



## Mass Concentrations and Carbonaceous Compositions of PM<sub>0.1</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub> at Urban Locations in Hanoi, Vietnam

Nguyen Thi Thu Thuy<sup>1,2</sup>, Nghiem Trung Dung<sup>1\*</sup>, Kazuhiko Sekiguchi<sup>3\*</sup>, Ly Bich Thuy<sup>1</sup>,  
Nguyen Thi Thu Hien<sup>1</sup>, Ryosuke Yamaguchi<sup>3</sup>

<sup>1</sup> School of Environmental Science and Technology, Hanoi University of Science and Technology, Hanoi, Vietnam

<sup>2</sup> Faculty of International Training, Thai Nguyen University of Technology, Thai Nguyen, Vietnam

<sup>3</sup> Graduate School of Science and Engineering, Saitama University, Sakura, Saitama, Japan

### ABSTRACT

24-hour samples of PM<sub>0.1</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub> were collected simultaneously for the first time at a roadside site (Vinacomin) and a mixed site (HUST) in Hanoi, Vietnam, during the wet (August) and dry seasons (October to December) in 2015. High levels of PM<sub>0.1</sub> ( $6.06 \pm 2.71 \mu\text{g m}^{-3}$ ), PM<sub>2.5</sub> ( $71.06 \pm 47.52 \mu\text{g m}^{-3}$ ), and PM<sub>10</sub> ( $106.47 \pm 63.95 \mu\text{g m}^{-3}$ ) were observed, especially in the rice straw open burning episode. The influence of some meteorological factors and trajectories on PM<sub>0.1</sub> concentrations was negligible compared to larger particles. The average concentrations of organic carbon (OC) and elemental carbon (EC) for PM<sub>0.1</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub> were  $2.77 \pm 0.98 \mu\text{g m}^{-3}$  and  $0.63 \pm 0.32 \mu\text{g m}^{-3}$ ,  $23.81 \pm 21.16 \mu\text{g m}^{-3}$  and  $6.17 \pm 5.87 \mu\text{g m}^{-3}$ , and  $34.93 \pm 20.07 \mu\text{g m}^{-3}$  and  $8.38 \pm 4.92 \mu\text{g m}^{-3}$ , respectively. The total carbon (TC) accounted for 59.19%, 44.65%, and 43.79% of the mass of PM<sub>0.1</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub>, respectively. The OC/EC ratios ranged 3.62–5.68, in which the ratios of PM<sub>0.1</sub> were the highest, except for those in the biomass burning period. The char-EC/soot-EC ratios widely fluctuated (0.94–4.61), meaning higher efficiency in the source identification. Strong correlations between the OC and EC in all particle sizes were found ( $R^2 = 0.84\text{--}0.99$ ), excluding those of PM<sub>0.1</sub> in the dry season at Vinacomin ( $R^2 = 0.61$ ), implying the influence of biomass burning. The concentrations of Secondary Organic Carbon (SOC) were  $1.12 \pm 0.43 \mu\text{g m}^{-3}$ ,  $9.49 \pm 8.26 \mu\text{g m}^{-3}$ , and  $9.59 \pm 7.72 \mu\text{g m}^{-3}$ , accounting for 42.7%, 42.3%, and 27.9% of the total OC for PM<sub>0.1</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub>, respectively, indicating the dominant contribution of secondary sources to OC, especially in the finer particles. These results are highly valuable to Vietnam's database of atmospheric particles.

**Keywords:** Nanoparticles; Organic carbon; Elemental carbon; SOC; PM<sub>2.5</sub>; PM<sub>10</sub>; Hanoi; Vietnam.

### INTRODUCTION

Particulate matter (PM) has been believed to have adverse short- and long-term effects on human health (Dockery and Pope, 1994; Stölzel *et al.*, 2007), visibility and climate change (Anastasio and Martin, 2001; IPCC, 2007). Information on the chemical compositions of atmospheric aerosols at a given size is important for the identification of their potential impacts on human health and environment (Lin *et al.*, 2005; Lim *et al.*, 2012). In the past decade, it has been found that the smaller fractions of PM, respirable particles (PM<sub>2.5</sub> or, especially, ultrafine particles), pose a higher risk to human health. Due to intensive research, there is emerging evidence that exposure to nanoparticles (NPs or PM<sub>0.1</sub>) may adversely

affect human health (Dockery and Pope, 1994; Stölzel *et al.*, 2007), visibility, and global climate (Anastasio and Martin, 2001; IPCC, 2007). Such negative impacts could be attributed to (i) a tiny size that can penetrate deeply to and accumulate in the organs of our bodies, (ii) a very high number concentration, and (iii) a greater specific surface area that can be bounded by toxic compounds.

The carbonaceous matter is a major component of the ambient atmospheric particles (Cass *et al.*, 2000; Geller *et al.*, 2002; Kim *et al.*, 2002; Sardar *et al.*, 2005). These carbonaceous aerosols are commonly classified into two fractions: elemental carbon (EC), and organic carbon (OC). Whereas EC originates from the burning of carbonaceous matter, OC may be emitted directly in the particulate phase or formed from a gas-to-particle conversion process in the atmosphere. Therefore, information of carbonaceous compositions, especially EC, OC, plays a vital role in not only evaluating the impacts of atmospheric particles but also understanding their source type and strength.

Hanoi has been facing serious air pollution problems, especially with particulate matter (MONRE, 2017).

\* Corresponding author.

E-mail address: dung.nghiemtrung@hust.edu.vn

\*\* Corresponding author.

E-mail address: kseki@mail.saitama-u.ac.jp

According to the database of AirNow (US Embassy), the annual average concentration of  $PM_{2.5}$  in Hanoi in 2016 reached  $50.5 \mu g m^{-3}$  which was about two times higher than the annual standard of Vietnam ( $25 \mu g m^{-3}$ ) and about five times higher than the annual mean of WHO guideline ( $10 \mu g m^{-3}$ ). Such high PM levels were associated with an increase in the risk of admission for respiratory diseases among children in Hanoi and the admission increased when the particle sizes decreased (Ly *et al.*, 2017). However, only few studies on  $PM_{2.5}$  and  $PM_{10}$  (Hien *et al.*, 2002, Oanh *et al.*, 2006; Cohen *et al.*, 2010a; Hai and Kim Oanh, 2013) in Hanoi are found. Especially, to the best of our knowledge, no data on  $PM_{0.1}$  in Hanoi are available in the open literature except some of our preliminary studies (Thuy *et al.*, 2016, Yamaguchi *et al.*, 2016; Thuy *et al.*, 2017). So far, there is no report on the simultaneous monitoring of the ultrafine, fine and coarse aerosols and their ratios in Vietnam. To fill this gap in this region, an ambient aerosol measurement focusing on the characteristics of carbonaceous components in  $PM_{0.1}$ ,  $PM_{2.5}$ , and  $PM_{10}$  was conducted from August to December of 2015 in Hanoi. The objectives of this study are: (i) to monitor the mass concentrations of  $PM_{0.1}$ ,  $PM_{2.5}$ , and  $PM_{10}$ , (ii) to examine the influence of meteorological factors and different trajectories on mass concentration of these particle sizes, (iii) to characterize the atmospheric carbonaceous components of PM in Vietnam in which, the correlations between carbonaceous components are analyzed deeply. These correlations would be valuable for the primary prediction of possible emission sources of aerosols in the atmosphere.

## METHODS

### Sampling

Hanoi, located in the Red River delta in the North

Vietnam (21.021 N, 105.851 E), about 100 km west of the East Sea, is the capital of Vietnam and the second largest city in the country. Hanoi has a tropical monsoon climate with two monsoon seasons. This area is under the influence of northeast monsoon during winter and southeast monsoon during summer. From October to December, continental air flow coming from the inland of China brings dry and cold air. From January to March/April, maritime air flows travel a long way over the Pacific Ocean brings warm, humid and better dispersion conditions. In summer, air masses coming from the Highs over the Indian Ocean and the subtropical High over the East Sea bring moist air and monsoon rains. However, heavy rains mainly occur in July and August in association with tropical depressions. The mean annual rainfall in Hanoi is 1800 mm, 80% of which is recorded from May to September (Hien *et al.*, 2002).

The 24-h sampling campaigns were conducted in August (wet season) and from October to December (dry season) in 2015. These sampling campaigns covered the periods of the lowest and the highest levels of PM in Hanoi in a year (Cohen *et al.*, 2010a). Therefore, these sampling periods would reflect the influence of the weather conditions on the concentrations of PM in Hanoi, Vietnam.

In order to investigate the characteristics of PM in Hanoi, two sites, located at Gia Lam district (Vinacomin, 21°03.01'N and 105°53.04'E) and Hanoi University of Science and Technology (HUST, 21°00.17'N and 105° 50.37'E), were selected to be sampling sites (Fig. 1). The first sampling site (Vinacomin) was located on the 5<sup>th</sup> floor of Vinacomin building, at a roadside of Nguyen Van Cu road; it was near an intersection of two main roads, Gia Lam bus station, and Gia Lam railway station. Gia Lam district is also one of the places that have strong activities of rice straw open burning after harvests. The second sampling site (HUST) was located on the 3<sup>rd</sup> floor of the Center of Foreign

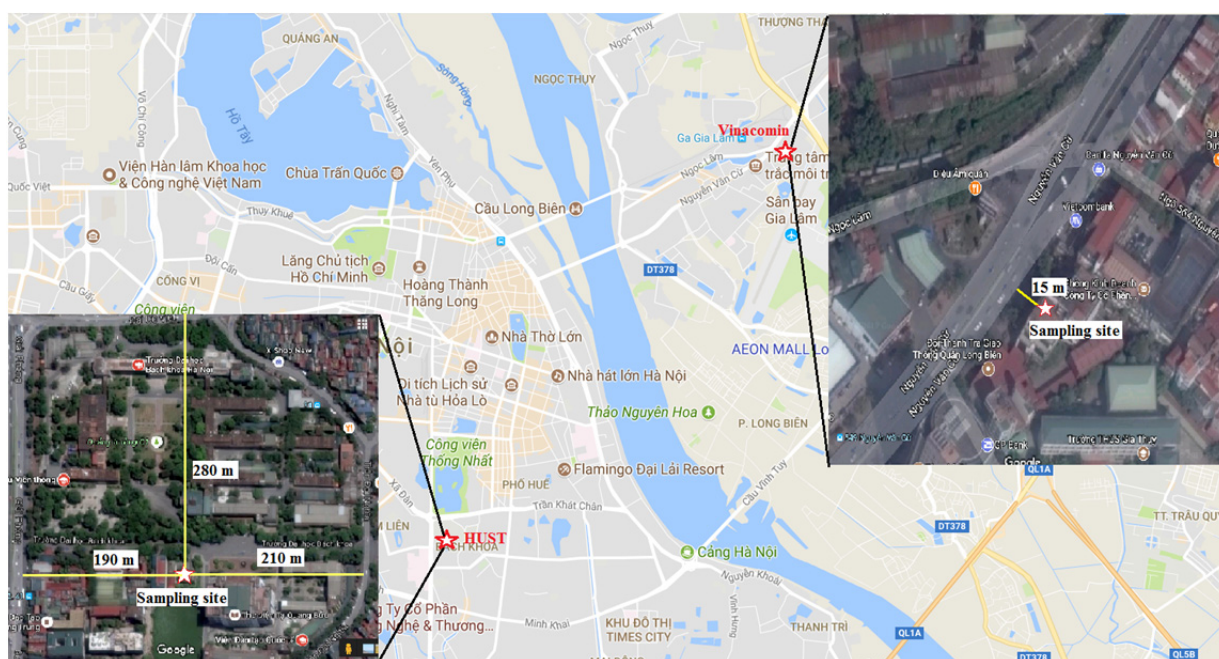


Fig. 1. Locations of the two sampling sites in Hanoi.



Languages, inside the campus of HUST. This sampling site could be considered as a mixed one, affected by different activities including transportation, construction, domestic cooking, etc. All those sources could contribute to the levels and compositions of PM. Summary of sampling campaign and meteorological conditions is shown in Table S1.

PM<sub>0.1</sub> was sampled using a sampler with an inertial fibrous filter (INF sampler, the newest prototype version KU-TSC 26A57C1, Kanazawa University, Japan). PM<sub>2.5</sub> and PM<sub>10</sub> were collected by a cyclone system with a filter holder (URG-2000-30EH, University Research Glassware Co., Chapel Hill, NC, USA) and a MiniVol sampler (Airmetrics, USA), respectively. Before sampling, all samplers were calibrated to obtain the recommended flow rates (40.0 L min<sup>-1</sup> for PM<sub>0.1</sub>, 16.7 L min<sup>-1</sup> for PM<sub>2.5</sub>, and 5.0 L min<sup>-1</sup> for PM<sub>10</sub>). Quartz filters (2500 QAT-UP, Pall Corp., USA) were used to collect these particles. Before being used, quartz filters were pre-baked at 900°C for four hours to remove possible contaminants (Desert Research Institute, 2005). A sampled quartz filter was placed in a Petri dish and kept in a separate airtight bag. The samples were refrigerated at HUST and then transported in a dry ice box to the Saitama University's laboratory in Japan for subsequent analyses. The field blanks of each set (Table S1) were pre-treated, transported to the field, followed the sampling procedure for the real samples but without running the pump, and then stored, preserved and analyzed as the sample filters.

### Analytical Methods

To determine the mass of particles, the filters were weighed on an electronic micro-balance with the accuracy of 10<sup>-6</sup> g (Model ME2, Sartorius, Germany) before and after sampling. Prior to being weighed, the filters were equilibrated in the balance room for at least 24 hours. Relative humidity of the balance room was maintained at a range of 30–40% and the temperature was kept from 20°C to 23°C (Chow *et al.*, 2001). The electrostatic charge of the

filters was eliminated by a constant ionizing air blower (Model CSD-0911, MEISEI, Japan) before weighing.

The OC/EC was analyzed in the Saitama University's laboratory in Japan. A 0.503 cm<sup>2</sup> sample punched out from a quartz fiber filter was used to determine OC and EC using a thermal/optical carbon analyzer (DRI model 2001, Atmoslytic Inc., Calabasas, CA, USA). Temperature was set up with the IMPROVE (Interagency Monitoring of Protected Visual Environments) (Chow *et al.*, 2001) with four OC fractions (OC1, OC2, OC3, OC4 at 120, 250, 450 and 550°C, respectively in a non-oxidizing helium atmosphere) and three EC fractions (EC1, EC2 and EC3 at 550, 700 and 800°C, respectively in an oxidizing helium atmosphere of 2% O<sub>2</sub> and 98% of helium). The pyrolysis of OC (POC) was continuously monitored by reflectance or transmittance of laser signals. OC is operationally defined as OC1 + OC2 + OC3 + OC4 + POC, and EC is defined as EC1 + EC2 + EC3 – POC. EC1 is defined as measured EC1 minus POC (Kim *et al.*, 2013). The EC fraction was divided into char-EC and soot-EC. Char-EC is EC1, and soot-EC is defined as the sum of EC2 and EC3 (Han *et al.*, 2009; Lim *et al.*, 2012). In all sets, blank samples were also analyzed to get the average blank OC and EC concentrations and the sample results were corrected by subtracting the blank values. The detection limits of OC and EC, defined as three times the standard deviation of the field blank results, were 0.89 and 0.19 µg cm<sup>-2</sup>, respectively.

The meteorological data such as wind direction, wind speed, temperature, relative humidity, pressure, and radiation were obtained from the ambient air monitoring station operated by Vietnam Environment Administration, located at 556 Nguyen Van Cu road. To determine the effect of biomass burning on the particulate matter concentrations, the hotspot data rebuilt by MODIS satellite were presented in Fig. 2 (produced by the US NASA, <https://firms.modaps.eosdis.nasa.gov/firemap/>). In addition, to characterize the effect of long-range transport, air mass back trajectories were

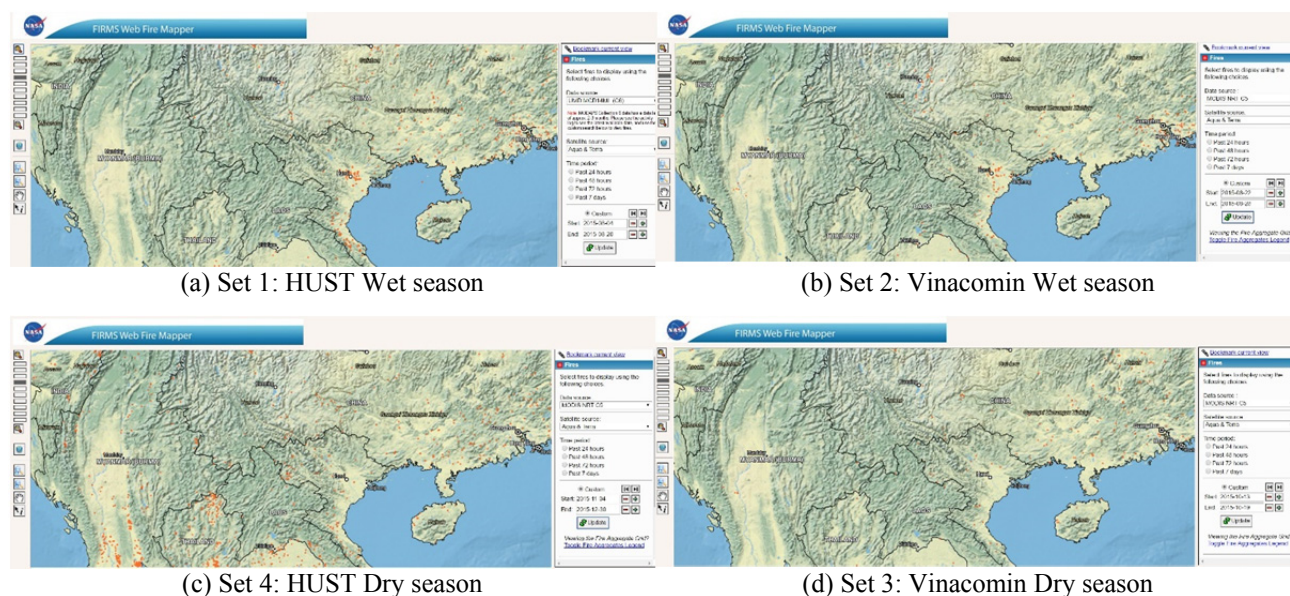


Fig. 2. MODIS active fire data in the sampling period.

examined by The HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model. Back trajectories at starting heights of 300 and 500 meters recommended by Cohen *et al.* (2010b) for every 24-hour sampling period were calculated to classify the different trajectory types arriving Hanoi during the sampling period.

## RESULTS AND DISCUSSIONS

### Meteorological Conditions, Trajectories and Hotspot Records in Sampling Period

Meteorological parameters in each set are shown in Table S1 in Supplementary Material. Generally, only temperature and radiation of seven meteorological factors had the significant differences between seasons. The average temperature was 31.2°C and 22.3°C and the radiation was 197.8 W m<sup>-2</sup> and 92.1 W m<sup>-2</sup> in the wet and dry season, respectively.

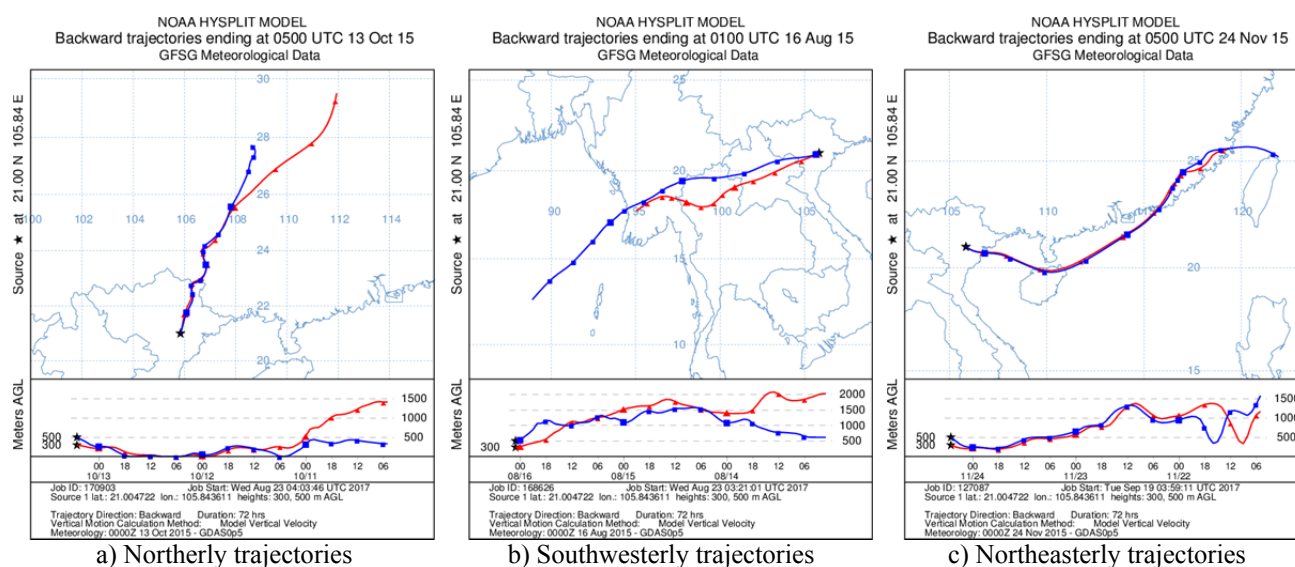
Based on the HYSPLIT model, the trajectory types arriving in Hanoi were classified into three categories, including the northerly trajectories (N) that come from Southern China, the northeasterly from South China Sea (NE), and the southwesterly trajectories (SW) from the Indian Ocean. These presentative trajectories in the sampling periods are shown in Fig. 3. In the sampling periods, trajectories of N, NE and SW occurred on 41, 40 and 6 days, respectively. In particular, the dominant trajectories of Set 1 and Set 2 (August) were NE and SW while those of Set 3 (October) and Set 4 (November–December) were N and NE. All meteorological parameters and trajectories would be used in considering the correlation between them with the PM concentrations.

In order to determine the influence of the biomass burning activities, the data of hotspots were reported by MODIS satellite. As shown in Fig. 2, the number of hotspots during sampling period in Set 3 was fewer than that in Set

1 and Set 2. However, in fact, the annual rice straw open burning activities occur in May and October (MONRE, 2017). The fewer hotspots in Set 3 could be explained by the less sensitive satellite which might not detect the small hotspots, even though the proof of adverse impacts of intense biomass burning activities in October on the atmospheric quality and human health were reported according to MONRE (2017). This demonstrates the importance of the local atmospheric studies for reflecting the reality of the certain region.

### Variation of PM Mass Concentrations

The possibility of long-range transport of air pollutants was examined in this study. The average mass concentrations based on N, NE and SW trajectories of PM<sub>0.1</sub> were 6.90 ± 3.48 µg m<sup>-3</sup>, 5.23 ± 1.46 µg m<sup>-3</sup> and 5.82 ± 1.21 µg m<sup>-3</sup>, respectively; those of PM<sub>2.5</sub> were 76.68 ± 46.43 µg m<sup>-3</sup>, 70.61 ± 50.28 µg m<sup>-3</sup> and 35.40 ± 9.87 µg m<sup>-3</sup>, respectively; and those of PM<sub>2.5-10</sub> were 33.39 ± 20.85 µg m<sup>-3</sup>, 39.15 ± 23.11 µg m<sup>-3</sup> and 24.27 ± 11.12 µg m<sup>-3</sup>, respectively. This means that the north-northeasterly trajectories could bring more pollutants from inland China and the East China Sea that highly contribute to the level of PM<sub>2.5</sub> and PM<sub>2.5-10</sub> than those from the southwest. This point also agreed with the research of Hien *et al.* (2004). However, the variation of PM<sub>2.5</sub> was more significant than that of PM<sub>2.5-10</sub>, and especially, the influence of trajectories on PM<sub>0.1</sub> concentrations was negligible. This can be explained by the different removal mechanisms that depend primarily upon particle size. Gravitational settling is dominant removal mechanism for coarse mode because of its large sizes; whereas diffusion is prevailing sink of NPs. Therefore, the residence time of these two types is short, ranging from minutes to days, preventing them from travelling long distance. In contrast, PM<sub>2.5</sub> is not removed by diffusion and gravitational settling, the predominant removal mechanism



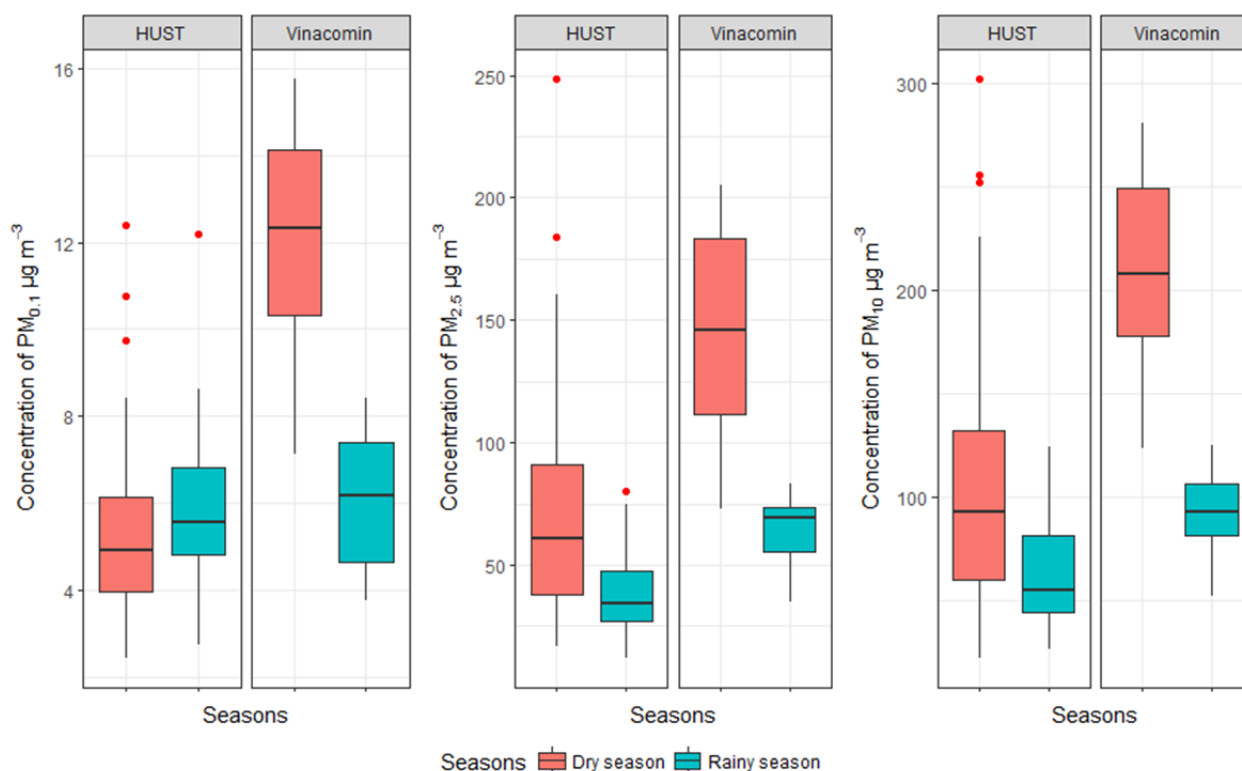
**Fig. 3.** Representatives for 3-day backward air mass trajectories arriving at 300 and 500 m (above geological level) over the Hanoi site during the sampling period. (a) Northerly trajectories (N), (b) Southwesterly trajectories (SW), and (c) Northeasterly trajectories (NE). The solid star represents the sampling site in Hanoi, Vietnam.

of this size is precipitation, thus it has the longest lifetime ranging days to weeks (Anastasio and Martin, 2001), meaning that it has ability to transport over a long distance and bring more pollutants than other sizes. This demonstrates the fact that trajectories affected negligibly on  $PM_{0.1}$  compared to larger particles.

Fig. 4 and Table 1 show the differences in seasonal variation of particulate sizes. As anticipated, the daily mass concentrations of  $PM_{2.5}$  and  $PM_{10}$  at the both sites in the dry season were higher than those in the wet season. This was caused by a number of reasons including the wet removal in the wet season and the long-range transport from inland China in the dry season. However, the concentrations of  $PM_{0.1}$  seemed to be relatively stable during the year. The average mass concentrations of nanoparticles at the mixed site (HUST) were relatively similar for both seasons and were also the same level as that in the wet season at the roadside site (Vinacomin). The very high concentrations of PM including nanoparticles observed at Vinacomin site in the dry season might be related to rice straw open burning activities in October in the suburban areas of Hanoi (MONRE, 2017), the period in which the collection of particles was also conducted. These results suggested that the seasonal concentrations of  $PM_{2.5}$  and  $PM_{10}$  widely fluctuated but those of  $PM_{0.1}$  were relatively unchanged during the year, except for abnormal event periods.

The sampling sites also contributed to the variation of PM concentrations. The daily mass concentrations of all size particles at the roadside site were generally higher than those at the mixed site. The mass concentrations of all

size particles at Vinacomin were two times higher than those at HUST in the dry season. In the wet season, the  $PM_{2.5}$  and  $PM_{10}$  concentrations at Vinacomin were 1.2 times higher than those at HUST whereas the  $PM_{0.1}$  concentrations were almost the same level. The mixed site is located inside the HUST campus, about 200 m away from the nearest main street (Giai Phong one). This site is surrounded by the green belt of trees which can serve as an effective barrier to prevent PM, especially those with the larger sizes, from reaching deep inside the campus. Whereas, it can be obviously seen that, the Vinacomin site is strongly affected by traffic activities, especially from Nguyen Van Cu road, the main road from Hanoi downtown to the North. In addition, the Vinacomin site was also directly affected by the biomass burning activities in October. These might be the main reasons for the low levels of  $PM_{2.5}$  and  $PM_{10}$  at the HUST site compared to those at the Vinacomin site. With  $PM_{0.1}$ , in the wet season, mass concentrations at Vinacomin were as the same as those at HUST; whereas those at HUST were two times lower than those at Vinacomin in the dry season. The removal mechanisms of NPs were considered as the reason for the stability of  $PM_{0.1}$  concentrations. Just in case of a temporary event such as biomass burning in the dry season at Vinacomin, were the concentrations of  $PM_{0.1}$  transiently changed. NPs could be removed by diffusing to the earth's surface, diffusing and colliding with larger particles or by growing out of NP size range through condensation of gases (Anastasio and Martin, 2001). This implies that sampling site category in a small scale (Hanoi city) had the negligible influence on NP's concentration.



**Fig. 4.** Concentrations of particulate matter in Hanoi (box plots denote minimum values, 1<sup>st</sup> quartile, median, 3<sup>rd</sup> quartile and maximum values).

**Table 1.** Concentrations of PM and comparison with other studies in Hanoi, Vietnam.

Period	Seasons	PM <sub>10</sub> (μg m <sup>-3</sup> )	PM <sub>2.5</sub> (μg m <sup>-3</sup> )	PM <sub>0.1</sub> (μg m <sup>-3</sup> )	PM <sub>0.1</sub> /PM <sub>10</sub>	PM <sub>2.5</sub> /PM <sub>10</sub>	Studies
Set 1 (8/4–8/20, 2015, HUST)	Wet	73.90	46.84	5.97	0.10	0.62	This study
Set 2 (8/22–8/28, 2015, Vinacomin)	Wet	86.59	58.14	6.06	0.07	0.68	This study
Set 3 (10/13–10/19, 2015, Vinacomin)	Dry	201.52	136.87	11.90	0.06	0.66	This study
Set 4 (11/4–12/30, 2015, HUST)	Dry	104.75	70.37	5.36	0.06	0.67	This study
2001–2008	Over years	-	54.2	-	-	-	Cohen et al. (2010a)
2001–2004	Dry	186	124	-	-	0.74	Oanh et al. (2006)
2001–2004	Wet	79	33	-	-	0.62	Oanh et al. (2006)
12/2006–2/2007	Dry	98	76	-	-	0.78	Hai and Oanh (2013)
9/1998–8/1999	Over years	87.1	36.1	-	-	0.41	Hien et al. (2002)

(-) Data not available.

### Correlations of PM Mass Concentrations with Meteorological Conditions

To find differences among the mass concentrations of three fractions, the correlations of meteorological factors such as wind speed (Ws), wind direction (Wd), temperature (T), relative humidity (RH), surface pressure (P), radiation (R), and precipitation event (Pr) on the mass concentrations of PM<sub>0.1</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub> also were examined in this study and presented in Table 2. Ws, Wd and Pr were correlated with all particulate sizes, particularly, the regression slopes between PM<sub>0.1-2.5</sub>, PM<sub>2.5</sub> and PM<sub>10</sub> with Ws, Wd and Pr were similar and higher than those between PM<sub>2.5-10</sub> and PM<sub>0.1</sub> and the three factors. The negative correlations between Ws and mass concentrations suggest the proportion of the decreasing of PM and the increasing of wind speed. Strong winds generally dilute pollution, therefore, it could eliminate the level of PM in the atmosphere. The negative correlations between PM<sub>2.5</sub> concentration and Ws were found by Zhang *et al.* (2015). The correlations between PM<sub>1-2.5</sub> and wind speed in several environmental categories during the winter also were observed by Kozáková *et al.* (2017). In this study, the regression slopes between PM<sub>0.1-2.5</sub>, PM<sub>2.5</sub>, PM<sub>10</sub> and Ws were 20 times higher than that between PM<sub>0.1</sub> and Ws, and 4 times higher than that between PM<sub>2.5-10</sub> and Ws. Similarly, the regression slopes between PM<sub>0.1</sub> and Wd, Pr were about 20 times lower than those between PM<sub>0.1-2.5</sub>, PM<sub>2.5</sub> and PM<sub>10</sub> with these factors. The regression slopes between PM<sub>2.5-10</sub> and Wd, Pr were also 2 to 3 times lower than those between PM<sub>0.1-2.5</sub>, PM<sub>2.5</sub> and PM<sub>10</sub> with these factors. This implied the significant influence of Ws, Wd, and Pr on PM<sub>0.1-2.5</sub> and the negligible influence of Ws, Wd, and Pr on PM<sub>0.1</sub> concentrations among particle sizes. More interestingly, only PM<sub>0.1</sub> had significant correlations with RH and radiation. RH has the different influence on size distribution. High RH could cause the growth of atmospheric particles, which shifts their size distribution toward larger particles (Kozáková *et al.*, 2017). Therefore, the correlations will be positive between RH and larger particle sizes and negative between RH and smaller ones. However, neither too low nor too high RH would be conducive to the rapid rise in PM<sub>2.5</sub> concentration (Zhang *et al.*, 2017). In the present study, RH of 72/87 days ranged from 45–84%, implying the possibility of shifting the smaller particles to the larger ones. This demonstrates that the negative correlation between PM<sub>0.1</sub> concentration and RH was reasonable. To sum up, the influence of some meteorological factors on the concentrations of PM<sub>0.1</sub> was negligible compared to larger particle sizes.

### Comparison of PM Mass Concentration with Other Studies

High mass concentrations of PM<sub>2.5</sub> and PM<sub>10</sub> were observed, suggesting serious PM pollution in Hanoi. Most measurements in this study were higher than 24-h WHO guideline of 25 μg m<sup>-3</sup> for PM<sub>2.5</sub> (79 exceeding days, ~91% measurements) and 50 μg m<sup>-3</sup> for PM<sub>10</sub> (73 exceeding days, ~84% measurements). These concentrations also exceeded the 24-h National Ambient Air Quality Standard of Vietnam of 150 μg m<sup>-3</sup> and 50 μg m<sup>-3</sup> in 19 days (~22%



**Table 2.** Correlations between meteorological factors and mass concentrations.

	Ws	Wd	T	RH	P	R	Pr
PM <sub>0.1</sub>	<b>−1.40 **</b>	<b>0.01 **</b>	0.06	<b>−0.15 **</b>	−0.01	<b>0.01 **</b>	<b>−1.83**</b>
PM <sub>0.1-2.5</sub>	<b>−29.76**</b>	<b>0.19*</b>	−0.94	−0.38	1.26	−0.02	<b>−21.0*</b>
PM <sub>2.5</sub>	<b>−31.16 **</b>	<b>0.20 *</b>	−0.88	−0.53	−1.25	−0.01	<b>−22.8 *</b>
PM <sub>2.5-10</sub>	<b>−8.67*</b>	<b>0.09*</b>	0.16	−0.23	0.18	0.04	<b>−13.3**</b>
PM <sub>10</sub>	<b>−39.83 **</b>	<b>0.29 **</b>	−0.72	−0.76	−1.43	0.03	<b>−36.18 **</b>

T, RH, Ws, Wd, P, R, Pr denote the temperature, relative humidity, wind speed, wind direction, surface pressure, the radiation and precipitation event in the sampling period; The numbers in the table are regression slopes; The statistically significant values at p-value < 0.05 are bolded; \* and \*\* for the confident level of 0.01 and 0.05.

measurements) and 52 days (~60% measurements) for PM<sub>10</sub> and PM<sub>2.5</sub>, respectively. The concentrations of PM<sub>2.5</sub> and PM<sub>10</sub> observed in this study had the good agreement with the real-time data from the ambient air monitoring station of Vietnam Environment Administration, located at 556 Nguyen Van Cu road ( $R^2 = 0.87$  and  $R^2 = 0.86$  for PM<sub>2.5</sub> and PM<sub>10</sub>, respectively). The levels of PM<sub>2.5</sub> and PM<sub>10</sub> in this study were also compared with those in previous others conducted in Hanoi and shown in Table 1. The results of PM<sub>2.5</sub> and PM<sub>10</sub> agreed with the studies of Hien *et al.* (2002), Oanh *et al.* (2006) and Hai and Kim Oanh (2013), which confirmed again that Hanoi had higher PM concentrations than those in many other cities of developed countries (Pennanen *et al.*, 2007; Lu *et al.*, 2011; Gugamsetty *et al.*, 2012; Lim *et al.*, 2012). Moreover, the concentrations of PM<sub>2.5</sub> and PM<sub>10</sub> in Hanoi were similar with those in some seriously polluted cities of China and India (Cao, 2004; Wang, 2008; Piplal, 2011), meaning Hanoi has alarming status about PM pollution. The high level of PM<sub>2.5</sub> and PM<sub>10</sub> in Hanoi also was unchanged in the last five years, from 2012–2016 (MONRE, 2017); whereas the PM<sub>2.5</sub> in some heavily polluted cities such as Shijiazhuang and Beijing generally decreased because of pollution control measures (Lang *et al.*, 2017; Wang *et al.*, 2017), implying the necessity of efficient air pollution control policy to improve the air quality in Vietnam.

The study also found out that Hanoi, Vietnam, has the high concentrations of not only PM<sub>2.5</sub> and PM<sub>10</sub> but also PM<sub>0.1</sub>. The NP's concentrations were roughly from 2 to 10 times higher than those in other urban sectors shown in Table 3 (cited in Thuy *et al.*, 2016; Thuy *et al.*, 2017). The reasons for that might be road vehicles (backward buses, a very high number of motorcycles) and high activities of rice straw open burning (MONRE, 2017). However, to quantitatively answer the questions what the main sources that contribute to the higher concentrations of PM in Vietnam are and what the effects of these higher concentrations on human health and environment are, further studies on PM in Vietnam are needed to conduct.

To consider the major fraction contributing to PM concentrations, the average ratios of PM were calculated and illustrated in Table 1. The average ratios of PM<sub>0.1</sub>/PM<sub>10</sub> and PM<sub>2.5</sub>/PM<sub>10</sub> are  $0.07 \pm 0.03$  and  $0.66 \pm 0.11$ , respectively. Generally, the PM<sub>2.5</sub>/PM<sub>10</sub> ratios in this study were the same range as those of other studies in Hanoi. Hien *et al.* (2002) found that this ratio was 0.41 during a year while Oanh *et al.* (2006) observed PM<sub>2.5</sub>/PM<sub>10</sub> ratio to be 0.62

and 0.74 in the wet and dry season, respectively. The study of Hai and Kim Oanh (2013) also found that this ratio was 0.78 in the dry season. These results demonstrate that PM<sub>2.5</sub> constituted the major fraction of PM<sub>10</sub> from site to site, from season to season, which emphasizes the significant contribution of the secondary particles to the PM in Hanoi. Although PM<sub>0.1</sub> only constituted 7% of PM<sub>10</sub> and 11% of PM<sub>2.5</sub>, these ratios were also higher than those in studies of Rovenlli *et al.* (2017) in Italy, Lin *et al.* (2015) and Gugamsetty *et al.* (2012) in Taiwan, demonstrating that Hanoi had not only the high NPs' concentrations but also the higher contribution of this size to the larger sizes, leading to potential adverse effects on human health and environment.

#### OC and EC Fractions

Investigating the average OC and EC concentrations of all PM<sub>0.1</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub> indicated the different characteristics of EC and OC in PM<sub>0.1</sub>. OC and EC concentrations in both seasons at HUST site were unchanged and approximated those in the wet season at Vinacomin; whereas their mass concentrations of the three sizes of particles at the roadside site in the dry season were roughly two times higher than that in wet season. Once again, the high concentrations of these components in the dry season at Vinacomin were attributed to the strong biomass burning activities in October mentioned above. More significantly, it is known that seasonal variation of the mass concentrations of PM<sub>2.5</sub> and PM<sub>10</sub> was marked while the concentrations of EC and OC of those particles seemed to be unfluctuating except in the dry season at Vinacomin. Just in case of an abnormal event such as biomass burning, were the concentrations of EC and OC temporarily changed. This demonstrated the higher contributions of other components such as ions, elements, etc. on mass concentrations of PM<sub>2.5</sub> and PM<sub>10</sub> in the dry season. The OC and EC concentrations in the dry season at Vinacomin were roughly two times higher than any other sampling sets. In contrast with PM<sub>2.5</sub> and PM<sub>10</sub>, mass concentrations of PM<sub>0.1</sub> and OC and EC concentrations had the same characteristics, that was the stability in two seasons at both sites excluding in dry season at Vinacomin when having biomass burning activities. This indicated that the carbonaceous components were the prevailing composition of PM<sub>0.1</sub> and had a strong influence on PM<sub>0.1</sub> mass concentration. The result also agreed with the relative contributions of total carbon (TC) to total mass. It accounted for 59.19% of PM<sub>0.1</sub> while it was 44.65% and 43.79% of PM<sub>2.5</sub> and PM<sub>10</sub>, respectively,

**Table 3.** Concentrations of NPs at different locations.

Location	Site feature	Concentration ( $\mu\text{g m}^{-3}$ )	Studies
HUST, Hanoi	Mixed	5.36–5.97	This study
Gia Lam, Hanoi	Traffic	6.06–11.90	This study
California, US	Urban-industrial	0.60–1.20	Cass <i>et al.</i> (2000)
Taiwan	Urban-industrial	$1.42 \pm 0.56$	Gugamsetty <i>et al.</i> (2012)
Finland	Rural	0.52	Pakkanen <i>et al.</i> (2001)
Finland	Urban	0.49	Pakkanen <i>et al.</i> (2001)
Dunkrink, France	Industrial	0.80	Mbengue <i>et al.</i> (2014)
Dunkrink, France	Urban-industrial	0.50	Mbengue <i>et al.</i> (2014)
Hsinchu, Taiwan	Traffic	$2.21 \pm 0.59$	Chen <i>et al.</i> (2010)
Hsinchu, Taiwan	Forest	$0.65 \pm 0.31$	Chen <i>et al.</i> (2010)
Hsinchu, Taiwan	Tunnel	$33.2 \pm 6.5$	Chen <i>et al.</i> (2010)
Los Angeles, US	Riverside	1.34	Kim <i>et al.</i> (2002)
Los Angeles, US	Urban	4.11	Kim <i>et al.</i> (2002)
Sanghai, China	Roadside	4.6	Lu <i>et al.</i> (2011)
Sanghai, China	Urban	2.7	Lu <i>et al.</i> (2011)

revealing that carbonaceous compounds were one of the most abundant components in particles, especially in  $\text{PM}_{0.1}$ .

The contributions of OC and EC fractions to PM are vital to identify the emission sources. These contributions to  $\text{PM}_{10}$  were ranked in the following order: OC3 (25.7%) > EC1 (23.5%) > OC4 (16.6%) > OC2 (16.0%) > POC (11.0%) > EC2 (4.9%) > OC1 (2.3%) > EC3 (0%). The ranking for  $\text{PM}_{2.5}$  was: EC1 (25.7%) > OC3 (24.5%) > OC4 (16.6%) > OC2 (15.2%) > POC (11.6%) > EC2 (4.1%) > OC1 (2.3%) > EC3 (0%). The average contribution of each carbonaceous component of  $\text{PM}_{0.1}$  was OC3 (29.8%) > OC2 (21.3%) > EC1 (17.9%) > OC4 (12.8%) > POC (9.9%) > EC2 (6.4%) > OC1 (1.7%) > EC3 (0.1%). OC3 and EC1 were predominant in  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$  while OC3 and OC2 were the prevailing carbonaceous fractions of  $\text{PM}_{0.1}$ . The abundance of OC3 relatively in cooking exhaust, vegetative burning (Panicker *et al.*, 2015), gasoline motor vehicle (Li *et al.*, 2012), and road dust (Gu *et al.*, 2010). The major sources for EC1 were found in gasoline motor vehicle (Li *et al.*, 2012), vegetative burning, coal combustion, and cement Kline (Panicker *et al.*, 2015). OC2 is carbonaceous of coal combustion (Gu *et al.*, 2010, Li *et al.*, 2012). Therefore, the rankings suggested that the major sources of carbonaceous components in this area are gasoline motor vehicle, coal combustion, cooking exhaust and vegetative burning. To confirm the major sources contributing to carbonaceous components, EC/OC ratios were calculated and discussed in the next section.

### OC/EC Ratios

The average OC/EC ratios were calculated for each site in each season and presented in Table 4. These ratios had the same range for all sizes of particles, all seasons, all sites including Vinacomin in the dry season when the event of abnormal higher concentrations of EC and OC occurred, supporting the theory that consistent OC/EC ratios can be found corresponding to a certain location and season (Kudo *et al.*, 2012). Although the concentrations were totally different between particle sizes, seasons, and sites, the OC/EC ratios did not fluctuate so much. The less

variation of these ratios might be caused by the constant sources of the contribution of EC and OC.

OC/EC ratios of  $\text{PM}_{0.1}$ ,  $\text{PM}_{2.5}$ , and  $\text{PM}_{10}$  were generally similar; however, there were some differences. Firstly, the OC/EC ratios of  $\text{PM}_{0.1}$  were the highest in three particle sizes, except in the dry season at Vinacomin. When biomass burning occurred in October, the OC/EC ratio of  $\text{PM}_{0.1}$  was the lowest. The variation of OC/EC ratio of NPs enhances the efficiency of source identification. Secondly, the very high correlations between OC and EC of three size particles also were found, except for this correlation of  $\text{PM}_{0.1}$  in the dry season at Vinacomin (Fig. 5). The high correlations implied the presence of common dominant sources for OC and EC because the relative rates of OC and EC would be proportional to each other (Pachauri *et al.*, 2013). Moreover, these high correlations indicated OC was generated mostly by primary emissions and not much by secondary gas-to-particle formations for all three sizes. The lower correlation between EC and OC of  $\text{PM}_{0.1}$  in the dry season at Vinacomin site pointed out that the complex of emission sources could influence the characteristics of OC and EC of  $\text{PM}_{0.1}$  but did not affect strongly those of  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$ .

The OC/EC ratios in the present study were comparable with other studies. The OC/EC ratios of  $\text{PM}_{0.1}$  in this study were higher than those measured at Taiwan that varied from 0.21 to 1.71 (Chen *et al.*, 2010, Zhu *et al.*, 2010) and the ratios of  $\text{PM}_{2.5}$  were higher than those reported in Japan, Germany, and Taiwan that were 1.64, 2.44 and 1.26, respectively (Zhu *et al.*, 2010; Kudo *et al.*, 2012). However, the ratios of  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$  were a little lower than those measured in Hanoi, that were 6.78 and 7.17, respectively (Hai and Kim Oanh, 2013). The ratios also were lower than those measured near-source biomass burning smoke in Sonla. Lee *et al.* (2016) found that the OC/EC ratio of  $\text{PM}_{2.5}$  in this area was 6.1 in 2012 and 6.8 in 2013; whereas, Popovicheva *et al.* (2016) observed the ratio of  $\text{PM}_1$  was 7.6 on days of low smoke and up to 18.3 during high smoke periods.

The OC/EC ratio can be used as an indicator of emission sources because EC can emit from primary sources only



**Table 4.** Mass concentrations ( $\mu\text{g m}^{-3}$ ) of carbon fractions and OC/EC ratios.

Set	PM	OC1	OC2	OC3	OC4	POC	EC1	EC2	EC3	OC	EC	OC/EC
1 (Wet season, HUST)	PM <sub>10</sub> <sup>a</sup>	0.62	8.69	11.15	6.43	4.29	4.22	2.26	ND <sup>c</sup>	31.19	6.48	4.77
	PM <sub>10</sub> <sup>b</sup>	0.50	10.38	4.39	3.14	2.40	2.56	0.72	ND <sup>c</sup>	19.12	3.17	0.77
	PM <sub>2.5</sub> <sup>a</sup>	0.27	4.08	7.10	4.59	2.79	3.23	1.29	ND <sup>c</sup>	18.83	4.52	4.50
	PM <sub>2.5</sub> <sup>b</sup>	0.29	3.49	4.87	4.73	2.33	4.05	0.41	ND <sup>c</sup>	15.54	4.26	0.73
	PM <sub>0.1</sub> <sup>a</sup>	0.01	0.64	0.97	0.41	0.27	0.26	0.21	ND <sup>c</sup>	2.31	0.46	5.68
	PM <sub>0.1</sub> <sup>b</sup>	0.02	0.14	0.36	0.18	0.17	0.21	0.05	ND <sup>c</sup>	0.84	0.26	1.86
	PM <sub>10</sub> <sup>a</sup>	1.10	6.70	11.19	6.50	6.18	5.57	3.14	ND <sup>c</sup>	31.67	8.71	3.75
	PM <sub>10</sub> <sup>b</sup>	0.30	2.42	3.19	2.73	1.65	2.64	1.02	ND <sup>c</sup>	9.43	3.40	0.56
	PM <sub>2.5</sub> <sup>a</sup>	0.44	3.91	6.83	3.38	3.24	4.20	1.00	ND <sup>c</sup>	17.80	5.20	3.62
	PM <sub>2.5</sub> <sup>b</sup>	0.24	1.92	4.49	1.77	1.55	2.61	0.45	ND <sup>c</sup>	8.28	2.57	0.86
2 (Wet season, Vinacomin)	PM <sub>0.1</sub> <sup>a</sup>	0.04	0.70	0.94	0.40	0.31	0.27	0.27	0.01	2.39	0.54	4.67
	PM <sub>0.1</sub> <sup>b</sup>	0.04	0.12	0.21	0.12	0.13	0.14	0.08	0.01	0.55	0.21	0.93
	PM <sub>10</sub> <sup>a</sup>	2.02	15.84	26.48	21.46	10.80	14.74	4.39	ND <sup>c</sup>	76.77	19.13	4.00
	PM <sub>10</sub> <sup>b</sup>	0.32	3.63	6.82	5.92	2.99	3.35	2.25	ND <sup>c</sup>	18.85	4.01	0.39
	PM <sub>2.5</sub> <sup>a</sup>	2.04	10.23	17.95	13.56	7.41	11.38	2.46	ND <sup>c</sup>	51.19	13.86	3.92
	PM <sub>2.5</sub> <sup>b</sup>	1.57	5.69	8.20	7.51	1.77	8.04	0.53	ND <sup>c</sup>	24.34	8.05	0.56
	PM <sub>0.1</sub> <sup>a</sup>	0.12	1.06	1.60	0.84	0.72	0.85	0.30	0.03	4.34	1.18	3.79
	PM <sub>0.1</sub> <sup>b</sup>	0.04	0.14	0.28	0.17	0.20	0.34	0.07	0.07	0.79	0.32	0.68
	PM <sub>10</sub> <sup>a</sup>	1.19	6.46	11.11	6.89	4.81	5.39	2.01	ND <sup>c</sup>	30.56	7.40	4.31
	PM <sub>10</sub> <sup>b</sup>	0.43	2.82	5.01	4.07	2.41	3.5	0.60	ND <sup>c</sup>	14.43	3.67	0.79
3 (Dry season, Vinacomin)	PM <sub>2.5</sub> <sup>a</sup>	0.83	4.95	7.39	5.06	3.92	4.37	1.31	ND <sup>c</sup>	22.15	5.68	4.22
	PM <sub>2.5</sub> <sup>b</sup>	0.86	4.67	6.56	5.47	3.87	4.86	1.05	ND <sup>c</sup>	21.06	5.57	0.85
	PM <sub>0.1</sub> <sup>a</sup>	0.05	0.60	0.80	0.33	0.26	0.16	0.17	ND <sup>c</sup>	2.77	0.63	4.78
	PM <sub>0.1</sub> <sup>b</sup>	0.04	0.19	0.23	0.14	0.15	0.11	0.06	ND <sup>c</sup>	0.90	0.28	1.29
4 (Dry season, HUST)	PM <sub>10</sub> <sup>a</sup>	0.62	8.69	11.15	6.43	4.29	4.22	2.26	ND <sup>c</sup>	31.19	6.48	4.77
	PM <sub>10</sub> <sup>b</sup>	0.50	10.38	4.39	3.14	2.40	2.56	0.72	ND <sup>c</sup>	19.12	3.17	0.77
	PM <sub>2.5</sub> <sup>a</sup>	0.27	4.08	7.10	4.59	2.79	3.23	1.29	ND <sup>c</sup>	18.83	4.52	4.50
	PM <sub>2.5</sub> <sup>b</sup>	0.29	3.49	4.87	4.73	2.33	4.05	0.41	ND <sup>c</sup>	15.54	4.26	0.73
	PM <sub>0.1</sub> <sup>a</sup>	0.01	0.64	0.97	0.41	0.27	0.26	0.21	ND <sup>c</sup>	2.31	0.46	5.68
	PM <sub>0.1</sub> <sup>b</sup>	0.02	0.14	0.36	0.18	0.17	0.21	0.05	ND <sup>c</sup>	0.84	0.26	1.86

<sup>a</sup> Concentration, <sup>b</sup> Standard Deviation, <sup>c</sup> Not detected.

whereas OC might be created from both primary and secondary sources (Han *et al.*, 2009). For example, the OC/EC ratios for 2.5 to 10.5 correspond to residential coal burning, 12 to long-range transport, 1.0 to 4.2 represent high motor vehicle emission (Panicker *et al.*, 2015), 4.3 to 7.7 suggest kitchen exhaust, 3.8 to 13.2 for biomass burning (Pachauri *et al.*, 2013), 5.67 for rice straw field (Oanh *et al.*, 2011). In the present study, the OC/EC ratios at the roadside site were a little lower than those at the mixed site, reflecting the influence of the vehicle emission at Vinacomin site. However, the OC/EC ratios in this study were generally similar to those reported in the literature for the motor vehicle, cooking exhaust, biomass burning and coal smoke. Moreover, the OC/EC ratios in the present study exceeded 2.0, indicating the presence of secondary organic aerosols at both sites (Cao *et al.*, 2006). Therefore, OC in this area could derive from various burning sources and secondary chemical reactions as well as the gas condensation. To establish a control strategy for particulate matter pollution, the contributions of primary and secondary OC to the total OC need to be estimated.

#### Estimation of Secondary Organic Carbon (SOC)

The SOC fraction in aerosols is either estimated using the EC-tracer method (Turpin *et al.*, 1995) or by adding up all the oxidation products found in aerosols (Ram *et al.*, 2010). In this study, EC-tracer method was used to estimate the contribution of SOC to the measured OC. This technique has been used to distinguish primary OC from secondary OC in numerous studies. The underlying

hypothesis is that EC and primary OC often have the same sources, so there is a representative ratio of primary OC/EC for a given area ( $[\text{OC/EC}]_{\text{pri}}$ ). Herein, the primary organic carbon concentrations,  $[\text{OC}]_{\text{pri}}$ , were estimated as follows:

$$[\text{OC}]_{\text{pri}} = [\text{OC/EC}]_{\text{pri}}[\text{EC}] \quad (1)$$

where  $[\text{OC}]_{\text{pri}}$  is the primary organic aerosol concentration,  $[\text{OC/EC}]_{\text{pri}}$  is the ratio of OC to EC for the primary sources. Then, the secondary organic carbon (SOC) concentration is simply the difference between the measured total OC,  $[\text{OC}]_{\text{tot}}$ , and the estimated primary OC,  $[\text{OC}]_{\text{pri}}$ .

$$\text{SOC} = [\text{OC}]_{\text{tot}} - [\text{OC}]_{\text{pri}} \quad (2)$$

Numerous methods for determining the value of  $[\text{OC/EC}]_{\text{pri}}$  have been used in previous studies. Castro *et al.* (1999) reported that the consistent presence of a clear minimum ratio for OC/EC in urban and rural areas, in winter and summer, suggesting that samples having the lowest OC/EC ratios contain almost exclusively primary carbonaceous compounds. The  $[\text{OC/EC}]_{\text{pri}}$ ,  $[\text{OC}]_{\text{pri}}$ , and SOC and its contribution to TC are presented in Table 5.

Although the  $[\text{OC/EC}]_{\text{pri}}$  could be affected by meteorological factors and emission source, the obtained values in the study were the same range with those at traffic site (3.6; Pachauri *et al.*, 2013), urban site (1.2–2.43; Panicker *et al.*, 2015), and mixed sites (2.26–4.48; Duan *et al.*, 2007). As shown Table 5, the  $[\text{OC}]_{\text{pri}}$  concentrations of all size particles were generally similar, except those in the dry

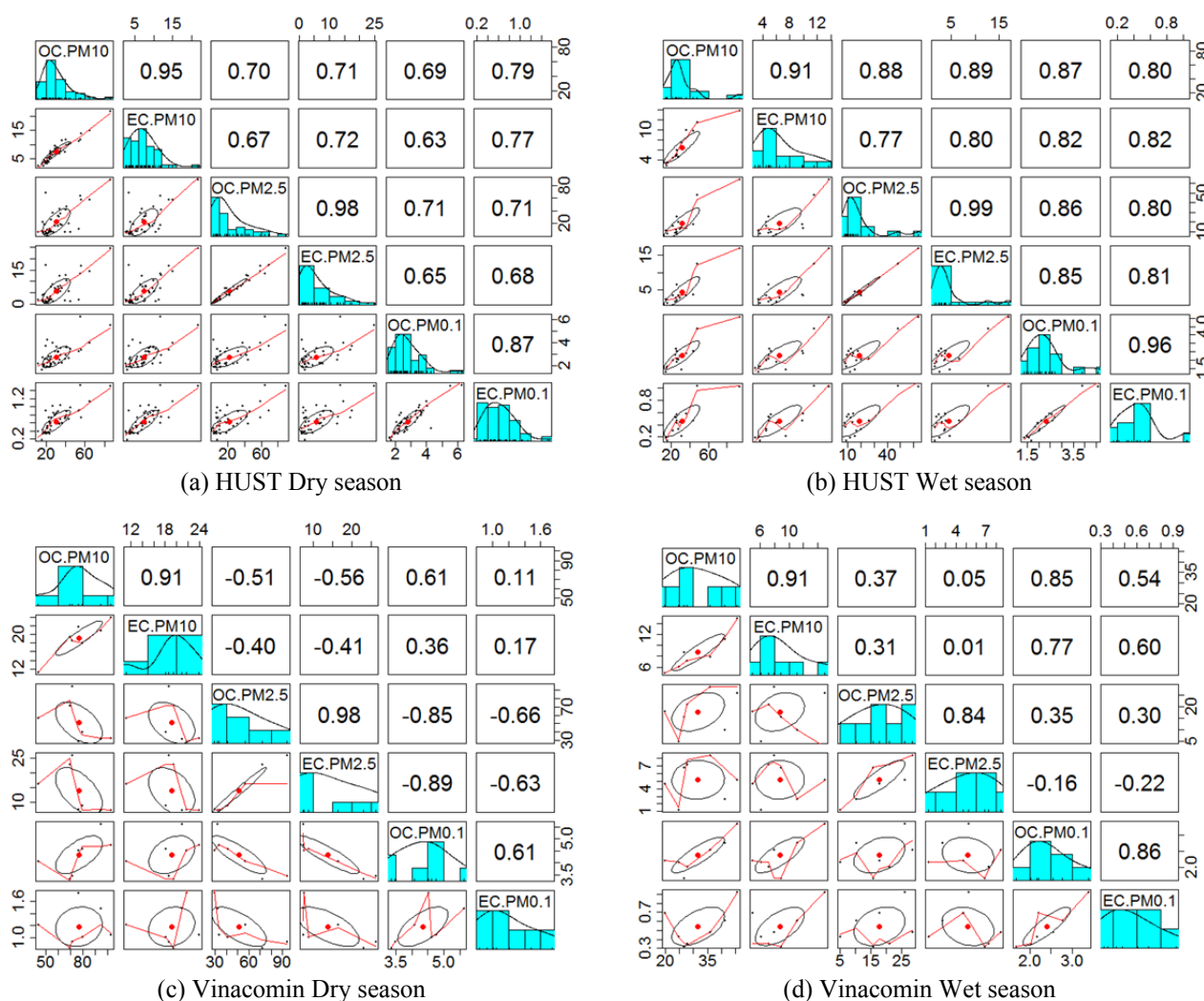


Fig. 5. Correlations between OC and EC in two seasons at both sites.

Table 5. Levels of SOC estimated from minimum OC/EC ratios.

	(OC/EC) <sub>pri</sub>			OC <sub>pri</sub> ( $\mu\text{g m}^{-3}$ )			SOC ( $\mu\text{g m}^{-3}$ )			SOC/OC (%)		
	PM <sub>10</sub>	PM <sub>2.5</sub>	PM <sub>0.1</sub>	PM <sub>10</sub>	PM <sub>2.5</sub>	PM <sub>0.1</sub>	PM <sub>10</sub>	PM <sub>2.5</sub>	PM <sub>0.1</sub>	PM <sub>10</sub>	PM <sub>2.5</sub>	PM <sub>0.1</sub>
Set 1	3.64	3.20	3.74	23.55	14.44	1.73	7.64	4.13	0.58	22.04	27.15	29.04
Set 2	3.02	2.32	3.19	26.34	12.06	1.74	5.33	5.74	0.66	17.84	32.42	28.88
Set 3	3.52	3.10	2.60	67.32	42.97	3.07	9.45	8.21	1.27	11.37	19.41	29.24
Set 4	3.06	2.36	2.76	22.63	13.42	1.74	7.93	8.73	1.03	26.78	41.49	38.52
Roadside site	3.02	2.32	2.60	42.08	22.12	2.24	12.14	12.38	1.12	20.85	36.05	35.61
Mixed site	3.06	2.36	2.76	21.92	12.66	1.63	8.79	8.57	1.03	28.70	42.79	40.64
Whole sampling	3.02	2.32	2.60	25.34	14.32	1.65	9.59	9.49	1.12	27.94	42.27	42.71

season at the mixed site (HUST). The  $[\text{OC}]_{\text{pri}}$  concentrations of PM<sub>2.5</sub> and PM<sub>10</sub> in set 3 were approximately three times higher than those in other sets; whereas the proportion of PM<sub>0.1</sub> was only 1.8. The very high  $[\text{OC}]_{\text{pri}}$  concentrations in set 3 indicated that there was an abnormal event that emitted the primary OC in this period, which confirmed the influence of rice straw open burning in October. At the mixed site, SOC concentrations in dry season at HUST were higher than those in the wet season. During the dry

season, the stable atmospheric conditions that might strengthen atmospheric oxidation and the low temperature that could enhance the condensation of volatile secondary organic compounds on pre-existing aerosol are two main reasons to explain for the higher SOC/OC in the dry season (Duan *et al.*, 2007; Pachauri *et al.*, 2013). At Vinacomin, SOC contributions of PM<sub>2.5</sub> and PM<sub>10</sub> in the wet season were 1.6–1.7 times higher than those in the dry season while this value of PM<sub>0.1</sub> was similar. The abnormal phenomena

could be explained by the biomass burning activities that could increase the primary sources of OC in the dry season at this sampling site. In general, the SOC contributions in whole sampling periods were 42.71%, 42.27% and 27.94% for PM<sub>0.1</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub>, respectively, indicating the significant contribution of secondary sources to OC concentrations, especially with the finer particles.

#### Char-EC and Soot-EC Concentrations and their Ratios

Similar to OC/EC ratios, the relationships between char-EC and soot-EC are widely used as a source indicator. The char-EC and soot-EC ratios were even more effective than OC/EC ratios for they were able to avoid the great bias caused by SOC formation (Han *et al.*, 2009). As mentioned above, there was a significant contribution of secondary sources to OC concentrations. Moreover, no correlation between char-EC/soot-EC and OC/EC of PM<sub>10</sub> demonstrated their differences in source identification of coarse particles. The relationships between char-EC/soot-EC and OC/EC of PM<sub>2.5</sub> and PM<sub>0.1</sub> showed the relatively moderate correlations ( $R^2 = 0.62$  and  $0.50$ , respectively), indicating their similarity in source indicator of finer particles although the differences between them still existed. Therefore, it was crucial to calculate the char-EC/soot-EC to primarily predict the sources of particulate matter in the atmosphere. The average char-EC and soot-EC concentrations and their ratios of each set were calculated and shown in Table 6. The mean concentrations of char-EC and soot-EC of whole sampling period were  $0.39 \pm 0.31$  and  $0.25 \pm 0.07 \mu\text{g m}^{-3}$ ;  $5.80 \pm 3.76$  and  $1.52 \pm 0.65 \mu\text{g m}^{-3}$ ; and  $7.48 \pm 4.88$  and  $2.95 \pm 1.08 \mu\text{g m}^{-3}$  for PM<sub>0.1</sub>, PM<sub>2.5</sub> and PM<sub>10</sub>, respectively. These results were in the same range as those of other studies although the concentrations of char-EC and soot-EC of NPs in this study were different from those of other studies (Table 6). Among the three sizes, the contributions of char-EC to the total EC were ordered: PM<sub>2.5</sub> (78%) > PM<sub>10</sub> (70%) > PM<sub>0.1</sub> (56%), indicating that soot-EC was composed of much smaller particles, which agreed with Zhu *et al.* (2010).

In the literature, the char-EC/soot-EC ratios were normally lower than 1.0 for motor vehicles (Chow *et al.*, 2004; Cao *et al.*, 2006), between 1.0 and 2.0 for coal combustion, and more than 10 for biomass burning (Chow, 2004; Cao, 2005). The individual char-EC/soot-EC ratios in this study ranged from 0.94 to 2.58 for PM<sub>0.1</sub>, from 2.5 to 4.6 for PM<sub>2.5</sub>, and from 1.8 to 3.8 for PM<sub>10</sub>, which presented minor mixed contributions from several sources such as coal-combustion, motor vehicle exhaust, and biomass burning.

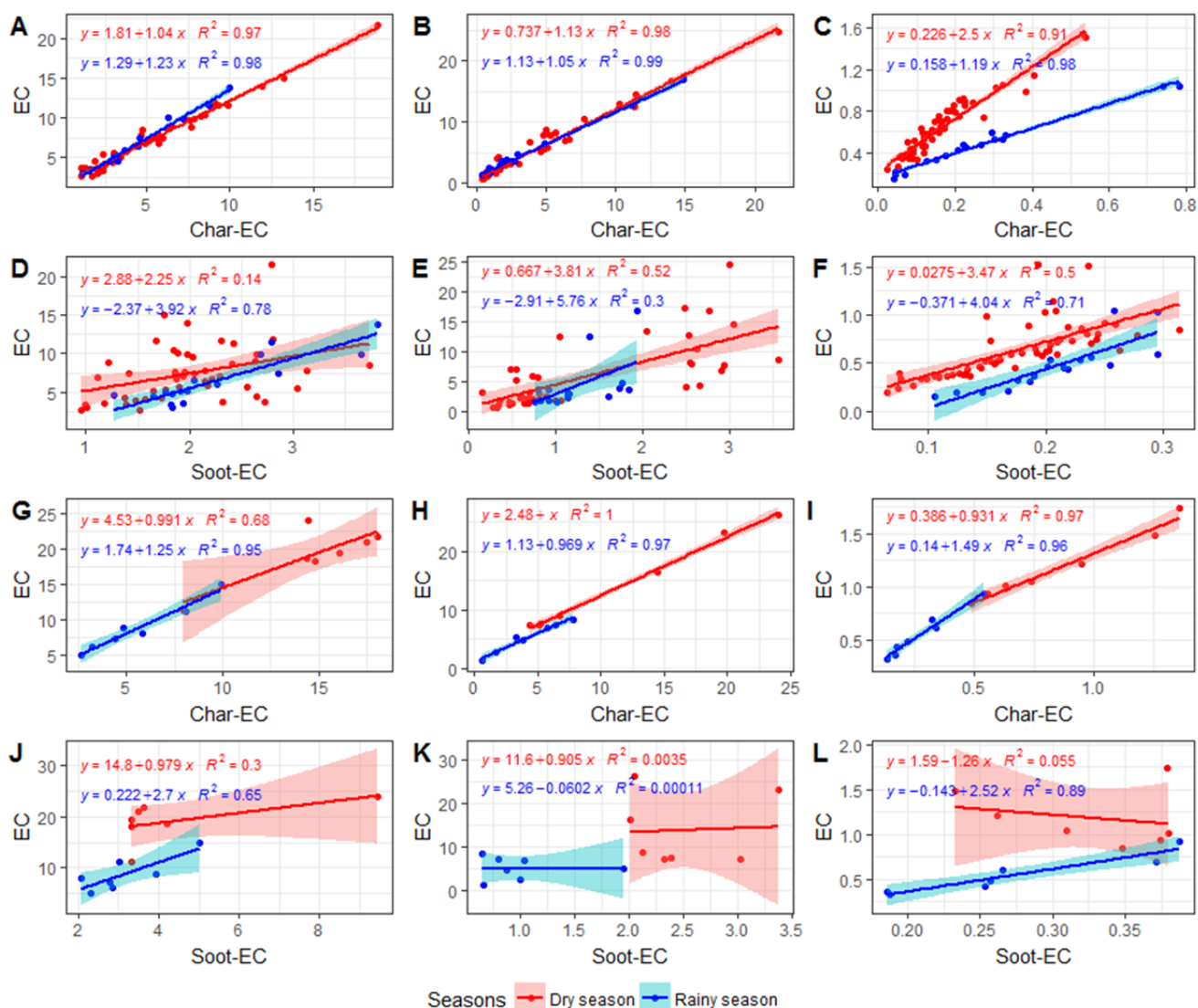
Unlike OC/EC ratios, the char-EC and soot-EC ratios had the wider fluctuant range (0.94–4.61), implying that char-EC/soot-EC ratios could be more efficient in source identification. Considering Vinacomin site in the dry season when biomass burning activities occurred, the char-EC and soot-EC ratios of all three particle sizes increased, especially the changing of PM<sub>0.1</sub> was the most significant (2.1–2.7 times), indicating this ratio was more useful in primarily predicting the emission sources for NPs.

Most relationships between char-EC and EC (Fig. 6) showed the strong correlations in two seasons at both sites

Table 6. Mass concentrations ( $\mu\text{g m}^{-3}$ ) of char-EC and soot-EC and their ratios.

Season	Site	PM <sub>10</sub>			PM <sub>2.5</sub>			PM <sub>0.1</sub>			Studies
		Char-EC	Soot-EC	Ratio	Char-EC	Soot-EC	Ratio	Char-EC	Soot-EC	Ratio	
Dry	HUST	5.39	2.01	2.68	4.37	1.31	3.33	0.16	0.17	0.94	This study
Wet	HUST	4.22	2.26	1.88	3.23	1.29	2.50	0.26	0.21	1.24	This study
Dry	Vinacomin	14.74	4.39	4.04	11.38	2.47	4.61	0.85	0.33	2.58	This study
Wet	Vinacomin	5.57	3.14	1.77	4.20	1.00	4.20	0.27	0.27	1.00	This study
Yearly	Korea	1.40	0.30	4.67	1.30	0.40	3.25	-	-	-	Lim <i>et al.</i> (2012)
Winter	China	-	-	-	8.67	1.26	6.88	-	-	-	Han <i>et al.</i> (2009)
Summer	China	-	-	-	2.41	1.21	1.98	-	-	-	Han <i>et al.</i> (2009)
Summer	Japan	-	-	-	1.85	0.47	3.94	0.06	0.02	3.00	Kudo <i>et al.</i> (2012)
Summer	Germany	-	-	-	1.86	0.28	6.64	0.08	0.06	1.33	Kudo <i>et al.</i> (2012)

Ratio is Char-EC/Soot-EC, (-) Data not available.



**Fig. 6.** Correlations between Char-EC and Soot-EC with EC in two seasons at both sites (A, B, C are correlation between char-EC with EC of PM<sub>10</sub>, PM<sub>2.5</sub>, PM<sub>0.1</sub> and D, E, F are correlation between soot-EC with EC of PM<sub>10</sub>, PM<sub>2.5</sub>, PM<sub>0.1</sub> at HUST, respectively; G, H, I are correlation between char-EC with EC of PM<sub>10</sub>, PM<sub>2.5</sub>, PM<sub>0.1</sub> and J, K, L are correlation between soot-EC with EC of PM<sub>10</sub>, PM<sub>2.5</sub>, PM<sub>0.1</sub> at Vinacomin, respectively).

for all PM<sub>0.1</sub>, PM<sub>2.5</sub> and PM<sub>10</sub> except for PM<sub>10</sub> in the dry season at Vinacomin site, showing that char-EC dominated the total EC and suggesting there were common combustions sources such as biomass burning and residential heating at both sites. In contrast, the correlations between soot-EC and EC of these three sizes appeared to be complicated (Fig. 6). These correlations implied that the variation of EC fractions was mainly caused by soot-EC. Considering Vinacomin site in the dry season when biomass burning activities happened, there were relatively moderate correlations between char-EC and soot-EC with EC for PM<sub>10</sub>, whereas there were very strong correlations between char-EC and EC for PM<sub>2.5</sub> and PM<sub>0.1</sub>, respectively, and very poor correlations between soot-EC and EC (Fig. 6). These demonstrated that the biomass burning activities had the strong influence on char-EC of larger size particles and on soot-EC of smaller size ones.

Further studies need investigating to determine the apportionment of each source on the level of atmospheric particulate matters, which will make the significant contribution to build up the efficient air pollution control measures in Hanoi and in megacities generally.

## CONCLUSIONS

Different characteristics of PM<sub>0.1</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub>, including the mass and the carbonaceous components, were measured at two urban locations in Hanoi, Vietnam, during the wet and dry seasons. High mass levels of PM<sub>0.1</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub> were observed in Hanoi, especially in rice straw open burning episode. The mass concentrations of PM<sub>2.5</sub> and PM<sub>10</sub> had temporal variations depending on the sampling site, season, and trajectory, whereas those of PM<sub>0.1</sub> did not seem to fluctuate significantly. The variation



in carbonaceous components was small, except during the biomass burning period. There were still some differences in the characteristics of EC and OC between  $PM_{0.1}$  and larger particles. While OC3 and EC1 were the most abundant in  $PM_{2.5}$  and  $PM_{10}$ , OC3 and OC2 were higher than any other carbonaceous fraction in  $PM_{0.1}$ , implying the major sources of carbonaceous components in this area are gasoline motor vehicles, coal combustion, cooking exhaust, and vegetative burning. Although the concentrations were totally different between particle sizes, seasons, and sites, the OC/EC ratios did not fluctuate much. These ratios confirm the mixed combustion sources that were previously predicted based on the dominant carbonaceous fractions. The char-EC/soot-EC ratios presented more efficiency in source identification with these sources. Moreover, the OC/EC ratios also indicated the presence of secondary organic aerosols. The secondary sources prevailed in the OC concentrations, accounting for 43%, 42%, and 30% of the  $PM_{0.1}$ ,  $PM_{2.5}$ , and  $PM_{10}$ , respectively. These results form a significant contribution to Vietnam's database of atmospheric particles.

## ACKNOWLEDGMENTS

This study was funded by the Ministerial level project coded B2016-BKA-28.

Kanazawa University, Japan is acknowledged for providing the sampler (KU-TSC 26A57C1) for this study.

## SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at <http://www.aaqr.org>.

## REFERENCES

- Anastasio, C. and Martin, S.T. (2001). Atmospheric nanoparticles. In *Nanoparticles and the environment*, Banfield, J.F. and Navrotsky, A. (Eds.), Mineralogical Society of America, Washington, DC, pp. 293–349.
- Cao, J.J., Lee, S.C., Ho, K.F., Zou, S.C., Fung, K., Li, Y., Watson, J.G. and Chow, J.C. (2004). Spatial and seasonal variations of atmospheric organic carbon and elemental carbon in Pearl River Delta Region, China. *Atmos. Environ.* 38: 4447–4456.
- Cao, J.J., Chow, J.C., Lee, S.C., Li, I., Chen, S.W., An, Z.S., Fung, K., Watson, J.G., Zhu, C.S. and Liu, S.X. (2005). Characterization and source apportionment of atmospheric organic and elemental carbon during fall and winter of 2003 in Xi'an, China. *Atmos. Chem. Phys.* 5: 3127–3137.
- Cao, J.J., Lee, S.C., Ho, K.F., Fung, K., Chow, J.C. and Watson, J.G. (2006). Characterization of roadside fine particulate carbon and its eight fractions in Hong Kong. *Aerosol Air Qual. Res.* 6: 106–122.
- Cass, G.R., Hughes, L.A., Bhawe, P., Kleeman, M.J., Allen, J.O. and Salmon, L.G. (2000). The chemical composition of atmospheric ultrafine particles. *Philos. Trans. R. Soc. London, Ser. A* 358: 2581–2592.
- Castro, L.M., Pio, C.A., Harrison, R.M. and Smith, D.J.T. (1999). Carbonaceous aerosol in urban and rural European atmospheres: Estimation of secondary organic carbon concentrations. *Atmos. Environ.* 33: 2771–2781.
- Chen, S.C., Tsai, C.J., Chou, C.C.K., Roam, G.D., Cheng, S.S. and Wang, Y.N. (2010). Ultrafine particles at three different sampling locations in Taiwan. *Atmos. Environ.* 44: 533–540.
- Chow, J.C., Watson, J.G., Crow, D., Lowenthal, D.H. and Merrifield, T. (2001). Comparison of IMPROVE and NIOSH carbon measurements. *Aerosol Sci. Technol.* 34: 23–34.
- Chow, J.C., Watson, J.W., Kuhns, H., Etyemezian, V., Lowenthal, D.H., Crow, D., Kohl, S.D., Engelbrecht, J.P. and Green, M.C. (2004). Source profiles for industrial, mobile, and area sources in the Big Bend regional aerosol visibility and observational study. *Chemosphere* 54: 185–208.
- Cohen, D.D., Crawford, J., Stelcer, E. and Bac, V.T. (2010a). Characterisation and source apportionment of fine particulate sources at Hanoi from 2001 to 2008. *Atmos. Environ.* 44: 320–328.
- Cohen, D.D., Crawford, J., Stelcer, E. and Bac, V.T. (2010b). Long range transport of fine particle windblown soils and coal fired power station emissions into Hanoi between 2001 to 2008. *Atmos. Environ.* 44: 3761–3769.
- Desert Research Institute (2005). DRI SOP #2-216.1, In *DRI Standard operating procedure, DRI Model 2001 Thermal/Optical Carbon Analysis (TOR/TOT) of Aerosol Filter Samples*. Desert Research Institute, USA.
- Dockery, D.W. and Pope, C.A. (1994). Acute respiratory effect of particulate air pollution. *Annu. Rev. Public Health* 14: 107–132.
- Duan, J., Tan, J., Cheng, D., Bi, X., Deng, W., Sheng, G., Fu, J. and Wong, M.H. (2007). Sources and characteristics of carbonaceous aerosol in two largest cities in Pearl River Delta Region, China. *Atmos. Environ.* 41: 2895–2903.
- Geller, M.D., Kim, S., Misra, C., Sioutas, C., Olson, B.A. and Marple, V.A. (2002). A methodology for measuring size-dependent chemical composition of ultrafine particles. *Aerosol Sci. Technol.* 36: 748–762.
- Gu, J., Bai, Z., Liu, A., Wu, L., Xie, Y., Li, W., Dong, H. and Zhang, X. (2010). Characterization of atmospheric organic carbon and element carbon of  $PM_{2.5}$  and  $PM_{10}$  at Tianjin, China. *Aerosol Air Qual. Res.* 10: 167–176.
- Gugamsetty, B., Wei, H., Liu, C.N., Awasthi, A., Hsu, S.C., Tsai, C.J., Roam, G.D., Wu, Y.C. and Chen, C.F. (2012). Source characterization and apportionment of  $PM_{10}$ ,  $PM_{2.5}$  and  $PM_{0.1}$  by using positive matrix factorization. *Aerosol Air Qual. Res.* 12: 476–491.
- Hai, C.D. and Kim Oanh, N.T. (2013). Effects of local, regional meteorology and emission sources on mass and compositions of particulate matter in Hanoi. *Atmos. Environ.* 78: 105–112.
- Han, Y.M., Lee, S.C., Cao, J.J., Ho, K.F. and An, Z.S. (2009). Spatial distribution and seasonal variation of char-EC and soot-EC in the atmosphere over China. *Atmos. Environ.* 43: 6066–6073.
- Hien, P.D., Bac, V.T., Tham, H.C., Nhan, D.D. and Vinh,

- L.D. (2002). Influence of meteorological conditions on  $PM_{2.5}$  and  $PM_{2.5-10}$  concentrations during the monsoon season in Hanoi, Vietnam. *Atmos. Environ.* 36: 3473–3484.
- Hien, P.D., Bac, V.T. and Thinh, N.T.H. (2004). PMF receptor modelling of fine and coarse  $PM_{10}$  in air masses governing monsoon conditions in Hanoi, northern Vietnam. *Atmos. Environ.* 38: 189–201.
- IPCC (2007). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (Eds.), Cambridge University Press, Cambridge, United Kingdom.
- Kim, K.H., Sekiguchi, K., Kudo, S., Kinoshita, M. and Sakamoto, K. (2013). Carbonaceous and ionic components in ultrafine and fine particles at four sampling sites in the vicinity of roadway intersection. *Atmos. Environ.* 74: 83–92.
- Kim, S., Shen, S., Sioutas, C., Zhu, Y. and Hinds, W.C. (2002). Size distribution and diurnal and seasonal trends of ultrafine particles in source and receptor sites of the Los Angeles basin. *J. Air Waste Manage. Assoc.* 53: 297–307.
- Kozáková, J., Pokorná, P., Černíková, A., Hovorka, J., Braniš, M., Moravec, P. and Schwarz, J. (2017). The association between intermodal ( $PM_{1-2.5}$ ) and  $PM_{10}$ ,  $PM_{2.5}$ , coarse fraction and meteorological parameters in various environments in central Europe. *Aerosol Air Qual. Res.* 17: 1234–1243.
- Kudo, S., Sekiguchi, K., Kim, K.H., Kinoshita, M., Wang, Q., Yoshikado, H., Sakamoto, K. and Möller, D. (2012). Differences of chemical species and their ratios between fine and ultrafine particles in the roadside environment. *Atmos. Environ.* 62: 172–179.
- Lang, J., Zhang, Y., Cheng, S., Zhou, Y., Chen, D., Guo, X., Li, X., Xing, X., Chen, S. and Wang, H. (2017). Trends of  $PM_{2.5}$  and chemical composition in Beijing, 2000–2015. *Aerosol Air Qual. Res.* 17: 412–425.
- Lee, C.T., Ram, S.S., Loc, D.N., Chou, C.C.K., Chang, S.Y., Lin, N.H., Chang, S.C., Hsiao, T.C., Sheu, G.R., Ou-Yang, C.F., Chi, K.H., Wang, S.H. and Wu, X.W. (2016). Aerosol chemical profile of near-source biomass burning smoke in Sonla, Vietnam during 7-SEAS Campaigns in 2012 and 2013. *Aerosol Air Qual. Res.* 16: 2603–2617.
- Li, P.H., Han, B., Huo, J., Lu, B., Ding, X., Chen, L., Kong, K.F., Bai, Z.P. and Wang, B. (2012). Characterization, meteorological influences and source identification of carbonaceous aerosols during the autumn-winter period in Tianjin, China. *Aerosol Air Qual. Res.* 12: 283–294.
- Lim, S., Lee, M., Lee, G., Kim, S., Yoon, S. and Kang, K. (2012). Ionic and carbonaceous compositions of  $PM_{10}$ ,  $PM_{2.5}$  and  $PM_{1.0}$  at gosan abc superstation and their ratios as source signature. *Atmos. Chem. Phys.* 12: 2007–2012.
- Lin, C.C., Chen, S.J. and Huang, K.L. (2005). Characteristics of metals in nano/ultrafine/fine/coarse particles collected beside a heavily trafficked road. *Environ. Sci. Technol.* 39: 8113–8122.
- Lu, S., Feng, M., Yao, Z., Jing, A., Yufang, Z., Wu, M., Sheng, G., Fu, J., Yonemochi, S., Zhang, J., Wang, Q. and Donaldson, K. (2011). Physicochemical characterization and cytotoxicity of ambient coarse, fine, and ultrafine particulate matters in Shanghai atmosphere. *Atmos. Environ.* 45: 736–744.
- Ly, L.M.T., Dung, P., Peter, S.D., Lidia, M. and Phong, T.K. (2017). The association between particulate air pollution and respiratory admissions among young children in Hanoi, Vietnam. *Sci. Total Environ.* 578: 249–255.
- Mbengue, S., Alleman, L.Y. and Flament, P. (2014). Size-distributed metallic elements in submicronic and ultrafine atmospheric particles from urban and industrial areas in northern France. *Atmos. Res.* 135–136: 35–47.
- MONRE (2017) National state of environment report 2016 on air quality Vietnam environment administration.
- Oanh, N.T.K., Upadhyay, N., Zhuang, Y.H., Hao, Z.P., Murthy, D.V.S., Lestari, P., Villarin, J.T., Chengchua, K., Co, H.X., Dung, N.T. and Lindgren, E.S. (2006). Particulate air pollution in six Asian cities: Spatial and temporal distributions, and associated sources. *Atmos. Environ.* 40: 3367–3380.
- Oanh, N.T.K., Thuy, L.B., Tipayarom, D., Manandhar, B.R., Prapat, P., Simpson, C.D. and Liu, L.J.S. (2011). Characterization of particulate matter emission from open burning of rice straw. *Atmos. Environ.* 45: 493–502.
- Pachauri, T., Satsangi, A., Singla, V., Lakhani, A. and Kumari, K.M. (2013). Characteristics and Sources of carbonaceous aerosols in  $PM_{2.5}$  during wintertime in Agra, India. *Aerosol Air Qual. Res.* 13: 977–991.
- Pakkanen, T.A., Kerminen, V.M., Korhonen, C.H., Hillamo, R.E., Aarnio, P., Koskentalo, T. and Maenhaut, W. (2001). Urban and rural ultrafine ( $PM_{0.1}$ ) particles in the Helsinki area. *Atmos. Environ.* 35: 4593–4607.
- Pennanen, A.S., Sillanpää, M., Hillamo, R., Quass, U., John, A.C., Branis, M., Hünová, I., Meliefste, K., Janssen, N.A.H., Koskentalo, T., Castaño-Vinyals, G., Bouso, L., Chalbot, M.C., Kavouras, I.G. and Salonen, R.O. (2007). Performance of a high-volume cascade impactor in six European urban environments: Mass measurement and chemical characterization of size-segregated particulate samples. *Sci. Total Environ.* 374: 297–310.
- Panicker, A.S., Ali, K., Beig, G. and Yadav, S. (2015). Characterization of particulate matter and carbonaceous aerosol over two urban environments in northern India. *Aerosol Air Qual. Res.* 15: 2584–2595.
- Pipal, A.S., kulshrestha, A. and Taneja, A. (2011). Characterization and morphological analysis of airborne  $PM_{2.5}$  and  $PM_{10}$  in Agra located in North central India. *Atmos. Environ.* 45: 3621–3630.
- Popovicheva, O.B., Engling, G., Diapouli, E., Saraga, D., Persiantseva, N.M., Timofeev, M.A., Kireeva, E.D., Shonija, N.K., Chen, S.H., Loc, N.D., Eleftheriadis, K. and Lee, C.T. (2016). Impact of smoke intensity on size-resolved aerosol composition and microstructure during

- the biomass burning season in northwest Vietnam. *Aerosol Air Qual. Res.* 16: 2635–2654.
- Ram, K. and Sarin, M.M. (2010). Spatio-temporal variability in atmospheric abundances of EC, OC and WSOC over Northern India. *J. Aerosol Sci.* 41: 88–98.
- Rovelli, S., Cattaneo, A., Borghi, F., Spinazzè, A., Campagnolo, D., Limbeck, A. and Cavallo, D.M. (2017) Mass concentration and size-distribution of atmospheric particulate matter in an urban environment. *Aerosol Air Qual. Res.* 16: 1142–1155.
- Sardar, S.B., Fine, P.M., Mayo, P.R. and Sioustas, C. (2005). Size-fractionated measurements of ambient ultrafine particle chemical composition in Los Angeles using the nano moudi. *Environ. Sci. Technol.* 39: 932–944.
- Stölzel, M., Breitner, S., Cyrys, J., Pitz, M., Wölke, G., Kreyling, W., Heinrich, J., Wichmann, H.E. and Peters, A. (2007). Daily mortality and particulate matter in different size classes in Erfurt, Germany. *J. Exposure Sci. Environ. Epidemiol.* 17: 458–467.
- Thuy, N.T.T., Dung, N.T., Sekiguchi, K., Yamaguchi, R., Thuy, P.C., Nam, D.T., Bang, H.Q. and An, T.T. (2016). Seasonal variation of concentrations and carbonaceous components of nanoparticles at a roadside location of Hanoi, Vietnam. Proceedings of International Conference on Environmental Engineering and Management for Sustainable Development, Hanoi University of Science and Technology, 2016, Hanoi, Vietnam, pp. 81–86.
- Thuy, N.T.T., Dung, N.T., Sekiguchi, K., Yamaguchi, R., Thuy, P.C. and Bang, H.Q. (2017). Characteristics of elemental carbon and organic carbon in atmospheric nanoparticles at different sampling locations in Vietnam. *Vietnam J. Scie. Technol.* 55: 305–315.
- Turpin, B.J. and Huntzicker, J.J. (1995). Identification of secondary organic aerosol episodes and quantitation of primary and secondary organic aerosol concentrations during SCAQS. *Atmos. Environ.* 29: 3527–3544.
- Wang, G., Cheng, S., Lang, J., Yang, X., Wang, X., Chen, G., Liu, X. and Zhang, H. (2017). Characteristics of PM<sub>2.5</sub> and assessing effects of emission-reduction measures in the heavy polluted city of Shijiazhuang, before, during, and after the ceremonial parade 2015. *Aerosol Air Qual. Res.* 17: 499–512.
- Wang, W.C., Chen, K.S., Chen, S.J., Lin, C.C., Tsai, J.H., Lai, C.H. and Wang, S.K. (2008). Characteristics and receptor modeling of atmospheric PM<sub>2.5</sub> at urban and rural sites in Pingtung, Taiwan. *Aerosol Air Qual. Res.* 8: 112–129.
- Yamaguchi, R., Sekiguchi, K., Sankoda, K., Kuwabara, H., Kumagai, K., Fujitani, Y., Thuy, N.T.T. and Dung, N.T. (2016). Seasonal variation of chemical components in PM<sub>2.5</sub> and PM<sub>0.1</sub> in Hanoi. Proceedings of International Conference on Environmental Engineering and Management for Sustainable Development, Hanoi University of Science and Technology, 2016, Hanoi, Vietnam, pp. 75–80.
- Zhang, L., Cheng, Y., Zhang, Y., He, Y., Gu, Z. and Yu, C. (2017). Impact of air humidity fluctuation on the rise of PM mass concentration based on the high-resolution monitoring data *Aerosol Air Qual. Res.* 17: 543–552.
- Zhang, Z., Zhang, X., Gong, D., Quan, W., Zhao, X., Ma, Z. and Kim, S.J. (2015). Evolution of surface O<sub>3</sub> and PM<sub>2.5</sub> concentrations and their relationships with meteorological conditions over the last decade in Beijing. *Atmos. Environ.* 108: 67–75.
- Zhu, C.S., Chen, C.C., Cao, J.J., Tsai, C.J., Chou, C.C.K., Liu, S.C. and Roam, G.D. (2010). Characterization of carbon fractions for atmospheric fine particles and nanoparticles in a highway tunnel. *Atmos. Environ.* 44: 2668–2673.

Received for review, December 7, 2017

Revised, March 21, 2018

Accepted, May 8, 2018