganic compounds in ambient air). Several sampling filters (n = 5) were tested by dividing into two parts, first, the part was extracted normally, for the second part after extraction, the filter residue was extracted again and compared with a blank filter. Quality assurance (QA) and quality control (QC) were confirmed by digesting and analyzing the standards and blanks in common with each sample batch. The quantification was compared by a standard curve (R^2 > 0.99) [23,30].

2.5. Source Apportionment Analysis

The PM0.1 and TSP as well as their carbon and trace elements concentration were conducted by using the OriginPro 8.6 program and SPSS (version 22). All PCA were used to categorize possible patterns in the data [35]. The findings show the existence of a correlation between PM0.1 and TSP-bound carbon as well as trace elements and other factors (sources). To identify the specific sources, PCA was run using monthly data. The Kaiser–Meyer–Olkin’s (KMO) test was performed and KMO value > 0.6 was obtained, which suggested that all data were suitable for PCA [36]. In each chemical species, greater
than 80% of the samples found a signal-to-noise ratio (S/N) of unity and were carefully chosen as variables in the analysis [30].

2.6. Hot Spots and Backward Trajectories

Hotspots or active fires from open burning were derived from the satellite imagery, namely, moderate resolution imaging spectroradiometer (MODIS). The resolution of the hot spots is represented at a 1 km$^2$ resolution for each spot. This study analyzes the five-day isentropic back-trajectories of air masses to classify the most likely biomass burning source regions influencing the measured PMs at the selection sites in Hat Yai, Thailand. Five days were likely to be sufficient time for most trajectories to pass through the possible source regions in SEA. Back-trajectories were produced using the Hybrid Single-Particle Lagrangian Integrated Trajectory model version 4 (HYSPLIT-4) [37]. It was accessed and run through the NOAA website (https://www.ready.noaa.gov/HYSPLIT.php; accessed on 9 March 2022). As shown in an earlier report, the ending height from 500 m AGL is calculated liable on the reference of the backward trajectory in Thailand [38].

3. Results and Discussion

3.1. PM$_{0.1}$ and TSP Mass Concentrations

Figure 2 displays the PM$_{0.1}$ and TSP mass concentrations for the sampling period. The averaged PM$_{0.1}$ and TSP mass concentrations were 10.4 ± 1.2 and 58.3 ± 7.8 µg/m$^3$, respectively. These TSP mass concentrations are lower than the TSP standard value from the WHO and Thailand guidelines (100 and 330 µg/m$^3$, respectively) representing that the sources of PM emission were lower around the sampling site. Nevertheless, there is no standard for ambient PM$_{0.1}$ in Thailand and other countries. The wet season has a higher mass concentration of PM$_{0.1}$ and TSP than the dry season. The highest PM$_{0.1}$ and TSP were found in August, as 12.7 ± 2.0 and 73.5 ± 18.4 µg/m$^3$, respectively. The level of PM$_{0.1}$ ranges from 14.5 to 20.7% that of TSP. The high mass concentration during the wet season is related to transboundary pollution from other countries. Particulate pollution during the haze period over southern Thailand was affected by peat-land fires in Indonesia [19,39]. High levels of PM pollution transport affect the air quality in southern Thailand almost annually during June–August [19]. In 2019, the high level of PM$_{0.1}$ and TSP found in August at the sampling site indicates that long-range atmospheric transport accounts for an increased level of particulate matter at this time.

![Figure 2. Average mass concentrations of PM$_{0.1}$ and TSP in Hat Yai, Songkhla, Thailand during dry and wet seasons, 2019.](image-url)
The averaged PM$_{0.1}$ level of 10.4 ± 1.2 µg/m$^3$ was lower than the corresponding values for Bangkok, and Chiang Mai, Thailand, Hanoi, Vietnam, and North Sumatra, Indonesia [16,17,20]. However, the PM$_{0.1}$ levels were roughly four times higher than those in other urban areas in Asia (Table 2). The mass concentration in Kanazawa, Japan is 4.7, and 2.6–5.4 µg/m$^3$ in other cities in Japan [40,41]. In other Asian cities, Chen et al. (2010) [42] described that the PM$_{0.1}$ in an urban-traffic area in Taiwan was 1.4 ± 0.6 µg/m$^3$. However, Ding et al. (2017) [43] reported high levels of PM$_{0.1}$ in a municipal area of Shanghai, China. In Kolkata, India, the PM$_{0.1}$ level reaches levels as high as 8.8 ± 0.6 µg/m$^3$ during episodes of biomass fires [44]. In the United Kingdom (UK), the mass concentration of PM$_{0.1}$ based on the estimated PM$_{10}$ fraction for each emission source are as follows: waste incineration (4%), industrial combustion (7%), energy combustion in industries (8%), industrial off-road mobile machinery (9%), agriculture (9%), non-road transportations (14%), and production process (15%) [21]. Moreover, the PM$_{0.1}$ mass concentration is very low in western countries. Venecek et al. (2019) [45] studied the county levels of PM$_{0.1}$ across the USA and found that PM$_{0.1}$ surpassed 2 µg/m$^3$ during a smog period. However, the annual average mass concentration of ambient PM$_{0.1}$ is very small (around 1 µg/m$^3$). Particle number concentration (PNC) is widely used to measure PM$_{0.1}$ due to a small fraction in many cities [46]. In south part of Thailand, there was a fluctuation, probably related to local emission sources, especially, wood biomass burning in ago-industries [31].

### Table 2. Mass concentration of the PM$_{0.1}$ fraction at different locations in Asia (µg/m$^3$).

| Location                     | Site Description | Concentration | References |
|------------------------------|------------------|---------------|------------|
| Hat Yai, Thailand            | Mixed            | 10.4 ± 1.2    | This study |
| Bangkok, Thailand            | Urban-traffic    | 14.8 ± 2.0    | [16]       |
| Chiang Mai, Thailand         | Suburban         | 25.2 ± 4.7    | [16]       |
| Hanoi, Vietnam               | Urban-traffic    | 6.0 ± 2.7     | [17]       |
| North Sumatra, Indonesia     | Urban-traffic    | 16.8 ± 4.0    | [20]       |
| North Sumatra, Indonesia     | Rural            | 7.1 ± 2.5     | [20]       |
| Kanazawa, Japan              | Mixed            | 4.7           | [40]       |
| Kanazawa, Japan              | Mixed            | 2.6 ± 1.2     | [41]       |
| Suzu, Japan                  | Rural            | 2.8 ± 0.9     | [41]       |
| Toyama, Japan                | Urban            | 5.4 ± 1.6     | [41]       |
| Hsinchu, Taiwan              | Urban-traffic    | 2.2 ± 0.6     | [42]       |
| Shanghai, China              | Urban            | 13.4          | [43]       |
| Kolkata, India               | Urban            | 8.8 ± 2.6     | [44]       |

### 3.2. Carbon Components in PM$_{0.1}$ and TSP

The seasonal and total averaged carbon species occurrence in PM$_{0.1}$ and TSP from January to August 2019, including OC, EC, Char-EC, Soot-EC, and TC concentrations, OC/EC, and Char-EC/Soot-EC ratio are listed in Table 2. The wet season showed a higher carbon content than the dry season both for PM$_{0.1}$ and TSP. The averages for Char-EC in the PM$_{0.1}$ were high in the wet season compared to the dry season. It is interesting that Soot-EC in the TSP was quite similar in the wet season, although a difference in PM$_{0.1}$ was observed. Almost every year in the wet season in southern Thailand, a southeast-Asian haze with elevated PM rises from Sumatra and the Kalimantan islands, Indonesia and often blankets southern Thailand during June–September [7,47]. Tham et al. (2019) [48] reported that during a PM$_{2.5}$ episode from peat-land fires on Sumatra Island, a large amount of carbon species, i.e., PyC and Soot-EC was released into the atmosphere.

### 3.3. OC/EC and Char-EC/Soot-EC Ratios

The ratio of OC/EC can be used to identify sources of emitted carbonaceous aerosols. OC/EC ratios from diesel engines, coal burning, and biomass fires are different. Biomass fires have higher OC/EC ratios, while fossil fuel burning results in lower ratios [12,44]. Pongpiachan et al. (2014) [49] described a ratio of OC/EC for biomass burning of ~7–8, while Allen et al. (2001) [50] and Pio et al. (2011) [51] reported a value of ~1–2 from fossil
fuel burning. Table 3 displays the annual ratios of OC/EC in PM$_{0.1}$ and TSP in Hat Yai city, which have relatively higher values in the wet season (2.6 ± 0.7 and 4.2 ± 1.5 for PM$_{0.1}$ and TSP, respectively).

Table 3. Average seasonal and total concentrations of OC, EC, Char-EC, Soot-EC, TC (µg/m$^3$) and OC/EC, Char-EC/Soot-EC ratio in Hat Yai.

| Size | Season | OC     | EC     | Char-EC | Soot-EC | TC     | OC/EC (−) | Char-EC/Soot-EC (−) |
|------|--------|--------|--------|---------|---------|--------|-----------|---------------------|
| PM$_{0.1}$ | Dry    | 1.6 ± 0.2 | 0.7 ± 0.1 | 0.1 ± 0.1 | 0.5 ± 0.1 | 2.3 ± 0.4 | 2.5 ± 0.5 | 0.3 ± 0.2 |
|       | Wet    | 4.9 ± 0.9 | 1.8 ± 0.5 | 0.4 ± 0.1 | 1.4 ± 0.1 | 6.7 ± 0.3 | 2.7 ± 0.7 | 0.3 ± 0.2 |
| Total | Dry    | 3.3 ± 0.6 | 1.2 ± 0.4 | 0.3 ± 0.1 | 0.9 ± 0.1 | 4.5 ± 0.4 | 2.6 ± 0.6 | 0.3 ± 0.2 |
| TSP   | Dry    | 5.0 ± 1.2 | 1.4 ± 0.4 | 0.4 ± 0.2 | 1.1 ± 0.3 | 6.4 ± 2.9 | 3.8 ± 1.6 | 0.3 ± 0.1 |
|       | Wet    | 5.5 ± 3.6 | 1.5 ± 0.9 | 0.3 ± 0.2 | 1.1 ± 0.3 | 7.0 ± 4.2 | 4.2 ± 1.5 | 0.2 ± 0.1 |
| Total |        | 5.3 ± 4.6 | 1.4 ± 1.0 | 0.3 ± 0.2 | 1.1 ± 0.3 | 6.7 ± 5.4 | 4.0 ± 1.3 | 0.3 ± 0.2 |

The ratios of OC/EC reported in this result are in general agreement with the results described in other studies [32,40]. The ratios of OC/EC for PM$_{0.1}$ in this study are higher than those from Taiwan, which ranged from 0.2 to 1.7 [40,52], but lower than the values for Hanoi, Vietnam, which ranged from 3.8 to 5.9 [46]. In this study, the ratios of OC/EC in southern Thailand were nearly constant, which suggests that the same emission sources might contribute to OC and EC. However, the OC/EC ratios in TSP were in the range of 1.9–6.3 indicating the influence of more varying emission sources than in PM$_{0.1}$ (OC/EC, 1.6–3.5). Thumanu et al. (2009) [32] discussed the OC/EC ratios in Songkhla province in a study of the sources of PM$_{10}$. The measured OC/EC ratios were as follows: 1.2–1.3 (road traffic), 1.6–2.3 (industrial sources), and 3.9–4.2 (biomass fires). These results show that the origin of the higher OC/EC ratios in PM$_{0.1}$ and TSP could be a variety of sources, i.e., the industrial sector and biomass burning that contributes considerably to the carbon composition in the ambient air above southern Thailand. OC, which dominates especially in PM$_{0.1}$, may be largely attributed to biomass burning. Conversely, the ratio of OC/EC depends on three main causes for correctly classifying the emission source. The three issues are primary emission sources, secondary organic aerosols (SOA), and wet scavenging [53].

Unlike the OC/EC ratio, the Char-EC/Soot-EC ratio is distinct for different primary sources and can be used to identify the source at the origin. Only two factors can affect the char/soot ratio: the wet deposition level and primary emission source. A higher ratio of char/soot is indicative of biomass fires associated with the influence of Char-EC to the total EC content; while ratios smaller than 1.0 indicate that soot from the motor exhaust is a major contributor to the total EC content [15]. The char/soot ratio in the PM$_{0.1}$ fraction in the present study was constantly smaller than 1.0, 0.3 ± 0.2, and in the case of TSP, the value was 0.3 ± 0.2. The char/soot ratio is an index of fossil fuel combustion (0.3–0.5 for diesel soot) [16,19,20]. This suggests that fossil fuels from local transportation exert an important influence on the PM$_{0.1}$ and TSP fractions. No seasonal difference was found for the total EC. The ratios of OC/EC and char/soot were also different from the size distribution [21]. Data on other size-fractionated particulate matter and carbon components are vital for future studies directed at investigating the development of carbonaceous aerosols in more detail.

3.4. Distribution of Metals

The total concentration of thirteen elements in PM$_{0.1}$ and TSP was 161.5 ± 20.7 and 910.6 ± 157.4 ng/m$^3$, respectively (Table 4). The highest mass concentration of element species in PM$_{0.1}$, was found to be for K, followed by Na > Mg > Al > Fe > Zn, as well as small portions (approximately 1 ng/m$^3$) of Cu, Ba, Ti, Pb, Ni, Mn and Cr. The high levels of K, Na, Mg, Al, and Fe could be related to crustal elements [54]. Instead, the high Zn could have resulted from anthropogenic activities, for example, industrial activities and road transportation [25,55]. The PM$_{0.1}$-bound trace elements in the wet season were higher than in the dry season. The element K, a tracer for biomass fires [56] is also two times higher.
during the wet season. Na, Al, and Fe are often produced from non-road transportation sources, particularly the re-suspension of surface dust into the atmosphere [27,57]. As described by Nghiem et al., (2020) [26], to investigate the distribution of the elemental composition in Hanoi, Vietnam, the total mass concentration of trace elements in the PM\(_{0.1}\) fraction accounted for 1.1% ± 0.9% of the total elements, with the most abundant elements being Na, Al, K, Mg, Zn, and Fe. Moreover, Adachi and Buseck (2010) [58] found that 50% of metallic PM\(_{0.1}\) contains more than one element and that Ni, Fe, Cr, Ti, and Zn are frequently originated in PM\(_{0.1}\) particles containing more than one element.

Table 4. Concentration of trace elements in Hat Yai, southern Thailand (ng/m\(^3\)).

| Species | PM\(_{0.1}\) | TSP |
|---------|------------|-----|
|        | Dry       | Wet | Annual | Dry   | Wet | Annual |
| Al      | 13.1 ± 8.8 | 19.1 ± 6.4 | 16.1 ± 8.1 | 33.6 ± 16.2 | 54.6 ± 32.6 | 44.1 ± 27.4 |
| Ba      | 0.5 ± 0.3  | 1.2 ± 0.8  | 0.8 ± 0.7  | 0.8 ± 0.4  | 1.6 ± 0.5  | 1.2 ± 0.6  |
| Cr      | 0.04 ± 0.01 | 0.09 ± 0.05 | 0.07 ± 0.41 | 0.13 ± 0.06 | 0.20 ± 0.11 | 0.16 ± 0.10 |
| Cu      | 2.12 ± 0.66 | 1.16 ± 0.91 | 1.64 ± 0.91 | 2.22 ± 0.61 | 1.99 ± 0.67 | 2.11 ± 0.64 |
| Fe      | 11.0 ± 11.9 | 15.3 ± 8.3 | 13.1 ± 10.2 | 56.0 ± 35.2 | 93.2 ± 40.7 | 74.6 ± 41.8 |
| K       | 32.2 ± 22.3 | 55.2 ± 19.6 | 43.7 ± 23.5 | 204.2 ± 185.8 | 422.3 ± 213.1 | 313.3 ± 225.1 |
| Mg      | 23.4 ± 17.3 | 44.4 ± 24.6 | 33.9 ± 23.5 | 131.2 ± 56.5 | 91.5 ± 48.4 | 111.4 ± 55.3 |
| Mn      | 1.26 ± 0.18 | 2.30 ± 1.65 | 1.78 ± 1.26 | 2.25 ± 1.40 | 4.78 ± 2.16 | 3.52 ± 2.20 |
| Na      | 39.7 ± 38.9 | 43.6 ± 30.2 | 41.6 ± 33.7 | 540.2 ± 335.2 | 151.7 ± 93.3 | 346.0 ± 311.9 |
| Ni      | 0.20 ± 0.09 | 0.31 ± 0.09 | 0.26 ± 0.10 | 0.29 ± 0.11 | 0.34 ± 0.22 | 0.32 ± 0.17 |
| Pb      | 0.11 ± 0.11 | 0.99 ± 1.25 | 0.55 ± 0.97 | 1.35 ± 1.42 | 1.20 ± 0.83 | 1.27 ± 1.14 |
| Ti      | 0.71 ± 0.17 | 0.61 ± 0.10 | 0.66 ± 0.14 | 1.36 ± 0.72 | 2.38 ± 1.59 | 1.87 ± 1.31 |
| Zn      | 5.10 ± 1.49 | 9.12 ± 3.39 | 7.11 ± 3.27 | 9.80 ± 5.06 | 11.94 ± 4.48 | 10.87 ± 4.80 |
| Total   | 129.5 ± 18.5 | 193.5 ± 22.5 | 161.5 ± 20.7 | 983.4 ± 173.5 | 837.8 ± 131.1 | 910.6 ± 157.5 |

The highest mass concentration of trace elements in TSP was for Na, followed by K > Mg > Fe > Al > Zn and a small portion (less than 10 ng/m\(^3\)) was found for Mn, Cu, Ba, Ti, Pb, Ni, and Cr (Table 3). It is also interesting that in the PM\(_{0.1}\) fraction, K represents a tracer for biomass fires increases during the wet season. Pollution Control Department (PCD), Thailand reported the Emission Inventory (EI) in the Songkhla province, they found that industries (85%), road traffic (10%), and others (5% including household and various types of transportation) are the main TSP emission sources in the Songkhla province [59].

3.5. Source Apportionment of PM\(_{0.1}\) and TSP Bound Carbon and Metals

3.5.1. PM\(_{0.1}\) Source Apportionment

In Table 5, PCA shows the factors for each season. To interpret the results for each season, four main factors were extracted for the dry season and four for the rainy season.

In the dry season, the PCA analysis suggested that four main clusters account for up to 86.2% of the cumulative variance. The first factor contains Al, K, Mg, Na, Cu, Mn, Fe, and Zn which reveals that this group of metals may have a common source. The total 38.3% of the PM\(_{0.1}\) in the dry season could be the result of human-caused activities, particularly diesel and gasoline engines [25,60]. Miller et al. (2007) [61] described a high density of elemental nanoparticles in 30–300 nm diesel exhaust particles, including Cu, Fe, Zn, and Mg. Diesel engines are major contributors of traffic-related PM\(_{0.1}\) in the ambient air [58].

The second factor (26.8%) is related to Ba, K, Mg, Na, TC, OC, and EC which may have a common origin. Biomass combustion and crustal dust sources produce particles in an ultrafine size range [62]. Factor 3 includes Cr and Pb and accounts for around 11.9% of the total. These elements indicate that combustion can be considered to be essential. The last factor is deepened on Cu and Ni. It was reported that Ni and Cu primarily originate from vehicular sources from both combustion and non-combustion sources [63].
Table 5. Principal components in the PM$_{0.1}$ fraction by season.

| Species | Dry Season (Jan–Apr) | Wet Season (May–Aug) |
|---------|----------------------|----------------------|
|         | PC1   | PC2   | PC3   | PC4   | PC1   | PC2   | PC3   | PC4   |
| Al      | 0.87  |       |       |       | 0.63  |       |       |       |
| Ba      | 0.82  | 0.47  | 0.80  | 0.41  | 0.52  | 0.53  | 0.48  | 0.53  |
| Cr      | 0.60  | 0.37  | 0.61  | 0.42  | 0.77  | −0.35 |       |       |
| Cu      | 0.89  |       |       |       | 0.69  | −0.57 |       |       |
| K       | 0.50  | 0.60  | −0.42 | 0.92  |       |       |       |       |
| Mg      | 0.57  | 0.57  | −0.42 | 0.80  | 0.45  |       |       |       |
| Mn      | 0.92  | 0.22  |       | −0.45 | 0.52  | 0.39  | 0.33  |       |
| Na      | 0.71  | 0.64  |       | 0.94  | 0.30  |       |       |       |
| Ni      | −0.36 | −0.43 | 0.65  | 0.34  | −0.59 | −0.61 |       |       |
| Pb      | 0.37  | −0.36 | 0.64  | −0.38 | 0.62  | 0.63  | 0.40  |       |
| Ti      | 0.48  | −0.69 | 0.41  | −0.34 | 0.56  | −0.48 | 0.59  |       |
| Zn      | 0.72  | −0.31 |       | 0.87  | −0.36 | 0.18  |       |       |
| TC      | −0.61 | 0.69  |       | 0.42  | 0.90  |       |       |       |
| OC      | −0.52 | 0.76  |       | 0.36  | 0.92  |       |       |       |
| EC      | −0.76 | 0.51  |       | 0.60  | 0.68  |       |       |       |

Initial eigenvalue: 6.13, 4.28, 1.897, 1.483, 6.09, 4.58, 1.94, 1.45
% Variance: 38.31, 26.75, 11.85, 9.26, 38.07, 28.60, 12.10, 9.03
% Cumulative Variance: 38.31, 65.06, 76.92, 86.19, 38.07, 66.67, 78.77, 87.80

During the wet season, the PCA analysis revealed that four main factors account for up to 87.8% of the cumulative variance. PC1 included Al, Na, K, Fe, Mg, Pb, Zn, Ti, and EC that accounted for 38.1% of the total variance. This factor is suggestive of mixed sources from road traffic, with diesel particles (Fe, Mg, Na, Pb, Zn, and EC) and road dust (Al, Na, and Ti) together with contributions from the industrial sector (Fe, Pb, and Zn) [27,64]. PC2 included Ba, Pb, TC, OC, and EC that accounted for 28.6%. This is similar to PC2 during the dry season, representing common sources from biomass fires and crustal dust sources which release nano-size range particles [65–67]. PC3, which was loaded with Cu, suggests that contributions from non-exhaust traffic sources, i.e., brakes and tire wear [54] accounted for 14.0%. PC4 is comprised of Pb, Cr, and Ti that accounted for around 9.0% indicating that Ba, Cr, and Ti are derived from construction dust [54].

3.5.2. TSP Source Apportionment

As shown in Table 6, PCA revealed the factors that are important for each season. To interpret the results obtained from the dry and wet seasons, the dry season was extracted, accounting for 4 main factors and the wet season accounted for 3 factors.

In the dry season, 4 PC factors account for 83.2% of the total variance. PC1 accounts for 38.5% and is derived from mixed sources, namely, traffic emissions, the industrial sector, and road soil dust [64]. It represents most of the metals including Ba, K, Pb, Mn, Ti, and Zn. In PC2, accounting for 20.6%, Al, Cr, Mn, Na, and Ti represent markers for crustal elements. In PC3, accounting for 15.3%, TC, OC, and EC appear to arise from biomass combustion. PC4, accounting for 8.7%, is associated with Pb and EC from vehicle emissions [66].

During the wet season, PCA revealed that 3 main factors account for up to 86.9% of cumulative variance. PC1, accounting for 57.2% of the variance, includes all of the metals except Cu (K, Mn, Mg, Al, Ti, Fe, Na, and Ni); this cluster represents mixed sources including road and soil dust [13], as well as diesel exhaust (Mn, Mg, Al, Zn, and Fe) [27]. A considerable amount of road dust is also released by the mechanical abrasion of the road pavement, which contains high levels of Fe, Mg, and Al [67]. PC2 has in height loading factor (more than 0.8) of TC and OC as tracers of biomass burning, which contribute around 20.5% [7]. PC3 contributes 9.2% from vehicular emission with a high loading of Pb and EC [13].
Table 6. Principal components in the TSP fraction by season.

| Species | Dry Season (Jan–Apr) | Wet Season (May–Aug) |
|---------|----------------------|----------------------|
|         | PC1 | PC2 | PC3 | PC4 | PC1 | PC2 | PC3 |
| Al      | 0.38 | 0.78 |     | 0.85 |     | 0.46 |     |
| Ba      | 0.86 |     |     | 0.91 |     |     |     |
| Cr      | 0.46 | 0.69 | −0.36 | 0.96 |     |     |     |
| Cu      | 0.33 | 0.30 | −0.55 | 0.49 | −0.67 | 0.40 |     |
| Fe      | 0.90 |     |     | 0.95 |     |     |     |
| K       | 0.88 | −0.33 |     | 0.70 | −0.50 | −0.31 |     |
| Mg      | −0.35 | 0.84 | 0.32 | 0.95 |     |     |     |
| Mn      | 0.97 |     |     | 0.83 |     | −0.32 |     |
| Na      | −0.57 | 0.72 | 0.31 | 0.82 | 0.34 |     |     |
| Ni      | 0.42 | 0.40 |     | 0.93 |     |     |     |
| Pb      | 0.24 |     |     | 0.51 | 0.68 | 0.50 |     |
| Ti      | 0.75 | 0.54 |     | 0.94 |     | −0.08 |     |
| Zn      | 0.88 |     |     | 0.66 | −0.39 | 0.29 |     |
| TC      |     |     |     | 0.93 | 0.91 | 0.28 |     |
| OC      |     |     |     | 0.89 | 0.90 | −0.06 |     |
| EC      |     |     |     | 0.46 | 0.74 | 0.35 | 0.45 | 0.69 |
| % Variance | 38.52 | 3.30 | 2.46 | 1.40 | 9.15 | 3.29 | 1.47 |
| % Cumulative Variance | 38.52 | 20.63 | 15.35 | 8.75 | 57.18 | 20.56 | 9.20 |

Factor loads < 0.3 are left in the blanks and factor loads > 0.5 are presented in bold.

3.6. Possible Local and Long-Range Transport of PM

The HYSPLIT-4 model was used to study the potential long-term transport of particle-bound carbon and trace elements at the monitoring site [19]. To detect the influence of long-range transportation of PM-bound chemicals, high levels were considered for this analysis. The transport times were five days (26–31 August 2019) during the wet season. Figure 3 demonstrates the backward trajectories during high PM concentrations for the above-mentioned times. As shown in Figure 3, the 120-h air mass originated from the northern part of Sumatra Island, Indonesia, where peat-land fires were reported by researchers [68]. Air masses moved from southeast Thailand which contributed to high TC and OC concentrations detected at the study site.

Figure 3. Distribution of hot spots and air mass trajectories during the high episode (August 2019).
4. Conclusions

In this study, particle-bound OC and EC, and Char-EC and Soot-EC as well as trace elements in the PM$_{0.1}$ and TSP fractions were investigated from January–August 2019 in southern Thailand. The possible emission sources of PM$_{0.1}$ and TSP based on analyses for carbon and metals were evaluated. The averaged PM$_{0.1}$ and TSP mass concentrations were found to be 10.4 ± 1.2 and 58.3 ± 7.8 µg/m$^3$, respectively. The highest concentrations of PM occurred in the wet season with the corresponding values for the dry season being lower. The OC to EC ratio for PM$_{0.1}$ and TSP was somewhat similar between the seasons, i.e., 2.5–2.7 (PM$_{0.1}$) and 3.8–4.2 (TSP). The char to soot ratio was consistently less than 1 for both the PM$_{0.1}$ and TSP fractions, indicating that land transportation appears to be the main emission source. PCA showed that road transportation (combustion and non-combustion), the industrial sector, and biomass burning are the main sources. These findings emphasize the importance of focusing emission control strategies on particles in southern Thailand, as well as elsewhere. However, cross-border pollution over countries in this area could also be a significant factor that merits future study in a more detailed investigation.

Author Contributions: Conceptualization, W.P., M.H. and M.F.; investigation, M.I. and P.W.; resources, M.I. and W.P.; data curation, M.I., P.P. and M.H.; writing—original draft preparation, M.I.; writing—review and editing, W.P., M.H. and M.F.; visualization, M.I. and P.P.; supervision, M.H. and M.F.; project administration, W.P. and M.H.; funding acquisition, W.P. and P.W. 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 of Higher Education, Science, Research and Innovation (Grant No. RGNS 63-253). This research work was partially supported by Chiang Mai University and Thailand Science Research and Innovation (TSRI, formerly the Thailand Research Fund, TRF) (Grant number RDG6230005).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors wish to thank Surajit Tekasakul, Perapong Tekasakul, and Hisam Samea for general support in sampling and the chemical analysis. Additionally, the authors also wish to thank Milton S. Feather and Alvin Yoshinaga for improving this manuscript’s English.

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

References

1. Deng, Q.; Deng, L.; Xiao, Y.; Guo, X.; Li, Y. Particle deposition in the human lung: Health implications of particulate matter from different sources. *Environ. Res.* 2019, 169, 237–245. [CrossRef] [PubMed]
2. Kampa, M.; Castanas, E. Human health effects of air pollution. *Environ. Pollut.* 2008, 151, 362–367. [CrossRef] [PubMed]
3. Jacobson, M.Z. *Air Pollution and Global Warming: History, Science, and Solutions*; Cambridge University Press: Cambridge, UK, 2012.
4. Lohmann, U.; Feichter, J. Global indirect aerosol effects: A review. *Atmos. Chem. Phys.* 2005, 5, 715–737. [CrossRef]
5. Alias, N.F.; Khan, M.F.; Sairi, N.A.; Zain, S.M.; Suradi, H.; Rahim, H.A.; Banerjee, T.; Bari, M.A.; Othman, M.; Latif, M.T. Characteristics, emission sources and risk factors of heavy metals in PM2.5 from Southern Malaysia. *ACS Earth Space Chem.* 2020, 4, 1309–1323. [CrossRef]
6. Chalermpong, S.; Thaithakul, P.; Anuchitchanchai, O.; Sanghawatana, P. Land use regression modeling for fine particulate matters in Bangkok, Thailand, using time-variant predictors: Effects of seasonal factors, open biomass burning, and traffic-related factors. *Atmos. Environ.* 2021, 246, 118128. [CrossRef]
7. ChooChuay, C.; Pongpiachan, S.; Tipmanee, D.; Deelaman, W.; Suttinun, O.; Wang, Q.; Xing, L.; Li, G.; Han, Y.; Palakun, J.; et al. Long-range Transboundary Atmospheric Transport of Polycyclic Aromatic Hydrocarbons, Carbonaceous Compositions, and Water-soluble Ionic Species in Southern Thailand. *Aerosol Air Qual. Res.* 2020, 20, 1591–1606. [CrossRef]
8. Ha Chi, N.N.; Kim Oanh, N.T. Photochemical smog modeling of PM2.5 for assessment of associated health impacts in crowded urban area of Southeast Asia. *Environ. Technol. Innov.* 2021, 21, 101241. [CrossRef]
9. Moon, C.S. Correlation among PM10, PM2.5, Cd, and Pb Concentrations in Ambient Air and Asian Dust Storm Event. *J. Environ. Health Sci.* 2020, 46, 532–538. [CrossRef]
10. Nuthammachot, N.; Phairuang, W.; Stratoulas, D. Estimation of carbon emission in the Ex-mega rice project, Indonesia based on sar satellite images. *Appl. Ecol. Environ. Res.* 2019, 17, 2489–2499. [CrossRef]
11. Phairuang, W. Biomass Burning and Their Impacts on Air Quality in Thailand. In Biomass Burning in South and Southeast Asia; CRC Press: Boca Raton, FL, USA, 2021; pp. 21–38.

12. Boongla, Y.; Chanonmuang, P.; Hata, M.; Furuuchi, M.; Phairuang, W. The characteristics of carbonaceous particles down to the nanoparticle range in Rangsit city in the Bangkok Metropolitan Region, Thailand. Environ. Pollut. 2020, 272, 115940. [CrossRef]

13. Dahari, N.; Muda, K.; Latif, M.T.; Hussein, N. Studies of Atmospheric PM2.5 and its Inorganic Water Soluble Ions and Trace Elements around Southeast Asia: A Review. Asia-Pac. J. Atmos. Sci. 2021, 57, 361–385. [CrossRef]

14. Jamhari, A.A.; Latif, M.T.; Wahab, M.I.A.; Hassan, H.; Othman, M.; Hamid, H.H.A.; Tekasakul, P.; Phairuang, W.; Hata, M.; Furuuchi, M.; et al. Seasonal variation and size distribution of inorganic and carbonaceous components, source identification of size-fractioned urban air particles in Kuala Lumpur, Malaysia. Chemosphere 2021, 287, 132309. [CrossRef] [PubMed]

15. Han, Y.M.; Cao, J.; Lee, S.C.; Ho, K.F.; An, Z.S. Different characteristics of char and soot in the atmosphere and their ratio as an indicator for source identification in Xi’an, China. Atmos. Chem. Phys. 2010, 10, 595–607. [CrossRef]

16. Phairuang, W.; Suwattiga, P.; Chetiyanukornkul, T.; Hongtieab, S.; Limpaseni, W.; Ikemori, F.; Hata, M.; Furuuchi, M. The influence of the open burning of agricultural biomass and forest fires in Thailand on the carbonaceous components in size-fractionated particles. Environ. Pollut. 2019, 247, 238–247. [CrossRef]

17. Thuy, N.T.T.; Dung, N.T.; Sekiguchi, K.; Thuy, L.B.; Hien, N.T.T.; Yamaguchi, R. Mass Concentrations and Carbonaceous Compositions of PM0.1, PM2.5, and PM10 at Urban Locations of Hanoi, Vietnam. Aerosol Air Qual. Res. 2018, 18, 1591–1605. [CrossRef]

18. Amin, M.; Handika, R.A.; Putri, R.M.; Phairuang, W.; Hata, M.; Tekasakul, P.; Furuuchi, M. Size-Segregated Particulate Mass and Carbonaceous Components in Roadside and Riverside Environments. Appl. Sci. 2021, 11, 10214. [CrossRef]

19. Phairuang, W.; Inerb, M.; Furuuchi, M.; Hata, M.; Tekasakul, S.; Tekasakul, P. Size-fractionated carbonaceous aerosols down to PM0.1 in southern Thailand: Local and long-range transport effects. Environ. Pollut. 2020, 260, 114031. [CrossRef]

20. Putri, R.M.; Amin, M.; Suciari, T.F.; Faisal, M.A.F.; Auliani, R.; Ikemori, F.; Wada, M.; Hata, M.; Tekasakul, P.; Furuuchi, M. Site-specific variation in mass concentration and chemical components in ambient nanoparticles (PM0.1) in North Sumatra Province-Indonesia. Atmos. Pollut. Res. 2021, 12, 101062. [CrossRef]

21. Guo, Y. Carbonaceous aerosol composition over northern China in spring. Environ. Sci. Pollut. Res. 2015, 22, 10839–10849. [CrossRef]

22. Gustafsson, O.; Ramanathan, V. Convergence on climate warming by black carbon aerosols. Proc. Natl. Acad. Sci. USA 2016, 113, 4243–4245. [CrossRef]

23. Phairuang, W.; Inerb, M.; Hata, M.; Furuuchi, M. Characteristics of trace elements bound to ambient nanoparticles (PM0.1) and a health risk assessment in southern Thailand. J. Hazard. Mater. 2021, 425, 127986. [CrossRef] [PubMed]

24. Pongpiachan, S.; Iijima, A. Assessment of selected metals in the ambient air PM10 in urban sites of Bangkok (Thailand). Environ. Sci. Pollut. Res. 2016, 23, 2948–2961. [CrossRef] [PubMed]

25. Xu, J.; Jia, C.; Yu, H.; Xu, H.; Ji, D.; Wang, C.; Xiao, H.; He, J. Characteristics, sources, and health risks of PM2.5-bound trace elements in representative areas of Northern Zhejiang Province, China. Chemosphere 2021, 272, 129632. [CrossRef]

26. Nghiem, T.-D.; Nguyen, T.T.T.; Ly, B.T.; Sekiguchi, K.; Yamaguchi, R.; Pham, C.-T.; Ho, Q.B.; Nguyen, M.-T.; Duong, T.N. Chemical characterization and source apportionment of ambient nanoparticles: A case study in Hanoi, Vietnam. Environ. Sci. Pollut. Res. 2020, 27, 30661–30672. [CrossRef] [PubMed]

27. Sanderson, P.; Delgado-Saborit, J.M.; Harrison, R.M. A review of chemical and physical characterisation of atmospheric metallic nanoparticles. Atmos. Environ. 2014, 94, 353–365. [CrossRef]

28. IARC, International Agency for Research on Cancer. Agents Classified by the IARC Monographs; IARC: Lyon, France, 2011; Volumes 1–102.

29. IARC, International Agency for Research on Cancer. Arsenic, Metals, Fibres and Dusts. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans; IARC: Lyon, France, 2012.

30. Phairuang, W.; Suwattiga, P.; Hongtieab, S.; Inerb, M.; Furuuchi, M.; Hata, M. Characteristics, sources, and health risks of ambient nanoparticles (PM0.1) bound metal in Bangkok, Thailand. Atmos. Environ. X 2021, 12, 100141. [CrossRef]

31. Phairuang, W.; Tekasakul, P.; Hata, M.; Tekasakul, S.; Chomanee, J.; Otani, Y.; Furuuchi, M. Estimation of air pollution from ribbed smoked sheet rubber in Thailand exports to Japan as a pre-product of tires. Atmos. Pollut. Res. 2019, 10, 642–650. [CrossRef]

32. Thumanu, K.; Pongpiachan, S.; Ho, K.F.; Lee, S.C.; Sompongchaiyakul, P. 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. 2009, 123, 295–306. [CrossRef]

33. Thailand Meteorological Department (TMD). The Climate of Thailand. Available online: https://www.tmd.go.th/en/province.php?id=1443 (accessed on 23 March 2022).

34. Han, Y.; Cao, J.; Chow, J.C.; Watson, J.G.; An, Z.; Jin, Z.; Fung, K.; Liu, S. Evaluation of the thermal/ optical reflectance method for discrimination between Char- and Soot-EC. Chemosphere 2007, 69, 569–574. [CrossRef]

35. Li, T.; Zhang, H.; Yuan, C.; Liu, Z.; Fan, C. A PCA-based method for construction of composite sustainability indicators. Int. J. Life Cycle Assess. 2012, 17, 593–603. [CrossRef]

36. Jain, S.; Sharma, S.; Mandal, T.; Saxena, M. Source apportionment of PM10 in Delhi, India using PCA/APCS, UNMIX and PMF. Particuology 2018, 37, 107–118. [CrossRef]
37. Air Resource Laboratory (ALR). The Air Resource Laboratory (HYMSPLIP 4). Available online: http://ready.arl.noaa.gov/HYSPLIT.php (accessed on 9 March 2022).

38. Onishi, N.T.K.; Leelasakultum, K. Analysis of meteorology and emission in haze episode prevalence over mountain-bounded region for early warning. Sci. Total Environ. 2011, 409, 2261–2271. [CrossRef]

39. Shokoohinia, P.; Assareh, N.; Manomaiphiboon, K.; Chusai, C.; Kerkkäri, S.; Unapumnuuk, K.; Aman, N. Impacts of trans-boundary smoke haze from biomass burning in lower Southeast Asia on air quality in Southern Thailand. J. Sustain. Energy. 2020, 10, 1–10.

40. Hata, M.; Bai, Y.; Furuuchi, M.; Fukumoto, M.; Otani, Y.; Sekiguchi, K.; Tajima, N. Status and characteristics of ambient aerosol nano-particles in Kakuma, Kanazawa and comparison between sampling characteristics of air samplers for aerosol particle separation. Jpn. Sea Res. 2009, 40, 135–140.

41. Hongtiea, S.; Yoshikawa, F.; Matsuki, A.; Zhao, T.; Amin, M.; Hata, M.; Tekasakul, P.; Furuuchi, M. Seasonal behavior and emission sources of ambient PM0.1 in the Hokuriku region in Japan. Jpn. Sea Res. 2020, 49, 1–17.

42. Chen, S.C.; Tsai, C.-J.; Chou, C.C.-K.; Roam, G.D.; Cheng, S.-S.; Wang, Y.N. Ultrafine particles at three different sampling locations in Taiwan. Atmos. Environ. 2010, 44, 533–540. [CrossRef]

43. Ding, X.; Kong, L.; Du, C.; Zhanzakova, A.; Wang, L.; Fu, H.; Chen, J.; Yang, X.; Cheng, T. Long-range and regional transported size-resolved atmospheric aerosols during summertime in urban Shanghai. Sci. Total. Environ. 2017, 583, 334–343. [CrossRef] [PubMed]

44. Ghosh, A.; Roy, A.; Chatterjee, A.; Das, S.K.; Ghosh, S.K.; Raha, S. Impact of Biomass Burning Plumes on the Size-Segregated Aerosol Chemistry over an Urban Atmosphere at Indo-Gangetic Plain. Aerosol Air Qual. Res. 2019, 19, 163–180. [CrossRef]

45. Venneke, M.A.; Yu, X.; Kleeman, M.J. Predicted ultrafine particulate matter source contribution across the continental United States during summertime air pollution events. Atmos. Chem. Phys. 2019, 19, 9399–9412. [CrossRef]

46. De Jesus, A.L.; Rahman, M.; Mazaheri, M.; Thompson, M.; Knibbs, L.; Jeong, C.; Evans, G.; Nei, W.; Ding, A.; Qiao, L.; et al. Ultrafine particles and PM2.5 in the air of cities around the world: Are they representative of each other? Environ. Int. 2019, 129, 118–135. [CrossRef]

47. Adam, M.G.; Tran, P.T.; Bolan, N.; Balasubramanian, R. Biomass burning-derived airborne particulate matter in Southeast Asia: A critical review. J. Hazard. Mater. 2020, 407, 124760. [CrossRef]

48. Tham, J.; Sarkar, S.; Jia, S.; Reid, J.S.; Mishra, S.; Sudiana, I.; Swarup, S.; Ong, C.N.; Yu, L. Impacts of peat-forest smoke on urban PM2.5 in the Maritime Continent during 2012–2015: Carbaceous profiles and indicators. Environ. Pollut. 2019, 248, 496–505. [CrossRef]

49. Pongpiachan, S.; Ho, K.F.; Cao, J. Effects of Biomass and Agricultural Waste Burnings on Diurnal Variation and Vertical Distribution of OC/EC in Hat-Yai City, Thailand. Asian J. Appl. Sci. 2014, 7, 360–374. [CrossRef]

50. Allen, J.O.; Mayo, P.R.; Hughes, L.S.; Salmon, L.G.; Cass, G.R. Emissions of Size-Segregated Aerosols from On-Road Vehicles in the Caldecott Tunnel. Environ. Sci. Technol. 2001, 35, 4189–4197. [CrossRef] [PubMed]

51. Pio, C.; Cerqueira, M.; Harrison, R.M.; Nunes, T.; Mirante, F.; Alves, C.; Oliveira, C.; Sanchez de la Campa, A.; Artiñano, B.; Matos, M. OC/EC ratio observations in Europe: Re-thinking the approach for apportionment between primary and secondary organic carbon. Atmos. Environ. 2011, 45, 6121–6132. [CrossRef]

52. Zhu, C.S.; Chen, C.C.; Cao, J.J.; Tsai, C.J.; Chou, C.C.K.; Liu, S.C.; Roam, G.D. Characterization of carbon fractions for atmospheric fine particles and nanoparticles in a highway tunnel. Atmos. Environ. 2010, 44, 2668–2673. [CrossRef]

53. Cachier, H.; Lioussse, C.; Pertuisol, M.H.; Gaudichet, A.; Echaill, F.; Lacaux, J.P. African fine particulate emissions and atmospheric influence. In Biomass Burning and Global Change; Levine, E.J.S., Ed.; MIT Press: London, UK, 1996; pp. 428–440.

54. Saffari, A.; Daher, N.; Shafer, M.M.; Schauer, J.J.; Sioutas, C. Seasonal and spatial variation of trace elements and metals in quasi-ultrafine (PM0.25) particles in the Los Angeles metropolitan area and characterization of their sources. Environ. Pollut. 2013, 181, 14–23. [CrossRef] [PubMed]

55. Pongpiachan, S.; Liu, S.; Huang, R.; Zhao, Z.; Balakun, J.; Kositanont, C.; Cao, J. Variation in Day-of-Week and Seasonal Concentrations of Atmospheric PM2.5-Bound Metals and Associated Health Risks in Bangkok, Thailand. Arch. Environ. Contam. Toxicol. 2017, 72, 364–379. [CrossRef]

56. Xue, W.; Xue, J.; Mousavi, A.; Sioutas, C.; Kleeman, M.J. Positive matrix factorization of ultrafine particle mass (PM0.1) at three sites in California. Sci. Total Environ. 2020, 715, 136902. [CrossRef]

57. Yin, J.; Harrison, R.M. Pragmatic mass closure study for PM1.0, PM2.5 and PM10 at roadside, urban background and rural sites. Atmos. Environ. 2008, 42, 980–988. [CrossRef]

58. Adachi, K.; Buseck, P.R. Hosted and Free-Floating Metal-Bearing Atmospheric Nanoparticles in Mexico City. Environ. Sci. Technol. 2010, 44, 2299–2304. [CrossRef] [PubMed]

59. Pollution Control Department (PCD). Emission Inventory in Songkhla Province; Pollution Control Department: Bangkok, Thailand, 2009. (In Thai)

60. Liati, A.; Dimopoulos Eggeschwiler, P.; Müller Gubler, E.; Schreiber, D.; Aguirre, M. Investigation of diesel ash particulate matter: A scanning electron microscope and transmission electron microscope study. Atmos. Environ. 2012, 49, 391–402. [CrossRef] [PubMed]
62. Hata, M.; Chomanee, J.; Thongyen, T.; Bao, L.; Tekasakul, S.; Tekasakul, P.; Otani, Y.; Furuuchi, M. Characteristics of nanoparticles emitted from burning of biomass fuels. J. Environ. Sci. China 2014, 26, 1913–1920. [CrossRef] [PubMed]

63. Wang, K.; Wang, W.; Li, L.; Li, J.; Wei, L.; Hong, L.; Zhao, Q.; Jiang, J. Seasonal concentration distribution of PM1.0 and PM2.5 and a risk assessment of bound trace metals in Harbin, China: Effect of the species distribution of heavy metals and heat supply. Sci. Rep. 2020, 10, 8160. [CrossRef] [PubMed]

64. Reinard, M.S.; Adou, K.; Martini, J.M.; Johnston, M.V. Source characterization and identification by real-time single particle mass spectrometry. Atmos. Environ. 2007, 41, 9397–9409. [CrossRef]

65. Tolocka, M.P.; Lake, D.A.; Johnston, M.V.; Wexler, A.S. Number concentrations of fine and ultrafine particles containing metals. Atmos. Environ. 2004, 38, 3263–3273. [CrossRef]

66. Tran, T.D.; Nguyen, P.M.; Nghiem, D.T.; Le, T.H.; Tu, M.B.; Alleman, L.Y.; Nguyen, V.M.; Pham, D.T.; Ha, N.M.; Dang, M.N.; et al. Assessment of Air Quality in School Environments in Hanoi, Vietnam: A Focus on Mass-Size Distribution and Elemental Composition of Indoor-Outdoor Ultrafine/Fine/Coarse Particles. Atmos. Basel 2020, 11, 519. [CrossRef]

67. Ondráček, J.; Schwarz, J.; Ždímal, V.; Andělová, L.; Vodička, P.; Bízek, V.; Tsai, C.-J.; Chen, S.-C.; Smolík, J. Contribution of the road traffic to air pollution in the Prague city (busy speedway and suburban crossroads). Atmos. Environ. 2011, 45, 5090–5100. [CrossRef]

68. Buus Hansen, A.; Suzanne Witham, C.; Ming Chong, W.; Kendall, E.; Ning Chew, B.; Gan, C.; Craig Hort, M.; Lee, S.Y. Haze in Singapore-source attribution of biomass burning PM10 from Southeast Asia. Atmos. Chem. Phys. 2019, 19, 5363–5385. [CrossRef]